Chatham House Report

Johanna Lehne and Felix Preston

Making Concrete Change

Innovation in Low-carbon Cement and Concrete

#ConcreteChange

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Energy, Environment and Resources Department | June 2018

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Innovation in Low-carbon Cement and Concrete

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The Energy, Environment and Resources Department

The Energy, Environment and Resources Department at Chatham House carries out independent, thought-leading research on critical issues of energy security, environmental protection and resource governance. It plays an important role analysing and informing international processes, carrying out innovative research on major policy challenges, bringing together diverse perspectives and constituencies, and injecting new ideas into the international arena. Our approach views energy, environment and resources as central to issues of security, risk, commerce and sustainable development. This is reflected in our multidisciplinary staff with expertise in economics, political science, natural science and the humanities. The research approach combines analytical rigour with deep sector expertise and strong command of technical issues. This analytical capability is underpinned by our understanding of geopolitical and political economy challenges, and by an extensive global network of contacts that draws from the business community, civil society, academia and governments.

The impact of the department's work is recognized internationally and its research is widely read and used by decision-makers in the public, private and not for profit sectors. Our publications and experts receive regular international media coverage, including from the *Financial Times*, BBC, *New York Times*, Reuters, Bloomberg, *Wall Street Journal*, *Foreign Affairs* and Caijing.

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 hydroelectric 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;

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[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

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[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).

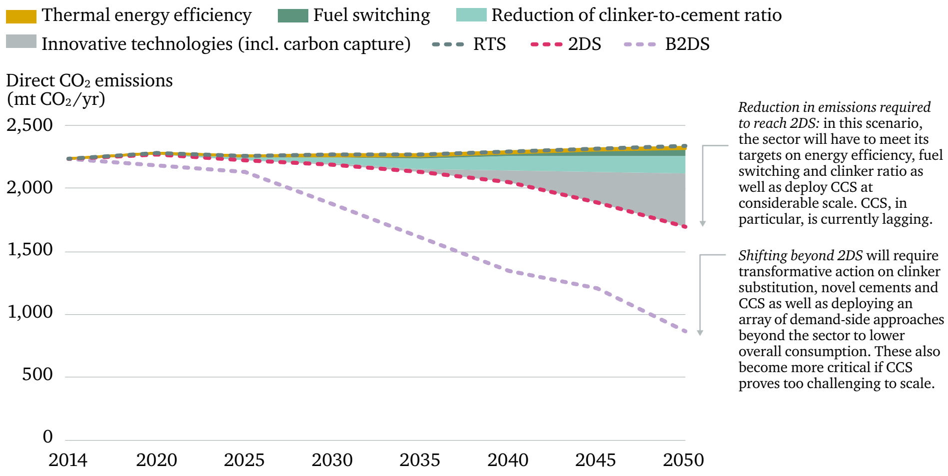
property consultancy, to conduct a major patent-landscaping exercise around innovation in clinker substitution and novel cements – examining where and why laboratory-based breakthroughs are happening, the kinds of firms involved, and which innovations have the potential to cross the 'valley of death' (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



Reduction in emissions required to reach 2DS: in this scenario, the sector will have to meet its targets on energy efficiency, fuel switching and clinker ratio as well as deploy CCS at considerable scale. CCS, in particular, is currently lagging.

Shifting beyond 2DS will require transformative action on clinker substitution, novel cements and CCS as well as deploying an array of demand-side approaches beyond the sector to lower overall consumption. These also become more critical if CCS proves too challenging to scale.

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.

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[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.

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[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.

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[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

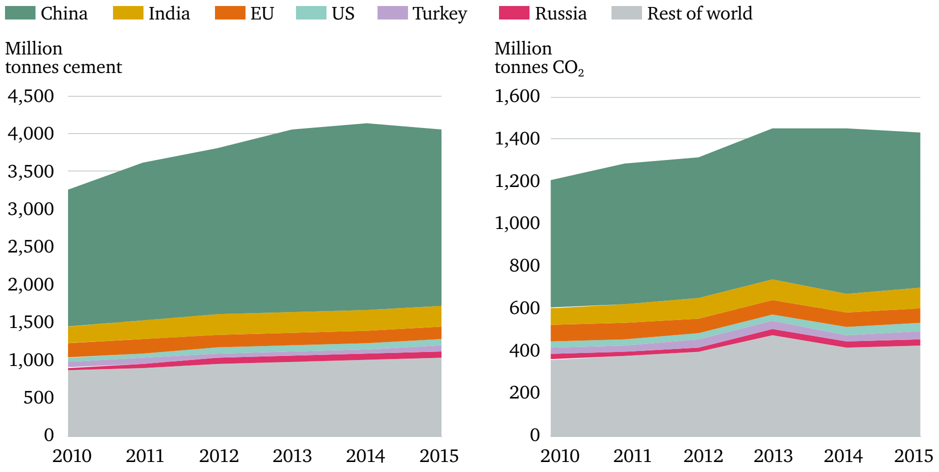
- Governments and major concrete-consuming companies should **grow the market for low-carbon building materials** by restructuring procurement processes. This will entail incorporating metrics on ‘embodied carbon’ (the emissions released during production of a material) into procurement processes; setting 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.

1. Introduction

Key points

- Significant changes in how cement and concrete are produced and used – and in how cities are designed, built and managed – will be needed if we are to meet the goals set out in the Paris Agreement on climate change and the Sustainable Development Goals (SDGs).
- Although efforts have been undertaken to decarbonize the cement and concrete sector, most relatively straightforward gains have already been made. The next phase of decarbonization will require more ambition and faster action than efforts to date.
- Increased ambition around clinker substitution (reflected in global targets) suggests that this is an area with further potential and where efforts will need to be increased.

Figure 2: Cement production and emissions, 2010–15



Source: Authors' analysis of data from Olivier et al. (2016), *Trends in global CO_2 emissions: 2016 Report*.

Cement is a key input into concrete, the most widely used construction material in the world. Every year, more than 4 billion tonnes of cement are produced. The chemical and thermal combustion processes involved in the production of cement are a major source of CO_2 emissions, contributing around 8 per cent of annual global CO_2 emissions.[13]

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[13] Olivier, J., Janssens-Maenhout, G., Muntean, M. and Peters, J. (2016), *Trends in global CO_2 emissions: 2016 Report*, The Hague: PBL Netherlands Environmental Assessment Agency, http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf (accessed 27 Nov. 2017).

Moreover, cement production is expected to grow. The total global building floor area in 2016 was around 235 billion square metres (m^2).[14] This is projected to double over the next 40 years – equivalent to adding the total building floor area of Japan to the planet every year to 2060.[15]

The bulk of this growth is expected to happen in emerging markets. While China's cement production – a key driver of the market in recent years – may have peaked,[16] urbanization in other industrializing countries such as India and Indonesia is likely to continue to boost global demand.[17] Some estimates project a threefold to fourfold increase in demand from developing countries in Asia by 2050.[18]

The Global Commission on the Economy and Climate estimates that $90 trillion will be invested in infrastructure through to 2030, and that two-thirds of this investment will be in developing countries

A substantial expansion of the built environment is needed to meet the SDGs. Expanding access to clean water and energy depends on replacing old and building new infrastructure.[19] The Global Commission on the Economy and Climate estimates that $90 trillion will be invested in infrastructure through to 2030, and that two-thirds of this investment will be in developing countries.[20] It also projects that, if developing countries expand their infrastructure to current average global levels, the production of the required materials alone will cumulatively emit 470 GT of CO_2 by 2050.[21]

Yet this potential expansion would take place during a critical period for global decarbonization. Greenhouse gas emissions need to fall by around half by 2030 to meet the Paris Agreement goal of keeping global warming to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5°C.[22] This scenario is even more demanding for the built environment. It will require carbon-neutral or carbon-negative construction everywhere from 2030 onwards, which implies the need to rapidly scale up the use of building materials with zero or negative emissions in the next decade.[23]

The urgency of early action implied by 'well below' 2°C is demonstrated by the scenarios shown in Figure 3. According to the IEA's 'Beyond 2°C Scenario' (B2DS)

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[14] UN Environment and International Energy Agency (2017), *Global Status Report 2017: Towards a zero-emission*, efficient, and resilient buildings and construction sector, Paris: UN Environment, http://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf (accessed 25 Apr. 2018).

[15] Ibid.

[16] Bleischwitz, R. and Nechifor, V. (2016), 'Saturation and Growth Over Time: When Demand for Minerals Peaks', *Prisme N34*, Paris: Centre Cournot. doi:10.13140/RG.2.2.24146.15049 (accessed 8 Oct. 2017).

[17] Edwards, P. (2015), 'The Rise and Potential Peak of Cement Demand in the Urbanized World', *Cornerstone*, 16 June 2015, http://cornerstonemag.net/the-rise-and-potential-peak-of-cement-demand-in-the-urbanized-world/ (accessed 21 Apr. 2017).

[18] Imbabi, M. S., Carrigan, C. and McKenna, S. (2012), 'Trends and developments in green cement and concrete technology', *International Journal of Sustainable Built Environment*, 1: pp. 194–216, doi: 10.1016/j.ijsbe.2013.05.001 (accessed 8 Jan. 2018).

[19] As set out in SDG 6 ('Ensure availability and sustainable management of water and sanitation for all') and SDG 7 ('Ensure access to affordable, reliable, sustainable and modern energy for all'). United Nations Department of Public Information (2015), 'Sustainable Development Goals', https://sustainabledevelopment.un.org/sdgs (accessed 19 Jan. 2017).

[20] The New Climate Economy (2016), *The Sustainable Infrastructure Imperative*.

[21] Seto, K. C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G. C., Dewar, D., Huang, L., Inaba, A., Kansal, A., Lwasa, S., McMahon, J. E., Müller, D. B., Murakami, J., Nagendra, H., and Ramaswami, A., (2014), 'Human Settlements, Infrastructure and Spatial Planning. In: Climate Change 2014: Mitigation of Climate Change', in Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T. and Minx, J. C. (eds) (2014) *Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge and New York: Cambridge University Press, p. 951.

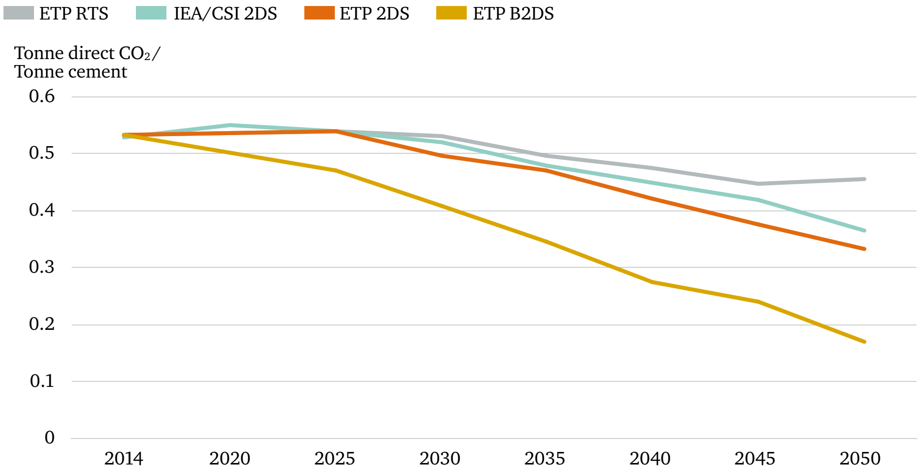
[22] Röckstrom, J., Gaffney, O., Rogelji, J., Meinshausen, M., Nakicen, N. and Schellnhuber, H. (2017), 'A roadmap for rapid decarbonization', Science, 355(6331): pp. 1269–1271, doi: 10.1126/science.aah3443 (accessed 8 Oct. 2017).

[23] Ibid.

articulated in its *Energy Technology Perspectives 2017* (ETP),[24] a 24 per cent reduction in direct emissions per tonne of cement produced by 2030 is required, relative to 2014 levels (equivalent to a 16 per cent absolute reduction in direct emissions).[25] The 2°C scenario (2DS) in the IEA's ETP suggests a reduction of 7 per cent by 2030, and the 2018 roadmap a reduction of 4 per cent over the same period.

In this context, the cement and concrete sector faces a considerable challenge: how to increase production to help roll out infrastructure services and tackle a growing global housing shortage while also achieving emissions reductions in line with global targets.

Figure 3: Direct CO_2 intensity of cement under different scenarios



Source: Authors' analysis. Data for ETP scenarios taken from International Energy Agency (2017), *Energy Technology Perspectives 2017*. Data for IEA/CSI 2DS from International Energy Agency and Cement Sustainability Initiative (2018), *Technology Roadmap*.

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 and roadmap models are not directly comparable as they are based on slightly different assumptions as to future demand for cement but emissions intensity reduction figures are shown together here as an indicative comparison.

1.1 CO_2 emissions from cement and concrete production

Cement comes in different forms, but it is generally made up of the following key elements: Portland clinker, gypsum, supplementary cementitious materials (SCMs) and fillers. SCMs and fillers include fly ash, granulated blast furnace slag (GBFS) and limestone. Portland clinker is the main ingredient in cement and accounts for the majority of the sector's emissions. More than 50 per cent of the sector's emissions are released from the calcination of limestone to produce Portland clinker.[26] These are known as 'process emissions'. A further 40 per cent are generated in the burning of fossil fuels to heat cement kilns to high temperatures for that process.[27]

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[24] In B2DS, the IEA explores the impact of moving beyond a 2°C target by analysing cost-effective pathways for meeting a 1.75°C trajectory with technologies that are commercially available or at demonstration stage. Although this is not exactly definitive of a 'well below 2°C' pathway, it provides a good illustration of what higher ambition could look like. International Energy Agency (2017), *Energy Technology Perspectives 2017*.

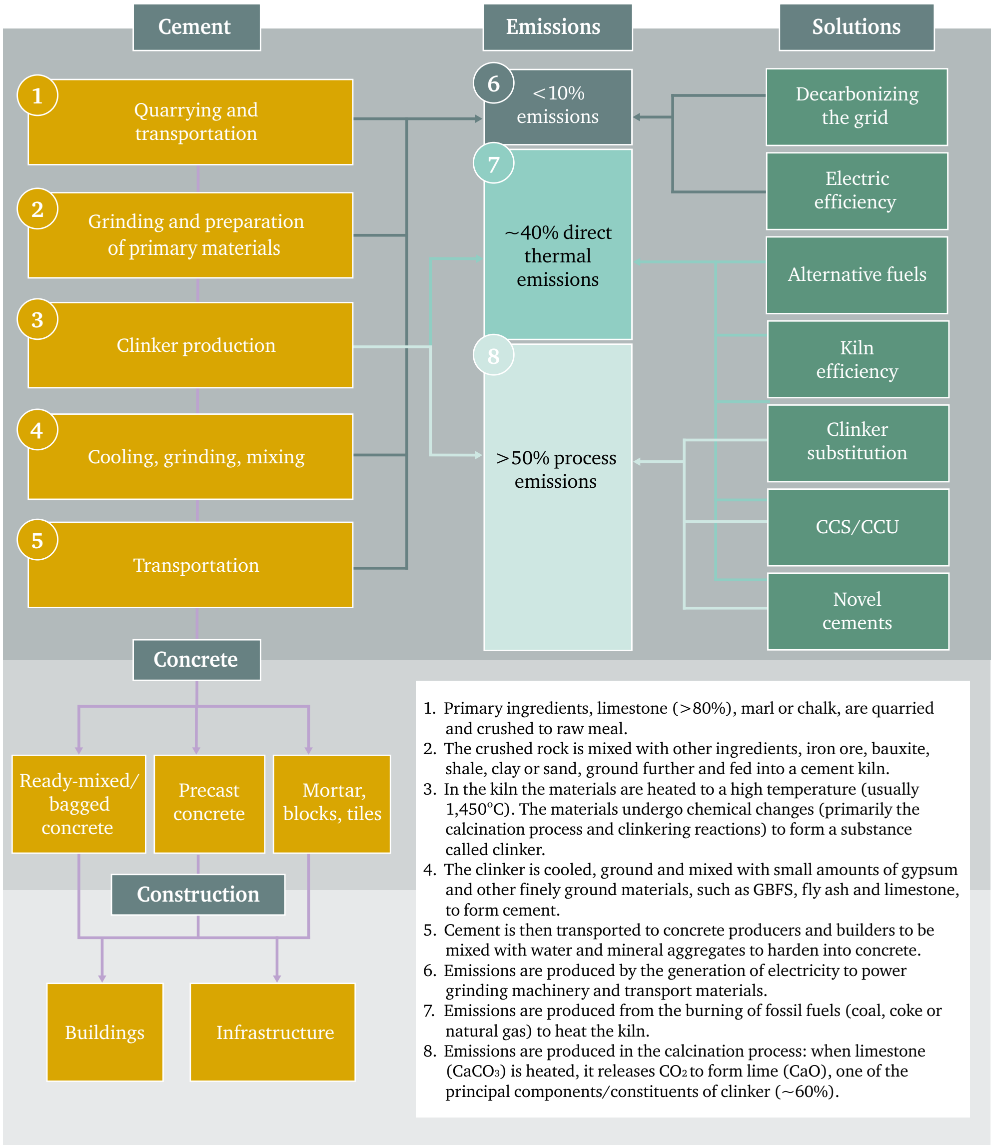
[25] International Energy Agency (2017), *Energy Technology Perspectives 2017*.

[26] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.

[27] Ibid.

Figure 4 highlights emissions and mitigation solutions at different stages along the cement production chain.

Figure 4: Emissions and mitigation solutions along the cement supply chain



1. Primary ingredients, limestone (>80%), marl or chalk, are quarried and crushed to raw meal.
2. The crushed rock is mixed with other ingredients, iron ore, bauxite, shale, clay or sand, ground further and fed into a cement kiln.
3. In the kiln the materials are heated to a high temperature (usually 1,450°C). The materials undergo chemical changes (primarily the calcination process and clinkering reactions) to form a substance called clinker.
4. The clinker is cooled, ground and mixed with small amounts of gypsum and other finely ground materials, such as GBFS, fly ash and limestone, to form cement.
5. Cement is then transported to concrete producers and builders to be mixed with water and mineral aggregates to harden into concrete.
6. Emissions are produced by the generation of electricity to power grinding machinery and transport materials.
7. Emissions are produced from the burning of fossil fuels (coal, coke or natural gas) to heat the kiln.
8. Emissions are produced in the calcination process: when limestone ($CaCO_3$) is heated, it releases CO_2 to form lime (CaO), one of the principal components/constituents of clinker (~60%).

Note: Not all the figures cited in this paper include direct as well as indirect emissions (from electricity generation and transport). Where indirect emissions are included, this will be noted.

Sources: Authors' own analysis. Emissions estimates from Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.

Variation in embodied emissions

The 'embodied emissions' of cement – the sum of greenhouse gas emissions associated with its production – are contingent on how much Portland clinker is included, the efficiency of the equipment used, the fuel used and the energy mix in a given location. The production of 1 kg of Ordinary Portland Cement (OPC), the most common type of cement used, with >90 per cent of its composition made up of Portland clinker, results in 0.93 kg of CO_2 on average. By comparison, a high-blend cement, i.e. one with a low share of Portland clinker and a high share of SCMs and fillers, can have an embodied-carbon figure as low as 0.25 kg CO_2/kg.[28]

The amount of Portland clinker that can be displaced depends on the type of substitute material used and the grade of concrete required for a given application. As Figure 4 indicates, cement has a variety of end uses. Reducing the Portland clinker content of cement may affect the properties of the final concrete product. Moreover, each clinker substitute has different characteristics and is therefore suitable for different applications.[29] Some clinker substitutes can improve the strength development and durability of concrete.[30] Cement and concrete standards therefore dictate the Portland clinker content required for a cement or concrete to fulfil criteria for specific applications.

A market dominated by Portland cement market

Portland cement, which tends to be made up of >75 per cent Portland clinker, is used in more than 98 per cent of concrete produced globally today

Although blended cements are already widely used in Europe, the global market is still dominated by high-clinker cements. Portland cement, which tends to be made up of >75 per cent Portland clinker,[31] is used in more than 98 per cent of concrete produced globally today.[32] There are good reasons for this: it is cheap, it produces a high-quality concrete, it is reliable and easy to use, and the raw materials needed to produce it (limestone, chalk and marl) tend to be abundantly available and co-located.[33] Maybe most importantly, it has an almost 200-year track record of being used as a construction material, giving engineers and builders confidence in its performance and long-term durability.[34]

Market structure

The global cement market is dominated by a few large producers: LafargeHolcim (the product of a 2015 merger between Lafarge of France and Holcim of Switzerland), HeidelbergCement (Germany), Cemex (Mexico) and Italcementi (an Italian firm in which HeidelbergCement has a 45 per cent stake).[35] While Chinese companies are

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[28] Hammond, G. P. and Jones, C. I. (2011), *Inventory of Carbon & Energy V2.0*, University of Bath, 2011, http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.Wli8PK5l_cs (accessed 12 Jan. 2018).

[29] Snellings, R. (2016), 'Assessing, Understanding and Unlocking Supplementary Cementitious Materials', *RILEM Technical Letters*, 1: pp. 50–55, doi: 10.21809/rilemtechlett.2016.12 (accessed 15 Oct. 2017).

[30] World Business Council for Sustainable Development (2002), *Toward a Sustainable Cement Industry*, http://www.wbcsd.org/Projects/Cement-Sustainability-Initiative/Resources/Toward-a-Sustainable-Cement-Industry (accessed 11 Mar. 2017).

[31] Portland cements on average contain around 20 per cent clinker substitutes, with 5 per cent gypsum content. This comes to around 75 per cent Portland clinker content. Scrivener, K., John, V., Gartner, E. (2016), *Eco-efficient cements: Potential, economically viable solutions for a low-CO_2, cement-based materials industry*, Paris: United Nations Environment Program, https://www.lc3.ch/wp-content/uploads/2017/03/2016-UNEP-Report-Complete6.pdf (accessed 20 Nov. 2016).

[32] Bernal, S. A., Rodriguez, E. D., Kirchheim, A. P. and Provis, J. L. (2016), 'Management and valorisation of wastes through use in producing alkali-activated cement materials', *Journal of Chemical Technology and Biotechnology*, 91(9): pp. 2365–2388, doi: 10.1002/jctb.4927 (accessed 9 Jan. 2018).

[33] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

[34] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan*.

[35] HeidelbergCement Group (2016), 'HeidelbergCement completes acquisition of 45% stake in Italcementi', press release, 1 July 2016, http://www.heidelbergcement.com/en/pr-01-07-2016 (accessed 21 Jan. 2018).

leading players in terms of production volumes, they largely continue to operate in their domestic market. Globally, cement firms tend towards vertical integration, producing their own concrete in downstream operations. The capital intensity of cement production[36] reinforces this concentration, making it difficult for smaller actors to enter the market and compete with larger firms.

In contrast, the global concrete market is much more fragmented than the cement market, and is built on many smaller companies serving local areas.[37] The key differences between concrete producers lie in how they deliver concrete to the end-user: ready-mixed, bagged or precast.[38]

Why is so much concrete used?

Every year more than 10 billion tonnes of concrete are used – which, according to some sources, makes it the second-most consumed substance on Earth (after water).[39] Given the environmental costs involved, why do we use so much concrete (and as a result cement) as opposed to other construction materials? Few materials have the versatility, resilience, ease of production, low cost and durability of concrete or can resist environmental extremes in the way concrete can. Its high thermal mass and low air infiltration help reduce the energy required to heat and cool buildings.[40]

Moreover, alternative materials often come with a higher carbon footprint.[41] Figure 5 shows embodied carbon values for cement, concrete, timber, glass, plasterboard and asphalt in the UK (note: aluminium, plastic and steel products are largely omitted from Figure 5, for reasons of space and clarity as their values for embodied energy and CO_2 emissions are greater than 16 MJ/kg and 1.2 kg CO_2/kg respectively). The obvious conclusion is that cement and concrete have relatively low embodied emissions on a per-kilogramme basis compared to other materials.

This comparison, however, misses some important dimensions and interactions. First, it does not distinguish between how much of each material is needed for a given application or performance level. Second, some of these materials can be substituted for concrete, but typically only for some applications. Third, materials are often best understood in combination: for instance, the strength offered by a combination of steel and concrete. The scope for doing more on the substitution front is explored in Chapter 4.

Finally, Figure 5 also highlights the large variation in embodied carbon levels across different types of cement. Given the vast quantities of concrete and cement consumed annually, it remains critically important to make these materials more sustainable.

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[36] Boston Consulting Group (2013), *The Cement Sector: A Strategic Contributor to Europe's Future*, https://cembureau.eu/media/1505/strategiccontributoreurope_bcg_2013-03-06.pdf (accessed 16 Jun. 2017).

[37] AggNet (2017), 'Ready-mixed concrete markets continue to be competitive', January 2017, https://www.agg-net.com/resources/articles/concrete/ready-mixed-concrete-markets-continue-to-be-competitive (accessed 20 Oct. 2017).

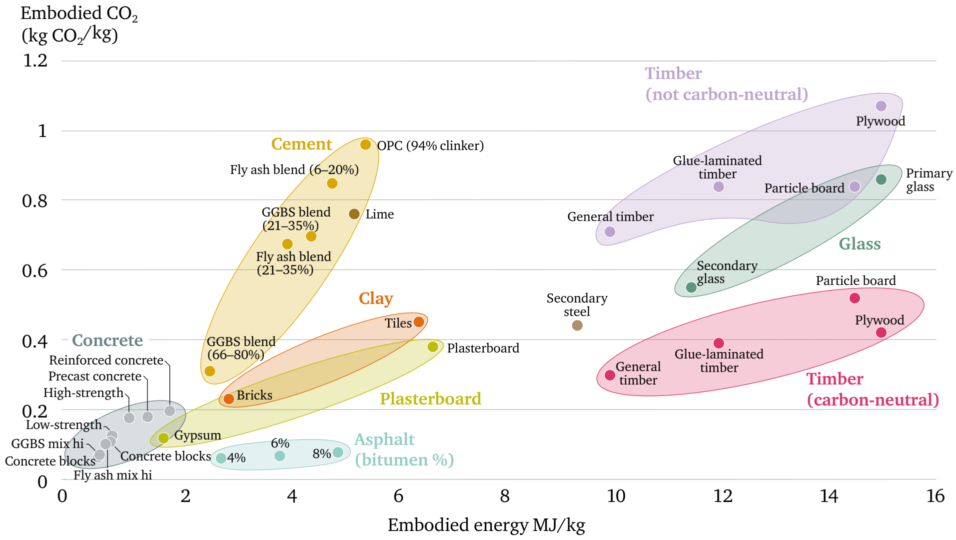
[38] Ready-mixed concrete is mixed at a concrete-mixing plant and then delivered to a building site as a pourable material in the rotating drum of a truck. Bagged concrete is delivered in bags and manually mixed by the builder. Precast concrete is mixed and set at a concrete-mixing plant and delivered as a solid product for assembly on site.

[39] See de Brito, J. and Saikia, N. (2013), *Recycled Aggregate in Concrete: Use of Industrial, Construction and Demolition Waste*, London: Springer-Verlag; Hasanbeigi, A., Price, L. and Lin, E. (2012), 'Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review', *Renewable and Sustainable Energy Reviews*, 16(8): pp. 6220–6238, doi: 10.1016/j.rser.2012.07.019 (accessed 8 Oct. 2017); Scrivener, John and Gartner (2016), Eco-efficient cements; Sakai, K. and Noguchi, T. (2012), *The Sustainable Use of Concrete*, Boca Raton: CRC Press.

[40] Greenspec (2018), 'Thermal mass', http://www.greenspec.co.uk/building-design/thermal-mass/ (accessed 23 Feb. 2018).

[41] Harris, M. (2017), 'Carbon fibre: the wonder material with a dirty secret', *Guardian*, 22 March 2017, https://www.theguardian.com/sustainable-business/2017/mar/22/carbon-fibre-wonder-material-dirty-secret (accessed 20 Oct. 2017).

Figure 5: Embodied emissions and energy for materials used in construction in the UK



Source: Authors' analysis of data from Hammond and Jones (2011), *Inventory of Carbon & Energy V2.0*.

Note: This analysis includes process emissions, fuel-related emissions and transport emissions within specified boundaries, i.e. typically cradle-to-gate: from resource extraction (cradle) to the factory gate (before it is transported to the consumer). The effects of carbon sequestration are excluded. Where a range of embodied CO_2 and energy is given, e.g. for the cement blends, the average is taken. For more detail on boundary conditions for individual materials, please consult the original source.

1.2 Existing strategies to lower emissions

The cement industry has pursued strategies to reduce CO_2 emissions since the 1990s. In particular, the major producers have worked together under the Cement Sustainability Initiative (CSI), and have devoted substantial effort to introducing mitigation solutions. Policymakers have also sought to encourage enhanced efficiency and accelerated decarbonization. These efforts have focused on four main levers:[42]

Thermal and electric efficiency

The first lever involves upgrading kilns and equipment so that less energy is needed to produce cement. Changing plant design, shifting towards higher-efficiency dry kilns, upgrading motors and mills, and using variable-speed drives can make a big difference to energy consumption and costs.[43] Firms are increasingly employing 'smart' devices to track and monitor operations, as well as machine learning to improve process control in their plants.[44] Optimizing the recovery of waste heat has been shown to

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[42] World Business Council for Sustainable Development, and International Energy Agency (2009), *Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050*, Paris: International Energy Agency Publications, https://www.iea.org/publications/freepublications/publication/Cement.pdf (accessed 22 Sept. 2017).

[43] Placet, M. and Fowler, K. (2002), *Substudy 7: How innovation can help the cement industry move toward more sustainable practices*, World Business Council for Sustainable Development, 2002, http://www.coprocem.org/documents/wbcsd-innovation-in-cement-final_report7.pdf (accessed 22 Sep. 2017).

[44] Institute for Industrial Productivity (2014), *Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis*, http://www.iipnetwork.org/62730%20WRH_Report.pdf2 (accessed 21 Apr. 2017).

reduce cement factories' operating costs by between 10 per cent and 15 per cent.[45] More efficient grinding processes can offer electricity savings, also benefiting overall energy efficiency.[46]

Although the industry has invested heavily in optimizing production processes, an efficiency gap remains. Producing cement using the current best available technology (BAT) and practice results in thermal energy consumption of around 2.9 GJ/tonne of clinker.[47] By comparison, the global average in 2014 was 3.5 GJ/tonne of clinker.[48] The efficiency gap largely reflects the use of older equipment in Europe and the US. Meanwhile, the Indian cement industry is one of the most energy-efficient in the world, with average thermal energy consumption of approximately 3.0 GJ/tonne of clinker.[49]

Alternative fuel use

The second lever consists of switching from fossil fuels to alternatives such as biomass and waste. Coal has been the main fuel used historically,[50] but cement kilns can safely burn biomass and waste instead of fossil fuels as the high processing temperature and the presence of limestone clean the gases released.[51] The type of alternative fuel used, however, depends on local availability and the quality of alternatives, which are often outside the control of cement producers.

