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Executive Summary | June 2018

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Making Concrete Change

Innovation in Low-carbon Cement and Concrete

#ConcreteChange

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Executive Summary

As a key input into concrete, the most widely used construction material in the world, cement is a major contributor to climate change. The chemical and thermal combustion processes involved in the production of cement are a large source of carbon dioxide (CO_2) emissions. Each year, more than 4 billion tonnes of cement are produced, accounting for around 8 per cent of global CO_2 emissions.

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To bring the cement sector in line with the Paris Agreement on climate change, its annual emissions will need to fall by at least 16 per cent by 2030.[1] Steeper reductions will be required if assumptions about the contribution from carbon capture and storage (CCS) technologies prove to be optimistic. Meanwhile, investors are increasingly expecting companies to report clear information on their exposure to climate risk. The trends all point to regulatory, financial and societal pressures on the horizon, especially for cement companies without a detailed plan for a Paris-compliant pathway.

Yet at the same time, cement is expected to play a vital role in the expansion of the built environment, especially in emerging economies. On a 'business as usual' trajectory, global cement production is set to increase to over 5 billion tonnes a year over the next 30 years.[2] Rapid urbanization and economic development in regions such as Southeast Asia and sub-Saharan Africa will increase demand for new buildings, and thus for concrete and cement. With as many as 3 billion people potentially living in slums by 2050, new rapidly deployable housing solutions are urgently needed.[3]

Moreover, the infrastructure demands of development and urbanization are not limited to housing. Providing clean water, sanitation and energy services typically relies on concrete, whether for transport infrastructure, wind farms or hydro-electric dams. In this context, continuing efforts to meet the UN Sustainable Development Goals (SDGs) are expected to result in $60 trillion being invested in such infrastructure in developing countries by 2030.[4]

The cement sector is thus facing a significant expansion at a time when its emissions need to fall fast. From a technical perspective, there are a number of solutions for reducing the emissions associated with cement production;

[1] Based on the Beyond 2°C Scenario (B2DS) in International Energy Agency (2017), *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*, Paris: Organisation for Economic Cooperation and Development/ International Energy Agency, https://www.iea.org/etp2017/ (accessed 6 Jun. 2017).
[2] International Energy Agency (2017), *Energy Technology Perspectives 2017*; Müller, N. and Harnisch, J. (2008), *A blueprint for a climate friendly cement industry*, WWF International, http://awsassets.panda.org/downloads/englishsummary__lr_pdf.pdf (accessed 1 Mar. 2018).
[3] Barbiere, C. (2017), 'French urban development expert: "In 2050, 3 billion people will live in slums"', *Euractiv*, 6 March 2017, https://www.euractiv.com/section/development-policy/interview/french-urban-development-expert-in-2050-3-billion-people-will-live-in-slums/ (accessed 3 Feb. 2018).
[4] The New Climate Economy (2016), *The Sustainable Infrastructure Imperative: Financing for Better Growth and Development*, Washington: World Resources Institute, http://newclimateeconomy.report/2016/wp-content/uploads/sites/4/2014/08/NCE_2016Report.pdf (accessed 15 Apr. 2017).

all will need to be deployed at scale to meet the decarbonization challenge. Some of these solutions are well recognized and common to other sectors: for instance, the energy efficiency of cement plants can be increased, fossil fuels can be replaced with alternatives, and CO_2 emitted can be captured and stored.

The main focus of this report, however, is on those emissions mitigation solutions that require the *transformation* of cement and concrete and are thus unique to the sector. More than 50 per cent of cement sector emissions are intrinsically linked to the process for producing clinker, one of the main ingredients in cement. As the by-product of a chemical reaction, such emissions cannot be reduced simply by changing fuel sources or increasing the efficiency of cement plants. **This report therefore focuses on the potential to blend clinker with alternative materials, and on the use of 'novel cements'** – two levers that can reduce the need for clinker itself by lowering the proportion of clinker required in particular cement mixtures. Despite widespread acceptance among experts that these are critical, they have received far less policy focus.