The use of alternative fuels in cement production is most prevalent in Europe, making up around 43 per cent of fuel consumption there compared to 15 per cent in North America, 8 per cent in China, South Korea and Japan, and around 3 per cent in India.[52] This indicates that a lot can still be achieved by simply increasing the use of alternative fuels, particularly in emerging markets such as China and India.[53] There is even scope for improvement in Europe, where the average cement plant could substitute around 60 per cent of its fuel with alternatives; some European producers are already running on >90 per cent waste fuel for extended periods.[54]

Clinker substitution

The third lever consists of reducing the amount of Portland clinker used by substituting it with clinker substitutes such as fly ash, GBFS and limestone. The IEA estimates that around 3.7 GJ and 0.83 tonnes of CO_2 can be saved per tonne of clinker displaced.[55] How much clinker substitute can be blended into cement or

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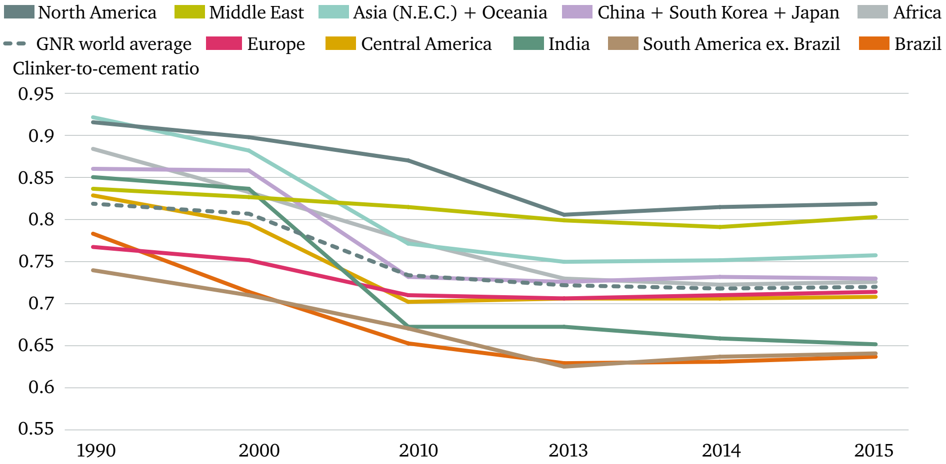
[45] Ibid.
[46] International Energy Agency (2017), *Energy Technology Perspectives 2017*.
[47] Ibid.
[48] Ibid.
[49] World Business Council for Sustainable Development (2017), *Getting the Numbers Right Project Emissions Report 2015*, http://www.wbcsdcement.org/index.php/key-issues/climate-protection/gnr-database (accessed 11 Nov. 2017).
[50] Institute for Industrial Productivity (Undated), 'Use of Alternative Fuels', http://ietd.iipnetwork.org/content/use-alternative-fuels (accessed 8 Oct. 2017).
[51] Allwood, J., Cullen, J., Carruth, M., Cooper, D., McBrien, M., Milford, R., Moynihan, M. and Patel, A., (2012), *Sustainable materials: with both eyes open*, Cambridge: UIT Cambridge.
[52] Thermal energy consumption data for 2015 (weighted average, excluding drying of fuels, grey clinker) from World Business Council for Sustainable Development (2017), *Getting the Numbers Right Project Emissions Report 2015*.
[53] International Finance Corporation (2017), *Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice*, Washington, DC: International Finance Corporation, https://www.ifc.org/wps/wcm/connect/cb361035-1872-4566-a7e7-d3d1441ad3ac/Alternative_Fuels_08+04.pdf?MOD=AJPERES (accessed 15 Oct. 2017).
[54] Ecofys (2016), *Market opportunities for use of alternative fuels in cement plants across the EU*, https://cembureau.eu/media/1231/ecofysreport_wastetoenergy_2016-07-08.pdf (accessed 16 Jan. 2018).
[55] International Energy Agency (2017), *Energy Technology Perspectives 2017*.

concrete depends on the type of clinker substitute and the grade of concrete required, but some substitutes – e.g. GBFS – theoretically allow for substitution levels of over 70 per cent,[56] potentially reducing emissions from production by over 60 per cent.

To date, clinker substitution has contributed on average to a 20–30 per cent decrease in CO_2 emissions per tonne of cement produced, compared to the 1980s.[57] The average clinker ratio was around 0.65 in 2014.[58] While the reduction in clinker use has been substantial, clinker ratios have recently levelled off (see Figure 6) and there is still considerable scope for improvement in most regions, as evidenced by the target set by the 2018 roadmap of reaching an average global clinker ratio of 0.60 by 2050.[59] This is considerably more ambitious than the target of 0.71 by 2050 set in the original 2009 roadmap.[60] The main constraints on clinker substitution tend to be the availability and cost of clinker substitute materials, which vary considerably by region, consumer acceptance and the barriers imposed by standards and regulations.[61]

Figure 6: Regional clinker-to-cement ratios (1990–2015)



Source: Data for clinker-to-cement ratio (weighted average, grey and white cement) from World Business Council for Sustainable Development (2017), *Getting the Numbers Right: Project Emissions Report 2015*. Data for 2013 are taken from the previous version of the Getting the Numbers Right (GNR) dataset.

Note: There are a number of reasons why these numbers do not reflect the 0.65 clinker ratio average cited in the text. First, GNR data only cover around 21 per cent of global cement production. Second, clinker substitutes can be added during the cement production process but also at the stage of mixing concrete. This graph only reflects the former. It therefore suggests an 'artificially' higher clinker ratio for some regions such as North America, where clinker substitutes are more likely to be added at the concrete production stage.

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[56] Schuldyakov, K. V., Kramar, L. Y. and Trofimov, B. Y. (2016), 'The Properties of Slag Cement and Its Influence on the Structure of Hardened Cement Paste', *International Conference on Industrial Engineering*, doi: 10.1016/j.proeng.2016.07.202 (accessed 9 Feb. 2018).

[57] Comparison of today's average clinker ratio of around 0.65–0.75 versus a clinker ratio of 0.95 in the 1980s. Olivier, J., Janssens-Maenhout, G., Muntean, M., Peters, J. (2015), *Trends in global CO2 emissions: 2015 Report*, The Hague: PBL Netherlands Environmental Assessment Agency, http://edgar.jrc.ec.europa.eu/news_docs/jrc-2015-trends-in-global-co2-emissions-2015-report-98184.pdf (accessed 21 Apr. 2017).

[58] International Energy Agency and Cement Sustainability Initiative (2018), *Technology Roadmap*.

[59] Ibid.

[60] Figure for low-demand scenario. World Business Council for Sustainable Development and International Energy Agency (2009), *Cement Technology Roadmap 2009*.

[61] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.

Carbon capture and storage (CCS)

The fourth lever consists of capturing the emissions from a cement kiln, and then securing and storing these. CCS is particularly attractive for cement producers, as the process emissions from heating limestone to produce clinker cannot be avoided by simply switching fuels and improving energy efficiency. Even with large-scale substitution of Portland clinker, emissions from the portion of clinker that would still be produced would continue to present a challenge.[62]

This is reflected in the emphasis on CCS in technology roadmaps. In the 2009 roadmap, CCS accounts for 56 per cent of the planned direct emissions reduction to 2050, compared with 10 per cent for clinker substitution, 24 per cent for alternative fuels and 10 per cent for energy efficiency.[63] The ETP 2017 B2DS relies on CCS for 83 per cent of cumulative emissions reductions in the cement sector.[64]

These levers – with the exception of CCS – have delivered an 18 per cent reduction in the global average CO_2 intensity of cement production since 1990

The cement industry has engaged in several projects to develop CCS.[65] However, as in other sectors, development has been slow. Most CCS technologies are still at the basic research or demonstration stage.[66] One of the main barriers so far has been cost.[67] Several countries also lack an adequate legal framework for CO_2 storage.[68] Finally, the lack of geographic clustering is a problem. Most cement plants are too small to justify by themselves the construction of the necessary distribution infrastructure for captured CO_2.[69] This is not a problem where they are clustered with other industrial sources of CO_2, but many may not be suitably located.

Progress across levers

These levers – with the exception of CCS – have delivered an 18 per cent reduction in the global average CO_2 intensity of cement production since 1990.[70] There have been even more impressive reductions in certain countries and regions: for example, Poland recorded a 42 per cent decrease in the same period.[71] Progress on each of the levers has also largely been in line with the 2015 indicators set in the 2009 roadmap.[72]

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[62] Allwood et al. (2012), *Sustainable materials: with both eyes open*.

[63] International Energy Agency and World Business Council for Sustainable Development (2009), 'Cement Roadmap', https://www.iea.org/publications/freepublications/publication/Cement_Roadmap_Foldout_WEB.pdf (accessed 6 Mar. 2018).

[64] International Energy Agency (2017), *Energy Technology Perspectives 2017*.

[65] Van der Meer, R. (2017), 'CCS and CCU in cement industry: Some projects', presentation delivered at 'Chatham House Low-carbon Innovation in Cement and Concrete Roundtable' on 12 May 2017.

[66] Napp, T. (Undated), *A survey of key technological innovations for the low-carbon economy*.

[67] The Energy Transitions Commission estimates that at current costs CCS would increase the costs of cement production by over 50 per cent. Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*.

[68] Levina, E. (2011), *Incentives for CCS and Regulatory Requirements, International Energy Agency*, 29 March 2011, https://www.iea.org/media/workshops/2011/ccsrussia/Levina.pdf (accessed 9 Feb. 2018).

[69] Global CCS Institute (2016), Understanding Industrial CCS Hubs and Clusters, https://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/content/page/123214/files/Understanding%20Industrial%20CCS%20hubs%20and%20clusters.pdf (accessed 9 Feb. 2018).

[70] Between 1990 and 2014, the carbon intensity at a global level of producing a tonne of grey and white cementitious products dropped from 755 kg CO_2 to 617 kg CO_2. This is a weighted average of absolute emission values excluding CO_2 from on-site power generation. World Business Council for Sustainable Development (2017), *Getting the Numbers Right Project Emissions Report 2015*.

[71] Carbon intensity of producing a tonne of grey and white cementitious products. World Business Council for Sustainable Development (2017), *Getting the Numbers Right Project Emissions Report 2015*.

[72] World Business Council for Sustainable Development and International Energy Agency (2009), *Cement Technology Roadmap 2009*.

But these gains have been more than matched by increasing demand. There has been an almost 50 per cent increase in the sector's gross emissions at the global level since 1990.[73] Moreover, the new scenarios set out by the 2018 roadmap and the 2017 ETP are more ambitious than the 2009 roadmap, especially for clinker substitution and CCS.[74] The cement sector has to not only continue to deploy all of these options but also do so faster, especially if it is to meet B2DS.

There are a number of reasons why the sector has not moved quickly in the past. The capital intensity of cement production relative to revenue means that it can take several years to recoup investments in infrastructure.[75] This can make producers reluctant to shift to new approaches that might 'strand' existing assets. There has been a lack of financial incentives for the sector to adopt mitigation solutions.[76] Finally, the broader construction sector, within which the cement and concrete sector is embedded, tends to be risk-averse.[77] Safety is naturally an overriding priority, leading to a strong preference for sticking with practices and products with proven track records.

There are also limits to what existing approaches can deliver in terms of deep decarbonization:

- BAT **energy efficiency** can only get the sector so far, and it will be difficult to achieve everywhere, not least because the levers set out above are not distinct from one another. The choice of fuel and clinker substitute and the use of CCS can affect plant operation and may require more heat energy.[78]
- Although the use of waste as an **alternative fuel** may be beneficial from a waste-management perspective, it is unlikely to be carbon-neutral. Some argue that burning waste does not even create a net emissions saving compared with disposing of it in a landfill.[79]
- A further constraint on the use of **alternative fuels** may come from the increased policy focus on shifting to a more 'circular economy' aimed at scaling up the reuse, remanufacturing and recycling of secondary materials and products. As the waste-management space becomes more crowded, the sector can expect to face more competition for waste feedstocks.
- The availability of **CO_2 storage** and transport infrastructure, and the pace at which it is rolled out, will place a ceiling on potential deployment of CCS even if the other barriers discussed above can be overcome.[80]

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[73] Gross emissions (excluding CO_2 from on-site power generation) for grey and white cement increased by 48 per cent. Gross emissions (excluding CO_2 from on-site power generation) for grey cement increased by 49 per cent. Ibid.
[74] Fernandez (2017), 'Industry Technology Roadmaps'.
[75] Placet and Fowler (2002), *Substudy 7*.
[76] *The Economist* (2016), 'Cracks in the surface', 26 August 2016, https://www.economist.com/news/business/21705861-why-grey-firms-will-have-go-green-cracks-surface (accessed 26 Jan. 2018); Neuhoff, K., Vanderborght, B., Ancygier, A., Atasoy, A. T., Haussner, M., Ismer, R., Mack, B., Ponssard, J.-P., Quirion, P., van Rooij, A., Sabio, N., Sartor, O., Sato, M. and Schopp, A. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*, Climate Strategies, February 2014, http://climatestrategies.org/wp-content/uploads/2014/02/climate-strategies-cement-report-final.pdf (accessed 26 Jan. 2018).
[77] Giesekam, J., Barrett, J. R. and Taylor, P. (2015), 'Construction sector views on low-carbon building materials', *Building Research & Information*, 44(4): pp. 423–444, doi: 10.1080/09613218.2016.1086872 (accessed 18 Jan. 2018).
[78] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.
[79] Ibid.
[80] International Energy Agency (2017), *Energy Technology Perspectives 2017*, p. 378.

Reaching a clinker ratio of 0.60 by 2050, as set out by the 2018 Technology Roadmap, will also present a significant challenge – implying regulatory and technical changes, as well as innovation throughout the cement and concrete sector and across regions. It will depend on the viability and availability of clinker substitutes at a time when traditional sources (slag and fly ash) are on the decline. Even if the 0.60 target is achieved, there will be residual process emissions from the share of Portland clinker that continues to be produced.

In short, the relatively easy decarbonization gains have largely been made. Given the increased ambition and urgency required to shift to a Paris-compatible pathway, the next phase of decarbonization will be technically and economically more challenging than efforts to date unless a new wave of innovation redraws the landscape.

1.3 Novel cements and concretes

Against this backdrop, there has been considerable interest in innovations that could steeply reduce overall emissions by introducing changes to cement composition. Low-carbon cements, or 'novel cements' as this report refers to them, are substances made from alternatives to Portland clinker that mimic the properties of conventional Portland cement but that can be produced using less energy and release fewer emissions in production. Some novel cements even enhance the properties of concrete.[81]

A decade ago, a British start-up called Novacem announced breakthroughs in carbon-negative cement.[82] More recently the buzz has been around companies such as Solidia Technologies, Blue Planet, CarbonCure and Skyonic, which are developing concretes that absorb and store CO_2. Solidia, a US firm now in a partnership with major cement producer LafargeHolcim, claims that its low-clinker-content CO_2-cured concrete reduces CO_2 emissions by 70 per cent compared with OPC.[83] LafargeHolcim itself has developed Aether, a belite ye'elimite-ferrite (BYF) clinker that has a lower limestone content than OPC and requires a lower production temperature,[84] resulting in CO_2 emissions reductions of 20 per cent or more per unit of clinker in cement.[85]

By altering the raw materials used (in most cases reducing the share of limestone), these clinkers can reduce process emissions from limestone calcination and thermal emissions from fuel combustion. For example, carbonatable calcium silicate clinkers (CCSC) of the kind used in Solidia concretes may lower process emissions by 43 per cent (see Figure 7). Magnesium oxides derived from magnesium silicates (MOMS), the technology promoted by Novacem, could in theory be made from materials that contain no carbon.[86] Geopolymer or alkali-activated binders can have embodied energy and carbon footprints that are up to 80–90 per cent lower than

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[81] World Business Council for Sustainable Development (2002), *Toward a Sustainable Cement Industry*.

[82] Dewald, U. and Achternbosch, M. (2015), 'Why more sustainable cements failed so far? Disruptive innovations and their barriers in a basic industry', *Environmental Innovations and Societal Transitions*, 19: pp 15–30, doi:10.1016/j.eist.2015.10.001 (accessed 21 Apr. 2017).

[83] DeCristofaro, N. (2017), 'A Cement and Concrete Technology Company Transforming CO2 into Profits and Performance', presentation at Chatham House workshop on 'Low-carbon Innovation in Cement and Concrete', 12 May 2017.

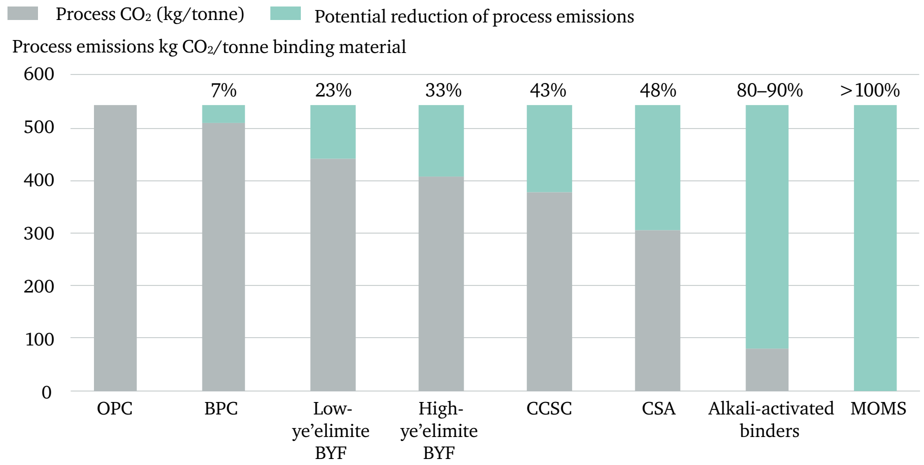
[84] Aether (undated), *Aether Lower Carbon Cements*, http://www.aether-cement.eu/fileadmin/_migrated/content_uploads/AETHER_laymans.pdf (accessed 30 Oct. 2017).

[85] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

[86] Gartner, E. and Sui, T. (2017), 'Alternative cement clinkers', *Cement and Concrete Research*, doi: 10.1016/j.cemconres.2017.02.002 (accessed 20 Jan. 2018).

those for Portland cement.[87] Both CCSC and MOMS can be hardened by carbonation (using CO_2 rather than water) – meaning that they could absorb and contain more CO_2 than is emitted in the manufacturing process, making them 'carbon-negative'.[88]

Figure 7: Process CO_2 emissions of alternative clinkers compared to OPC



Source: Data for clinker phase compositions (i.e. share of clinker compound in each type) for OPC, BPC, low- and high-ye'elimite BYF, CCSC and MOMS as well as process CO_2 emissions for clinker compounds from Gartner and Sui (2017), 'Alternative cement clinkers'. Data for clinker phase composition for CSA from Quillin, K. (2010), 'Low-CO2 Cements based on Calcium Sulfoaluminate', presentation, https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&uact=8&ved=0ahUKEwiuvZWS0ubYAhVCLMAKHfFIC70QFgg8MAQ&url=https%3A%2F%2Fwww.soci.org%2F-%2Fmedia%2FFiles%2FConference-Downloads%2F2010%2FLow-Carbon-Cements-Nov-10%2FSulphoaluminate_Cements_Keith_Quillin_R.ashx%3Fla%3Den&usg=AOvVaw0kPdXplmBcLMdGMnqzanlV (accessed 20 Jan. 2018).

Note: BPC stands for belite-rich Portland clinker, BYF stands for belite ye'elimite-ferrite and is also sometimes referred to as BCSA (or belite sulphoaluminate), CCSC stands for carbonatable calcium silicate clinker(s), CSA stands for calcium sulphoaluminate clinker, MOMS stands for magnesium oxides derived from magnesium silicates.

So far, however, these novel cements and concretes have failed to penetrate the market significantly.[89] Many of these products face resistance from consumers.[90] Almost all standards, design codes and protocols for testing cement binders and concrete are based on the use of Portland cement, making it difficult to experiment with and scale up the use of novel products.[91] Not all of these novel binder technologies have reached a level of maturation to be deployed at scale. Finally, there can be difficulties extending stakeholder participation beyond the manufacturers of novel cements and concretes.[92]

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[87] Taylor, G.M. (2013), *Novel cements*, http://cement.mineralproducts.org/documents/FS_12_Novel_cements_low_energy_low_carbon_cements.pdf (accessed 17 Apr. 2018).
[88] Gartner and Sui (2017), 'Alternative cement clinkers'.
[89] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[90] Placet and Fowler (2002), *Substudy 7*.
[91] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'; Van Deventer, J. S. J., Provis, J., and Duxson, P. (2012), 'Technical and commercial progress in the adoption of geopolymer cement', *Minerals Engineering*, 29: pp. 89–104, doi: 10.1016/j.mineng.2011.09.009 (accessed 9 Oct. 2017); Luta, A. and Lytton, W. (2016), *The Final Carbon Fatcat: How Europe's cement sector benefits and the climate suffers from flaws in the Emissions Trading Scheme*, Sandbag, March 2011, https://sandbag.org.uk/wp-content/uploads/2016/08/The_Final_Carbon_Fatcat_-_Sandbag_-_March_2016_v3.3_CLEAN.pdf (accessed 11 Oct. 2017).
[92] Miller, S. A., Horvath, A. and Monteiro, P. J. M. (2016), 'Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%', *Environmental Research Letters*, 11 (074029): pp: 1–7, doi: 10.1088/1748-9326/11/7/074029 (accessed 4 Jan. 2018).

1.4 Prospects for disruption

Given the rapid emissions savings needed for a climate-compatible cement and concrete sector, understanding the potential for disruption in the sector – i.e. breaking through the barriers outlined above – is vitally important.

The sector will need to move on two broad fronts:

- **Exploiting old technologies in new ways while harnessing new technologies and practices.** Rather than relying on any one technology, deep decarbonization will likely require matching the right solution to the right circumstances with the right incentives and deploying it accordingly. By aggregating lots of smaller opportunities tied to specific locations in a smarter way, incremental gains could deliver a step-change in emissions reductions. Often in this report we come back to the potential for data and digital tools to enable these shifts.
- **Identifying and developing the next generation of technologies.** The sector will need to move beyond incremental advances in efficiency and the optimization of current processes, both of which have been the mainstay of innovation efforts so far.[93] For the sector to achieve a transformative pathway, there will need to be a step-change in the pace at which key technologies are developed and deployed.[94]

Moreover, to decarbonize cement and concrete, it is necessary to look beyond the sector itself and consider the wider built environment, and even to examine assumptions around how we will live in the coming decades. Although a full examination of this is beyond the scope of this report, our analysis looks at key areas that could affect the decarbonization of cement and concrete, shape future demand, or unlock barriers to scaling up innovative technologies.

In this context, it needs to be remembered that the cement and concrete sector will not be immune to **broader disruptive trends stemming from digitalization and new business models**. Enhanced connectivity, remote monitoring, predictive analytics, 3D printing and urban design are already combining to transform traditional supply chains within the construction industry, as well as the interaction and management of actors along those chains.[95]

Another reason for looking at the wider context in which innovation in low-carbon cement and concrete must develop is that **countervailing trends in politics society and the workforce are reshaping the future of the built environment.**[96] If the decarbonization of the energy and transport sectors accelerates as expected, cement and concrete producers could find themselves next in line in terms of facing demands

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[93] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.

[94] Hutchinson, R. (2016), 'The cement industry needs a breakthrough, now', GreenBiz, 28 July 2016, https://www.greenbiz.com/article/cement-industry-needs-breakthrough-now (accessed 11 Oct. 2017).

[95] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction: A Breakthrough in Mindset and Technology*, http://www3.weforum.org/docs/WEF_Shaping_the_Future_of_Construction_full_report__.pdf (accessed 25 Apr. 2018); McKinsey Global Institute (2017), *Reinventing Construction: A Route to Higher Productivity*, https://www.mckinsey.com/~/media/McKinsey/Industries/Capital%20Projects%20and%20Infrastructure/Our%20Insights/Reinventing%20construction%20through%20a%20productivity%20revolution/MGI-Reinventing-construction-A-route-to-higher-productivity-Full-report.ashx (accessed 26 Feb. 2018).

[96] World Economic Forum (2016), *Shaping the Future of Construction*.

for radical change. Those that fail to adapt to public and consumer expectations around deep decarbonization and sustainability could find their licences to operate under threat. The urban landscape and infrastructure developments will be the battleground in which such issues play out.

1.5 Scope of the report

The ability of decision-makers to encourage and accelerate decarbonization in cement and concrete will rely on greater clarity around the most promising technologies and on opportunities for radical new approaches

The ability of decision-makers in business, government and civil society to encourage and accelerate decarbonization in cement and concrete will rely on greater clarity around the most promising technologies and on opportunities for radical new approaches. Innovation trends are also critical for informing investment into research and development (R&D) and as an input into low-carbon industrialization strategies for policymakers.

The report examines three questions:

1. What low-carbon cements are being developed, by whom and where?
2. What barriers hold back these new products, and how can they be overcome?
3. Where could disruption come from – within the sector or elsewhere?

It draws on nine months of research on low-carbon innovation in the cement and concrete sector, including a patent-landscaping exercise conducted by Chatham House and CambridgeIP (an innovation and intellectual property consultancy); 10 expert interviews; and two workshops held to discuss methodology, findings and recommendations, in which 10 companies were represented.

Patent landscaping

Patent landscaping involves creating databases of patents for individual sectors or ‘technology areas’. It is used to measure innovation, as well as to understand systems of innovation – for instance, by revealing geographical trends and changes in innovation patterns over time.[97]

There are several advantages to using patent data as a proxy for innovation. Patents provide a large amount of information on the nature of the invention, the inventor(s) and the applicant. The data are available, quantitative and discrete.[98] As a result, patents can be aggregated and compared using common metrics.

However, patent data provide an imperfect picture of innovation. First, the data can be incomplete. Second, non-technological innovations are not patentable. Third, even among innovations that can be patented, some may not be patented

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[97] For an example of this methodology applied in previous work by Chatham House and CambridgeIP, see Lee, B., Iliev, I. and Preston, F. (2009), *Who Owns Our Low Carbon Future? Intellectual Property and Energy Technologies*, Chatham House Report, September 2009, London: Royal Institute of International Affairs, https://www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy,%20Environment%20and%20Development/r0909_lowcarbonfuture.pdf (accessed 13 May 2017).

[98] Haščič, I. and Migotto, M. (2015), ‘Measuring environmental innovation using patent data’, *OECD Environment Working Papers*. No. 89, Paris: OECD Publishing, doi: 10.1787/5js009kf48xw-en (accessed 20 Apr. 2017).

as companies may not wish to reveal their technology in an open document. Finally, patent data alone reveal little about the potential importance or impact of an innovation.

To understand the drivers of and barriers to innovation, as well as which innovations present truly transformative steps, analysis needs to go beyond simple patent identification. We therefore overlay the trends derived from the patent analysis with additional analysis of key factors that affect the deployment of low-carbon cements. These will be explored in Chapter 3.

Box 2: Patent terminology

- A **patent** gives its owner protection over the covered invention from unauthorized use within a given territory for a limited period of time.
- An **assignee** is the owner of a patent.
- A **patent family** comprises all patents and patent applications resulting from one initial patent application.

Why focus on clinker?

We focus the patent search on technologies and processes to do with ‘clinker substitution and replacement’. One of the key reasons for this is the potential of this particular lever to contribute to deep decarbonization (see Figure 8). Clinker substitution and replacement can lower thermal emissions, as well as significantly reduce and potentially eliminate process emissions from cement production. Such approaches also potentially present relatively inexpensive routes to decarbonization.[99] Scaling up clinker substitution does not generally require changes in equipment or fuel sources.[100] Similarly, some of the novel cements discussed above can be produced in conventional cement kilns.[101] By contrast, most CCS technologies require substantial investment in new kilns.[102] Finally, increased ambition by the cement industry around clinker substitution (reflected in global targets) suggests that this is an area with further potential and where efforts will need to be increased.

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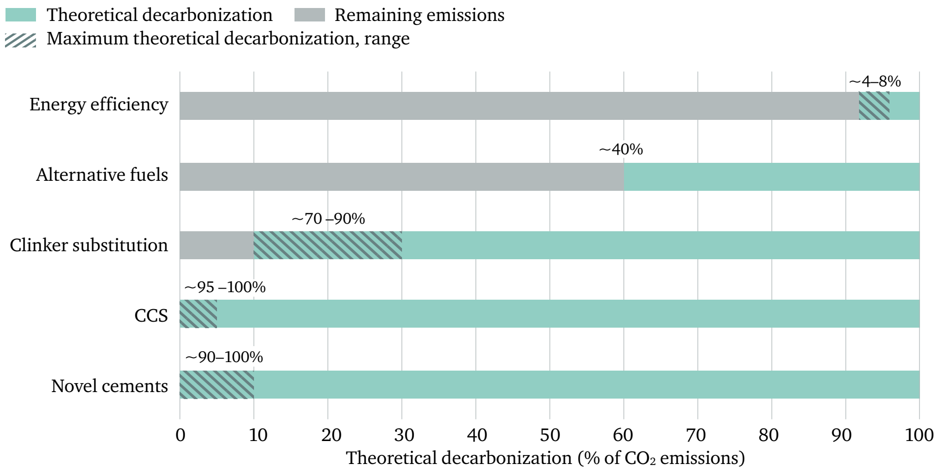
[99] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[100] Miller, Horvath and Monteiro (2016), ‘Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%’.
[101] Gartner and Sui (2017), ‘Alternative cement clinkers’.
[102] International Energy Agency (2017), *Energy Technology Perspectives 2017.*

Figure 8: Theoretical decarbonization potential of different levers



Source: Authors' analysis of mitigation potential estimates from various sources.[103]

The term 'clinker substitution' generally refers to lowering the Portland clinker content of cement by blending in alternative materials.[104] The patent search area also includes novel cements and concretes in order to capture the more radical innovations emerging in this area. The search area is defined as: **products and processes to do with lowering or entirely replacing the Portland clinker content of cement and concrete**. This includes two categories in particular:

- **Clinker-lowering technologies:** processes and products that lower the share of Portland clinker in cement and concrete. This category includes innovations around different types of SCMs and fillers as well as chemical admixtures. These are ingredients added to a concrete mix immediately before or during mixing that facilitate the use of clinker substitutes.[105] The addition of chemical admixtures helps mitigate any potential issues that might occur from lowering the Portland clinker content in the final concrete.[106]
- **Alternative-clinker technologies:** technologies and processes associated with cements made from alternatives to Portland clinker as the main reactive binder component. This category includes alternative-clinker cements – materials, ideally from a carbon-free raw material base, that, once ground to a fine powder,

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[103] Energy efficiency estimate based on data in International Energy Agency and Cement Sustainability Initiative (2018), *Technology Roadmap* and European Cement Research Academy and Cement Sustainability Initiative (2017), *CSI/ECRA-Technology Papers 2017*, which suggests that energy consumption could decrease by roughly 10–20 per cent. This would be a 10–20 per cent decrease on the 40 per cent emissions stemming from thermal combustion processes. Alternative fuels figure based on the fact that fuel combustion emissions account for around 40 per cent of cement production emissions Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'. Clinker substitution figure based on the fact that slag cements can contain more than 90 per cent slag Schuldyakov, Kramar and Trofimov (2016), 'The Properties of Slag Cement and Its Influence on the Structure of Hardened Cement Paste'. CCS figure assumes that virtually all CO_2 emitted could be captured European Cement Research Academy and Cement Sustainability Initiative (2017), *CSI/ECRA-Technology Papers 2017*. The novel cements estimate is based on data shown in Figure 7.
[104] See, for example, World Business Council for Sustainable Development and International Energy Agency (2009), *Cement Technology Roadmap 2009*.
[105] Portland Cement Association (2017), 'Chemical Admixtures', http://www.cement.org/cement-concrete-applications/concrete-materials/chemical-admixtures (accessed 15 Oct. 2017).
[106] Snellings (2016), 'Assessing, Understanding and Unlocking Supplementary Cementitious Materials'.

are capable of reacting rapidly with water and/or CO_2 to form a hardened mass that can be used as binder;[107] and geopolymers and alkali-activated binders – binders made by reacting a solid aluminosilicate material (e.g. fly ash, GBFS, clays, volcanic rocks) with an alkali activator.[108]

As a shorthand, the report refers to this technology area as ‘clinker substitution and replacement’, to SCMs and fillers collectively as ‘clinker substitutes’, and to alternative-clinker technologies as ‘novel cements’. For a full list of subcategories and definitions of technologies included, see Appendix 1.

1.6 Structure of this report

Chapter 2 sets out the focus and findings from the patent analysis, highlighting geographic and organizational patterns of innovation as well as the extent of technology diffusion thus far. China emerges as a key player in innovation. The chapter also explores the barriers holding back the commercialization and widespread deployment of low-carbon cements.

Chapter 3 explores the potential to overcome the barriers to the deployment of low-carbon cements and concretes. Possible solutions include higher carbon prices, as well as alternative strategies around product standards, the leveraging of public procurement, or new business models. The chapter also argues that the cement sector may not be immune from digital disruption, which could bring new opportunities for emissions reductions.

Chapter 4 highlights the potential for disruptive shifts in the built environment that could radically change how cement and concrete are used, or could open up the use of alternative materials. These areas could help to deliver deep decarbonization, but the scale of this opportunity is only just starting to come into focus. Moreover, a climate-safe pathway would need to combine these new opportunities with the strategies described in Chapter 3.

Chapter 5 provides conclusions, recommendations and practical suggestions on ways to move forward.

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[107] Gartner and Sui (2017), ‘Alternative cement clinkers’.
[108] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan*.

Box 3: Glossary

Cement is a powder used in construction made by grinding clinker together with various mineral components such as gypsum, limestone, blast furnace slag, coal fly ash and natural volcanic material. It sets usually by reaction with water, hardens and sticks to other materials such as sand, gravel or crushed stone, and binds them together to form concrete or mortar.[109]

Clinker is an intermediate product in cement production. Conventional clinker (also referred to as Portland clinker in this report) is a greyish substance, consisting of granules the size of a small marble, formed from heating limestone and other materials in a cement kiln.[110]

Alternative clinkers or binders are made from different materials or via different processes from those associated with the production of traditional clinker. They generally consist of natural or man-made materials (ideally from a carbon-free raw material base) that, once ground to a fine powder, are capable of reacting rapidly with water and/or CO_2 to form a hardened mass that can be used as a binder.[111]

Clinker substitutes are materials added to cement or concrete to lower the share of clinker. They include:

- **Supplementary cementitious materials (SCMs) –** These are materials with cementitious properties, and include fly ash from coal-fired power plants, granulated blast furnace slag (GBFS) from blast furnaces for iron and steel production, and silica fume. SCMs react with clinker, playing a role in the strength development of concrete.[112]
- **Fillers –** These are materials such as limestone and quartz, which are only slightly reactive with clinker.[113]

Cementitious is a term used to refer to materials that have a similar nature to cement, i.e. ‘of the nature of cement’.[114]

Portland cement is the most common type of cement used worldwide. Different standards around the world allow for the designation ‘Portland cement’ to apply to products containing varying shares of Portland clinker. For example, European cement standard EN 197-1 defines two main types of Portland cement: CEM I >95 per cent clinker and CEM II Portland-composite cement 65–94 per cent clinker.[115] Today, the proportion of clinker substitutes in Portland cements is generally around 20 per cent of the whole mix (i.e. making them >75 per cent clinker).[116]

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[109] World Business Council for Sustainable Development Cement Sustainability Initiative (2014), ‘Glossary and Abbreviations’, *Internet Manual,* http://www.cement-co2-protocol.org/en/#Internet_Manual/index_about.htm%3FTocPath%3DAbout%2520Internet%2520Manual%7C_____0 (accessed 25 Apr. 2018); Cemex (undated), *Educational guide to cementitious materials*, https://www.cemex.co.uk/documents/45807659/45840198/mortar-cementitious.pdf/46571b2a-3efd-4743-20c8-d33feb1aed9d (accessed 21 May 2018).
[110] Hendricks, C. A., Worrell, E., De Jager, D., Blok, K. and Riemer, P. (2003), ‘Emission reduction of greenhouse gases from the cement industry’, IEA Greenhouse Gas R&D, p. 3. http://www.moleconomics.org/files/sustainability%20documents/EmissionReductionofGreenhouseGasesfromtheCementIndustry.pdf (accessed 16 Oct. 2017).
[111] Gartner and Sui (2017), ‘Alternative cement clinkers’.
[112] Lothenbach, B., Skrivener, K., Martin, N. and Hooton, R. D. (2011), ‘Supplementary cementitious materials’, *Cement and Concrete Research*, 41 (12): pp 1244–1256, http://www.sciencedirect.com/science/article/pii/S0008884610002632 (accessed 11 Oct. 2017).
[113] Thomas, M. (2013), *Supplementary Cementing Materials in Concrete,* Boca Raton: Taylor & Francis Group.
[114] Malhotra, V. M. and Mehta, P. K. (1996), *Pozzolanic and Cementitious Materials*, Netherlands: Gordon and Breach Publishers.
[115] European Standard (2000), *Cement – Part 1: Composition, specifications and conformity criteria for common cements*, http://www.holcim.az/fileadmin/templates/AZ/images/Technical_Solutions/EN-197-1_en.pdf (accessed 1 Mar. 2017).
[116] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

Ordinary Portland Cement (OPC) is a common type of cement consisting of >90 per cent ground Portland clinker and about 5 per cent gypsum. OPC is often referred to by different names: Portland cement or CEM I in Europe, PI or PII in China, and Portland cement Types I to V in the US.[117]

Composite and blended cement are cement types with a lower share of clinker than OPC (i.e. <90 per cent).[118]

High-blend cements are cements with >50 per cent clinker substitutes as a share of the cement mix.[119] This report sometimes also refers to these as low-clinker cements.

Low-carbon cements contain less or no Portland clinker, and therefore release fewer CO_2 emissions in production and may require less energy to produce.

Ternary cements or concretes are mixtures including three different cementitious materials – e.g. a ternary concrete might be made up of a combination of Portland cement, GBFS cement and fly ash cement.

Concrete is cement mixed with water to form a paste and filled with mineral aggregates such as sand and gravel.[120] Concrete has characteristics that vary according to the concrete mix and are influenced by the cement used. These differences are reflected in the different grades assigned to varying mixes.

Low-carbon concrete is concrete with fewer embodied CO_2 emissions than conventional Portland-cement concrete. This can mean that it contains less Portland cement and more clinker substitutes, or that it contains alternative-clinker cement.

Carbon-negative concretes are concretes that capture and store more CO_2 than is released during their production. These concretes are hardened by carbonation (using CO_2) instead of hydration (using H_2O) – i.e. they absorb CO_2 as they harden.

Aggregate is inert filler, e.g. sand, gravel or crushed stone, within a concrete mix.[121]

Chemical admixtures are chemicals added to a concrete mix immediately before or during mixing to modify the properties of the mix.[122]

Embodied carbon is the sum of the carbon requirements associated, directly or indirectly, with the delivery of a good or service. In the context of building materials, it is the sum of CO_2 equivalent or greenhouse gas emissions associated with the production of the material.

Operational carbon is the sum of the carbon requirements associated, directly or indirectly, with the operation of a good or service. In the context of buildings, it is the sum of CO_2 equivalent or greenhouse gas emissions associated with the operation (heating, cooling, powering) of a building.

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[117] World Business Council for Sustainable Development Cement Sustainability Initiative (2014), 'Glossary and Abbreviations'; Cemex (undated), *Educational guide to cementitious materials*.
[118] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan*.
[119] Ibid.
[120] Worrell, E., Price, L., Martin, N., Hendriks, C. and Ozawa Meida, L. (2001), 'Carbon dioxide emissions from the global cement industry', *Annual review of Energy and Environment*, 26: pp 303–329, https://www.researchgate.net/profile/Lynn_Price/publication/228756550_Carbon_Dioxide_Emission_from_the_Global_Cement_Industry/links/02bfe50e9f4105dc8c000000/Carbon-Dioxide-Emission-from-the-Global-Cement-Industry.pdf (accessed 16 Oct. 2017).
[121] Alexander, M. and Mindess, S. (2005), *Aggregates in Concrete*, New York: Taylor & Francis.
[122] Portland Cement Association (2017), 'Chemical Admixtures'.

Direct emissions are emissions of greenhouse gases from sources owned or controlled by the reporting entity. Examples include the emissions from cement kilns, company-owned vehicles, quarrying equipment, etc.[123]

Indirect emissions are emissions that are a consequence of the reporting entity's operations but that occur at sources owned or controlled by another entity. Examples include emissions related to purchased electricity, employee travel and product transport in vehicles not owned or controlled by the reporting entity, and emissions occurring during the use of products made by the reporting entity.[124]

Process emissions are defined as the portion of CO_2 emissions from industrial processes that involve chemical transformations other than combustion. In the context of cement, these are CO_2 emissions released by limestone as it is calcined in a cement kiln.[125]

Calcination process refers to changing the chemical composition of a material by a thermal process. In clinker production, limestone is calcined (i.e. heated) to form lime, one of the principal components of clinker.[126]

Note: Throughout this report we refer to 'Portland cement' or 'traditional Portland cement' to signify a set of cements with a Portland clinker content generally >70 per cent. This, therefore, encompasses, OPC, CEM I and most of the CEM II cements. When we refer to OPC, we specifically mean cement with a Portland clinker content >90 per cent. Throughout this report we refer to traditional cement clinker, i.e. clinker made in a conventional way with a high share (>60 per cent) of calcium silicates, as 'Portland clinker'.

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[123] World Business Council for Sustainable Development Cement Sustainability Initiative (2014), 'Glossary and Abbreviations'; Cemex (undated), *Educational guide to cementitious materials*.

[124] Ibid.

[125] International Energy Agency (2017), *Energy Technology Perspectives 2017*, p. 423.

[126] Worrell et al. (2001), 'Carbon dioxide emissions from the global cement industry'.

2. Research, Development and Deployment in the Cement and Concrete Sector

Key points

- Clinker substitution and replacement is a growth area for R&D. There has been a large increase in patenting activity in this technology area in recent years.
- Innovation in the sector has tended to occur in incremental steps rather than via radical breakthroughs. Research has focused on established clinker-based cement technology, seeking to increase clinker substitution rather than radically alter the mix of raw materials used.
- Most innovations have failed to reach commercialization, with supply- and demand-side barriers having prevented any from reaching widespread application. Rather than pointing to a single ‘silver bullet’, the patent analysis highlights a range of potential solutions that offer different prospects under different circumstances.

The cement and concrete sector displays a high level of patenting activity compared with other heavy industries

The cement and concrete sector is not often considered as innovative or fast-moving.[127] As discussed in Chapter 1, the capital intensity of production processes, the lack of consumer demand for new products, and concerns around ensuring safety contribute to a conservative approach. These factors help explain why the sector has proved hard to disrupt. Although data on R&D spending are sparse,[128] the information available suggests comparatively low R&D intensity in the sector compared to others.[129]

That said, the cement and concrete sector displays a high level of patenting activity compared with other heavy industries (see Figure 9). Relative to steelmaking, another industry with a reputation for being conservative,[130] the cement and concrete sector has seen a steady increase in the number of patents filed.

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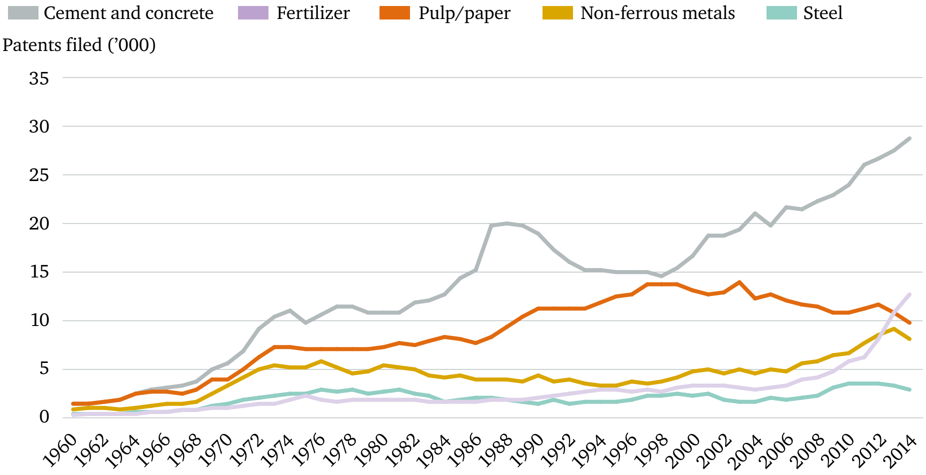
[127] Dewald and Achternbosch (2015), ‘Why more sustainable cements failed so far?’.

[128] A recent report by CDP, an organization based in the United Kingdom, which supports companies and cities to disclose the environmental impact of major corporations, drew attention to the lack of data on R&D spending: ‘Company disclosure on R&D spending and product development is currently inadequate to assess the extent to which companies are allocating their capital to benefit from a low-carbon transition.’ CDP (2016), Visible cracks, June 2016, https://b8f65cb373b1b7b15feb-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/cms/reports/documents/000/000/622/original/cement-report-exec-summary-2016.pdf?1470225644 (accessed 25 Apr. 2018).

[129] The average R&D intensity for eight cement companies included in the *2016 EU Industrial R&D Investment Scoreboard* was 1.2 per cent, versus 1.9 per cent for construction and materials more broadly and 4.3 per cent for oil and gas producers. European Commission (2016), *The 2016 EU Industrial R&D Investment Scoreboard*, http://iri.jrc.ec.europa.eu/scoreboard16.html (accessed 9 Feb. 2018).

[130] Rynikiewicz, C. (2008), ‘The climate change challenge and transitions for radical changes in the European steel industry’, *Journal of Cleaner Production*, 16 (7): pp. 781–789, doi: 10.1016/j.jclepro.2007.03.001 (accessed 12 Oct. 2017).

Figure 9: Patenting trends for heavy-industry sectors



Source: Compiled by authors.
Note: Cement and concrete patents gathered based on CPC code C04B;[131] steel patents gathered based on CPC code C21B; pulp/paper patents based on D21; non-ferrous metals patents based on C22B; and fertilizer patents based on C05. See Appendix 2 for more on the limitations of using CPC codes to analyse patents.

Only a fraction of these patents (approximately 4 per cent in 2014) are defined specifically as low-carbon technologies (under Cooperative Patent Classification (CPC) code Y02), but activity in this area has been rising and there are likely to be innovations that lie outside of the definition that contribute in some way to the overall efficiency of the cement and concrete sector.

Patenting in low-carbon cement technologies started from a low base in the 1970s but surged around 2008–09. This coincided with the introduction of stronger policies in key markets, including the start of Phase II of the EU Emissions Trading System (ETS); anticipation of a Copenhagen summit deal; and new source performance standards in the US for coal preparation and processing, including at cement plants.[132] Activity around clinker production, energy efficiency and CCS fell after 2009, in the wake of the Copenhagen climate summit (see Figure 10).

However, patenting around the reduction of clinker content in cement continues to rise. Not only has the number of patent filings related to this area increased rapidly in recent years, but the growth in such filings has outpaced that in other cement subsectors.

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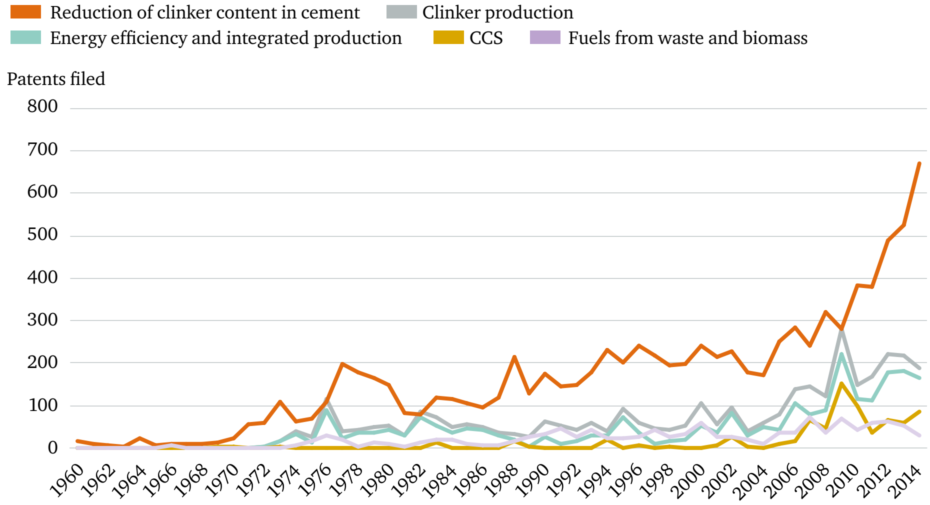
[131] Includes patents related to lime, magnesia, slag, cements and compositions thereof, e.g. mortars, concrete or like building materials, artificial stone, ceramics, refractories, treatment of natural stone.

[132] European Commission (2017), 'The EU Emissions Trading System (EU ETS)', https://ec.europa.eu/clima/policies/ets_en (accessed 12 Oct. 2017); Environmental Protection Agency (2008), *Amendments to Standards of Performance for Portland Cement Plants*, https://www3.epa.gov/airtoxics/nsps/pcemnsps/cement_fs.pdf (accessed 12 Oct. 2017).

Figure 10: Patenting trends for five low-carbon technology areas in the cement sector



Source: Compiled by authors.
Note: The following CPC codes were used for the technology areas: Y02P40/121 for energy efficiency and integrated production, Y02P40/12 for clinker production, Y02P40/14 for reduction of clinker content in cement, Y02P40/18 for CCS, and Y02P40/126 and 128 for fuels from waste and biomass. See Appendix 2 for more on the limitations of using CPC codes to analyse patents.

2.1 Research and development: clinker substitution and replacement

Incremental versus breakthrough innovation

Within the ‘clinker substitution and replacement’ space, research has largely focused on increasing clinker substitution and improving the efficiency of cement use in concrete through chemical admixtures, rather than on radically altering the mix of raw materials.[133] This can be seen in the technology subcategories displayed in Figure 11. Clinker-substitution technologies and chemical admixtures have more than double the patent families of alternative-clinker technologies. Waste and GBFS (both as SCMs) are the subcategories with the most patent families – 350 and 237 respectively.

These broad trends, however, mask the activity happening around new alternatives. These include: belite-rich Portland clinker (BPC), belitic clinkers containing ye’elimite (CSA), BYF clinkers, hydraulic and carbonatable calcium silicate clinkers (CCSC), and magnesium-based clinkers (including MOMS), all of which currently have between 20 and 30 patent families. Geopolymers stand out in the alternative-clinker technology area, making up the third-largest subcategory in the overall dataset. However, this level of activity is unsurprising considering that they have been the focus of research since the 1970s.[134]

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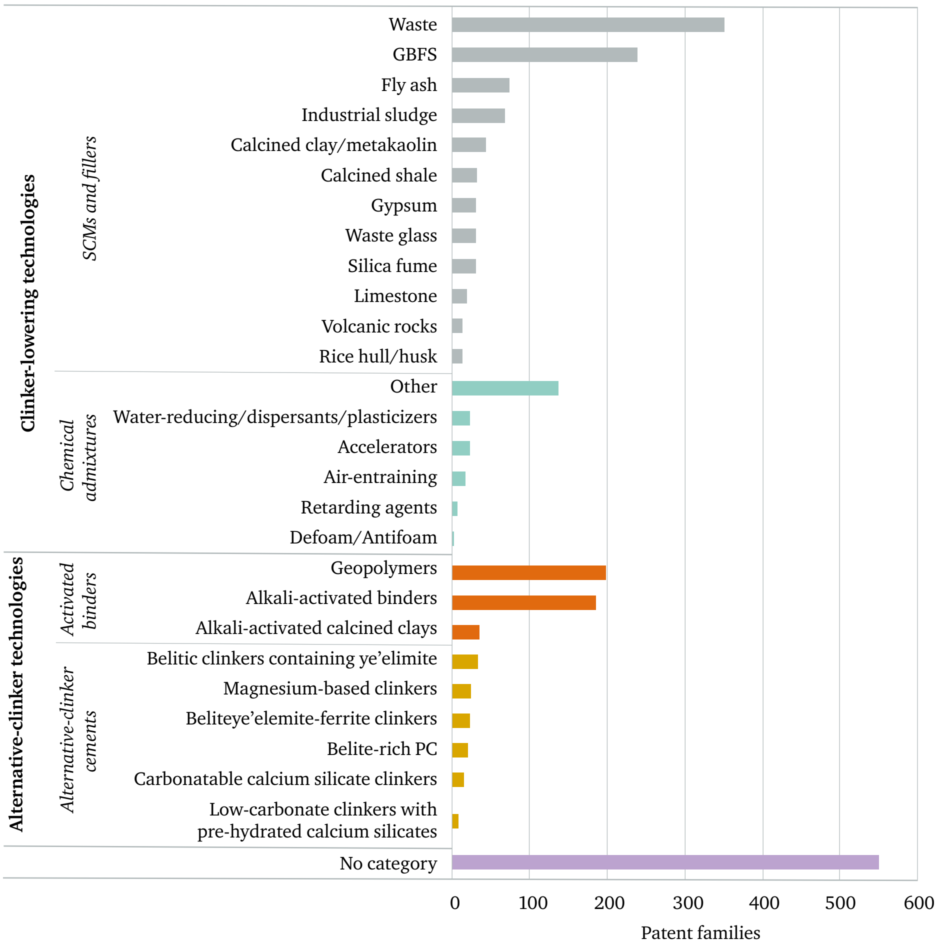
[133] Dewald and Achternbosch (2015), ‘Why more sustainable cements failed so far?’.
[134] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

Figure 11: Technology subcategories by number of patent families



Source: Compiled by authors.
Note: These categories are not mutually exclusive. In some cases, innovations refer to multiple materials or applications that may overlap with one or more of our subcategories. Around 24 per cent of the patents in the dataset do not fall into any of these categories. For information on the approach taken to disaggregate the subcategories, see Appendix 2.

Even within this group, one can distinguish gradations in the 'novelty' of products based on how far their compositions are from Portland cement. According to some experts, for example, BPC-based cement should not be considered a novel cement because it is still largely limestone-based, is covered by existing cement norms and has fairly low mitigation potential.[135] Meanwhile, magnesium-based cements, geopolymers and alkali-activated binders are non-limestone-based and have comparatively high mitigation potential (see Figure 7).

The lack of funding for R&D in cement and concrete,[136] and the lack of focus on industrial materials in the academic and research space more broadly, may partially explain this incremental approach to innovation.[137] Material scientists do not tend to work on concrete and instead focus on 'sexier' materials such as graphene.[138] The experts who do work on cement and concrete often come from the structural engineering end

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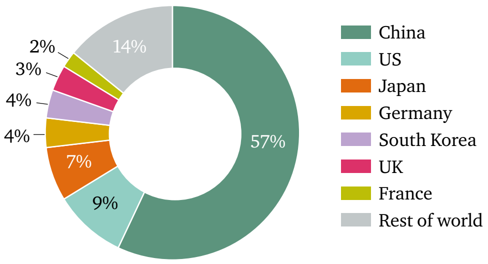
[135] Ibid.
[136] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[137] External workshop participant.
[138] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

of research and have not been specifically trained to focus on industrial materials. They are, moreover, often funded by the cement industry and may therefore be incentivized to keep their research within the current Portland cement-based research paradigm.[139]

A China story? The geographical distribution of patent ownership

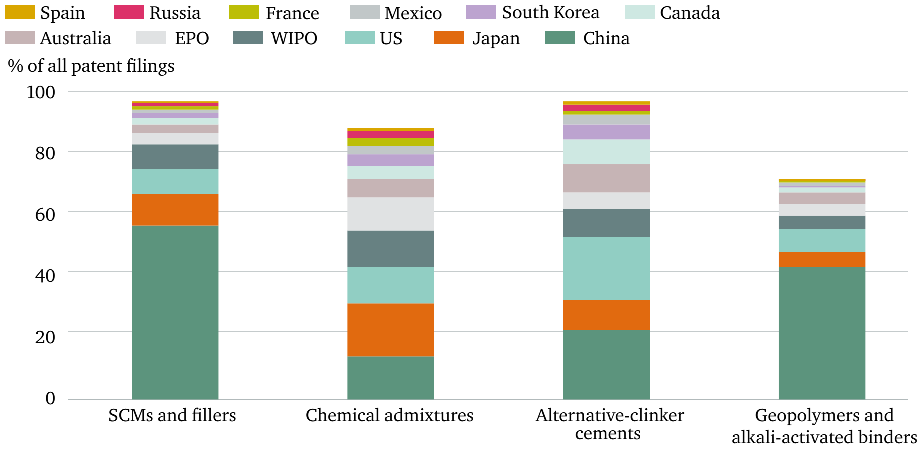
Over half of the patents in the search area are owned by Chinese companies and academic institutions (see Figure 12). The location of patent assignees generally provides an indication of where research activities are taking place. It can also be an indicator of the extent of local technological and innovation capacities. However, some of these patents might be registered by local subsidiaries of parent companies based in other countries, e.g. patents may be filed by a Chinese subsidiary of a global enterprise. LafargeHolcim, for example, has an R&D laboratory in Chongqing and a research partnership with the local university, which holds three patent families in the dataset.[140]

Figure 12: Share of patents by geographical origin



Source: Compiled by authors.

Figure 13: Share of patents by patent-filing location



Source: Compiled by authors.
Note: EPO is the European Patent Office. WIPO is the World Intellectual Property Organization. The technology subcategories in the patent-filing location chart are not mutually exclusive. In some cases, innovations refer to multiple materials or applications that may overlap with one or more of our subcategories. For information on the approach taken to disaggregate the subcategories, see Appendix 2.

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[139] Hutchinson (2016), 'The cement industry needs a breakthrough, now'.

[140] Lafarge (2011), 'Lafarge inaugurates its first sustainable construction development lab in Chongqing and signs alliance agreement with Chongqing University', media release, 28 September 2011, https://www.lafargeholcim.com/lafarge-inaugurates-its-first-sustainable-construction-development-lab-chongqing-and-signs-alliance (accessed 29 May 2017).

Companies generally choose to file patents in countries where they can see significant potential markets, rather than where they are physically located. In other words, each filing indicates the intent to sell, license or manufacture products containing the patented innovation, or to prevent others from doing so. Almost a third of all patent publications in the search area were filed in China (Figure 13). Most of these are again focused on clinker substitution, but there are also a disproportionate number of geopolymer and alkali-activated binder patents compared with other countries. This suggests that there may be a larger market for these novel cements in China than elsewhere.

Why is China so dominant? The following three factors are particularly significant.

- First is the size of its domestic cement market. China's building boom has been a key driver of global cement demand. The country accounted for 58 per cent of cement produced globally in 2015.[141]
- Second, market consolidation is resulting in the emergence of larger Chinese companies with meaningful R&D budgets and a greater capacity for innovation. Until recently, the market was largely supplied by 3,000 small players, with little or no research capacity, producing low-grade cement.[142] The China Cement Association has called for at least 60 per cent of the country's production capacity to be consolidated into 10 producers by 2020.[143]
- Third, there are strong drivers from China's public sector. R&D investment has risen from 0.9 per cent of GDP in 2000 to 2 per cent in 2015, and the government has launched several funds and programmes to encourage scientific research.[144] The authorities are also imposing tougher building requirements.[145]

The fact that China is a key innovation hub in this technology area is encouraging from a decarbonization perspective

Finally, some observers have expressed concern about the quality of patents currently being granted in China, given the recent drive by the government to boost patent applications and the potentially lower capacity (at least, historically) of patent examiners to evaluate large numbers of sometimes speculative patents.[146] Although this could be a significant factor, China's overall dominance in the dataset suggests that the underlying trend is a real one.

The fact that China is a key innovation hub in this technology area is encouraging from a decarbonization perspective, as the country is projected to continue to account for a major, if decreasing, share of global cement production.[147] However, given the growing markets in India and Asia-Pacific countries, R&D capacity and innovation dissemination in those regions will also be key.

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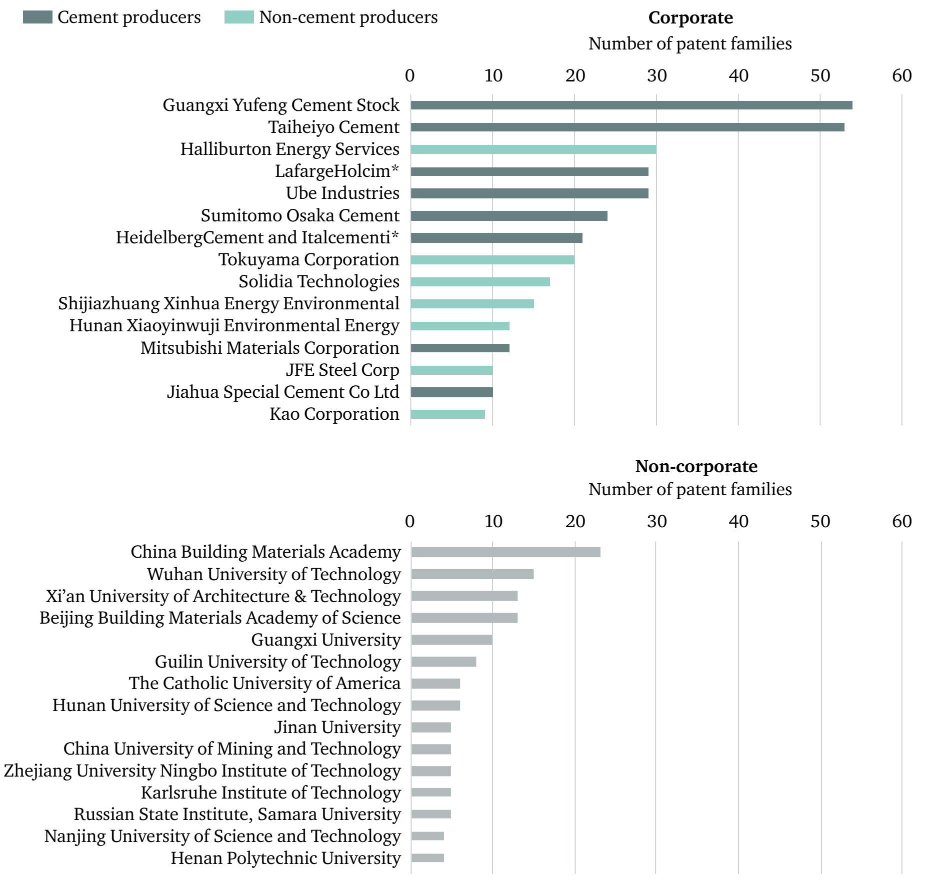
[141] Olivier et al. (2016), *Trends in global CO_2 emissions: 2016 Report*.
[142] Flannery, R. (2015), 'Innovation in China: Incinerating Waste May Ease A Big Cement Industry Shakeout', *Forbes Asia*, 24 June 2015, https://www.forbes.com/sites/russellflannery/2015/06/24/innovation-in-china-incinerating-waste-may-ease-a-big-cement-industry-shakeout/#69fa0cde3cac (accessed 29 May 2017).
[143] Global Cement (2016), 'China Cement Association asks government to speed up sector consolidation', 28 September 2016, http://www.globalcement.com/news/itemlist/tag/Consolidation (accessed 15 Oct. 2017).
[144] Gupta, A. and Wang, H. (2016), 'How China's Government Helps – and Hinders – Innovation', *Harvard Business Review*, 16 November 2016, https://hbr.org/2016/11/how-chinas-government-helps-and-hinders-innovation (accessed 15 Oct. 2017).
[145] Gov.cn (2008), 'China sets stricter construction standards for schools after earthquake', 27 December 2008, http://www.gov.cn/english/2008-12/27/content_1189560.htm (accessed 15 Oct. 2017).
[146] Kelion, L. (2016), 'China breaks patent application record', BBC News, 24 November 2016, http://www.bbc.co.uk/news/technology-38082210 (accessed 29 May 2017).
[147] Fernandez (2017), 'Industry Technology Roadmaps'.