Well-known barriers stand in the way of deep decarbonization of cement. The sector is dominated by a handful of major producers, which are cautious about pioneering new products that challenge their existing business models. In the absence of a strong carbon-pricing signal, there is little short-term economic incentive to make changes. Alternative materials are often not readily available at the scale required. Meanwhile, architects, engineers, contractors and clients are understandably cautious about novel building materials. Implementing new practices also implies a critical role for millions of workers involved in using concrete across the urban landscape.

Low expectations around the prospects for a radical breakthrough in cement production are reflected in the limited attention given to the sector in key assessments of low-carbon pathways in recent years.[5] As one recent report notes, 'When cement emissions are mentioned at all in public debate, it is typically to note that little can be done about them.'[6] There is, however, a growing sense not only of the urgency of the need to decarbonize cement production, but also of the expanding range of technological and policy solutions. The range of major organizations now working on relevant strategies includes the UN Environment Programme (UNEP), the International Energy Agency (IEA) – working with the industry-led Cement Sustainability Initiative (CSI) – and the Energy Transitions Commission, an initiative involving high-level energy experts and stakeholders aimed at accelerating the transition to low-carbon energy systems.

For decision-makers, more insight is needed into the potential for scalable, sustainable alternatives to traditional carbon-intensive cement and concrete. For this report Chatham House worked with CambridgeIP, an innovation and intellectual

[5] The New Climate Economy's *Seizing the Global Opportunity* report mentions energy-intensive sectors such as cement, chemicals and iron and steel 'where emissions are large and significant reduction poses undeniable challenges', without spelling out a potential pathway for reduction of those emissions. The Global Commission on the Economy and Climate (2015), *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*, Washington: World Resources Institute, p. 47, http://newclimateeconomy.report/2015/wp-content/uploads/sites/3/2014/08/NCE-2015_Seizing-the-Global-Opportunity_web.pdf (accessed 11 Oct. 2017). A 2017 Energy Transitions Commission report highlights the importance of carbon capture and storage/and utilization (CCS/U) for the cement sector, but does not engage with other potential decarbonization pathways. Energy Transitions Commission (2017), *Better Energy, Greater Prosperity: Achievable pathways to low-carbon energy systems*, http://energy-transitions.org/sites/default/files/BetterEnergy_fullReport_DIGITAL.PDF (accessed 11 Oct. 2017).

[6] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan: Rethinking Cement*, Fitzroy: Beyond Zero Emissions Inc., http://media.bze.org.au/ZCIndustry/bze-report-rethinking-cement-web.pdf (accessed 21 Sep. 2017).

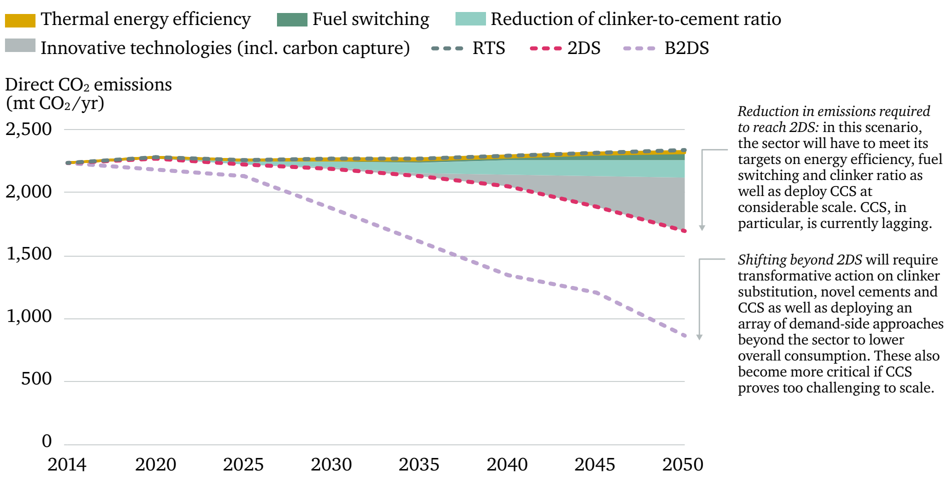
property consultancy, to conduct a major patent-landscaping exercise around innovation in clinker substitution and novel cements – examining where and why laboratory-based breakthroughs are happening, the kinds of firms involved, and which innovations have the potential to cross the 'valley of death' (the name given to the phenomenon in which innovations do not make it past the technology-creation stage) and make a meaningful impact on emissions pathways. Along with major global cement producers and technology service providers, Chinese firms and research organizations are among those jostling for pole position.