Organizational mix

Ten organizations and companies account for 20 per cent of patents in the 'clinker substitution and replacement' space. Patents can be held by different types of actors, including multinational corporations, universities, government departments, small and medium-sized enterprises (SMEs) and individual inventors. Each type of assignee tends to pursue different patent-filing strategies, underpinned by its respective strategic objectives and access to resources.

Figure 14: Top 15 corporate and top 15 non-corporate assignees in search area



Source: Compiled by authors.
Note: Corporate players marked in green have no cement production portfolios.

* These companies' patent portfolios are shown together as they have merged/consolidated recently. However, the data largely stem from before their mergers.

Non-corporate assignees hold fewer patents than the top companies do (see Figure 14), but activity in the non-corporate space can be a good measure of public-sector – and in particular local-government – involvement in the innovation system. Twelve of the top 15 non-corporate assignees are Chinese universities and publicly funded research organizations. This speaks to the success of the Chinese government in promoting home-grown innovation and engineering capabilities.[148] The China Building Materials Academy holds 13 per cent of patents in the search area and is considered a world-class research institute.[149] This track record has been built up over decades and followed an initially disappointing attempt to rely on domestic innovation to design, engineer and construct rotary kilns in the late 1970s.[150]

This growing innovation and technological capacity is also reflected in the international success of China's top cement producers. Sinoma International, for example, a publicly traded enterprise[151] that holds two patent families in the dataset, has been hugely successful. It holds a significant share of the Chinese market and has built plants in several overseas markets. Sinoma has pursued a different business model to those of its OECD competitors, focusing on offering a complete line of services from design to manufacture, installation, commissioning and operation of new production lines.[152] It is set to merge with China National Building Material (CNBM), the largest Chinese producer and the third-largest globally, as part of the government's consolidation plans.[153]

Two of the major producers outside China, LafargeHolcim and HeidelbergCement, are among the top assignees in novel-clinker production and substitution processes. There is a contrast here with the view of experts that these companies are not deriving significant monetary or strategic advantage from their patents.[154] If so, what explains this level of activity? One explanation is that management is pushing for new patents, even where the researchers involved see the process as unnecessarily costly and time-consuming. Some large firms and technology providers are reviewing their patent portfolios to make more strategic decisions on where to invest in patents.[155] Figure 15 reveals some diversity in patenting strategy across cement producers.

In contrast, the value of intellectual property protection for technology companies is relatively clear. Their patent portfolios can play an important role in attracting investment and securing interest from major cement producers, which ultimately buy their products or services. Halliburton Energy Services and Solidia Technologies are examples of top assignees that do not produce cement but instead provide technology or other services to firms that do.

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[148] Veugelers, R. (2017), 'China is the world's new science and technology powerhouse', Bruegel, 30 August 2017, http://bruegel.org/2017/08/china-is-the-worlds-new-science-and-technology-powerhouse/ (accessed 15 Oct. 2017).

[149] Industrial Efficiency Technology Database (2017), 'China Building Materials Academy (CBMA)', http://ietd.iipnetwork.org/content/china-building-materials-academy (accessed 15 Oct. 2017).

[150] Rock, M. T., Toman, M., Cui, Y., Jian, K., Song, Y. and Wang, Y. (2013), 'Technological Learning, Energy Efficiency, and CO_2 Emissions in China's Energy Intensive Industries', *The World Bank Development Research Group Policy Research Working Paper 6492*, p. 10, http://documents.worldbank.org/curated/en/548931468219309535/pdf/WPS6492.pdf (accessed 15 Oct. 2017).

[151] Although it is subject to the State-owned Assets Supervision and Administration Commission of the State Council (SASAC).

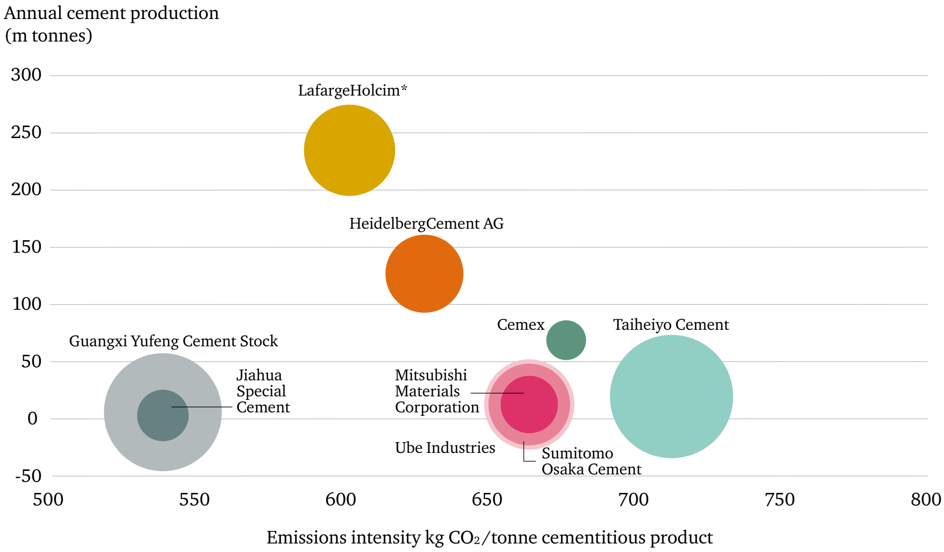
[152] Rock, M. T. and Toman, M. (2015), *China's Technological Catch-Up Strategy: Industrial Development, Energy Efficiency and CO_2 Emissions*, New York: Oxford University Press.

[153] Ng, E. (2017), 'China giants CNBM and Sinoma merge to become world's largest cement maker, eye Silk Road growth', *South China Morning Post*, 6 December 2017, http://www.scmp.com/business/companies/article/2123161/china-cement-giants-cnbm-and-sinoma-eye-expansion-belt-and-road (accessed 1 Mar. 2018).

[154] Internal workshop participant; expert interview.

[155] Expert interview.

Figure 15: Cement producers: top assignees by production volume and emissions intensity



Source: Production and emissions intensity data for LafargeHolcim, HeidelbergCement and Cemex, and emissions intensity data for Taiheiyo from Kisic, M., Ferguson, C., Clarke, C. and Smyth, J. (2018), *Building Pressure: Which companies will be left behind in the low-carbon transition?*, CDP Report, http://b8f65cb373b1b7b15feb-c70d8ead6ced550b4d987d7c03fcdd1d.r81.cf3.rackcdn.com/cms/reports/documents/000/003/277/original/Cement_Report_Ex_Summary.pdf?1523261813 (accessed 27 Apr. 2018). Production data for Taiheiyo from: CDP (2016), *Visible cracks*. Emissions intensity and cement production values for the other six companies based on various sources.[156]

Note: Size of bubble represents number of patents held in search area. LafargeHolcim's 2016 production data is a sales figure. The emissions intensity data for LafargeHolcim, HeidelbergCement, Taiheiyo and Cemex are averages of 2015 and 2016 figures.

* These companies' patent portfolios are shown together as they have merged recently. However, the data largely stem from before their mergers.

A number of the SMEs active in this space are not among the top corporate assignees but deserve mention for their low- and alternative-clinker cement products (see Table 2). Ecocem, EMC, Celitement, Zeobond and banahUK have developed alternative cement products that contain a small fraction of the embedded carbon of OPC. Many of these new products sequester carbon.

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[156] National emissions intensity factors for these companies were not available. Emissions factors are therefore based on national-level data. For China the emissions intensity figures are taken from Andrew, R. (2018), 'Global CO_2 emissions from cement production', *Earth System Science Data*, 10: pp. 195–217, doi: 10.5194/essd-10-195-2018 (accessed 9 May 2018). For Japan the emissions intensity figure comes from World Business Council for Sustainable Development (2009), *Cement Industry Energy and CO2 Performance: "Getting the Numbers Right"*, http://www.wbcsdcement.org/pdf/CSI%20GNR%20Report%20final%2018%206%2009.pdf (accessed 9 May 2018). Production data for Mitsubishi from Mitsubishi Materials (2016), *Annual Report: Challenge to become the World's Leading Business Group*, http://www.mmc.co.jp/corporate/en/ir/pdf/annual2016.pdf (accessed 27 Apr. 2018). Production data for Sumitomo Osaka from Sumitomo Osaka Cement (2015), *Annual Report*, http://www.soc.co.jp/wp-content/themes/soc/img/ir/document/document05/annual_report_2015.pdf (accessed 27 Apr. 2018). Production data for Ube Industries from US Geological Survey (2012), *Minerals Yearbook Area Report: International 2012*, Washington D.C.: US Geological Survey. Production data for Guangxi Yufeng from Gmdu.net (2018), Guangxi Yufeng Cement Stock Company Ltd., https://www.gmdu.net/corp-474104.html (accessed 27 Apr. 2018). Production data for Jiahua Special Cement from Xu, Y., Du, Y. Zeng, Y. and Li, S. (2012), 'Flexible Manufacturing of Continuous Process Enterprises with Large Scale and Multiple Products', *Technology and Investment*, 4(1): pp. 45–56, doi: 10.4236/ti.2013.41006 (accessed 9 May 2018).

Table 2: Smaller companies active in the 'clinker innovation' space

Technology		Company	Patent families*	Claimed mitigation potential**	Status of company/technology
Low-clinker cements	GBFS	Ecocem	1	70%[i]	Growing, recently increased its export capacity.[ii]
	Natural pozzolans	EMC	4	>90%[iii]	Active on a small scale. Various projects have used EMC cement, mainly in Texas.[iv]
Alternative-clinker cements	Geopolymer	Zeobond	2*	80–90%[v]	Growing, used in niche markets, primarily Australia and South Africa.[vi]
	Geopolymer	banahUK	1	80%[vii]	Active, received investments for a pilot plant that came online in 2016.[viii]
	Hydraulic calcium silicate clinkers	Celitement	5	>50%[ix]	Active, recently finished a three-year research period in collaboration with Germany's Federal Ministry of Education and Research.[x]
	Magnesium-based	Novacem	2*	>100%[xi]	Defunct, assets liquidated in September 2012.[xii]
CO_2-cured concretes	Low-clinker and mineral carbonation	Solidia	17	70%[xiii]	Growing, currently mainly used in precast products.[xiv]
	Mineral carbonation	CarbonCure	11	5%*[xv]	Growing, but mainly in smaller markets in the US. Approx. 60 concrete producers have partnered with CarbonCure.[xvi]
	Calcium carbonate-based	Calera	2		Active, but pursuing lower-ambition applications.[xvii]
	Accelerated-carbonation technology	Carbon 8			Active, but in smaller markets. Developing a plant in Leeds, UK, to be completed in 2018, and partnering with Grundon Waste Management.[xviii]
	Carbonate aggregates	Blue Planet	3*[xix]		Early stage, still looking to demonstrate technology.[xx]

Sources: For sources, see Appendix 4.

Note: * Not in our focus area patent dataset. ** The figures for mitigation potential are taken from the respective company website or literature. They are therefore unlikely to be directly comparable across rows, as each figure is likely to have a different benchmark/different boundaries.

Progress on R&D

The cement sector's reputation as a slow mover might be unfair in terms of R&D, and patents on lower-carbon cement and clinker substitution have been on the rise. However, research efforts have largely remained within the current Portland cement-based research paradigm.

This reflects the conservative approach to innovation in the sector and more broadly low R&D capacity. LafargeHolcim excepted, few large cement producers have major centralized research efforts,[157] and R&D finance for cement and concrete innovation is sparse. The cement sector also suffers from a 'low-tech' image, making it more difficult to recruit young material scientists and engineers.[158]

A considerable push is required to get the next generation of low-carbon cements out of the laboratory and into the market. Not all will succeed, but those that do might have significant decarbonization potential. Many novel cements are stuck in the research, pilot and demonstration stages (see Table 3); their economic viability and long-term sustainability thus remain unproven. None have scaled up sufficiently to make it possible to assess whether they can deliver their stated mitigation potential.

Table 3: Low-carbon cements at different stages of the innovation cycle

Phase	Technology	Examples
Research phase	Magnesium-based cements	Novacem
Pilot phase	Cements based on carbonation of calcium silicates (CCSC)	Solidia Cement, Calera
Demonstration phase	Low-carbonate clinkers with pre-hydrated calcium silicates	Celitement
	BYF clinkers (subset of CSA clinkers)	Aether
Commercialized	Cements with reduced clinker content (high-blend cements)	LC3, CEMX, L3K, Ecocem
	Geopolymers and alkali-activated binders	banahCEM, Zeobond cement
	Belite-rich Portland clinkers (BPC)	
	Belitic clinkers containing ye'elimite (CSA)	

Source: Authors' analysis expanding on box in International Energy Agency (2017), *Energy Technology Perspectives 2017* and analysis in Gartner and Sui (2017), 'Alternative cement clinkers'.

Despite significant investment in BYF clinkers, for example, these have not progressed past the R&D stage (see Appendix 3).[159] Today they are too expensive, due to the cost of their raw materials. But these costs might be brought down, through additional research and economies of scale, to a level at which BYF clinkers can compete with Portland clinker.[160]

Similarly, there is still excitement around carbon-negative, magnesium-based cements, but these are still in the early stage; pioneer company Novacem folded before viability could be demonstrated (see Appendix 3). Here, emissions mitigation potential depends on the source of magnesium.[161] Using magnesium carbonates would emit CO_2 much like limestone, but using carbon-free ultramafic rock (magnesium silicates) would drastically reduce CO_2 emissions. Unfortunately, there is no publicly disclosed energy-efficient industrial process for manufacturing magnesium oxides derived from magnesium silicates (MOMS).[162]

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[157] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[158] Ibid.
[159] Cembureau (2017), *Innovation in the Cement Industry*, https://cembureau.eu/media/1225/10819_cembureau_innovationbooklet_eu-ets_2017-02-01.pdf (accessed 15 Oct. 2017).
[160] Gartner and Sui (2017), 'Alternative cement clinkers'.
[161] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[162] Gartner and Sui (2017), 'Alternative cement clinkers'.

Carbonatable calcium silicate clinkers (CCSC) are also still in the R&D phase, but several companies are active in this area. The close commercial collaboration between Solidia and LafargeHolcim, in particular, suggests that this technology may be commercialized soon. CCSC generally face few raw material challenges, as they are manufactured from the same materials as Portland cement. One of the main limitations is the fact that this technology requires a concentrated source of CO_2, while the market for CO_2 is yet to be developed. CCSC also require a controlled setting in which to cure the concrete. At present this technology is limited to precast concrete products, which account for around 20–30 per cent of concrete applications in Europe and a lower share in the US, limiting the overall emissions mitigation potential.[163]

Low-carbon cements could benefit from additional public funding and from broader efforts to counteract the low-tech image of the industry

These low-carbon cements could benefit from additional public funding and from broader efforts to counteract the low-tech image of the industry. Imperial College London is among those institutions redefining how industrial materials are taught, bringing together experts from different disciplines.[164] Incubators and accelerators also have a role to play in building up innovation capacity in a sector that so far has failed to attract substantial amounts of venture capital.[165] LafargeHolcim has launched a start-up accelerator to improve its access to innovative solutions.[166]

There is also a need to explore collaborative models for innovation. Co-assignment of patents, i.e. cases in which more than one organization is listed as an owner of a patent, can be one indicator of cooperative innovation activity. Only 4.5 per cent of patents in our dataset are co-assigned. A large proportion of these are co-assigned within the same group of Chinese institutions and state entities. This suggests that cooperation between companies and countries on technology development in this area is fairly limited.

Intellectual property rights can act as a barrier to cooperation: a reluctance to share intellectual property can, for example, prevent cooperation on demonstration projects; or a concentration of patent ownership in one company can lead to blockage or monopolistic behaviour. In the case of low-clinker and novel cements, however, this does not appear to be a key factor. As highlighted above, companies are not deriving significant monetary or strategic advantage from their patents. Experts suggest that patents on cement materials and compositions are difficult to protect and less important for a company's profit margin than patents on production processes such as kiln design.[167] What is more likely is that the lack of cooperation reflects a natural reluctance to collaborate in a sector in which companies have had multiple brushes with antitrust legislation.

There are a number of tried and tested ways of encouraging increased cooperation on innovation: joint-venture companies, cross-training programmes, cross-licensing arrangements and joint manufacturing programmes. The research network Nanocem, founded in 2004, has shown the value of collaboration where there is a range of

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[163] Neeraj Jha, K. (2012), *Formwork for Concrete Structures*, New Delhi: Tata McGraw Hill Education Private Limited. p. 409.
[164] External workshop participant.
[165] Young, B. (2016), 'Why Venture Capital Will Revolutionize Construction', LinkedIn, 7 September 2016, https://www.linkedin.com/pulse/why-venture-capital-revolutionize-construction-brett-young (accessed 25 Feb. 2018).
[166] Global Cement (2017), 'LafargeHolcim to host innovation start-ups at Lyon Research and Development Centre', 10 February 2017, http://www.globalcement.com/news/item/5786-lafargeholcim-to-host-innovation-start-ups-at-lyon-research-and-development-centre (accessed 2 Oct. 2017).
[167] Expert interview.

technical difficulties to crack.[168] Nanocem brings together academic and industrial partners to research new materials and products. Project Aether brought together a public–private consortium to collaborate on industrial trials and deployment of LafargeHolcim's BYF clinker, Aether.[169] More broadly, cement companies have also been very active in partnering on the development of CCS technology.

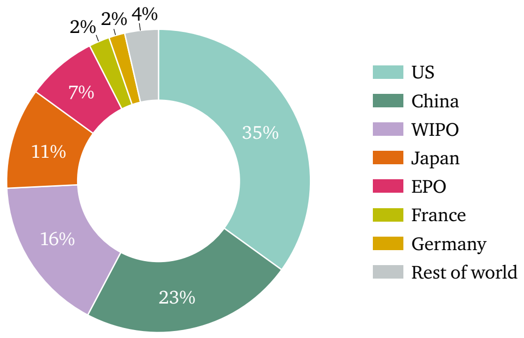
2.2 Technology deployment and diffusion: clinker substitution and replacement

For already commercialized technologies (see Table 3), a clearer understanding is needed of rates of adoption and diffusion. This is difficult to measure directly, but one commonly used proxy is the forward citation of patents, i.e. where a new patent cites a previous patent that it builds on.[170] In most sectors only a small number of patents receive the bulk of citations by future patents. These are sometimes called 'foundational', as they are important for many subsequent innovations. Forward citations therefore indicate a diffusion of knowledge, and in some cases may suggest that a novel approach has become widely adopted.

The most-cited patents in the search area include the following:

- **Patents for the use of conventional clinker substitutes** – for example, patents filed for high-blend cement compositions containing GBFS or for the use of ash and clays as clinker replacements.
- **Patents for methods to facilitate the use of conventional clinker substitutes** – e.g. a patent filed in 2003 by Taiheiyo for a method to remove unburned carbon in fly ash.
- **Patents for high-value niche applications of advanced cement** – e.g. patents assigned to Halliburton Energy Services for compositions comprising water, cement kiln dust and additives for use in, among other places, oil and gas wells.

Figure 16: Patent offices by number of forward citations



Source: Compiled by authors.

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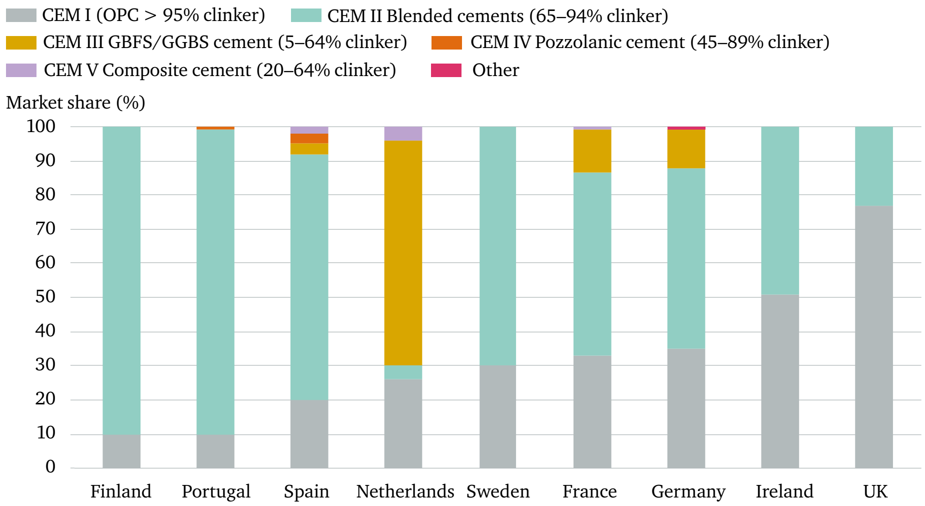
[168] Nanocem (2018), 'Introduction, overview and focus on fundamentals about Nanocem', http://www.nanocem.org/about-us (accessed 21 Jan. 2018).
[169] Aether Cement (undated), 'Lower Carbon Cements', http://www.aether-cement.eu/consortium.html (accessed 1 Jun. 2017).
[170] Cox, A. (2016), 'Using citation analysis to value patents', *Financier Worldwide Magazine*, Special Report: Intellectual Property, January 2016, https://www.financierworldwide.com/using-citation-analysis-to-value-patents/#.WePGRNOGNE4 (accessed 15 Oct. 2017).

The US accounts for just over a third of the widely cited patents in the search area, followed by China (just under a quarter) and Japan (around one-tenth) (see Figure 16). This can, in part, be explained by the fact that it takes time for patent citations to accumulate and for awareness of a given patent to trickle through to patent filers and examiners, which favours jurisdictions with long track records, including the US, Japan and the EU. In contrast, high levels of Chinese patents are a more recent phenomenon.

An alternative way to look at the adoption of clinker-substitution technologies and novel cements is to look at the market share of different types of cements in different regions. Freely available data on this are limited. However, the data available suggest that sales of high-blend cements are highest in Japan and Europe. In Japan, GBFS cements make up around 30 per cent of the cement market.[171]

Data for Europe from 2007 (see note, Figure 17) suggest that growing shares of blended cements are being used in many countries in the region. CEM II cements, in particular, which are blended cements in which up to 35 per cent of the overall mix consists of clinker substitutes (mostly limestone, slag and fly ash), make up the bulk of the market in six of the nine countries considered.

Figure 17: Market shares for different cement types in European countries, 2007



Source: Authors' analysis based on data from Cembureau (2013), *Cements for a low-carbon Europe*, https://cembureau.eu/media/1501/cembureau_cementslowcarboneurope.pdf (accessed 21 Jan. 2018).

Note: Although more recent data are available for some countries, 2007 was the most recent year for which data were available across all the countries considered.

However, lower-clinker cements (CEM III, IV and V) still only account for small shares of the market in the majority of countries. An exception is the Netherlands, where historical experience of using slag in cement for building canal locks, as well as favourable regulations, has encouraged the use of higher-blend cements.[172] Although the European

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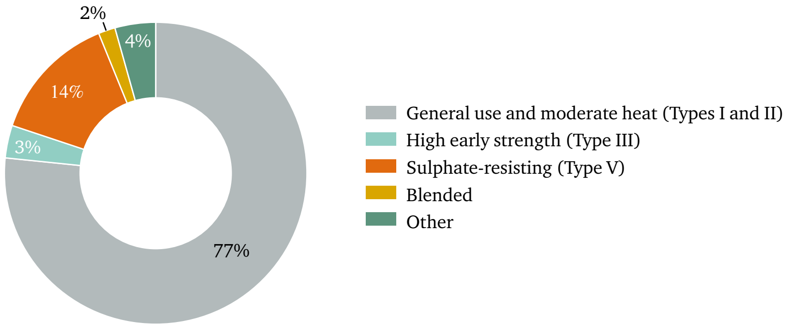
[171] Edwards, P. (2016), 'Lower SCM supplies demand a change in approach', *Global Cement,* 30 September 2016, http://www.globalcement.com/magazine/articles/994-lower-scm-supplies-demand-a-change-in-approach (accessed 9 Feb. 2018).

[172] Kemp, R., Bartekova, E. and Turkeli, S. (2017), 'The innovation trajectory of eco-cement in the Netherlands: A co-evolution analysis', *International Economics and Economic Policy*, 14: pp. 409–429, doi: 10.1007/s10368-017-0384-4 (accessed 16 Oct. 2017).

cement standard EN 197-1 specifies 27 different types of cement, only a few are sold at scale.[173] And, while Portland clinker replacement is permitted up to a level of 95 per cent (in CEM III), actual replacement levels do not near 50 per cent.[174]

Moreover, blended cements account for an even smaller share of the market in other regions (see data for the US in Figure 18). This suggests that, while clinker substitution is on the rise and related innovations are being deployed, the deployment of low-clinker cements is not yet happening at scale.

Figure 18: Market shares for different types of cement in the US, 2014



Source: Authors' analysis based on data from US Geological Survey (2017), *2014 Minerals Yearbook: Cement [Advance Release]*, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2014-cemen.pdf (accessed 5 Jan. 2018).

Data on the use of novel cements are even more limited than for blended cements. However, existing research indicates that, although some innovations in this area have been discussed for more than a decade within the research community, none have broken through to widespread adoption.[175] Where they are deployed, this tends to be in niche applications:[176]

- Belite-rich Portland clinkers have mainly been used in the construction of large concrete dams in China.[177]
- Belitic clinkers containing ye'elimite (CSA) have been used in niche applications in China since the late 1970s.[178] Estimates suggest that less than 2 million tonnes are produced annually.[179]

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[173] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[174] Sandbag (2017), *The Cement Industry of the Future: How Border Adjustment Measures Can Enable the Transition to a Low-Carbon Cement Industry*, https://sandbag.org.uk/wp-content/uploads/2017/01/170117-Cement-and-BAM-Digital-upd.pdf (accessed 11 Feb. 2017).
[175] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'; Calkins, M. (2017), 'Concrete Minus Carbon', *Landscape Architecture Magazine*, 25 July 2017, https://landscapearchitecturemagazine.org/2017/07/25/concrete-minus-carbon/ (accessed 1 Oct. 2017).
[176] Kemp, Bartekova and Turkeli (2017), 'The innovation trajectory of eco-cement in the Netherlands'; Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[177] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[178] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'; Hutchinson (2016), 'The cement industry needs a breakthrough, now'.
[179] European Cement Research Academy and Cement Sustainability Initiative (2017), *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead: CSI/ECRA Technology Papers 2017*, Düsseldorf, Geneva: European Cement Research Academy, https://www.wbcsdcement.org/pdf/technology/CSI_ECRA_Technology_Papers_2017.pdf (accessed 25 Apr. 2018).

- Geopolymers have been a focus of research since the 1970s. They have been used in Australia in roads, paving and panels in bridges,[180] and most recently in an airport.[181] Several producers also operate in Brazil, India, Ukraine and the US.

2.3 Barriers to diffusion

Technologies take a long time to get from laboratory to market in many sectors. However, low-carbon cements seem to face particular challenges. Why are these products and processes not reaching widespread application? The key barriers to deployment can be divided into supply-side and demand-side barriers, based on where they occur in the value chain and which actors they affect.

Supply-side barriers

Technologies take a long time to get from laboratory to market in many sectors. However, low-carbon cements seem to face particular challenges

A major concern of cement producers is the ‘stranding’ of assets: i.e. that clinker substitution and novel cements, if rapidly scaled, could significantly decrease demand for Portland clinker, lowering the value of thousands of clinker production installations (and hence of the companies that own them). In order to protect their position, cement producers may therefore be reluctant to pioneer innovations that would reduce the amount of Portland clinker needed.[182]

As a result, the players most able to test and leverage novel cements may lack the incentive to do just that.[183] Although several major cement companies have invested in R&D in this area, some of the SMEs discussed have struggled to attract greater industry participation and engagement in the development of their innovations.[184] Established firms have a natural incentive to keep the market as it is and/or to keep any innovation in-house.[185]

The second key supply-side factor is the availability of raw materials. To be able to displace large amounts of Portland clinker, alternative products have to be produced in large amounts, which is only possible if their raw materials are also available in sufficient volume and quality. While a few large cement producers own their own clinker supply chains,[186] elsewhere the availability and quality of these materials are often outside of the control of producers.

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[180] Van Deventer, Provis and Duxson (2012), ‘Technical and commercial progress in the adoption of geopolymer cement’.
[181] Wagners (2018), ‘Australia’s Newest Airport’, http://www.wagner.com.au/main/what-we-do/earth-friendly-concrete/efc-home (accessed 9 Feb. 2018).
[182] Hutchinson (2016), ‘The cement industry needs a breakthrough, now’.
[183] Ibid.
[184] Van Deventer, Provis and Duxson (2012), ‘Technical and commercial progress in the adoption of geopolymer cement’.
[185] Wesseling, J. H. and Van der Vooren, A. (2017), ‘Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands’, *Journal of Cleaner Production*, 155: pp. 114–124, doi: 10.1016/j.jclepro.2016.08.115 (accessed 16 Oct. 2017).
[186] LafargeHolcim produces large volumes of slag in North America. United States Geological Survey (2017), *2014 Minerals Yearbook: Cement [Advance Release]*.

Moreover, the future supply of two of the most-used clinker substitutes is in question.[187] Fly ash and blast furnace slag are by-products of coal combustion and iron and steel production respectively. In Europe, the local availability and quality of fly ash is decreasing as coal-fired power plants are phased out.[188] Blast furnace slag faces a slightly different issue. Steel production is projected to increase in line with cement production, but rising recycling levels and the adoption of scrap-based electric-arc furnaces in the steelmaking sector are affecting the quantity of blast furnace slag available.[189] Geopolymers and alkali-activated binders also rely on supplies of fly ash and blast furnace slag. Not only are these supplies diminishing, but those that exist are already largely used as clinker substitutes.[190]

A third factor is cost. In the absence of policy pressure, an alternative cement product has to be able to generate a similar economic value to that of Portland cement in order to appeal to cement manufacturing companies. However, the switch to alternative products may raise material and energy costs, or require additional investments in storage capacity and technical equipment for handling and processing the new materials. This factor varies considerably depending on the material in question and its local availability. The use of silica fume as a clinker substitute, for example, is limited by its high cost (see Table 4).[191] In contrast, in many cases fly ash, blast furnace slag and limestone can reduce costs for cement and concrete producers.[192]

Similarly, the potential expense of using a novel cement is highly contingent on the local availability of its constituent materials. CSA clinkers often rely on bauxite, a relative scarce metal that has rival uses in aluminium production.[193] A CSA clinker can cost 60 per cent more than Portland cement if bauxite shipping costs are high.[194] However, if cheap bauxite waste is available locally, this can bring the costs down.[195] Often the costs associated with the production of novel cements are exacerbated in the absence of widespread deployment and therefore economies of scale.

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[187] Miller, Horvath and Monteiro (2016), 'Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%'.

[188] Roderick Jones, M., Sear, L. K. A., McCarthy, M. J. and Dhir, R. K. (2006), *Changes in Coal Fired Power Station Fly Ash: Recent Experiences and Use in Concrete*, Conference paper presented at Ash Technology Conference, 15–17 May, http://www.ukqaa.org.uk/wp-content/uploads/2014/02/AshTech-2006-Jones-et-al.pdf (accessed 16 Oct. 2017); Department for Business, Energy & Industrial Strategy (2017), 'Fly Ash and Blast Furnace Slag for Cement Manufacturing', BEIS research paper no. 19, September 2017, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/660888/fly-ash-blast-furnace-slag-cement-manufacturing.pdf (accessed 8 Jan. 2018).

[189] International Energy Agency (2017), *Energy Technology Perspectives 2017*.

[190] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

[191] Edwards (2016), 'Lower SCM supplies demand a change in approach'.

[192] Cancio Diaz, Y., Sanchez Berriel, S., Heierli, U., Favier, A. R., Sanchez Machado, I. R., Scrivener, K. L., Martirena Hernandez, J. F. and Habert, G.] (2017), 'Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies', *Development Engineering*, 2(2017): pp. 82–91, doi: 10.1016/j.deveng.2017.06.001 (accessed 25 Apr. 2018).

[193] Gartner and Sui (2017), 'Alternative cement clinkers'.

[194] Hanein, T., Galvez-Martos, J. and Bannerman, M. (2018), 'Carbon footprint of calcium sulfoaluminate clinker production', *Journal of Cleaner Production*, 172: pp. 2278–2287, doi: 10.1016/j.jclepro.2017.11.183 (accessed 25 Jan. 2018).

[195] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

Table 4: Raw material inputs – costs and availability

Material	Price range ($/tonne)*	Estimated use (mt/y)**	Estimated availability	Rival uses
Limestone filler	~3[i]	300[ii]	Virtually unlimited[iii]	Yes
Fly ash (Class F)	~35–110[iv]	300[v]	600–900[vi] mt/y, variable quality and availability[vii]	Yes
Slag (GBFS)	<1–110[viii]	~290[ix]	480–560[x] mt/y, variable quality and availability	Yes
Clay	13 (for common clay)[xi] 150 (for kaolin)[xii] 600–700 (for metakaolin)[xiii]	2–3[xiv]	Clays are widely available, but supply of calcined clays, which require process facilities allowing their calcination, is more limited[xv]	Yes
Natural pozzolans, e.g. volcanic ash	35–90[xvi]	75[xvii]	Plentiful but localized[xviii]	
Silica fume	300–1,100[xix]	>1[xx]	1–2.5[xxi] mt/y	
Bauxite	~29–180[xxii]	100–150 (figure for bauxite waste)[xxiii]	55–75 bt[xxiv] but the bulk is already used for aluminium production	Yes
Rice husk	No data	No data	22 mt/y[xxv]	Yes

Sources: Authors' own analysis. For sources see Appendix 4.
Note: mt = million tonnes; bt = billion tonnes; y = year.

* Will vary greatly depending on location and transportation needs.
** Use as a clinker substitute will vary greatly depending on logistics required for extraction and the quality of the material available locally.

Demand-side barriers

Even in cases where cement producers could easily supply lower-carbon cements and concretes, they are not being asked to do so. Customers perceive novel products as too risky, more costly and more difficult to use.

One of the key barriers on the demand side is the impact of clinker substitution and novel cements on characteristics of concrete. High-blend cements often have lower early strength development in concrete and exhibit longer setting times than Portland cement.[196] Under normal circumstances, contractors generally like to cast concrete in the afternoon and de-mould it the next morning.[197] A high-blend cement can slow this process considerably.

A further barrier is the current lack of understanding of the technical performance of high-blend and novel concretes over time. Testing is generally needed to establish the effects of clinker substitutes and novel cements on the behaviour of concrete. However, current testing procedures were designed with Portland cement in mind, limiting their applicability to alternatives.[198]

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[196] National Institute of Standards and Technology US Department of Commerce (2017), 'Measurement Science to Assure the Performance of Innovative Concretes', https://www.nist.gov/programs-projects/measurement-science-assure-performance-innovative-concretes (accessed 12 Oct. 2017).
[197] Crow, J. M. (2008), 'The concrete conundrum', *Chemistry World*, March 2008, http://www.rsc.org/images/Construction_tcm18-114530.pdf (accessed 28 Feb. 2018).
[198] Van Deventer, Provis and Duxson (2012), 'Technical and commercial progress in the adoption of geopolymer cement'; National Institute of Standards and Technology US Department of Commerce (2017), 'Measurement Science to Assure the Performance of Innovative Concretes'.

The time needed to assess the durability of a concrete is a particular issue.[199] Most tests consist of exposing small samples to extreme conditions for short periods. Extrapolations are then made as to how well that concrete will perform under normal conditions over decades. However, these tests are only indicative, and it is generally still considered necessary to wait two to three decades before the durability of a concrete can be fully assessed.[200] Most of the products discussed have not been around for long enough to have accumulated the decades of in-service testing data required to 'prove' their durability. In the absence of certainty, customers are generally unwilling to experiment with novel cements and clinker substitutes apart from in niche or low-risk applications.[201]

Engineers, contractors, builders and architects are understandably wary of changes in a product that has to ensure safety often over decades

Concerns over the impact of novel materials on concrete, particularly on early strength development and durability requirements, are one reason why cement and concrete standards tend to be prescriptive, meaning that they dictate the composition required for a cement or concrete to fulfil criteria for specific applications. In most international standards, Portland clinker substitution is limited to 35 per cent, apart from for cements that are blended with slags, where 65 per cent of the Portland clinker can be replaced.[202] New approaches and especially new industry standards require a lot of discussion and testing. For example, it can take decades for a new standard to be approved and implemented in the EU.[203]

Standards reinforce and reflect the current lack of demand for innovative products. Engineers, contractors, builders and architects are understandably wary of changes in a product that has to ensure safety for people occupying buildings and infrastructure, often over decades. China recently abolished its lowest-grade cement standard as a means of blocking unsafe construction practices.[204] Moreover, there is a strong preference for a consistent and predictable product: a concrete that can be used in most applications, is easy to pour and place and does not necessitate additional training.[205] Industry players are also subject to financial and legal constraints that shape how innovative they can be in the construction materials they choose.

Discussion

These supply- and demand-side barriers are interlinked and reinforcing. Limited market demand for alternative cement products reinforces existing business models and heightens producer concerns over increased costs from developing new products. Meanwhile, cement producers play an important role in shaping demand for, and setting expectations of, new technologies.

The concentration of the global cement market means that a handful of major producers have particular agenda-setting power. They are well represented in industry associations that help outline technology roadmaps for the industry.[206] These firms

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[199] Wesseling and Van der Vooren (2017), 'Lock-in of mature innovation systems'.

[200] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'; Van Deventer, Provis and Duxson (2012), 'Technical and commercial progress in the adoption of geopolymer cement'.

[201] Van Deventer, Provis and Duxson (2012), 'Technical and commercial progress in the adoption of geopolymer cement'.

[202] Cancio Diaz et al. (2017), 'Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies'.

[203] Stakeholder workshop participants.

[204] Global Cement (2014), 'China to stop production OPC 32.5 grade cement soon', 30 April 2014, http://www.globalcement.com/news/item/2460-china-to-stop-production-opc-325-grade-cement-soon (accessed 15 Oct. 2017).

[205] External workshop participant.

[206] See, for example, the European Cement Research Association or the Cement Sustainability Initiative.

have the resources to interact with standards committees and other institutions that set guidelines; they are therefore in a good position to help create and maintain norms and regulations.[207] This results in a kind of soft lock-in of the status quo, whereby technical knowledge is funnelled through institutions, political lobbies and major producers that set the course for the sector based on their interests.

The flip side of this concentration is that innovations, when adopted by this handful of firms, can more quickly be deployed all along the supply chain. Similarly, radical action on sustainability by these players, if it does come, could make a considerable difference in a short time.

A cross-cutting factor holding back the deployment of low-carbon cement is the lack of cooperation along the value chain. The fragmented nature of the value chain means that, on a typical construction project, different groups of actors give input at different stages rather than all feeding into the design and planning process at the start.[208] Cement and concrete suppliers typically interact with contractors or sub-contractors only at a stage when material specifications have already been decided. Ideally, cement and concrete producers could be in direct communication with clients, architects, engineers and contractors at the start of projects to discuss the range of concretes available.

A further factor is that not all of the barriers discussed above affect all technologies equally (see Table 5). Geopolymers, for example, are generally described as competitive with Portland cement in cost and performance,[209] but they face raw material supply constraints, customer resistance and challenges attracting industry buy-in.[210] By contrast, raw material supply and standards are not a problem for belite-rich Portland clinkers, which use largely the same materials as Portland clinker,[211] but concretes containing these products gain strength more slowly than most of those based on Portland cement.[212]

Nor do such barriers necessarily apply in all locations. Raw material supply is highly contingent on local factors. While parts of Europe are already feeling the effects of decreasing fly ash supplies, India is currently producing huge volumes of it. Although the majority of standards worldwide are prescriptive, and although European and North American ones dominate,[213] these are not always strictly implemented in locations outside of those two markets. Moreover, some novel cements are accepted by standards regimes in some countries and not in others. China, for example, has standards for CSA clinkers.[214] Similarly, acceptance, use and approaches to clinker substitution and novel cements vary by region.

Rather than pointing to a single transformative factor or ‘silver bullet’, therefore, the patent analysis highlights a range of innovations that have different prospects under different circumstances. The key step will be to find the right combination of technology, practice-related and policy solutions for a given location. The next chapter makes a first attempt to do this: it considers how the barriers discussed above might be overcome and under which conditions.

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[207] Wesseling and Van der Vooren (2016), ‘Lock-in of mature innovation systems’.
[208] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.
[209] Imbabi, Carrigan and McKenna (2012), ‘Trends and developments in green cement and concrete technology’.
[210] Van Deventer, Provis and Duxson (2012), ‘Technical and commercial progress in the adoption of geopolymer cement’.
[211] Gartner and Sui (2017), ‘Alternative cement clinkers’.
[212] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[213] Van Deventer, Provis and Duxson (2012), ‘Technical and commercial progress in the adoption of geopolymer cement’.
[214] Mangabhai, R. (undated), ‘Raman Mangabhai reviews some developments in cements’, World Cement Association, http://www.worldcementassociation.org/images/pdf/Developments-in-cements-website.pdf (accessed 25 Jan. 2018).

Table 5: Low-carbon cements: barriers and opportunities in comparison to conventional Portland clinker

Technology	Phase	CO_2 mitigation potential	Raw material availability	Costs	Energy demand	Water demand	Concrete properties	Applications	Standards
Low- Portland-clinker cements	Commercialized	>70%	Variable	Lower	Lower	Variable	Slower strength development but more durable	Wide range	Covered by European/US standards. Some restrictions in concrete standards
Geopolymers and alkali-activated binders	Commercialized	>90%	Variable	Similar	Variable	Lower	Can match performance	Wide range in Australia	Not covered by standards
Belite-rich Portland cements (BPC)	Commercialized	~10%	High	Higher	Variable	Lower	Slower strength development but more durable	Niche	Meet Chinese standards
Belitic clinkers containing ye'elimite (CSA)	Commercialized	~50%	Limited	Higher	Less grinding energy	N/A	Can match performance	Niche	Some covered by Chinese standards. European standard being drafted
BYF clinkers (subset of CSA clinkers)	Demonstration	>20%	Variable	Higher	Less grinding energy	N/A	Similar strength development, better sulphate resistance. Tests still under way	Niche, but in theory wide range possible	Same as for CSA
Low-carbonate clinkers with pre-hydrated calcium silicates	Demonstration	>50%	High	Similar	Lower	Lower	Can match performance	Wide range	Not covered by existing standards
Carbonatable calcium silicate clinkers (CCSC)	Pilot	>70%	High	Similar	Lower	Lower	Can match performance	Limited to precast applications	Precast can be sold under local technical approvals
Magnesium-based cements	Research	>100%	Variable	N/A	N/A	N/A	N/A	N/A	N/A

Source: Authors' own analysis of various sources. See Appendix 6 for full table, additional details and list of sources.
Note: N/A means not available. Variable means that the factor varies by geography, material or both: The figures for mitigation potential are taken from various sources. They are therefore unlikely to be directly comparable across rows, as each figure is likely to have a different benchmark/different boundaries.

3. Overcoming Barriers to Deployment of Low-carbon Cement and Concrete

Key points

- It is possible to increase the availability of traditional clinker substitutes in the short term through targeted regulation and by facilitating trade. In parallel to this, scaling up the use of alternative clinker substitutes will be important for expanding the range of options for deep decarbonization in the medium term.
- Carbon pricing and the development of new product standards have long been seen as vital for driving change in the sector and stimulating demand for lower-carbon products. However, neither is likely to provide sufficient incentive to expand these markets and build a sustainable supply chain for them in the short term.
- Digital tools will play a key role in building the market for novel cement and concrete products. Such tools can address knowledge gaps and 'democratize' access to relevant information at different points along the value chain.

This chapter explores how to overcome barriers to the diffusion of clinker substitution and novel-cement technologies. It looks at a combination of existing and proposed policies and approaches, from carbon prices and new standards to leveraging public procurement and encouraging new, more service-oriented, business models. It also considers opportunities for digital disruption in the cement sector – a shift that could bring new opportunities for emissions reductions.

To achieve a steep decarbonization trajectory, a portfolio of these approaches will be needed, and these will have to be tailored to different markets. Each section below, therefore, discusses where a given solution can best be deployed, whether with respect to a specific location, technology or type of application.

3.1 Enhancing the availability of supply

Achieving an average global clinker ratio of 0.60 by 2050, as set out in the 2018 Technology Roadmap, would require roughly 2 billion tonnes of clinker substitutes to be consumed in 2050,[215] almost 40 per cent more than the quantity consumed today.[216] At the same time, the global availability of traditional clinker substitutes – fly ash and blast furnace slag – is likely to decline to around 16 per cent of cement production by 2050.[217] This would mean that 1.2 billion tonnes will need to come from alternative

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[215] The 2017 ETP projects a cement consumption figure of 5 billion tonnes in 2050. A 0.60 clinker factor would require 0.4*5 billion tonnes of clinker substitutes to be used that year.

[216] The 2017 ETP estimates a cement consumption figure of 4.1 billion tonnes and a global average clinker-to-cementitious ratio of 0.65 in 2014. 0.35*4.1 comes to 1.435 billion tonnes of clinker substitutes consumed in 2014.

[217] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

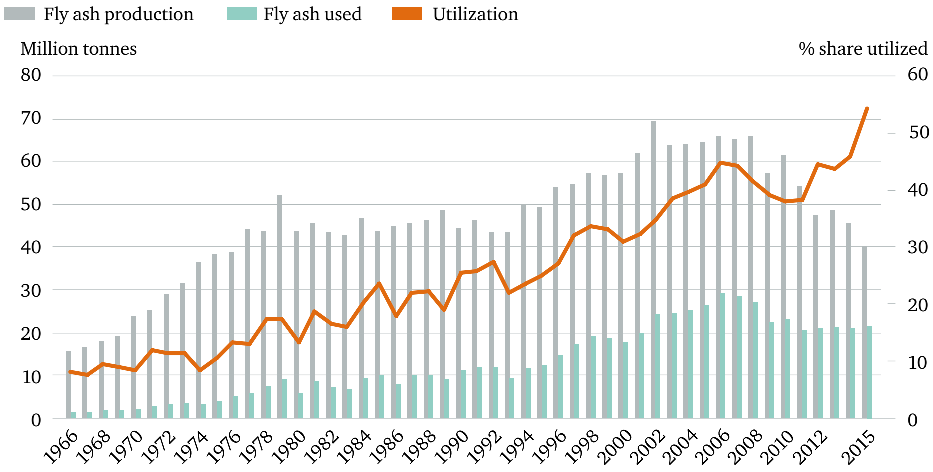
sources.[218] Increasing the supply and utilization of traditional and non-traditional clinker substitutes will therefore be critical for meeting emissions mitigation targets.

This section focuses primarily on the potential to address scarcity of raw materials for clinker substitutes rather than of those for novel cements. Geopolymers and alkali-activated binders largely depend on the same materials as clinker substitution. Any potential to increase the availability of clinker substitutes should also benefit geopolymers and alkali-activated binders. Several of the other novel cements discussed do not face material supply constraints; those that do face such constraints require further R&D in the first instance to overcome this issue.

Regulation

There is scope to increase the availability of traditional clinker substitutes in the short term through targeted regulation. The supply chain for clinker substitutes is heavily influenced by regulation. In the wake of an accident in 2008, for example, the US Environmental Protection Agency (EPA) considered reclassifying fly ash as hazardous waste.[219] Although the EPA ultimately opted not to do so in 2010, the regulatory uncertainty led to drops in fly ash use in the US (see Figure 19).[220] Conversely, in the Netherlands, the use of clinker substitutes has been facilitated by bans on waste disposal for fly ash and sewage sludge, as well as by a ban on the disposal of concrete waste in landfills. This has encouraged producers of these waste materials to collaborate with cement companies on waste management.[221]

Figure 19: US fly ash production and use, 1966–2015



Source: Authors' analysis of data from Kelly, T. D. and Matos, G. R. (2014), *Historical Statistics for Mineral and Material Commodities in the United States*, https://minerals.usgs.gov/minerals/pubs/historical-statistics/ (accessed 25 Jan. 2018).

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[218] Sixteen per cent of the 2017 ETP consumption figure of 5 billion tonnes in 2050 comes to 0.8 billion tonnes.

[219] Goguen, C. (2010), 'Fly Ash – A Hazardous Material?', National Precast Concrete Association, 23 August 2010, https://precast.org/2010/08/fly-ash-a-hazardous-material/ (accessed 25 Jan. 2018).

[220] Moon, S. T. (2013), 'Regulatory and Legal Applications: Fly Ash Use in Cement and Cementitious Products', 2013 World of Coal Ash (WOCA) Conference, 22–25 April 2013, http://www.flyash.info/2013/006-Moon-2013.pdf (accessed 25 Jan. 2018).

[221] Kemp, Bartekova and Turkeli (2017), 'The innovation trajectory of eco-cement in the Netherlands'.

Regulation is unlikely to substantially improve the availability of fly ash and blast furnace slag in Europe and the US, where overall supplies are decreasing due to shifts in the power and steel sectors.[222] However, policy could play a role in encouraging the screening, testing and reprocessing of fly ash and blast furnace slag from older disposal sites. This would increase supplies in the short term while mitigating environmental concerns about those sites.[223]

Regulation could play a substantial role in increasing the availability of clinker substitutes in the largest concrete-producing countries: China and India

In contrast, regulation could play a substantial role in increasing the availability of clinker substitutes in the largest concrete-producing countries: China and India. Both are projected to have large supplies of fly ash and blast furnace slag,[224] even under ambitious emissions reduction scenarios, and neither is currently making the most of this supply. Under the IEA's B2DS, China and India are expected to reach clinker ratios of 0.55 and 0.50 respectively by 2060.[225]

Official statistics in China suggest that the country's fly ash utilization rates are higher than 60 per cent, but a recent analysis by Greenpeace suggests the figure is around 30 per cent.[226] Regulation of fly ash takes place largely at the local level, with no specific national regulations.[227] The main reason for the deficit seems to lie in the lack of enforcement of existing environmental regulations.

In India, fly ash use has increased steadily, but around 40 per cent remains underutilized.[228] A recent paper analysing 16 Indian states suggests that 13 of the states studied require additional support to increase utilization – in the form of adjustments to tax regimes to encourage recycling, as well as better training and access to information.[229] In 2016, Maharashtra became the first Indian state to adopt a fly ash utilization policy.[230]

Trade

Trade in clinker substitutes can help overcome local shortages. Cement is cheap but heavy, making it uneconomic to transport very far. As a result, producers have tended to serve local markets within a 200–300 km radius.[231] Similar transport distances have applied to clinker substitutes.

However, this is increasingly changing. Although the volume traded still only amounts to a fraction of annual volumes used, trade in blast furnace slag and fly ash has risen

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[222] Miller, Horvath and Monteiro (2016), 'Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%'.
[223] Carroll, R. (2015), 'From ash to asset: fly ash as a vital secondary material', *Power engineering international*, 7 January 2015, http://www.powerengineeringint.com/articles/print/volume-23/issue-6/features/from-ash-to-asset-fly-ash-as-a-vital-secondary-material.html (accessed 25 Jan. 2018).
[224] Edwards (2016), 'Lower SCM supplies demand a change in approach'.
[225] International Energy Agency (2017), *Energy Technology Perspectives 2017*.
[226] Moon (2013), 'Regulatory and Legal Applications: Fly Ash Use in Cement and Cementitious Products'.
[227] Ibid.
[228] ENVIS Centre on Flyash (2018), *Summary of Fly Ash Generation and Utilization during the Year 2011–12, 2012–13, 2013–14, 2014–15 and 2015–16, 2016-2017 (First Half Year)* (accessed 9 Feb. 2018).
[229] Ahmed, S., Haleem, A. and Saurikhia, A. (2016), 'Geographical spread of fly ash generation and residual potential for its utilization in India', *International Journal of Innovative Research and Review*, 4(1): pp. 8–19, https://www.researchgate.net/publication/312198237_GEOGRAPHICAL_SPREAD_OF_FLY_ASH_GENERATION_AND_RESIDUAL_POTENTIAL_FOR_ITS_UTILIZATION_IN_INDIA (accessed 25 Jan. 2018).
[230] Minz, S. (2016), 'Maharashtra Becomes First Indian State to Adopt Fly Ash Utilization Policy', *Makaan iQ*, 21 November 2016, https://www.makaan.com/iq/news-views/maharashtra-becomes-first-indian-state-to-adopt-fly-ash-utilization-policy (accessed 9 Feb. 2018).
[231] Cembureau (2017), 'Key facts', https://cembureau.eu/cement-101/key-facts-figures/ (accessed 11 Oct. 2017).

almost 166 per cent since 2000.[232] Japan is the largest exporter.[233] The US and South Korea are among the top five importers.

Blast furnace slag is generally more cost-effective to ship over long distances than fly ash, as it has less volume.[234] Moreover, it is typically classified as a product, while fly ash is often classified as a waste material, requiring additional permits to trade.[235]

From a climate perspective, the benefits of trade in clinker substitutes need to be weighed against the carbon footprint of the transportation involved. However, potential increases in emissions are likely to be small relative to the potential gains from reducing the clinker content per tonne of cement: transporting cement by ship currently emits around 0.010 kg of CO_2 per tonne-kilometre.[236]

Trade may thus allow the likes of the US and Europe to supplement their decreasing domestic stocks of clinker substitutes with supplies from abroad. As importers increasingly look to China and India, a key difficulty will be establishing the necessary distribution networks and supply chain channels in these more fragmented markets.[237] In China, for example, there is a mismatch between fly ash utilization in the east of the country, where supplies are high and the construction sector competes for supply with exporters, and low utilization in less developed regions in the west.[238]

Alternative materials

In the medium to long term, fly ash and blast furnace slag availability is likely to decline as the use of coal in the energy sector is reduced and as secondary steel takes a growing share of the steel market. Increasing clinker substitution will therefore require alternative sources of clinker substitutes. Scaling these up needs to start immediately. In this context, there has been a rise in patenting around volcanic rocks and ash and calcined clays for use as clinker substitutes.

Volcanic rocks and ash will become important in regions where these materials are plentiful. Their use depends on local environmental conditions and legislative frameworks.[239] They also present a raft of technical difficulties,[240] including the fact that quality varies considerably.[241] Seventy-five million tonnes of these materials are already used as clinker substitutes every year.[242]

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[232] Data from resourcetrade.earth. Fly ash is included in the 'other clay & ash, including seaweed ash (kelp)' category. Slag is included in the 'granulated slag (slag sand) from iron, steel industry' category. Chatham House (2017), Resourcetrade.earth, https://resourcetrade.earth/data?year=2015&category=1114&units=value (accessed 16 Oct. 2017).
[233] Data from resourcetrade.earth. Fly ash is included in the 'other slay & ash, including seaweed ash (kelp)' category. Slag is included in the 'granulated slag (slag sand) from iron, steel industry' category. Chatham House (2017), Resourcetrade.earth
[234] Department for Business, Energy & Industrial Strategy (2017), 'Fly Ash and Blast Furnace Slag for Cement Manufacturing'.
[235] ZAG International (2015),' ASHTRANS Europe 2015', Presentation given at 3rd international ASHTRANS Conference, Copenhagen, 7 September 2015, http://ashtrans.eu/onewebmedia/15%20ASHTRANS%202015%20TDUVE.pdf (accessed 10 Mar. 2017).
[236] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.
[237] Edwards (2016), 'Lower SCM supplies demand a change in approach'.
[238] Moon (2013), 'Regulatory and Legal Applications: Fly Ash Use in Cement and Cementitious Products'.
[239] Snellings, R., Mertens, G., and Elsen, J. (2012), 'Supplementary Cementitious Materials', *Reviews in Mineralogy and Geochemistry*, 74: pp. 211–278, doi: 10.2138/rmg.2012.74.6 (accessed 21 May 2018).
[240] Ibid.
[241] Seraj, S., Cano, R., Liu, S., Whitney, D., Fowler, D., Ferron, R., Zhu, J. and Juenger, M. (2014), *Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete*, https://library.ctr.utexas.edu/ctr-publications/0-6717-1.pdf (accessed 26 Jan. 2017).
[242] Scrivener, John and Gartner (2016), *Eco-efficient cements.*

Studies suggest that calcined clays, in particular, present a significant opportunity to increase clinker substitution around the world, but especially in emerging markets.[243] Clays are widely available around the world – although reserves are not always easily accessible and not all clays are suitable for clinker substitution. Those containing kaolinite produce reactive materials when heated (calcined) to 700–850 °C.[244]

Although only used in a few countries so far, calcined clays have been shown to work at scale. In Brazil, for example, they now make up 3 per cent of the cement market.[245] Two reasons calcined clays are not more widely used are that they can be energy-intensive to produce relative to traditional clinker substitutes, although less energy-intensive than clinker,[246] and that they typically require additional processing facilities for drying, calcination and grinding.[247]

This discussion of alternative clinker substitutes is by no means comprehensive. Other novel clinker substitutes are also in use, mainly on a smaller scale, and are discussed in detail in other publications.[248] Due to the variety of materials and their dependence on local conditions, obtaining and disseminating enhanced data on their availability, quality and technical characteristics will be key to scaling up their use.

3.2 Strengthening the business case for innovation and deployment

This section looks at what could be done to strengthen the business case for deploying high-blend and novel cements. It explores three disruptive shifts: two from within the market in the form of new service-oriented business models and corporate social responsibility (CSR) initiatives; and one external driver in the form of carbon pricing.

Cement as a service

At first glance, the 'servitization' concept – wherein an input or product is enhanced by the provision of services or even repositioned as a service in itself – might not seem appropriate for a commodity such as cement.[249] Prescriptive standards allow for little differentiation in the product sold, and companies mainly compete on price rather than customer service. However, the largest multinational cement producers are increasingly offering a range of services, from speciality cements to intricate delivery services tailored to complex projects.[250]

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[243] Cancio Diaz et al. (2017), 'Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies'; Tironi, A. Castellano, C. C., Bonavetti, V., Trezza, M. A., Scian, A. N. and Irassar, E. F. (2015), 'Blended Cements Elaborated with Kaolinitic Calcined Clays', *Procedia Materials Science*, 8(2015): pp. 211–217, doi: 10.1016/j.mspro.2015.04.066 (accessed 25 Apr. 2018); Scrivener, John and Gartner (2016), *Eco-efficient cements*.

[244] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

[245] European Cement Research Academy and Cement Sustainability Initiative (2017), *CSI/ECRA-Technology Papers 2017*.

[246] Cancio Diaz et al. (2017), 'Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies'.

[247] European Cement Research Academy and Cement Sustainability Initiative (2017), *CSI/ECRA-Technology Papers 2017*.

[248] Snellings (2016), 'Assessing, Understanding and Unlocking Supplementary Cementitious Materials'.

[249] Pressman, J. (2017), 'The Not-So-New Promise of the Subscription Economy', *Forbes*, 17 May 2017, https://www.forbes.com/sites/valleyvoices/2017/05/17/not-so-new-promise-of-subscription-economy/#74d4c3943437 (accessed 18 Oct. 2017).

[250] World Economic Forum and the Boston Consulting Group (2017), *Shaping the Future of Construction: Inspiring innovators redefine the industry*, https://www.weforum.org/reports/shaping-the-future-of-construction-inspiring-innovators-redefine-the-industry (accessed 12 Mar. 2017); Cemex (undated), 'Blended Cement Concrete', https://www.ribaproductselector.com/Docs/8/21068/external/COL2721068.pdf (accessed 28 Feb. 2018).

A market geared towards service delivery would likely be a friendlier space for innovative products. Brands might seek to differentiate themselves on the basis of a range of special cements or by tailoring cements to end-user specifications.[251] In this context, a company might promote low-carbon cements on the basis of their durability characteristics as well as their sustainability credentials, for instance.

A shift towards a more service-oriented business model might offer the larger cement players new possibilities for value creation during a period in which market conditions have been challenging, and in which the financial performance of firms has been at best mixed.[252] Slowing economic growth in China has created a global cement glut. In Europe, there has been an imbalance between high production capacity and low market demand in recent years. At the same time, major cement producers are increasingly facing competition from high-performing regional players in emerging markets.[253]

CSR initiatives

Investors are increasingly expecting companies to be transparent about their exposure to climate change risks and how they are managing these

A lot can also be achieved by working closely with companies in the sector to engender disruption from within their organizations. Investors are increasingly expecting companies to be transparent about their exposure to climate change risks and how they are managing these. The cement sector is not immune to this trend and has developed reporting guidelines for climate-risk disclosure. However, a number of the largest firms do not follow them. The continued lack of clear targets for reducing emissions also makes it hard for investors to understand whether cement emissions will in fact decline in line with international targets.[254]

Firms are also increasingly subject to the demands of local communities. The environmental impacts of limestone mining and cement production in terms of air pollution and soil and water contamination have, for example, led to quarry and production site closures in the Netherlands.[255] The scandal surrounding the Lafarge plant that was kept running in Syria during the early stages of the civil war also underlines the increasingly global nature of maintaining a ‘licence to operate’.[256]

In response to these trends, the Cement Sustainability Initiative (CSI) has brought together major cement producers on a decarbonization platform, most notably improving transparency in respect of progress on different emissions mitigation levers.[257] Nine major cement and concrete producers from around the world

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[251] An example of tailored concrete service is the announcement by LafargeHolcim that it is supplying special concretes for the construction of Mexico City’s new international airport. LafargeHolcim (2017), ‘LafargeHolcim supplied eco-friendly high-performance concrete for new Mexico City airport’, press release, 19 October 2017, http://e3.marco.ch/publish/lafargeholcim/1184_305/10192017-press-lafargeholcim_mexico_airport-en.pdf (accessed 20 Oct. 2017).