No silver bullet

Shifting to a Paris-compliant pathway, with net-zero CO_2 emissions by around 2050,[7] will require going further and moving faster on all available solutions, as well as making sure that the next generation of innovative technology options is ready as soon as possible.

To illustrate the scale of this challenge, Figure 1 shows the decarbonization pathway set out by the IEA and CSI's 2018 Technology Roadmap.[8] This scenario shows action on four mitigation levers – energy efficiency, fuel switching, clinker substitution and innovative technologies (including CCS) – to achieve CO_2 reductions consistent with at least a 50 per cent chance of limiting the average global temperature increase to 2°C above pre-industrial levels by 2100.

Figure 1: Towards a Paris-compatible pathway



Source: Authors' analysis of scenario set out in International Energy Agency and Cement Sustainability Initiative (2018), *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, Paris: International Energy Agency, https://www.wbcsdcement.org/index.php/key-issues/climate-protection/technology-roadmap (accessed 24 Apr. 2018). The B2DS is based on data in International Energy Agency (2017), *Energy Technology Perspectives 2017.*

Note: RTS stands for 'reference technology scenario', 2DS stands for '2°C Scenario' and B2DS stands for 'Beyond 2°C Scenario'. For descriptions of each model, refer to the original source. The ETP B2DS and roadmap models are not directly comparable as they are based on slightly different assumptions as to future demand for cement but they are shown together here as an indicative comparison.

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[7] Climate Action Tracker (2017), *Manufacturing a low-carbon society: How can we reduce emissions from cement and steel?*, https://newclimate.org/wp-content/uploads/2017/10/memo_decarb_industry_final1.pdf (accessed 3 Apr. 2018).
[8] International Energy Agency and Cement Sustainability Initiative (2018), *Technology Roadmap: Low-Carbon Transition in the Cement Industry,* Paris: International Energy Agency, https://www.wbcsdcement.org/index.php/key-issues/climate-protection/technology-roadmap (accessed 24 Apr. 2018).

As recognized in the 2018 roadmap, there is a considerable gap between this scenario and a scenario consistent with countries' more ambitious aspirations in the Paris Agreement of limiting the temperature increase even further, towards 1.5°C. The IEA's Beyond 2°C Scenario (B2DS) is only an illustration of the challenge such an emissions reduction would represent in relation to current industry ambitions.

Shifting towards B2DS will require more ambition across each of these levers, particularly in the short term:

- Although many of the relatively straightforward gains have already been made, there is still scope for improvement in **energy efficiency**. Europe and the US now lag behind India and China on energy efficiency, due to the continuing use of older equipment, and will need to at least close this gap in the next decade if they are to meet industry targets. The key challenges will be the capital investment required and the fact that action on other levers such as alternative fuels and CCS may slow progress on energy efficiency.
- **Shifting away from the use of fossil fuels** in cement production will also be key. China and India, in particular, have significant potential to switch to sustainable lower-carbon fuels. In Europe, cement plants have been shown to run on 90 per cent non-fossil fuels. A key challenge will be to ensure the availability of biomass from truly sustainable sources. Currently, the sector relies largely on waste-derived biomass; however, shifting towards a majority share of alternative fuels may eventually prompt the sector to turn to wood pellets.
- **Clinker substitution** involves replacing a share of the clinker content in cement with other materials. This could play a greater role than currently anticipated. Achieving an average global clinker ratio of 0.60 by 2050, as set out by the 2018 Technology Roadmap, has the potential to mitigate almost 0.2 gigatonnes (GT) of CO_2 in 2050.[9] The share of clinker needed can be reduced even further in individual applications, with the potential to lower the CO_2 emissions of those applications by as much as 70–90 per cent. At the very ambitious end of the scale, if 70 per cent replacement was achieved on a global scale, this could represent almost 1.5 GT of CO_2 emissions saved in 2050.[10] Clinker substitution is not only a very effective solution, but also one that can be deployed cheaply today, as it does not generally require investments in new equipment or changes in fuel sources. It is, therefore, especially important to scale up clinker substitution in the near term while more radical options, such as the introduction of novel and carbon-negative cements, are still under development. The greatest constraints are the uncertain availability of clinker substitute materials and the lack of customer demand for low-clinker cements.