[252] Birhsan, M., Czigler, T., Periwal, S. and Schulze, P. (2015), ‘The cement industry at a turning point: A path toward value creation’, *McKinsey & Company*, December 2015, https://www.mckinsey.com/industries/chemicals/our-insights/the-cement-industry-at-a-turning-point-a-path-toward-value-creation (accessed 25 Apr. 2018).

[253] Ibid.

[254] Transition Pathway Initiative (2017), *Steel and cement companies falling short in transition to low-carbon economy*, http://www.lse.ac.uk/GranthamInstitute/tpi/steel-and-cement-companies-falling-short-in-transition-to-low-carbon-economy/ (accessed 6 Apr. 2018).

[255] Kemp, Bartekova and Turkeli (2017), ‘The innovation trajectory of eco-cement in the Netherlands’.

[256] Keohane, D. (2017), ‘Former CEO of Lafarge under investigation over Syria terrorism funding’, *Financial Times*, 8 December 2017, https://www.ft.com/content/9817c9c8-dfb9-3f29-bfe6-a59aa1028a6b (accessed 10 Feb. 2018).

[257] Rosenthal, E. (2007), ‘Cement Industry Is at Center of Climate Change Debate’, *New York Times*, 26 October 2007, http://www.nytimes.com/2007/10/26/business/worldbusiness/26cement.html (accessed 17 Oct. 2017); Schneider, M., Romer, M., Tschudin, M. and Bolio, H. (2011), ‘Sustainable cement production-present and future’, *Cement and Concrete Research*, 41(7): pp. 642–50, doi: https://doi.org/10.1016/j.cemconres.2011.03.019 (accessed 17 Oct. 2017).

recently launched the Global Cement and Concrete Association, which intends to promote innovation throughout the construction supply chain.[258]

There are still large differences between cement producers in terms of emissions intensity, innovation capacity, how ambitious they are in the targets they set, and how supportive they are of regulatory measures to cut emissions.[259] LafargeHolcim and HeidelbergCement, for example, already use internal carbon prices of $32 per tonne and $23 per tonne respectively.[260] In 2016, Italcementi committed itself to setting a science-based emissions target.[261] In contrast, Taiheiyo Cement of Japan and Italy's Cementir have highly emissions-intensive production processes and their emissions reduction targets are relatively low.[262]

Carbon pricing

Although market forces are putting pressure on cement majors to reform policies and operational practices, whether changes are actually likely without firmer regulation remains an open question. Carbon pricing has long been seen as vital for the cement and concrete sector, and policymakers have used it as a tool to create incentives for more action on sustainability.

In Europe, however, most stakeholders agree that the EU Emissions Trading Scheme (ETS) so far has fallen short of its ambitions, particularly with regard to the cement sector.[263] Two main problems are generally cited. The first is that carbon prices have been too low to trigger meaningful action. Prices have generally fluctuated between €4/tonne and €8/tonne since the beginning of Phase III in 2013, although 2017 saw prices rise to more than €10/tonne.[264] This has been too low to adequately compensate for price differentials between low-carbon cements and conventional Portland cements.[265] BYF clinkers, for example, would currently struggle to compete due to higher material costs, but they may be able to compete at a carbon price above €20–30/tonne.[266]

The second, related, issue is that the supply of free emissions allowances has been too high and has created perverse incentives.[267] Critics argue that this has slowed the

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[258] Global Cement (2018), 'Global Cement & Concrete Association launches', 31 January 2018, http://www.globalcement.com/news/item/7032-global-cement-concrete-association-launches (accessed 10 Feb. 2018).
[259] CDP (2016), *Visible cracks*.
[260] Soliman, T. and Fruitiere, C. (2016), 'Cement sector and EU ETS', presentation, CDP Investor Research, November 2016, https://carbonmarketwatch.org/wp-content/uploads/2016/11/Cement-sector-EU-ETS-Event-Nicolette-Bartlett.pdf (accessed 27 Jan. 2018).
[261] Science Based Targets (2018), 'Companies Taking Action', http://sciencebasedtargets.org/companies-taking-action/ (accessed 30 Jan. 2018).
[262] CDP (2016), Visible cracks; Kisic et al. (2018)*, Building Pressure*.
[263] KfW Bankengruppe and Zentrum für Europäische Wirtschaftsforschung GmbH (2016), *KfW/ZEW CO₂ Barometer 2016 – Carbon Edition: How the EU ETS can contribute to meeting the ambitious targets of the Paris Agreement,* Frankfurt am Main: KfW Bankengruppe, https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-CO2-Barometer/CO2-Barometer-2016-Carbon-Edition.pdf (accessed 10 Feb. 2018); Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.
[264] Elkerbout, M. (2017)*, A strong revision of the EU ETS, but the future may bring impetus for further reform,* CEPS Commentary, Centre for European Policy Studies, 14 November 2017, https://www.ceps.eu/system/files/ME_GoodDeal.pdf (accessed 26 Jan. 2018).
[265] Expert interviews.
[266] Expert interview; Gartner and Sui (2017), 'Alternative cement clinkers'; Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.
[267] Elkerbout (2017), *A strong revision of the EU ETS, but the future may bring impetus for further reform*; Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.

transition to a low-carbon cement sector by subsidizing the emissions of the largest cement producers in particular: raising their profit margins, locking in existing emissions-intensive production processes and distorting competition.[268] Free allocation is supposed to protect domestic industries from being undercut unfairly by those located abroad that are not subject to carbon pricing. The extent to which the cement sector needs this protection has been the subject of considerable negotiation during each phase of ETS reform.[269]

Against this background, 2017 saw the agreement of Phase IV (2021–30) of the EU ETS. Positive changes have been made, including reforms to make sure allocation levels more closely track actual output; a reduction of the emissions cap by 2.2 per cent every year; and the introduction of an innovation fund to support the deployment of breakthrough technologies.[270] However, proposals to end free allocation to cement companies and establish a 'border carbon adjustment', whereby European importers of clinker and cement would have to buy carbon allowances, were ultimately rejected by the European Parliament.[271]

The failure of these latter proposals has contributed to a general perception that the EU ETS is unlikely to bring about meaningful changes in the cement sector, at least in the short term. Member states that are more ambitious in this area, including the Netherlands, Portugal and France, are considering carbon floor prices, following the UK's approach, which could still affect the sector.[272]

In the meantime, however, there are lessons for other countries and regions that might hope to promote low-carbon cement through carbon pricing.[273] These include the following:

- **The importance of a strong price signal.** The trade-off between addressing carbon leakage[274] and reflecting the price of carbon in the price of cement has to be handled carefully. Two main solutions tend to be proposed: full auctioning and border carbon adjustments (a version of which was rejected during the last phase of EU ETS reform); and output-based allocation.[275]
- **The importance of clarity and predictability for stakeholder confidence.** The EU ETS has been in a near-constant state of reform since it started. Uncertainty,

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[268] Global Cement (2013), 'Lessons from the Europe ETS for the Chinese cement industry', 4 December 2013, http://www.globalcement.com/news/item/2129-lessons-from-the-europe-ets-for-the-chinese-cement-industry (accessed 26 Jan. 2017); Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*; Kemp, Bartekova and Turkeli (2017), 'The innovation trajectory of eco-cement in the Netherlands'.
[269] Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.
[270] Elkerbout (2017), *A strong revision of the EU ETS, but the future may bring impetus for further reform*.
[271] Vanderborght, B. (2017), 'Comment: Why is the EU cement sector resisting a CO_2 border measure?', Carbon Pulse, 31 January 2017, https://carbon-pulse.com/29833/ (accessed 27 Jan. 2018); Lytton, W. (2017), 'ETS reform vote expected to boost cement sector's subsidy to €2.8 billion by 2030', Sandbag, 21 February 2017, https://sandbag.org.uk/2017/02/21/ets-reform-boost-cement-subsidy/ (accessed 25 Sep. 2017).
[272] Carbon Market Watch (2017), 'Failure to align Europe's carbon market with Paris goals adds pressure on governments to price pollution', press release, 9 November 2017, https://carbonmarketwatch.org/2017/11/09/failure-align-europes-carbon-market-paris-goals-adds-pressure-governments-price-pollution/ (accessed 26 Jan. 2018).
[273] Kemp, Bartekova and Turkeli (2017), 'The innovation trajectory of eco-cement in the Netherlands'.
[274] Defined as a situation in which, for reasons or costs related to climate policies, businesses transfer production to other countries with less stringent emissions regulations.
[275] Branger, F. and Sato, M. (2015), *Solving the clinker dilemma with hybrid-output based allocation*, Centre for Climate Change Economics and Policy Working Paper No. 227, http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2015/08/Working-Paper-201-Branger-and-Misato.pdf (accessed 27 Jan. 2018).

along with the complexity of the system, has eroded confidence and made it difficult to factor the carbon price into business decisions.[276]

- **Differences in impact on firms of different size.** Larger producers have been better able to cope with the EU ETS than smaller players. They have the resources to deal with the administrative cost, roll out emissions-assessment protocols and liaise with scheme planners.[277]
- **The importance of coordination with other policy levers.** The EU ETS has generally been deemed insufficient as an instrument on its own. EU regulation in other areas, including waste management and energy efficiency, as well as support for innovation alongside carbon pricing, are needed to stimulate mitigation activities.[278]

Elsewhere, China approved the first phase of its own emissions trading scheme, which will focus on the power sector, in December 2017.[279] Cement will likely be included in the next phase along with a raft of other industrial sectors. The government's 13th Five-Year Plan (2016–20) also has ambitious targets for cutting overcapacity in the building materials sector.[280] These targets may have a larger impact on emissions from the sector than any plans for the emissions trading scheme. In India, the main trading initiative so far has been the Perform, Achieve and Trade scheme, which has already achieved results in the cement sector.[281] Significant carbon prices are unlikely in India in the short to medium term.

3.3 Navigating technical concerns

This section looks at how technical characteristics that hold back the adoption of high-blend and novel cements might be overcome. These characteristics include the following:

- **Difficulty of application.** Very-low-carbon concretes may not flow as well, slowing down the application process and increasing the labour required to get a smooth finish.[282]
- **Setting times and strength development.** High-blend cements may exhibit slow early-stage strength development, which can delay construction processes.[283]
- **Uncertain long-term durability.** Most high-blend and novel cements face challenges demonstrating that they perform safely over the long term.

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[276] Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.
[277] Global Cement (2013), 'Lessons from the Europe ETS for the Chinese cement industry'.
[278] Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.
[279] Tetrault, M. (2018), 'Taking Stock: A Recap of 2017 Climate Change Policy Initiatives and What to Expect in 2018', Lexology, 23 January 2018, https://www.lexology.com/library/detail.aspx?g=98e3ae17-862e-4fa5-a8fe-2b06b2522172 (accessed 26 Jan. 2018).
[280] Yan, L. (2016), 'China Issues 13th Five Year Plan for the Building Materials Industry', King & Spalding, 18 October 2016, https://www.kslaw.com/blog-posts/china-issues-13th-five-year-plan-building-materials-industry (accessed 23 Feb. 2018).
[281] Bandyopadhyay, K. R. (2016), *Emission Trading in India: A Study of Two Schemes*, TERI University Working Paper Series Vol. 2016-03, January 2016, http://www.agi.or.jp/workingpapers/WP2016-03.pdf (accessed 27 Jan. 2018); Ministry of Power Government of India Bureau of Energy Efficiency (2017), *Achievements under Perform, Achieve and Trade (PAT)*, https://beeindia.gov.in/sites/default/files/Booklet_Achievements%20under%20PAT_May%202017.pdf (accessed 27 Jan. 2018).
[282] The Constructor Civil Engineering Home (2017), 'Factors Affecting Strength of Concrete', https://theconstructor.org/concrete/factors-affecting-strength-of-concrete/6220/ (accessed 20 Oct. 2017).
[283] Nili, M., Tadayon, M. and Mojtaba, N. (2013), 'The Relationships between Setting Time and Early Age Strength of Concrete containing Silica fume, Fly ash and Slag', Third International Conference on Sustainable Construction Materials and Technologies, http://www.claisse.info/2013%20papers/data/e393.pdf (accessed 22 Jan. 2018).

Disseminating best practice

These impacts vary considerably depending on the decisions made by those producing cement and concrete. Advances in the understanding of the nanoscale structures of cement are opening up new ways to improve the performance of concrete. For example, many high-blend and novel cements display slower early-stage strength development than Portland cement but achieve higher compressive strength and superior durability later on. Using nanotechnology, researchers are experimenting with modifying particle size and distribution through grinding and packing to enhance early-stage strength development.[284]

Chemical admixtures can also be used to influence the technical characteristics of low-clinker and novel concretes. Dispersants such as plasticizers and superplasticizers help with ease of application by lowering the amount of water needed to make concrete flow well and enabling higher levels of clinker substitution. Admixtures can also address durability concerns.[285] Moreover, decisions taken when mixing concrete (which aggregates to use, what size and in what proportion) can mitigate impacts.[286]

Using several clinker substitutes in combination in ternary cements can also improve overall performance.[287] Combining limestone filler and fly ash, or limestone filler and blast furnace slag, can result in a high-durability concrete.[288] With advances in this area, clinker substitution increasingly becomes not just a cost-saving or sustainability measure but also a means of optimizing performance and outperforming traditional concrete.

However, this type of optimization is currently only practical in advanced production settings – i.e. in plants where additional grinding equipment can be used, and where workers have access to chemical admixtures and have the requisite skills and knowledge to take these decisions. The vast majority of concrete production in emerging markets is done on site by workers who lack training and specialist knowledge.[289]

This is an area in which digitalization will have an important role to play. Digital tools could be used to disseminate best practice for optimizing a particular concrete mix consisting of locally available materials, or to allow a worker on site to quickly call up details on the compatibility of a given SCM with a given admixture. Better dissemination of know-how will be a key factor in facilitating the use of higher-blend and novel cements in emerging markets.

Rethinking standardization

There may not be a single low-carbon cement that provides all the functions that Portland cement does. However, given the advances in optimizing the properties

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[284] Cement Sustainability Initiative (2013), *Existing and Potential Technologies for Carbon Emissions Reductions in the Indian Cement Industry*, http://www.ifc.org/wps/wcm/connect/0a7431004fa1997eac97ee0098cb14b9/india-cement-carbon-emissions-reduction.pdf?MOD=AJPERES (accessed 27 Feb. 2018).
[285] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[286] Ibid.
[287] Edwards (2016), 'Lower SCM supplies demand a change in approach'.
[288] Müller, C. (2012), 'Use of cement in concrete according to European standard EN 206-1', *HBRC Journal*, 8(1): pp. 1–7, doi: 10.1016/j.hbrcj.2012.08.001 (accessed 28 Jan. 2018).
[289] Scrivener, John and Gartner (2016), *Eco-efficient cements*.

of concretes, and given the range of different applications for cement – from mortar and concrete blocks to reinforced concrete – a single cement that provides all of these functions may not be needed.

Prescriptive standards require that novel products match the characteristics of Portland cement for the majority of applications, even when this might not be necessary

The current 'one size fits all' approach poses a considerable barrier to the use of alternative cements; prescriptive standards require that novel products match the characteristics of Portland cement for the majority of applications, even when this might not be necessary. Carbonation, [290] for example, is only a problem for a subset of concrete applications – the 25 per cent of concrete used in reinforced concrete – but most standards require the majority of cements to be carbonation-resistant.[291]

This approach also precludes flexibility in accommodating local differences in climate and soil conditions, variances that make novel compositions more or less viable in some locations. In Japan, for instance, where buildings have to withstand earthquakes, strength and durability are particularly important.[292] In Scandinavia, structures have to withstand extreme temperatures in winter.[293] Conversely, in places unlikely to have to endure regular tremors or extreme temperatures, more buildings could be built using high-blend or novel cements.

In this context, stakeholders have called for a shift away from prescriptive standards towards those that focus instead on whether a cement can demonstrate a performance sufficient for a given application in a given context. Belite-rich clinkers, for example, have been used in large concrete dam projects in China where strength gain after a few days is not as important as it might be on a typical construction project.[294] Ideally, solutions would allow the lowest-carbon cements to be matched to their most viable use-cases, with higher-carbon cements reserved only for those applications where they might still be needed.

Application-oriented, performance-based standards in cement would need to be complemented by equivalent standards for concrete, as well as by changes in construction and infrastructure codes (and vice versa), as such rules provide separate but interlinked levels of certification. According to industry stakeholders, concrete standards generally pose a greater barrier than cement standards to the use of high-blend cements.[295] In Norway, for example, CEM I (>95 per cent Portland clinker) is the only cement allowed in most concrete applications.[296]

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[290] As concrete ages, it reacts with and removes CO_2 from the atmosphere through a process called carbonation. Some have argued that this process should be seen as offsetting emissions released during production, but it is generally considered too slow to be a viable solution. Xi, F., Davis, S., Ciais, P. G., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J., Wei, W., Yang, K.-H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y. and Liu, Z. (2016), 'Substantial global carbon uptake by cement carbonation', *Nature Geoscience*,9: pp. 880–83, doi:10.1038/ngeo2840 (accessed 19 Oct. 2017).
[291] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[292] Teshigawara, M. (2012), 'Outline of earthquake provisions in the Japanese building codes', *Geological and Earthquake Engineering 23*, doi: 10.1007/978-4-431-54097-7 (accessed 19 Oct. 2017).
[293] Hanson Concrete (undated), 'Using concrete in cold weather', http://www.hanson.co.uk/en/system/files_force/assets/document/b7/e3/hanson-cold-weather-pouring-info.pdf?download=1 (accessed 15 Apr. 2017); Portland Cement Association (2017), 'Freeze-Thaw Resistance', http://www.cement.org/Learn/concrete-technology/durability/freeze-thaw-resistance (accessed 9 Jul. 2017).
[294] Sui, T., Fan, L., Wen, Z., Wang, J. (2015), 'Properties of Belite-Rich Portland Cement and Concrete in China', *Journal of Civil Engineering and Architecture*, 9 (2015): pp. 384-392. doi: 10.17265/1934-7359/2015.04.002, (accessed 3 Jul. 2017).
[295] External workshop participant.
[296] Müller (2012), 'Use of cement in concrete according to European standard EN 206-1'.

The degree to which prescriptive standards are considered a barrier to innovation in the composition and production of cement depends on the low-carbon cement in question, and whether one believes that a specific cement could be used for mainstream applications or will remain a niche product.

Application-specific flexibility already exists for some niche products, as certain applications do not require standards. CCSC cements, for example, are currently restricted to precast concrete articles, which can be sold under local technical approvals and do not necessarily require standardization at national level.[297] In Europe, the European Organization for Technical Assessment route allows manufacturers to put forward novel products not covered by existing standards to be independently assessed and validated.[298] Finally, if a construction company needs a niche type of cement for a given application or simply wants to use it, the firm can generally acquire special permission to do so.[299]

More fundamental barriers prevent high-blend or novel cements from becoming mainstream products everywhere; the most notable is the lack of local availability of raw materials (see sections 2.3 and 3.1). For example, if CSA clinkers are not deployed at scale due to their cost and the limited availability of bauxite, and if they can be used in niche applications in certain places regardless of this, then it may prove less important to develop national standards for their use.

Given the shift towards a more service-oriented business model, it is reasonable to ask whether there will even be such a thing as a mainstream cement product in the future. A more diversified cement market, no longer dominated by Portland cement but instead made up of a broader set of bespoke products, would require a paradigm shift in standardization. Moreover, as explored in the next chapter, structural shifts in practices in the construction sector could result in the emergence of completely new requirements for building materials. For example, would early-stage strength development be more or less important in a building site populated by robots? On the one hand, a company may be better able to afford irregular working shifts and longer gaps between shifts if it is using robots rather than paying workers' salaries, and safety concerns may be diminished. On the other hand, construction work may speed up with the ability to work through the night, and waiting longer to demould concrete may be even less viable than it is today.

New approaches to testing

One of the main challenges for performance-based standards is the current lack of rapid and accurate tests to predict the performance of novel concretes over their lifetime.[300] In many cases, high-blend and novel cements have not been in use for long enough to have accumulated the decades of in-service data to 'prove' their

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[297] Gartner and Sui (2017), 'Alternative cement clinkers'.

[298] Kathage, K. (2017), 'ETA- a reliable way to CE marking for construction products EOTA – a competent partner for the construction industry', presentation, 15 November 2017, https://www.eota.eu/ckfinder/userfiles/files/1%20ETA%20route%20and%20EOTA_SAG%20Nov2017_Kathage1.pdf (accessed 28 Jan. 2018).

[299] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan: Rethinking Cement.*

[300] McCarter, W. J., Chrisp, T. M., Starrs, G., Basheer, P. A. M., Nanukuttan, S., Srinivasan, S. and Magee, B. J. (2015), 'A durability performance-index for concrete: developments in a novel test method', *International Journal of Structural Engineering*, 6(1): pp. 2–22, doi: 10.1504/IJSTRUCTE.2015.067966 (accessed 28 Feb. 2018).

durability; at the same time, predictive models are treated with scepticism.[301] However, advances in material analytics, nanotechnology and characterization techniques (including atomic force microscopy, scanning and x-ray diffraction) are transforming the understanding of the chemistry of concrete formation.[302] In addition, standards bodies are developing faster testing methods specifically for high-blend cements.[303]

Building up trust in the durability of new materials will also require a shift to greater in situ testing of materials and monitoring of structures throughout their operational life cycles.[304] Developing user-friendly diagnostic tools, and field-based detection tools that provide rapid results, will be key. Increased collection and dissemination of data on in-service performance could dramatically speed up the understanding of novel products and their impact on concretes, allowing the improvement of existing tools and the development of new ones to accurately predict the properties of concretes. Similar developments in the water industry have led to a move away from sample-based water quality measurement to in-line continuous measurement, i.e. measurement where sensors or instruments are situated in a water flow-through system.[305]

Finally, the traditional route of pilot/demonstration projects will remain an important way to build confidence in novel products. Most of the innovative products considered above are moving through the typical steps from early use in non-structural, low-risk applications to large-scale demonstration in structural applications.[306]

3.4 Fostering demand for innovative approaches

To overcome customer resistance to high-blend and novel cements, buy-in is needed across a range of stakeholders: from the client who commissions a project to the design team that implements it to the end-user who inhabits or works in a given building. However, four sets of actors have a particularly strong influence over material selection in construction projects: architects, clients, structural engineers and contractors (see Figure 20).[307]

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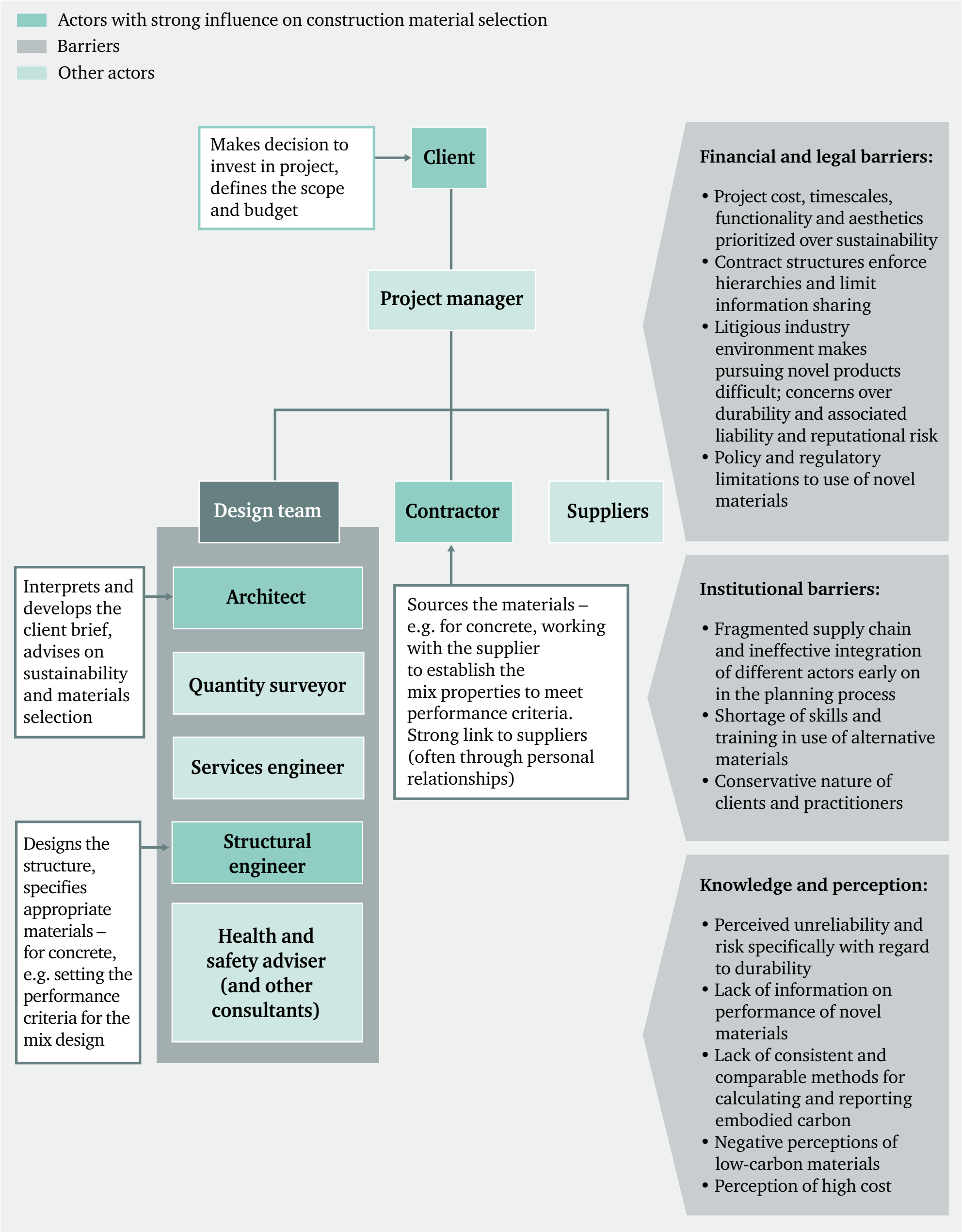
[301] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[302] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'; Wesseling and Van der Vooren (2017), 'Lock-in of mature innovation systems'; Crow (2008), 'The concrete conundrum'.
[303] National Institute of Standards and Technology US Department of Commerce (2017), 'Measurement Science to Assure the Performance of Innovative Concretes'.
[304] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[305] Labs, W. (2013), 'Inline monitoring aids in food safety and quality', *Food Engineering*, 13 May 2013, https://www.foodengineeringmag.com/articles/90659-inline-monitoring-aids-in-food-safety-and-quality (accessed 20 Oct. 2017).
[306] Taylor (2013), *Novel cements*.
[307] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.

Figure 20: Actors in construction project value chain, and barriers to innovation in material selection



Makes decision to invest in project, defines the scope and budget

Interprets and develops the client brief, advises on sustainability and materials selection

Designs the structure, specifies appropriate materials – for concrete, e.g. setting the performance criteria for the mix design

Sources the materials – e.g. for concrete, working with the supplier to establish the mix properties to meet performance criteria. Strong link to suppliers (often through personal relationships)

Financial and legal barriers:

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

Institutional barriers:

- Fragmented supply chain and ineffective integration of different actors early on in the planning process
- Shortage of skills and training in use of alternative materials
- Conservative nature of clients and practitioners

Knowledge and perception:

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

Source: Authors' analysis. Barriers based on survey data in Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.

This section therefore focuses on shifting the preferences and incentives of these groups of actors through three entry points: the development of better indicators, alongside stricter regulation; enhanced coordination through digitalization; and endorsement and activism by early-mover consumer groups.

As will be discussed in Chapter 4, a wide variety of sustainable material options exist outside of the cement and concrete paradigm. This section, therefore, more broadly addresses the need to increase demand for innovative building products and does not limit the discussion to low-carbon concretes.

Changing preferences through better indicators and regulation

Enhanced information could be key to enabling more sustainable approaches. Addressing knowledge and perception barriers, for instance, depends on access to good-quality information on lower-carbon materials. A commonly cited concern is the lack of simple and consistent indicators to compare different construction materials based on their embodied carbon.[308]

The number of tools for calculating and comparing embodied carbon levels has proliferated in recent years.[309] In the Netherlands, the Milieu Kosten Indicator expresses the economic cost associated with the environmental impacts of a material.[310] More broadly, Environmental Product Declarations (EPDs) communicate information about the life-cycle environmental impact of products.[311]

However, there are still huge inconsistencies in the data used and the outcomes of different assessments.[312] Although several national EPD databases exist, these are largely voluntary and there is a lack of globally comparable benchmarks for materials.[313] Credible benchmarks are difficult to establish as projects are extremely site-specific.

Developing good indicators will require more robust data gathering over years. The following steps could help speed this along:

- **Establishment of an industry-wide methodology.** The European Standards Committee has already published standards for whole-life-cycle impact assessments for buildings.[314] However, implementation of this methodology continues to vary.[315]
- **Development of simple tools and a central database.** According to industry stakeholders, undertaking a carbon calculation does not have to be complicated.[316] Ideally, tools and databases would integrate existing systems such as EPD databases.
- **Restructuring of the typical tender route so that it factors in embodied carbon.** This would be a huge step in motivating material suppliers to gather data.[317]

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[308] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[309] McAlinden, B. (2015), 'Embodied Energy and Carbon', Institution of Civil Engineers, 15 May 2015, https://www.ice.org.uk/knowledge-and-resources/briefing-sheet/embodied-energy-and-carbon (accessed 11 Jan. 2018).
[310] Rijkswaaterstaat (2018), 'DuboCalc' (Dutch), https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/inkoopbeleid/duurzaam-inkopen/duurzaamheid-bij-contracten-en-aanbestedingen/dubocalc/index.aspx (accessed 30 Jan. 2018).
[311] EPD International (undated), 'What is an EPD?', https://www.environdec.com/What-is-an-EPD/ (accessed 30 Jan. 2018).
[312] De Wolf, C., Pomponi, F. and Moncaster, A. (2017), 'Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice', *Energy and Buildings*, 140: pp. 68–80, doi: 10.1016/j.enbuild.2017.01.075 (accessed 30 Jan. 2018); Simonen, L. Rodriquez, B. X. and De Wolf, C. (2017), 'Benchmarking the Embodied Carbon of Buildings', *Technology Architecture and Design*, 1 (2017): 10.1080/24751448.2017.1354623 (accessed 30 Jan. 2018).
[313] De Wolf, Pomponi and Moncaster (2017), 'Measuring embodied carbon dioxide equivalent of buildings.'
[314] Ibid.
[315] Ibid.
[316] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[317] Ibid.

- **Use of labelling indicating the carbon footprint of each type of cement or concrete.** This could be another way to build closer consumer engagement with these products.[318]
- **Legislation mandating the measurement of these indicators.** This might be the most effective means of increasing data gathering and getting stakeholders to use indicators.[319]

Legislation can play an important role in shifting stakeholder approaches. In the UK, for example, the focus of building regulations on operational efficiency[320] – i.e. the energy use of a building over the course of its lifetime – has helped shift the concept of operational-carbon metrics from a niche consideration to a mainstream one.[321]

Better information and tools are only the first step towards sustainability becoming a widely established factor in material selection

Policymakers may also pursue stricter regulatory options by, for example, limiting the embodied carbon allowed in the construction of certain types of buildings. Local authorities could make planning permission contingent on a building design meeting certain targets on embodied carbon. Regulation also has an important role to play in shifting the industry's financial incentives. Tax cuts or business-rate reductions for buildings that meet a given embodied-carbon grade, or cuts in value-added tax (VAT) for low-carbon materials, could help change the financial calculus of those using these materials.

The choice of materials for a project is highly site- and application-specific. Given this, it is important to ensure that regulations are not too prescriptive. Instead, they need to guide consumers towards choosing more sustainable options while allowing them to find the most appropriate option for a given project. Rather than taxing a particular material, for example, clients might be incentivized to comply with a maximum embodied-carbon threshold for a given structure. Ultimately, the design of such policies will be subject to local conditions. However, improvements in data sharing and the lessons learned from this process will be a global effort.

Enhancing coordination and communication through digitalization

Better information and tools are only the first step towards sustainability becoming a widely established factor in material selection. A further key barrier to tackle is the fragmented nature of the supply chain.[322]

Reflecting this, there has been growing interest in software tools such as building information modelling (BIM), which allows users to build a data-rich, computer-generated model of a building. Structural engineers and architects are using BIM to explore the optimal design and materials for a given building at the very beginning of a project.[323] BIM also helps to communicate decisions to the client, the contractor and suppliers.

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[318] Neuhoff et al. (2014), *Carbon Control and Competitiveness Post 2020: The Cement Report*.
[319] De Wolf, Pomponi and Moncaster (2017), 'Measuring embodied carbon dioxide equivalent of buildings'; Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[320] McAlinden (2015), 'Embodied Energy and Carbon'.
[321] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.
[322] Ibid.
[323] Azhar, S., Hein, M. and Sketo, B. (2014), 'Building Information Modeling (BIM): Benefits, Risks and Challenges', https://www.researchgate.net/publication/237569739_Building_Information_Modeling_BIM_Benefits_Risks_and_Challenges (accessed 12 Jan. 2018); Aranda-Mena, G., Crawford, J., Chevez, A. and Froese, T. (2009), 'Building information modeling demystified: does it make business sense to adopt BIM?', *International Journal of Managing Projects in Business*, 2(3): pp. 419–434, doi: 10.1108/17538370910971063 (accessed 28 Feb. 2018).

Although BIM is not directly aimed at promoting low-carbon materials, it may help to challenge perceptions of, and guide decisions about, the use of novel materials.[324] Integrating embodied-carbon calculations into BIM, for example, could allow architects and structural engineers to see how their design is performing against similar buildings and how their choice of materials is affecting the embodied carbon of their design. This would also help to build familiarity with these metrics.

In order to be effective, however, BIM has to be used by a wide set of stakeholders at different points along the value chain. Questions have been raised as to whether BIM is likely to achieve widespread acceptance beyond design teams. In theory, manufacturers of materials can also link into BIM platforms, receiving data about product specifications and also uploading embodied-carbon data for their own products (in order to compete for contracts on the basis of those data). However, evidence suggests that uptake in the concrete sector has been slow.[325]

Improving BIM to offer the right kind of services to material suppliers and accelerating its uptake will be part of the solution. But addressing weak links in the supply chain will require more traditional forms of stakeholder engagement in the meantime: for example, training sessions to encourage design teams and contractors to work directly with material producers to better understand their products and overcome concerns about performance and costs.[326]

Early-mover consumers

In the absence of strong regulatory and financial drivers, motivated groups of clients who are in a strong position to innovate or possess strong agenda-setting power have a particularly important role to play in setting targets at a regional and global level, as well as in demanding more innovative solutions from their suppliers. This section considers two such groups: governments; and companies with ambitious CSR commitments.

Governments spend a huge amount on construction every year, and are in prime positions to drive the development of markets for low-carbon building materials.[327]

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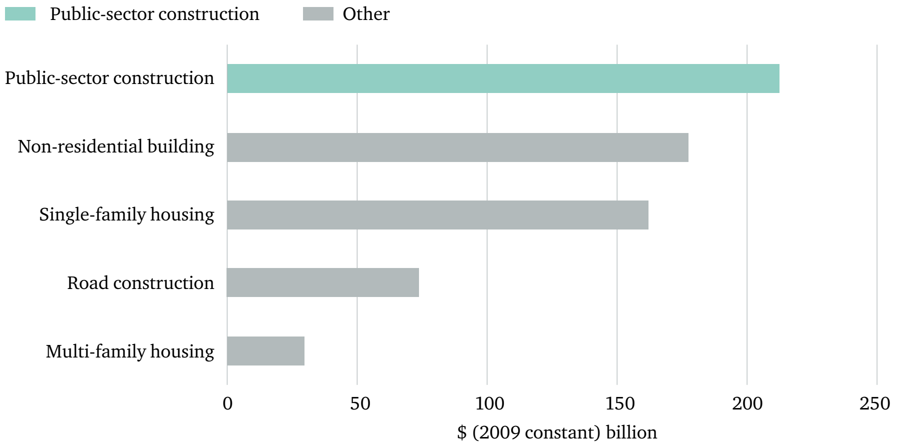
[324] Ruuska, A. and Häkkinen, T. (2014), 'Material efficiency of building construction', *Buildings*, 4: pp. 266–294, doi:10.3390/buildings4030266 (accessed 17 Oct. 2017).

[325] Khalfan, M., Khan, H. and Maqsood, T. (2015), 'Building Information Model and Supply Chain Integration: A Review', *Journal of Economics, Business and Management*, 3(9): pp. 912–916, doi: 10.7763/JOEBM.2015.V3.308 (accessed 30 Jan. 2018).

[326] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'.

[327] Baron, R. (2016), *The Role of Public Procurement in Low-carbon Innovation*, Background Paper for the 33rd Round Table on Sustainable Development, 12–13 April 2016, Paris: OECD, https://www.oecd.org/sd-roundtable/papersandpublications/The%20Role%20of%20Public%20Procurement%20in%20Low-carbon%20Innovation.pdf (accessed 17 Oct. 2017).

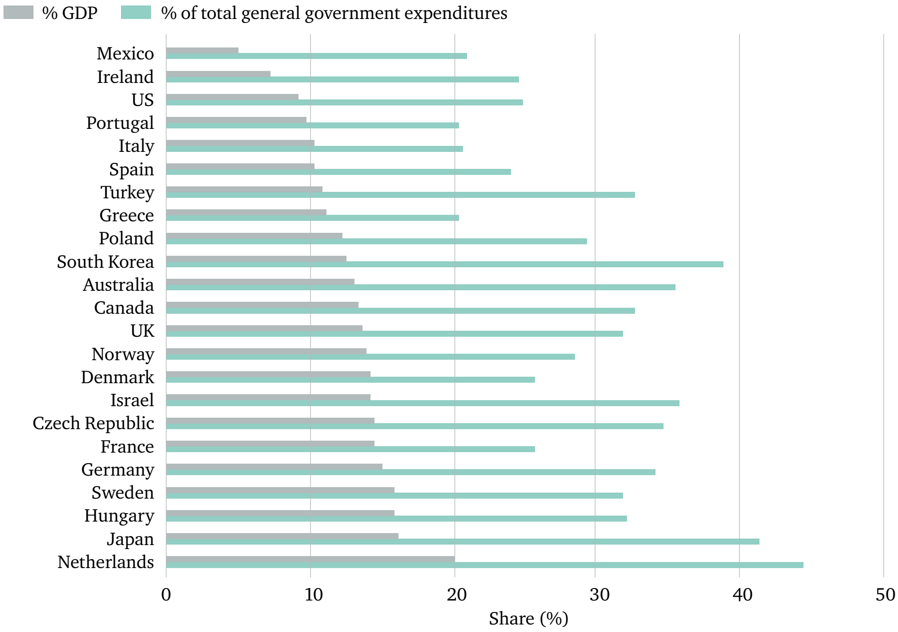
Figure 21: Spending on construction in the US, 2014



Source: United States Geological Survey (2017), *2014 Minerals Yearbook: Cement [Advance Release]*.

The public sector's share of construction spending varies considerably by country. In the US, it made up 32 per cent of the total in 2014 (see Figure 21). In the UK, it accounts for around 40 per cent per year.[328] In China, approximately 20 per cent of all construction spending involves public-works projects, and the central government and regional governments are responsible for the majority of infrastructure spending.[329]

Figure 22: Public procurement in selected OECD countries, 2015



Source: Organization for Economic Cooperation and Development (2017), 'Size of public procurement', *Government at a Glance 2017*, Paris: OECD Publishing, doi: 10.1787/gov_glance-2017-en (accessed 30 Jan. 2018).

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[328] Designing Buildings Wiki (2017), 'Government Construction Strategy 2016 2020', 7 December 2017, https://www.designingbuildings.co.uk/wiki/Government_Construction_Strategy_2016_2020 (accessed 30 Jan. 2018).

[329] Yan, E., Tu, C. and Liu, B. (2016), 'Construction and projects in China: overview', Thomson Reuters Practical Law, 1 March 2016, https://uk.practicallaw.thomsonreuters.com/2-521-5363?transitionType=Default&contextData=(sc.Default)&firstPage=true&bhcp=1 (accessed 30 Jan. 2018).

Given the spending power of the public sector, there has been an increasing focus on public procurement of low-carbon building materials.[330] In the Netherlands, for example, where public procurement is comparatively high (see Figure 22), the government uses a tool called DuboCalc that gives suppliers a reduction in the price of their bid based on how 'clean' it is. Proposals with lower environmental impacts will have a competitive advantage over other proposals.[331] This has increased demand for low-carbon cement among local authorities and housing corporations.[332]

Moreover, the embodied-energy and -carbon indicators and digital tools discussed above can be integrated into public procurement strategies. Governments can set maximum embodied-energy and -carbon levels in public tenders or set targets for public agencies to meet.[333] Since May 2015, the United Arab Emirates has required all major infrastructure projects to use cements that contain at least 60 per cent blast furnace slag or fly ash.[334] In the UK, a requirement to use Level 2 BIM on centrally procured public projects has been in place since April 2016.[335]

Although it is widely accepted that public procurement is a valuable tool, it is not always easy to implement. The amount of money involved and the financial interests at stake mean that corruption is a common problem in construction-related public procurement, even in developed economies.[336] This can be exacerbated in cases where sustainability is integrated into the process, as the more complex a process is, the more vulnerable it becomes to manipulation and corruption.[337] Good governance, fair and transparent procurement procedures, and clear practices regarding the prosecution of corruption are all key to establishing a corruption-resilient procurement environment.[338]

The second group of early-mover consumers consists of commercial clients motivated by CSR commitments. There are now 39 built-environment firms that have either set or committed to setting science-based targets (SBTs) (see Figure 23).[339] Landsec's SBT, for example, commits the UK-based property developer to reducing greenhouse gas emissions by 40 per cent per square metre by 2030 on 2014 levels. It also requires the firm to encourage contractors to set SBTs so that the embodied carbon of key materials can be reduced.[340]

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[330] Casier, L. and Wuennenberg, L. (2017), *Leveraging the Power of the Public Purse: Using public procurement of low-carbon innovation for sustainable infrastructure*, policy brief, International Institute for Sustainable Development, December 2017, https://www.iisd.org/library/leveraging-power-public-purse-using-public-procurement-low-carbon-innovation-sustainable (accessed 30 Jan. 2018).

[331] Wesseling and Van der Vooren (2017), 'Lock-in of mature innovation systems'; Wuennenberg, L. and Casier, L. (2018), *Low-Carbon Innovation For Sustainable Infrastructure: The Role of Public Procurement*, Brussels: i24c, https://www.iisd.org/library/low-carbon-innovation-sustainable-infrastructure-role-public-procurement (accessed 4 Apr. 2018), p. 59.

[332] Kemp, Bartekova and Turkeli (2017), 'The innovation trajectory of eco-cement in the Netherlands'.

[333] Casier and Wuennenberg (2017), *Leveraging the Power of the Public Purse*.

[334] Edwards (2016), 'Lower SCM supplies demand a change in approach'.

[335] Aproplan (undated), 'UK Follows Through on BIM Level 2 Mandate', https://www.aproplan.com/blog/efficiency/uk-government-follows-bim-level-2-mandate (accessed 30 Jan. 2018).

[336] Organisation for Economic Cooperation and Development (2016), *Preventing Corruption in Public Procurement*, http://www.oecd.org/gov/ethics/Corruption-Public-Procurement-Brochure.pdf (accessed 6 Apr. 2018).

[337] Ibid.; Hoare, A., Hong, L., and Hein, J. (2018), *The Role of Investors in Promoting Sustainable Infrastructure Under the Belt and Road Initiative*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/publication/role-investors-promoting-sustainable-infrastructure-under-belt-and-road-initiative.

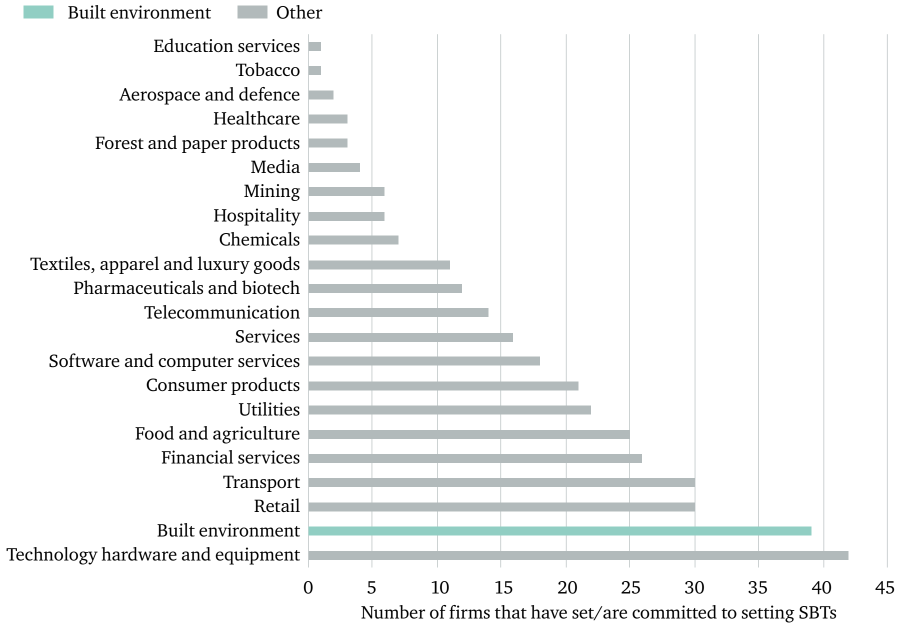
[338] World Economic Forum and Boston Consulting Group (2017), *Shaping the Future of Construction: Inspiring innovators redefine the industry*.

[339] This figure includes firms in 'construction and engineering', 'building products', 'construction materials' and 'homebuilding' under a broader 'built environment' category. Authors' analysis of data from Science Based Targets (2018), 'Companies Taking Action'.

[340] Ibid.

A growing number of construction clients are also setting carbon-intensity targets for their projects and supply chains. There is huge potential for more firms to adopt such targets voluntarily, as well as for targets to be introduced through regulatory means. Major companies could also band together, along the lines of the RE100,[341] to set commitments to lower the embodied carbon of the construction materials they use or procure. Given the collective purchasing power of these companies, this could generate significant market appeal for low-carbon products.

Figure 23: Sectors by science-based-targets (SBTs)



Source: Authors' analysis of data from Science Based Targets (2018), 'Companies Taking Action'.

Note: The sectors listed above are sets of more specific sectors that have been aggregated, e.g. firms in 'construction and engineering', 'building products', 'construction materials' and 'homebuilding' are all included under a broader 'built environment' category, while 'utilities' includes 'electric utilities', 'energy-related utilities', 'solid-waste management utilities', 'gas utilities' and 'water utilities.'

3.5 Digital disruption

Although the cement and concrete sector is only at the early stages of digital transformation,[342] there is growing interest in the role that digital tools could play in overcoming barriers to low-carbon innovation. Many of the barriers discussed above require action that involves matching solutions to local conditions, and improving coordination and communication – areas where digital technologies have significant advantages. Throughout this chapter there are examples of digital tools already starting to play an important role.

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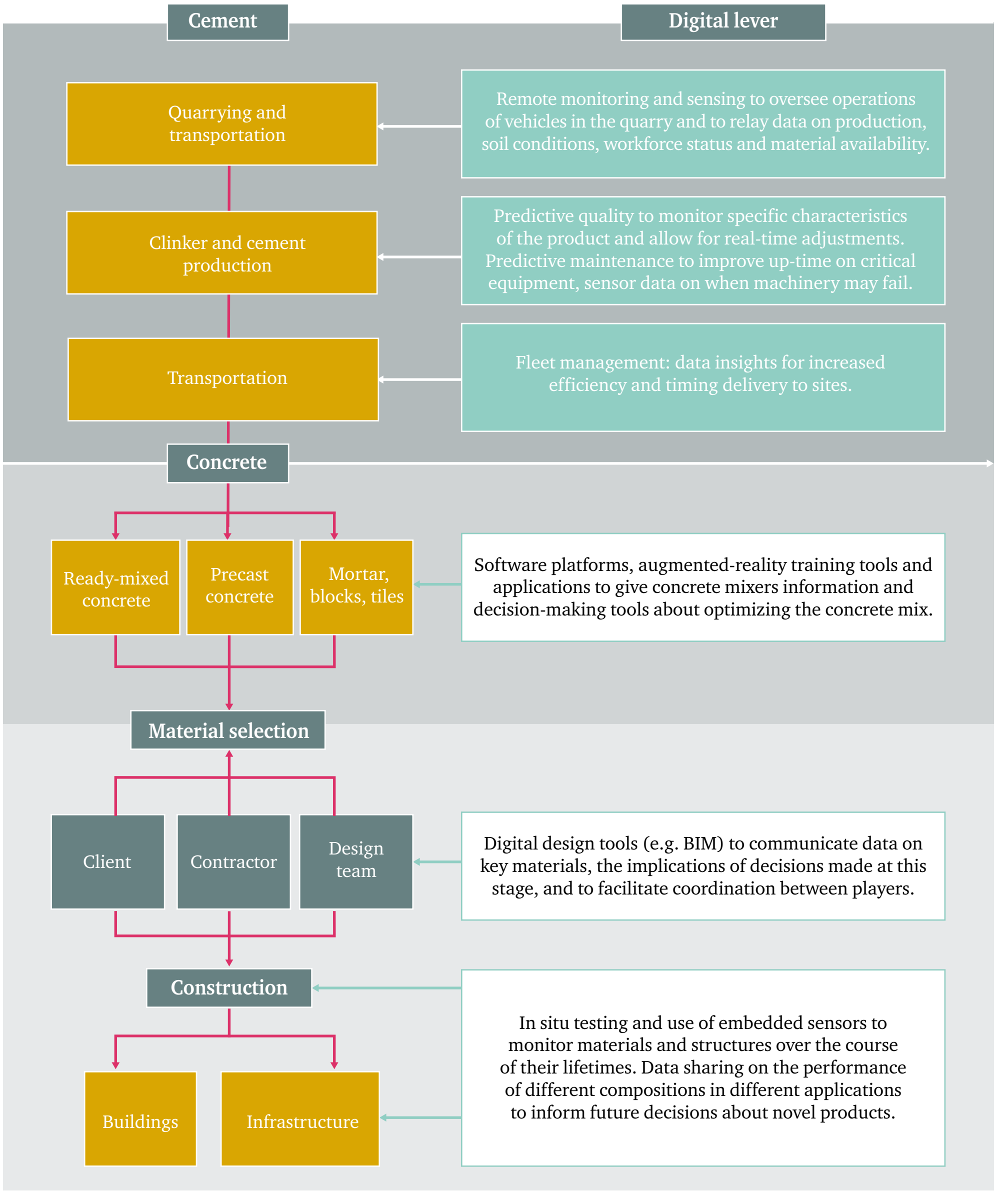
[341] Companies that have committed to shift to 100 per cent renewable energy.

[342] Burfeind, A., Rahne, U., Heck, P. and Gross, I. (2015), 'Bringing Digital Disruption to Building Materials', Boston Consulting Group, 13 November 2015, https://www.bcgperspectives.com/content/articles/process-industries-go-to-market-strategy-bringing-digital-disruption-building-materials-reinventing-customer-journey/?chapter=2 (accessed 9 Oct. 2017).

Figure 24: Digital tools along the cement, concrete and construction supply chain



Remote monitoring and sensing to oversee operations of vehicles in the quarry and to relay data on production, soil conditions, workforce status and material availability.

Predictive quality to monitor specific characteristics of the product and allow for real-time adjustments. Predictive maintenance to improve up-time on critical equipment, sensor data on when machinery may fail.

Fleet management: data insights for increased efficiency and timing delivery to sites.

Software platforms, augmented-reality training tools and applications to give concrete mixers information and decision-making tools about optimizing the concrete mix.

Digital design tools (e.g. BIM) to communicate data on key materials, the implications of decisions made at this stage, and to facilitate coordination between players.

In situ testing and use of embedded sensors to monitor materials and structures over the course of their lifetimes. Data sharing on the performance of different compositions in different applications to inform future decisions about novel products.

Source: Authors' own analysis with some examples from Scholze, J. (2015), 'How IoT and Digitization can reinforce the cement industry', *Digitalist Magazine*, 1 December 2015, http://www.digitalistmag.com/digital-economy/2015/12/01/iot-digitization-reinforce-cement-industry-03814141 (accessed 16 Oct. 2017).

Figure 24 summarizes these examples and introduces new cases, some of which are more ground-breaking than others. The turquoise shading indicates examples already likely to be in place for most industrialized cement producers – for example, for modern quality control and fleet management. The areas shaded in white indicate examples where digital solutions are not yet widespread.

Digital disruption could help disparate and apparently incremental changes across the cement and concrete sector to deliver system-level optimization and deep decarbonization. For instance, analytics could be used to predict product characteristics for a given mixture in a given climate and for a given use (the number of factors involved and the need for very-fine-tuning suggest that machine learning is well suited to tackling this problem). Remote sensing could help track and record the performance of different concretes over time. Augmented-reality and information-driven decision tools, when used on site, could enable an individual worker mixing concrete to make the best decisions for a given context.[343]

There are many entry points for innovative practices and materials, but all depend on better data collection and, crucially, on making the data available to a range of market participants, including new players. The importance of digital disruption will also depend on the degree to which it reshapes the largest cement markets: China and India.

3.6 Pathways to deployment

This chapter has highlighted the potential of several solutions to overcome the current barriers to wider deployment of clinker substitution and novel-cement technologies. It has also set out the conditions under which different solutions might be more or less valuable, and over what time frame their uptake within the industry might occur. In this context, three factors are important to consider: the interplay between different technologies considered in this report, the interplay between the solutions set out above, and the key locations that need to be targeted for deep decarbonization to occur.

Early action is needed on readily available mitigation options to maximize their emissions-reduction potential

Early action is needed on readily available mitigation options to maximize their emissions-reduction potential, and to bridge the gap until more innovative early-stage technology options are available.[344] In practice this would mean scaling up clinker substitution by using the materials available today, improving distribution networks for them, and optimizing the use of these networks. It would also require expanding the use of alternative fuels and adding to improvements in energy efficiency.

However, a short-term focus on the solutions currently available should not delay long-term efforts to advance potential breakthrough technologies such as novel cements and CCS. The challenge is that there may be limited incentive for cement makers to invest in novel cements while approaches such as clinker substitution still have a lot to offer and are cheaper and quicker to bring to market. Similarly, progress on alternative fuels and clinker substitution could reduce the total amount of CO_2 from cement production available for capture relative to the capital cost of CCS, with the result that investing in CCS may seem less worthwhile.

Even clinker substitution may reach the limits of its commercial and practical viability relatively quickly, particularly with fewer traditional sources available. Moreover, the use of alternative fuels is likely to become increasingly expensive.[345] In this context, and given the importance of deep decarbonization in the sector, industry-wide adoption of novel cements and CCS would still be worthwhile. A parallel track, therefore, will be needed to accelerate the development and commercialization of technologies such as novel cements and CCS.

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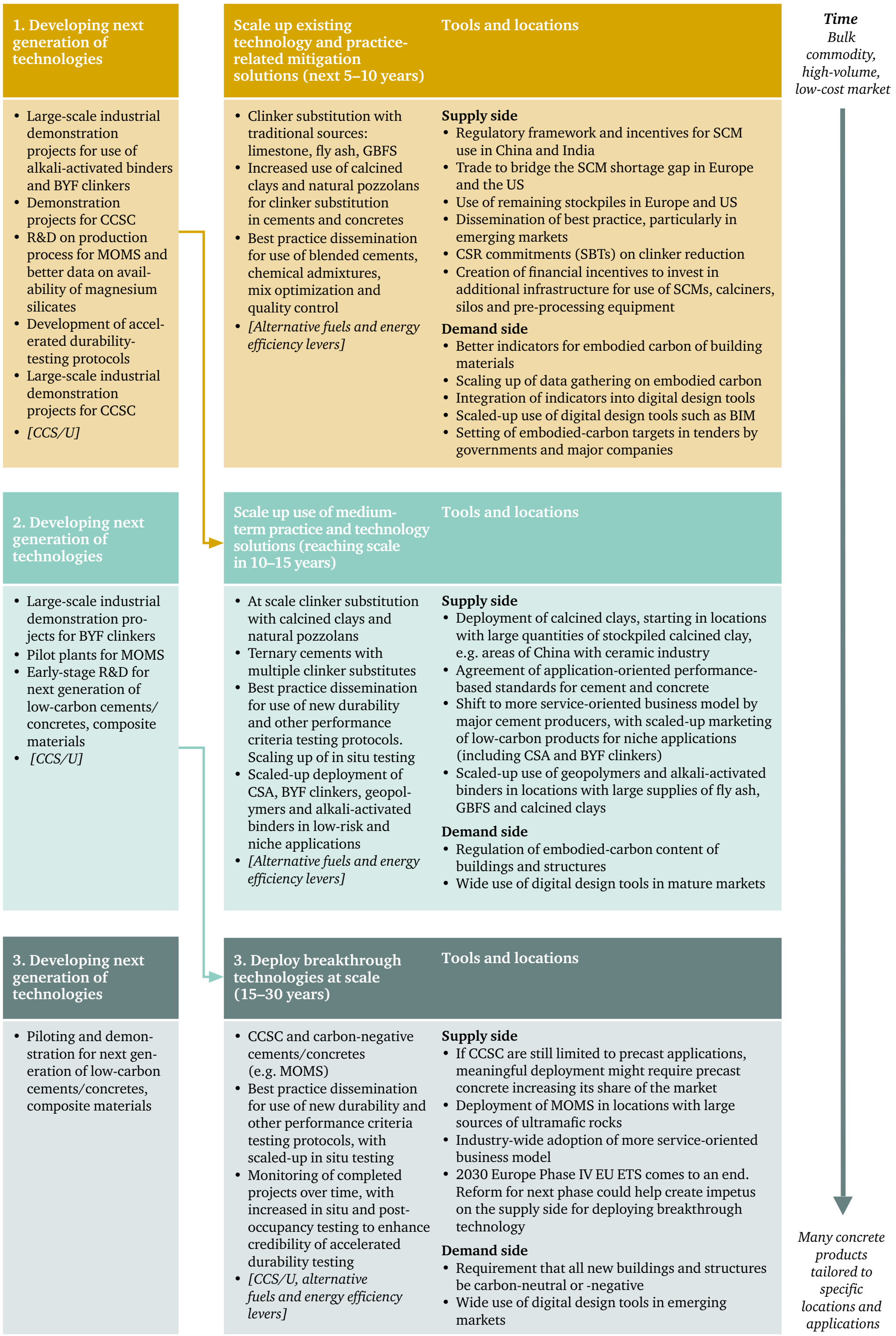
[343] SafeCement (2017), *Project*, http://www.safecement.com/en/project/ (accessed 15 Aug. 2017).
[344] International Energy Agency (2017), *Energy Technology Perspectives 2017*.
[345] World Business Council for Sustainable Development and International Energy Agency (2009), *Cement Technology Roadmap 2009*.

Figure 25: Low-carbon innovation pathway



1. Developing next generation of technologies

- Large-scale industrial demonstration projects for use of alkali-activated binders and BYF clinkers
- Demonstration projects for CCSC
- R&D on production process for MOMS and better data on availability of magnesium silicates
- Development of accelerated durability-testing protocols
- Large-scale industrial demonstration projects for CCSC
- *[CCS/U]*

Scale up existing technology and practice-related mitigation solutions (next 5–10 years)

- Clinker substitution with traditional sources: limestone, fly ash, GBFS
- Increased use of calcined clays and natural pozzolans for clinker substitution in cements and concretes
- Best practice dissemination for use of blended cements, chemical admixtures, mix optimization and quality control
- *[Alternative fuels and energy efficiency levers]*

Tools and locations

Supply side
- Regulatory framework and incentives for SCM use in China and India
- Trade to bridge the SCM shortage gap in Europe and the US
- Use of remaining stockpiles in Europe and US
- Dissemination of best practice, particularly in emerging markets
- CSR commitments (SBTs) on clinker reduction
- Creation of financial incentives to invest in additional infrastructure for use of SCMs, calciners, silos and pre-processing equipment

Demand side
- Better indicators for embodied carbon of building materials
- Scaling up of data gathering on embodied carbon
- Integration of indicators into digital design tools
- Scaled-up use of digital design tools such as BIM
- Setting of embodied-carbon targets in tenders by governments and major companies

2. Developing next generation of technologies

- Large-scale industrial demonstration projects for BYF clinkers
- Pilot plants for MOMS
- Early-stage R&D for next generation of low-carbon cements/concretes, composite materials
- *[CCS/U]*

Scale up use of medium-term practice and technology solutions (reaching scale in 10–15 years)

- At scale clinker substitution with calcined clays and natural pozzolans
- Ternary cements with multiple clinker substitutes
- Best practice dissemination for use of new durability and other performance criteria testing protocols. Scaling up of in situ testing
- Scaled-up deployment of CSA, BYF clinkers, geopolymers and alkali-activated binders in low-risk and niche applications
- *[Alternative fuels and energy efficiency levers]*

Tools and locations

Supply side
- Deployment of calcined clays, starting in locations with large quantities of stockpiled calcined clay, e.g. areas of China with ceramic industry
- Agreement of application-oriented performance-based standards for cement and concrete
- Shift to more service-oriented business model by major cement producers, with scaled-up marketing of low-carbon products for niche applications (including CSA and BYF clinkers)
- Scaled-up use of geopolymers and alkali-activated binders in locations with large supplies of fly ash, GBFS and calcined clays

Demand side
- Regulation of embodied-carbon content of buildings and structures
- Wide use of digital design tools in mature markets

3. Developing next generation of technologies

- Piloting and demonstration for next generation of low-carbon cements/concretes, composite materials

3. Deploy breakthrough technologies at scale (15–30 years)

- CCSC and carbon-negative cements/concretes (e.g. MOMS)
- Best practice dissemination for use of new durability and other performance criteria testing protocols, with scaled-up in situ testing
- Monitoring of completed projects over time, with increased in situ and post-occupancy testing to enhance credibility of accelerated durability testing
- *[CCS/U, alternative fuels and energy efficiency levers]*

Tools and locations

Supply side
- If CCSC are still limited to precast applications, meaningful deployment might require precast concrete increasing its share of the market
- Deployment of MOMS in locations with large sources of ultramafic rocks
- Industry-wide adoption of more service-oriented business model
- 2030 Europe Phase IV EU ETS comes to an end. Reform for next phase could help create impetus on the supply side for deploying breakthrough technology

Demand side
- Requirement that all new buildings and structures be carbon-neutral or -negative
- Wide use of digital design tools in emerging markets

Time
Bulk commodity, high-volume, low-cost market

Many concrete products tailored to specific locations and applications

The timing of policy solutions relative to one another is also a key factor. Uptake of application-oriented, performance-based standards depends on the development of improved and accelerated durability-testing protocols. The introduction of digital tools that familiarize stakeholders with the methods for assessing embodied-carbon metrics would be an important, though not essential, precursor to setting regulations limiting embodied-carbon content in infrastructure.