[9] Authors' calculation. The baseline used is a 'frozen technology' scenario in which 5 GT of cement are consumed in 2050 with a clinker emissions intensity of 0.813 (GNR Database figure for 2015) and an average clinker-to-cement ratio of 0.65 (IEA ETP figure for 2014), emitting 2.64 GT CO_2 in 2050. This is compared to a scenario in which the emissions intensity and consumption remain the same but the clinker-to-cement ratio drops to 0.60, resulting in 2.44 GT CO_2 emitted under this new scenario.
[10] Authors' calculation. The baseline used is a 'frozen technology' scenario in which 5 GT of cement are consumed in 2050 with a clinker emissions intensity of 0.813 (GNR Database figure for 2015) and an average clinker-to-cement ratio of 0.65 (IEA ETP figure for 2014), emitting 2.64 GT CO_2 in 2050. This is compared to a scenario in which the emissions intensity and consumption remain the same but the clinker-to-cement ratio drops to 0.3, resulting in 1.22 GT CO_2 emitted under this new scenario.

- Many experts are understandably sceptical about the potential to rapidly **scale up CCS**. Although other technologies are included in this lever, as presented in Figure 1, in practice hopes are currently pinned on CCS. This is reflected in both the 2018 roadmap and other major modelling exercises today. Even if hopes for CCS prove optimistic, carbon-capture technology could still prove critical in moving to B2DS. Moreover, CCS could complement the development of some novel concretes, which rely on a source of pure captured CO_2 for carbonation curing. One of the key challenges facing CCS is the cost of the technology versus that of other levers.

However, it will be impossible to even get close to B2DS without also achieving radical changes in cement consumption and breakthroughs in the development of novel cements:

- Most cement emissions scenarios depend on projections of **consumption** that deserve far greater scrutiny. Concrete demand can be reduced, sometimes by more than 50 per cent, by taking a new approach to design, using higher-quality concretes, substituting concrete for other materials, improving the efficiency with which it is used on construction sites, and increasing the share of concrete that is reused and recycled. Deploying an array of such demand-side approaches in key growth markets such as China, India and African countries will be essential if the sector is to reach net-zero emissions. Action on material efficiency will, however, depend on the cooperation and motivation of a host of actors beyond the cement sector.
- Moving towards net-zero emissions for all new construction will require a rapid scale-up in the deployment of **novel cements**. Some can achieve emissions reductions of more than 90 per cent. Others can sequester carbon, theoretically capturing more carbon than is emitted in their production, rendering them carbon-negative. So far, however, the majority of these products have failed to achieve commercial viability. Achieving breakthroughs in this area will require concerted investment in research and large-scale demonstration projects, as well as education and training of consumers to build the market for novel products.

Even with ambitious projections across all mitigation levers to meet the B2DS, more than 0.8 GT of CO_2 would still be emitted in 2050. These ‘residual emissions’ would need to be offset by other means. Achieving zero CO_2 emissions, therefore, needs to remain an objective beyond 2050. Failure to do so will imply a greater reliance on negative-emissions technologies that have so far failed to scale.

Searching for potential breakthroughs

Against this backdrop, this report analyses the potential for breakthrough innovations in low-clinker and novel cements. As a proxy for innovation, it presents an extensive analysis of patent ownership of key technologies related to these areas. The study involved nine months of research, during which a database of around 4,500 patents spanning 14 years was compiled.

The study shows that the cement sector is more technically innovative than its reputation suggests. There has been considerable patenting activity in the sector in recent years, especially in comparison with other heavy industries such as steel. One of the fastest-growing technology spaces is focused on the reduction of clinker content in cement. The number of patents filed in this area has outstripped those in other technology subsectors.

Research efforts have largely – though by no means exclusively – remained within the traditional clinker-based cement paradigm. They have tended to focus on increasing clinker substitution rather than on radically altering the mix of raw materials used. Our analysis of patent ownership shows that clinker-substitution technologies and chemical admixtures have more than double the patent families of novel-cement technologies. Although the latter, as noted below, are nonetheless attracting significant research interest, this finding indicates a fairly incremental approach to innovation in the sector.

Given the urgency of the challenge and the time taken historically for technology systems to evolve, a considerable push will be needed to get the next generation of low-carbon cements out of the lab and into the market

China has emerged as a key innovation hub; it has invested more than any other country in cement research and development (R&D). It dominates our patent analysis, both in terms of patent filings and assignees. This is encouraging from a decarbonization perspective, as China is projected to continue to account for a major share of global cement production.[11] However, given the growth in markets in India and other Asia-Pacific countries, R&D capacity and deployment in those regions will also be key.

Cement producers own the key knowledge assets needed for decarbonization; they make up eight of the 15 top assignees. Companies' strategies vary, but few large cement producers currently have major centralized research efforts – one exception is LafargeHolcim. Companies with smaller patent portfolios can also be influential, and several small and medium-sized enterprises (SMEs) outside the top 15 have developed novel cements with a fraction of the emissions of conventional cement. Such firms' patent portfolios play an important role in attracting investment and interest from major cement producers. For example, LafargeHolcim is partnering with a US firm, Solidia Technologies, on development of the latter's carbon-cured low-clinker concrete.

Crucially, while there has been lots of R&D on low-clinker and novel cements, few of these products have been commercialized, and none has reached widespread application. Some novel cements have been discussed for more than a decade within the research community, without breaking through. At present, these alternatives are rarely as cost-effective as conventional cement, and they face raw material shortages and resistance from customers. Regulations designed to prevent anti-competitive behaviour also pose a significant barrier to greater industry cooperation.

The upshot is that technological innovation and diffusion will take too long under a business-as-usual scenario. Given the urgency of the challenge and the time taken historically for technology systems to evolve, a considerable push will be needed to get the next generation of low-carbon cements out of the lab and into the market. Not all will succeed, but those that do could have significant decarbonization potential.

[11] Fernandez, A. (2017), 'Industry Technology Roadmaps: a focus on Cement', presentation at COP 23 in Bonn, Germany, 12 November 2017, https://www.iea.org/media/workshops/2017/cop23/presentations/12NovFernandezPales.pdf (accessed 12 Dec. 2017).

Aligning with broader disruptive trends

Disruptive trends surrounding the sector could create new opportunities to accelerate the use of low-carbon cement or concrete technology. The cement and concrete sector is far from immune to the disruptive effects of digitalization, the introduction of new business models, and the sustainability expectations of investors and consumers – expectations that are buffeting a wide range of industries. A combination of enhanced connectivity, remote monitoring, predictive analytics, 3D printing and innovation in design is already transforming traditional supply chains within the construction sector. McKinsey recently published research on potential use cases for artificial intelligence (AI) in the engineering and construction sector, predicting that AI will play an increasingly significant role in the sector in the coming years.[12] Such changes could feed back into consumption of cleaner cement and concrete, as well as lower overall cement demand.

Meanwhile, the major cement players are increasingly facing competition from regional producers in emerging markets. Slower economic growth in China has helped create a global cement glut, and in Europe there has been a substantial imbalance between high production capacity and low market demand in recent years. The Chinese market is rapidly consolidating: a few years ago, there were 3,000 small players producing low-grade cement; by 2020, as few as 10 firms may account for 60 per cent of the country's production capacity. China National Building Material (CNBM) and Sinoma, the country's largest and fourth-largest producers, are merging to become one of the world's largest cement companies.

At the same time, trends in politics and society are reshaping the future of the built environment. In recent years, governments have come under increasing pressure to improve urban air quality, especially in China and India. In South Africa, the recent drought in Cape Town has brought home the vulnerability of cities to climate change, with the construction of 2,000 residential units put on hold in 2017 due to water shortages. Finally, the Grenfell Tower fire in 2017 in the UK led to growing calls for accountability over decisions taken with regard to cladding and materials used in public housing.

Growing public concern, investor expectations around climate-risk disclosure, and a challenging period for financial performance are forcing cement majors to re-examine their business models. The largest multinational producers are already offering a growing range of services, from speciality cements to intricate delivery services tailored for complex projects. There could be a first-mover advantage for companies that align deep cuts in emissions with the significant opportunities for value creation and improved profitability in this evolving market.

[12] Blanco, J. L., Fuchs, S., Parsons, M. and Ribeirinho, M. J. (2018), 'Artificial intelligence: Construction technology's next frontier', *McKinsey & Company*, https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/artificial-intelligence-construction-technologys-next-frontier?cid=other-eml-alt-mip-mck-oth-1804&hlkid=9cffea706869405a958e0695fbaa6785&hctky=3020283&hdpid=af68edb8-20a1-45a9-a41e-015991519e06 (accessed 9 May 2018).

Box 1: Tailoring solutions

Our patent analysis highlights technical innovations that face a variety of context-specific challenges. These can only be overcome by finding the optimal combination of technology, practice-related and policy solutions for each location.

Raw material supply, for example, helps determine which technologies are viable in a given location. While supplies of potential clinker substitutes such as fly ash (a by-product of coal combustion) and blast furnace slag (a by-product of iron- and steelmaking) are expected to decrease in parts of Europe and the US over the coming decades, China and India are currently producing huge volumes of these materials. Volcanic rocks and ash will become important in regions such as Italy, Greece and the west coast of North America, where these materials are plentiful. Calcined clays present a significant opportunity to increase clinker substitution in emerging markets, especially in locations with existing stockpiles of suitable clays associated with the presence of large ceramics industries.

There is scope to increase clinker substitution in these locations by (a) regulating the utilization of waste materials; (b) growing the market for lower-clinker cements through engagement with standards bodies and construction sector stakeholders; and (c) securing supply chains for these materials.

The maturity of supply chains, markets and housing stocks in different locations also determines policy options. In the UK, for example, the ready-mixed-concrete industry has largely automated supply, while in India 90 per cent of the concrete market is still supplied through bags of cement transported to construction sites for mixing on site. These differences will shape the potential impact and the penetration of new technologies.

Table 1: Actions needed in different regions

Region	Action
China The scale of China's market, the materials it has available locally and its role as a key innovator place it in a unique position to bring new low-carbon cement and concrete technologies to maturity.	In the context of the 14th Five-Year Plan (2021–25), priorities for China could include to: • Scale up clinker substitution with fly ash and blast furnace slag, and increase use of sustainable alternative fuels, through targeted regulation, investment in distribution infrastructure and best-practice dissemination. • Hold large-scale demonstration projects and pilots for clinker substitution using calcined clays from clay stockpiles. Build on experience using belite clinkers in major infrastructure projects, to support the use of novel products in smaller projects by sharing lessons with construction firms and material suppliers. • Establish technology cooperation agreements on low-carbon cement and concrete with 'Belt and Road Initiative' participant countries. Target the use of lower-carbon building materials in Belt and Road projects.
Europe With the majority of major multinational cement producers headquartered in the region, and a long track record of policy action on cement sustainability, Europe is a key agenda-setter.	Priorities for Europe could include to: • Set ambitious retrofit, reuse and recycling targets for the construction sector in the European Union Circular Economy Package, building on guidelines being developed for sorting, processing and recycling waste from construction and demolition. • Build on ambitious targets on energy efficiency for buildings, as set out in the Energy Performance of Buildings Directive, to set targets for embodied energy and carbon for new-builds. • Increase public funding for R&D, and financial support for incubation facilities and demonstration projects working on novel and low-clinker cements. Specifically, explore the potential to scale up the use of volcanic rocks and ash in southern Europe.
India As a fast-growing cement market with increasing vulnerability to climate impacts, India has a key role to play in establishing the baseline for effective climate-smart infrastructure, urban planning and decision-making.	In the context of the country's Strategy on Resource Efficiency, priorities for India could include to: • Scale up the use of fly ash and blast furnace slag through dissemination of best practice and training, through better access to data on material availability, and through reductions in value-added tax (VAT) on high-blend cements and concretes. In the longer term, prepare for the phasing out of coal by exploring the use of alternative clinker substitutes such as calcined clays. • Develop climate-resilient infrastructure and city plans. Establish a city-level working group to explore best practice in climate-resilient urban planning, design and construction, and to encourage joint scenario and investment planning exercises between cities. • Establish a national framework for sustainable public procurement for construction. This could consist of making training, tools and technical knowledge available to procurers, in order to professionalize and enhance existing processes. It would also involve making available clear and verifiable information on the environmental footprints and performance of products and services.
United States As a prime location for technology and business model innovation in the past, and as the location of major construction clients, the US could be at the forefront of digital shifts in the built environment.	Priorities for the US at the federal and state level could include to: • Provide education and guidance to major corporate clients and their advisers on how material selection can affect the carbon footprint of their projects, and on the digital tools that can transform material selection. • Work with universities, construction companies and digital providers to host open innovation platforms for exploring the potential for digital technologies to transform processes in the built environment. Work with such organizations to help build the stack of digital assets needed to integrate real-time decision tools, supply chain optimization and lesson-sharing from experience into the development of new materials. • Support coordination among US cities on tendering for similar infrastructure projects, so that the scale necessary for material suppliers to provide lower-carbon solutions can be achieved.

Source: Authors' own analysis. For the full list of regional actions and regional profiles, see Appendix 5.

Summary of key recommendations

- Governments and major concrete-consuming companies should **grow the market for low-carbon building materials** by restructuring procurement processes. This will entail incorporating metrics on 'embodied carbon' (the emissions released during production of a material) into procurement processes; setting ambitious carbon-intensity targets for major projects; and engaging with construction companies, design teams, contractors and material suppliers to encourage them to find the lowest-carbon, most viable options for a given project.
- Governments, cement companies and construction and engineering companies need to **build the supply chain for net-zero-emissions materials**. This will involve incentivizing investment in distribution networks for clinker substitutes, and in the additional processing equipment and storage infrastructure that may be required; and scaling up best-practice dissemination and support to make the use of novel products viable.
- Industry stakeholders, governments and research funds should **expand the portfolio of next-generation materials** by providing sustained funding for R&D; supporting and collaborating on large-scale demonstration projects; enhancing joint R&D capacity (e.g. through innovation challenges, patent pools and patent legislation); and developing effective diagnostic and field-based detection tools for assessing the strength and durability of concrete.
- Material-science laboratories, universities, cement companies and engineering firms should work with leading technology firms and internet platform providers to **harness digital disruption in the sector**. Their collaboration should explore the beneficial uses of machine learning and wider AI, and establish open innovation platforms for assessing the potential of digital technologies in the sector. Collaboration will also necessarily entail building the stack of digital assets, so that real-time decision tools, supply chain optimization and lesson-sharing from experience can be integrated into the development and commercial roll-out of new materials and blends.
- Governments, cement companies, construction companies and cities should **establish partnerships for climate-compatible pathways**. They will need to agree international commitments on a net-zero-emissions, resilient built environment; set science-based targets as soon as possible and work together to achieve them; mobilize a coalition to explore what it would mean to have a 'circular' built environment; and scale up finance for sustainable infrastructure.

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