Finally, it is important to think about where the biggest markets will be, and thus where novel technologies and solutions are likely to have the greatest disruptive and decarbonization potential. As China, India and other emerging markets will continue to make up the bulk of future demand for cement,[346] it is essential that low-carbon innovations are cheap and easy to use, and that relevant players in those markets have access to the requisite information to make use of new products.

Figure 25 introduces a staged approach to the introduction of these different technologies and solutions. It highlights how we might move from the current bulk, high-volume, low-cost commodity market to one characterized by tailored solutions with the potential for increased value added through ‘cement as a service’ offerings.

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[346] Ionita, R., Würtenberger, L., Mikunda, T. and de Coninck, H. (2013), *Climate Technology & Development: Energy efficiency and GHG reduction in the cement industry*, Climate Technology & Development, http://climatestrategies.org/wp-content/uploads/2014/10/Climate-Technology-and-Development-Case-study-Cement-Ionita-et-al-final.pdf (accessed 25 Apr. 2018).

4. Disruption in the Built Environment

Key points

- Disruptive trends in the built environment could change the role of cement and concrete, and redefine the opportunities for innovation and decarbonization in the sector.
- Changing how we build could have a major impact on the volume of concrete needed, and there are many exciting developments around materials and design.
- The changing politics around the built environment are reshaping the expectations of publics and policymakers and affecting what is built and why. This is occurring in the context of growing popular interest in 'inclusive' built environments, rising environmental sensitivity and increased awareness of the need for resilience to climate shocks.

So far this report has focused on disruptive innovations that could lower the carbon content of cement and concrete. This chapter considers disruptive innovations that could lower the carbon content of buildings and structures and reduce the carbon emissions associated with their construction and use. It also considers innovations in terms of the implications for so-called 'end of first life' processes – such as the demolition of buildings, the recycling or reuse of materials from them, the repurposing of buildings and structures for other uses, and so on.

Considering the role of cement and concrete within the broader context of the built environment is important for two reasons. First, it introduces the possibility of establishing a new set of emissions mitigation levers, based on design and material efficiency and how buildings are used. Second, it allows us to think about solutions to the larger environmental impact of buildings and construction, which respectively account for 28 per cent and 11 per cent of global energy-related CO_2 emissions.[347] Decarbonizing cement and concrete alone will not solve this broader issue, but it could play a contributory role. At the same time, changes in the built environment could feed back into the cement and concrete sector – promoting consumption of cleaner products or helping lower overall demand.

Broadening the boundaries of the debate might reduce clarity over 'ownership' of – and responsibility for – decarbonization, but new approaches could be developed to address these issues. This question of boundaries is not limited to cement and concrete; there are examples across the economy as traditional sectoral demarcations blur. Assessing progress on decarbonization across the wider built environment is a logical end-game, but narrower, sector-specific goals will remain critical given the scale of cement use.

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[347] UN Environment and International Energy Agency (2017), *Global Status Report 2017*.

This chapter maps out the landscape of emerging or prospective disruptive changes in the built environment. It starts to explore what these changes could mean for the decarbonization of construction, as well as – where possible – for the decarbonization of cement and concrete specifically.

The chapter divides these disruptive trends into two categories. First, there are the profound changes in what we build – led by different expectations, shifts in behaviour and the need for resilience to more turbulent climatic conditions. Second, and underpinning these changes, are the shifts in how we build, underpinned by breakthroughs in design and construction methods and the leveraging of data to optimize the use of buildings and infrastructure. This latter category of trends centres on developments in technical innovation, engineering, and the services around them.

At present, it is challenging to put numbers on the likely impact of each of these changes, let alone estimate their aggregate impact at the system level. These are fast-evolving trends and there are few robust models; suggestions for ways to help fill this gap form part of this report's recommendations (see Chapter 5).

4.1 Building for the future

There remains much uncertainty over how changes in society will shape the future urban environment. Yet to a great extent these will determine what a climate-compatible pathway for cement and concrete could look like.[348] Several factors are important in this regard:

Shifts in demographics and behaviour

Demographic shifts are a key factor shaping the types of buildings needed. In many regions, populations are getting older,[349] requiring a greater focus on subsidized supportive housing, accessible workplaces, and mobile health and personal support services. At the same time, in many countries younger people are increasingly choosing to live in urban spaces within walking distance of public amenities.[350] Another trend is that more people are choosing to live alone.

Although city planners need to respond to these trends, they can also help define patterns of energy and resource consumption.[351] The way in which a building or a city is laid out strongly influences how people and materials move around – and, once built, infrastructure can lock in behavioural pathways for better or worse. Urban design based on a 'capillary web' system and around pedestrians rather than cars, for example, can lead to two-thirds less driving and one-third less concrete being used.[352]

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[348] The New Climate Economy (2016), *The Sustainable Infrastructure Imperative.*

[349] Weber, V. (2017), 'How automation and technology will change the buildings we live in', World Economic Forum, 10 August 2017, https://www.weforum.org/agenda/2017/08/how-automation-and-connected-technology-will-change-the-buildings-we-live-in/ (accessed 18 Oct. 2017).

[350] McKinsey & Company (2012), *Mobility of the future: Opportunities for automotive OEMs*, https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/automotive%20and%20assembly/pdfs/mobility_of_the_future_brochure.ashx (accessed 19 Oct. 2017).

[351] Granoff, I., Hogarth, J. R. and Miller, A. (2016). 'Nested barriers to low-carbon infrastructure investment', *Nature Climate Change*, 6: pp. 1065–1071, doi: 10.1038/nclimate3142 (accessed 6 Jun. 2017).

[352] Lovins, A. B. (2017), 'Disruptive energy futures', presentation at Chatham House, 8 June 2017.

Emerging and developing countries have an advantage here: by making the right choices today, they can avoid some of the environmentally costly effects of urbanization in developed economies.[353] Growth in urbanization in the US around the 1920s, at a time when private car ownership was on the rise, resulted in cities designed around cars.[354] These sprawling cities in turn reinforced dependency on car ownership. A climate-compatible built environment will, therefore, depend just as much on building the *right* infrastructure as on building *more* infrastructure.

Accountability and public expectations

A climate-compatible built environment will depend just as much on building the right *infrastructure as on building* more *infrastructure*

Cement is largely a hidden material, in that end-users do not generally think about their consumption of it or consider the environmental implications of that consumption. Although the choice of building materials can have a large impact on living standards, prospective house owners do not tend to choose dwellings based on the materials used; nor do they think about the long-term effects of those materials on the environment and their enjoyment of the structure in question.

The choice of building materials only seems to be revealed in the event of catastrophe. Earthquakes in China and Italy, for example, raised awareness of shoddy building standards and of corruption that allowed regulations to be circumvented.[355] The 2017 Grenfell Tower fire in the UK led to increased political demand for accountability about the decisions taken with regard to cladding and materials used in public housing and more broadly.[356]

As public awareness of the climate impacts from infrastructure and construction increases, publics may well demand a more environmentally friendly built environment; after all, consciousness around urban air quality has soared in recent years, and the same may one day be true of public attitudes towards the built environment. There may also be demand for stronger, more durable and more flexible buildings.

Digital trends shaping urban life

New technologies are changing approaches to city planning and management. Real-time information from connected devices has given cities new ways of delivering services (examples include the shift towards digital traffic management in Nairobi, Kenya;[357] and the use of smart, connected waste-management systems by some local

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[353] The New Climate Economy (2016), *The Sustainable Infrastructure Imperative*.
[354] Norton, P. (2008), *Fighting Traffic: The Dawn of the Motor Age in the American City*, London: MIT press.
[355] Lim, L. (2013), 'Five Years after a Quake, Chinese Cite Shoddy Reconstruction', NPR, 13 May 2013, http://www.npr.org/sections/parallels/2013/05/14/183635289/Five-Years-After-A-Quake-Chinese-Cite-Shoddy-Reconstruction (accessed 19 Oct. 2017); Schiavenza, M. (2013), 'Why Earthquakes in China Are So damaging', *The Atlantic*, 25 July 2013, https://www.theatlantic.com/china/archive/2013/07/why-earthquakes-in-china-are-so-damaging/278092/ (accessed 19 Oct. 2017); Hooper, J. (2016), 'Italy earthquake throws spotlight on lax construction laws', *Guardian*, 24 August 2016, https://www.theguardian.com/world/2016/aug/24/italy-earthquake-throws-spotlight-on-lax-construction-laws (accessed 19 Oct. 2017).
[356] Booth, R. (2017), 'Combustible cladding found on 120 tower blocks so far, says PM', *Guardian*, 28 June 2017, https://www.theguardian.com/politics/2017/jun/28/combustible-cladding-found-on-120-tower-blocks-so-far-says-pm-pmqs-grenfell-tower (accessed 19 Oct. 2017).
[357] IBM (undated), 'Outthink urban planning', https://www.ibm.com/events/ke/en/ted-outthink-urban.html [URL no longer works] (accessed 18 Oct. 2017).

governments in the UK).[358] Enhanced transport and logistics allow for good-quality urban living at much higher densities than used to be thought possible.[359] This can dramatically reduce energy and resource consumption.

The trend towards automation in the workplace could affect the types of buildings constructed. Fewer office buildings may be needed, less space and lighting will be needed in some workspaces, and there may be more demand for communal and multi-purpose spaces.[360] Office buildings could end up offering a large stock of new living spaces, reducing the need for construction of new buildings.

Spillover effects between different sectors shifting towards a low-carbon economy could have an impact on what is built. Electric cars, for example, will lead to cleaner air and less noise. This could encourage the use of natural ventilation and passive heating and cooling – designing a building to be warm or cool without the need for heating or cooling – in place of air-conditioning as a means of temperature control.[361] More energy-efficient buildings can reduce fuel consumption for heating and contribute to improved air quality.[362] In northern China, for example, high-performance building envelopes – the physical barrier between the exterior and interior of a structure, i.e. walls, floors, roofs and doors – could help reduce air pollution as less coal would be burnt for heating in winter.[363]

Climate-compatible infrastructure

Resilient infrastructure will be particularly important in emerging economies and developing countries, which are likely to experience the worst effects of climate change in the short to medium term.[364] The future built environment has to be resilient to climate-impact risks (e.g. sea-level rise) and address growing concerns over natural hazards (notably flooding and hurricanes). There will likely continue to be a need for high-strength traditional building materials, including concrete to build higher sea walls and stronger flood defences, and to strengthen critical infrastructure.

Novel, smarter and more adaptable materials will likely also come into play, with use in structures that can withstand extreme temperature changes and very high winds.[365] These materials will be particularly important where traditional materials are affected by climate change. Several studies highlight the impacts of climate change on concrete infrastructure. Humidity and increased concentrations of atmospheric CO_2 can speed up corrosion in concrete.[366] In regions where these effects are expected to be more pronounced, the use of thicker concrete, more rigorous maintenance,

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[358] Jefferies, D. (2015), 'How the internet of things could revolutionise council services', *Guardian*, 31 March 2015, https://www.theguardian.com/public-leaders-network/2015/mar/31/internet-of-things-revolutionise-council-services (accessed 18 Oct. 2017).
[359] Weber (2017), 'How automation and technology will change the buildings we live in'.
[360] Ibid.
[361] External workshop participant.
[362] International Energy Agency (2017), *Energy Technology Perspectives 2017*.
[363] Ibid.
[364] The New Climate Economy (2016), The Sustainable Infrastructure Imperative.
[365] Design Exchange (2016), 'Can 4D Printing Be A Game Changer In Architecture?', 25 April 2016, http://www.demagazine.co.uk/architecture/can-4d-printing-be-a-game-changer-in-architecture (accessed 18 Oct. 2017).
[366] CSIRO (2015), 'Climate impacts on concrete infrastructure', case study, 26 February 2015, https://www.csiro.au/en/Research/LWF/Areas/Resilient-cities-21C/Climate-adaptation/Concrete (accessed 10 May 2017).

and the application of surface coatings are being suggested as potential means of mitigating damage.[367]

Beyond reducing emissions from the construction and operation of buildings and infrastructure, there may be an opportunity to leverage the built environment as a carbon sink. Opportunities in this area range from the fairly non-technical (covering the walls and roofs of buildings with plants)[368] to the highly technical (using building materials designed to sequester CO_2).[369]

4.2 Building differently

A more sustainable built environment may not only rest on *what* is built but on *how* we choose to build in the next few decades. Changing how we build could have a considerable impact on CO_2 emissions. This will be contingent on disruptive innovation at five key points along the construction value chain: design, materials, construction, operations and use, and end-of-first-life.

The share of emissions that stem from these different stages can vary considerably depending on location, design and application.[370] However, in general, the bulk of emissions lie in the operations and use phase of buildings and structures. For example, in 2008, an estimated 83 per cent of UK construction-sector CO_2 emissions came from the use phase versus 15 per cent from the supply of construction materials; of the latter, 28 per cent came from the use of cement, lime and concrete products (see Figure 26).

As a result, the focus of policymakers has tended to be on ‘operational carbon’: the emissions created during a structure’s operations and use phase. Emissions, such as embodied carbon, from other life-cycle phases are generally considered less important.[371]

As operational carbon has been reduced due to concerted policy efforts and broader shifts in the energy sector, however, embedded carbon has assumed greater relative importance in the total life cycle of building structures.[372] In the past few years, global operations-related carbon emissions from buildings seem to have reduced, yet emissions from building construction have continued to grow.[373] In the longer term, operational emissions are contingent on factors like the future energy mix and energy generating technology that are to some extent outside of the control of construction sector stakeholders.[374]

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[367] Wang, X., Nguyen, M., Stewart, M. G., Syme, M. and Leitch, A. (2010), *Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Part 3: Case Studies of Concrete Deterioration and Adaptation*, Canberra: CSIRO, https://publications.csiro.au/rpr/download?pid=csiro:EP104734&dsid=DS5 (accessed 11 Jun. 2017).

[368] Metsä Group (2017), ‘Construction is the best use of wood’, http://www.metsagroup.com/en/media/Pages/Case-Wood-building-a-carbon-sink.aspx (accessed 18 Oct. 2017).

[369] Deich, N. (2014), ‘Buildings: an untapped source for Greenhouse Gas Removal’, Virgin Earth Challenge, 22 July 2014, http://www.virginearth.com/2014/07/buildings-an-untapped-source-for-greenhouse-gas-removal/ (accessed 18 Oct. 2014).

[370] MIT Building Tech (2017), DeQo Database of embodied Quantity outputs, https://www.carbondeqo.com/ (accessed 1 Feb. 2018).

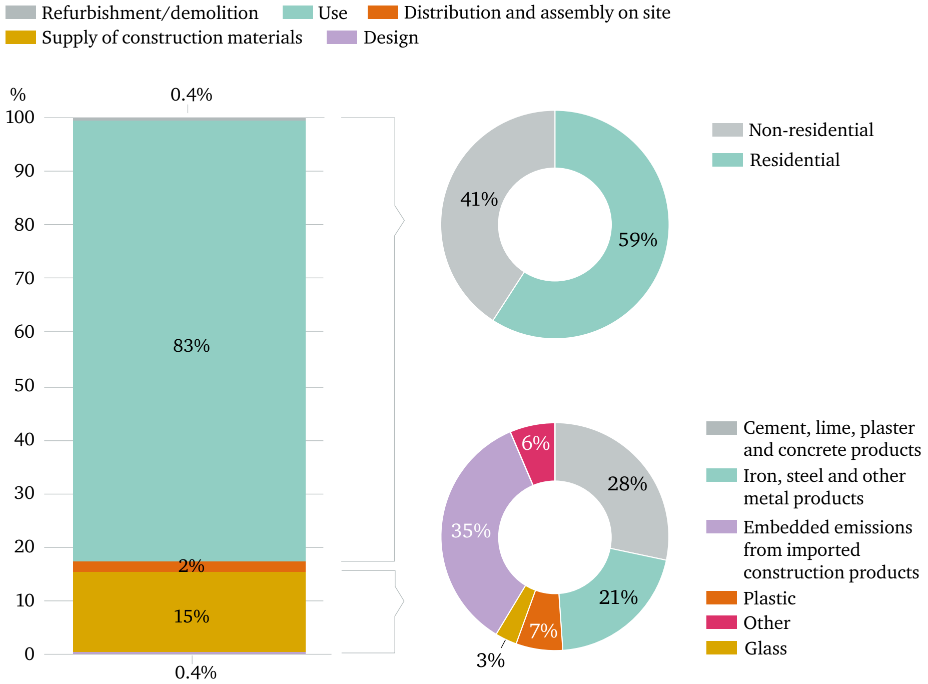
[371] Pöyry, A., Saeynaejoki, A., Heinonen, J., Junnonen, J. M. and Junnilla, S. (2015), ‘Embodied and construction phase greenhouse gas emissions of a low-energy residential building’, *Procedia Economics and Finance*, 21: pp. 355–365, doi:10.1016/S2212-5671(15)00187-2 (accessed 12 Jan. 2018); UN Environment and International Energy Agency (2017), Global Status Report 2017; Laski, J. and Burrows, V. (2017), *From Thousands to Billions: Coordinated Action towards 100 % Net Zero Carbon Buildings by 2050*, London: UK Green Building Council.

[372] MIT Building Tech (2017), DeQo Database of embodied Quantity outputs.

[373] UN Environment and International Energy Agency (2017), *Global Status Report 2017*.

[374] Pöyry et al. (2015), ‘Embodied and construction phase greenhouse gas emissions of a low-energy residential building’.

Figure 26: Share of emissions by factor, UK construction sector, 2008



Source: Authors' analysis of data from Department for Business Innovation & Skills (2010), *Estimating the Amount of CO_2 Emissions that the Construction Industry can influence*, Supporting material for the Low-carbon Construction IGT Report, Autumn 2010, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31737/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report.pdf (accessed 11 Jan. 2018).

Note: For assumptions and caveats used in calculations, refer to original source.

Decarbonization in the built environment will therefore require disruptive innovation all along the supply chain, targeting the embodied carbon of building materials as well as emissions from the construction, use and end-of-first-life phases. Policymakers' short-term focus on operational carbon, important though it is for efficiency measures in buildings, should not be an excuse for delaying action in these other areas.

Design

The design and planning stage has a profound impact on emissions from the sector. Section 3.4 discusses the importance of material selection for emissions, but this section considers the potential for design to reduce the *amount* of building materials, including concrete, required.

Key decisions include:

- **Designing components to fulfil their function using less material.** 'Topology optimization' is design aimed at optimizing material use within a given shape.[375] This entails, for example, designing the shape of a beam so that material is only placed where it is necessary to carry out its function.[376] Design principles from

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[375] Bendsøe, M. P. and Sigmund, O (2004), *Topology optimization – theory, methods and applications*, Berlin: Springer-Verlag.

[376] Moynihan, M. C. and Allwood, J. M. (2014), 'Utilization of structural steel in buildings', *Proceedings of the Royal Society* A, doi: 10.1098/rspa.2014.0170 (accessed 12 Jan. 2018).

Gothic cathedrals have been used to design modern concrete floors that are 2 cm thick and 70 per cent lighter than their conventional counterparts.[377]

- **Designing components for modularity and disassembly.** Designing a building from prefabricated components that are assembled on site has benefits all along the value chain. Modularity can halve the duration of the construction process, as well as reduce energy consumption and labour costs.[378] A modular building can be more easily retrofitted, and its disassembly at end of first life produces less waste and uses less energy.[379]
- **Designing buildings to last longer and be more adaptable.** A 'long life, loose fit' approach consists of designing a building to be flexible but also to have the structural durability to support many alternative functions over the course of its lifetime.[380] Taller walls and more space are key to ensuring a long life and extending the usefulness of buildings.

Computer software is also transforming design methods.[381] In combination with BIM, virtual reality and augmented reality are transforming the ways in which architects, engineers and clients can engage with a new design, allowing them to explore how a space feels in simulated walk-throughs and get a much more accurate view of a building before construction.[382] Constraints with such approaches include the cost of specialized software, the additional time taken to approach design in a different way, and potential complications over the client brief and the budget. There is also currently a skills shortage: competent building information modellers are scarce.[383]

Design in different parts of the built environment has to be 'joined up' if problematic trade-offs are to be avoided

Design in different parts of the built environment has to be 'joined up' – with decisions in one area complementing, anticipating or integrated with those in others – if problematic trade-offs are to be avoided. Reducing the amount of materials used can, for example, result in less resilient and less robust structures. A building in which material efficiency has been prioritized may also be less easily adapted later on. For example, the shallow floor-to-ceiling height of many 1960s office blocks was advanced in terms of material efficiency, but this is now making them difficult to adapt. Currently, modularity often relies on less resilient materials; even if a building can be adapted, it might not have the resilience to support further use in the future. Architects and structural engineers are actively seeking ways to balance these different considerations to come up with optimal, sustainable designs.[384]

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[377] Rüegg, P. (2017), 'Gothic cathedrals inspire very thin concrete floors', Futurity, 12 April 2017, http://www.futurity.org/concrete-floors-1399952-2/ (accessed 11 Dec. 2017).

[378] Designing Buildings Wiki (2016), 'Modular vs traditional construction', 29 June 2016, https://www.designingbuildings.co.uk/wiki/Modular_vs_traditional_construction (accessed 9 May 2017).

[379] Rauland, V. and Newman, P. (2015), *Decarbonising Cities: Mainstreaming Low-carbon Urban Development*, Cham: Springer International Publishing.

[380] Langston, C. (2014), 'Measuring Good Architecture: Long life, loose fit, low energy', *European Journal of Sustainable Development*, 3(4): pp. 163–174, doi: 10.14207/ejsd.2014.v3n4p163 (accessed 2 Feb. 2018).

[381] University of Liverpool (2013), 'Minimising Material Waste by Utilising BIM and Set-based Design in the Structural Design of Reinforced Concrete Slabs', https://livrepository.liverpool.ac.uk/2007735/1/C2013.02%20Minimising%20Material%20Waste%20by%20Utilisation%20of%20BIM.pdf (accessed 2 Aug. 2017).

[382] Arch Daily (2017), 'Will Virtual Reality Transform the Way Architects Design?', 30 May 2017, http://www.archdaily.com/872011/will-virtual-reality-transform-the-way-architects-design (accessed 15 Jun. 2017).

[383] Azhar, Hein and Sketo (2014), 'Building Information Modeling (BIM)'.

[384] University of Liverpool (2013), 'Minimising Material Waste by Utilising BIM'.

Material supply chain

Innovations in building materials that could change the carbon content of buildings and structures can be separated into three broad areas.

First, it is possible to substitute traditional building materials – concrete, steel and reinforced concrete – with lower-carbon, often bio-based, alternatives. Substitutability depends on the type of end use. More alternative materials are available for housing construction than for infrastructure projects.[385] Depending on location, the density of structures and the required performance, bio-based alternatives to concrete include wood, hempcrete, timbercrete, straw bales, rammed earth, mycelium and bioMASON (which uses bacteria to grow cement to make bricks).[386] A recent report also draws attention to the potential for the use of organic waste in construction.[387]

Wood currently seems to be the most versatile of these materials. Cross-laminated timber has been used in place of concrete and steel in structural floor and wall elements of buildings.[388] However, commercial timber can itself be energy-intensive to produce, as it has to be dried in kilns;[389] moreover, in many countries the availability of timber is restricted by land-use constraints. Where appropriate, however, using timber from sustainably managed farms could become an increasingly attractive option, especially given the potential for wood to lock in CO_2 for decades, if not longer.[390]

The second area of innovation involves enhancing the properties of traditional building materials to lower the amount of materials needed and extend the durability of buildings. It includes developing ways to increase the strength of concrete, speed up hardening times, enable the transmission of light,[391] and improve flexibility through nanoscience.[392] Luminescent concrete has been used in the Netherlands to light roads and structures at night, cutting down on the need for electric lighting.[393] Self-repairing or 'self-healing' concrete has been developed to increase the lifespan of concrete,[394] with the potential to reduce lifetime operational costs by up to 50 per cent.[395] HeidelbergCement is piloting a concrete that could store thermal energy from solar panels.[396] Photocatalytic concrete – which decomposes airborne pollutants – has been trialled as a means of abating air pollution.[397]

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[385] Zerelli, N., Korner, C., Putz, W., Krückeberg, L. and Willemeit, T. (2016), *Architecture Activism*, Basel: Birkhäuser De Gruyter, p. 65.

[386] bioMASON (2018), 'Technology', https://biomason.com/technology/ (accessed 25 Feb. 2018).

[387] Arup (2017), *The Urban Bio-Loop: Growing, Making and Regenerating*, Milan: Arup.

[388] Harris, R. (2015), 'Cross laminated timber', in Ansell, M. (ed.) (2015), *Wood Composites*, Cambridge: Woodhead Publishing Limited.

[389] Allwood et al. (2012), *Sustainable materials: with both eyes open*.

[390] Metsä Group (2017), 'Construction is the best use of wood'.

[391] Dogne, N. and Choudhary, A. (2014), 'Smart Construction Materials & Techniques', Conference Paper for National Conference on Alternative & Innovative Construction Materials and Techniques, https://www.researchgate.net/publication/297167802_SMART_CONSTRUCTION_MATERIALS_TECHNIQUES (accessed 11 May 2017).

[392] Stauffer, N. W. (2016), 'Designing climate-friendly concrete, from the nanoscale up', MIT News, 21 July 2016, http://news.mit.edu/2016/designing-climate-friendly-concrete-at-the-nanoscale-0721 (accessed 25 Feb. 2018). Lafarge developed Ductal concretes with high compressive and flexural strength. Dogne and Choudhary (2014), 'Smart Construction Materials & Techniques'.

[393] Carreño, B. (2016), 'Glow-Hard: Luminous Cement Could Light Roads, Structures', *Scientific American*, 16 June 2016, https://www.scientificamerican.com/article/glow-hard-luminous-cement-could-light-roads-structures/ (accessed 17 Oct. 2017).

[394] Spinks, R. (2015), 'The self-healing concrete that can fix its own cracks', *Guardian*, 29 June 2015, https://www.theguardian.com/sustainable-business/2015/jun/29/the-self-healing-concrete-that-can-fix-its-own-cracks (accessed 17 Jul. 2017); Calkins (2017), 'Concrete Minus Carbon'.

[395] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.

[396] Energy Matters (2015), 'Energy Storage – The Concrete Battery', 29 June 2015, https://www.energymatters.com.au/renewable-news/concrete-battery-storage-em4894/ (accessed 17 Oct. 2017).

[397] Calkins (2017), 'Concrete Minus Carbon'.

Finally, innovators have explored new ways of combining materials. Using carbon-fibre composites instead of steel reinforcements, for example, reduces the amount of steel and concrete needed for a given building.[398] Research around cement and concrete nanocomposites seeks to enhance the strength and durability characteristics of these materials.[399] There has also been an increase in hybrid engineered timber/steel structures. These approaches have the potential to displace concrete use in conventional composite construction, particularly for multi-storey buildings, an area in which timber has featured little to date.[400] These examples highlight the importance of thinking 'across materials' – i.e. not just thinking about 'steel' or 'concrete' or 'timber' in isolation but thinking about how these materials can be combined – to find innovative solutions.

Beyond the selection and combination of materials, there is a range of opportunities around their fabrication and delivery. Prefabrication, for example, could have a large impact on resource use in the cement and concrete sector.[401] Historically, ready-mixed concrete has dominated the market. Precast concrete is mostly used in public-sector projects, due to its limitations for complex projects, the transport and storage costs involved, and the need for additional training of construction workers. However, the market share of precast concrete is increasing as developers recognize its potential benefits. These include material and process efficiency, cost effectiveness and sustainability.[402]

In time, 3D printing may lower costs of production, particularly in remote locations,[403] and allow for more precision and efficiency in the application of materials, potentially lowering demand for them.[404] Although the technology is still at an early stage of deployment, a Chinese company, Winsun, has successfully printed residential houses using a special 'ink' made of cement, sand, fibre and a proprietary additive.[405]

Construction processes

Some of the biggest changes may occur in construction. Compared with other parts of the value chain, it includes the largest number of low-skilled actors and is currently

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[398] Reute, A. (2017), 'Eine neue Art des Bauens' [A new way of building], C³ – Carbon Concrete Composite e. V., 9 February 2015, https://www.bauen-neu-denken.de/eine-neue-art-des-bauens/ (accessed 17 Oct. 2017).

[399] Chuah, S., Pan, Z., Sanjayan, J. G., Wang, C. M. and Duan, W. H. (2014), 'Nano reinforced cement and concrete composites and new perspective from graphene oxide', *Construction and Building Materials*, 73: pp. 113–124, doi: 10.1016/j.conbuildmat.2014.09.040 (accessed 17 Oct. 2017).

[400] Cotgrave, A. and Riley, M. (2013), *Total Sustainability in the Built Environment*, Basingstoke: Palgrave Macmillan.

[401] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.

[402] National Precast Concrete Association (2010), 'Precast Concrete Manufacturing and the Environment', 28 July 2010, http://precast.org/2010/07/precast-concrete-manufacturing-and-the-environment/ (accessed 18 Oct. 2017).

[403] Becker, R. and Vincent, J. (2017), 'Autonomous robot 3D printers like this could help build homes for us on other planets', *The Verge*, 27 April 2017, https://www.theverge.com/2017/4/27/15447578/autonomous-robot-3d-printers-mit-homes-planets (accessed 19 Oct. 2017).

[404] Gosselin, C., Duballet, R., Roux, Ph., Gaudillière, N., Dirrenberger, J. and Morel, Ph. (2016), 'Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders', *Materials and Design*, 100: pp. 102–109, https://www.researchgate.net/profile/Justin_Dirrenberger/publication/299444698_Large-scale_3D_printing_of_ultra-high_performance_concrete_-_a_new_processing_route_for_architects_and_builders/links/57018f0908ae650a64f8c3fc.pdf (accessed 10 Jul. 2017).

[405] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.

the most fragmented.[406] It is potentially the area with the largest social and political implications in terms of jobs losses.[407]

Potential disruption can be broken into three types of changes around how construction processes are managed and monitored:

- **On-site automation** is already being used for complex tasks such as excavating construction sites, increasing efficiency and lowering production costs.[408] Technological advances in intelligent machines are speeding up this trend. They are allowing increasingly complex tasks to be carried out by machines, monitored by human operators.
- **Embedded sensors, mobile platforms and drones** can be used to monitor projects, track assets and deliver real-time information to construction sites so that builders can make informed decisions about progress on projects and avoid mistakes or delays.[409] In the context of concrete, these technologies could facilitate the tracking of usage, help users optimize application, and inform builders when concrete slabs or columns have reached the required strength.[410]
- **Augmented-reality and mobile interfaces** can be used to train builders on site, communicate with them and transmit important data to them during the performance of complex tasks.[411] Providing visual instructions to workers mixing and pouring concrete, for instance, may improve the efficiency of application and facilitate the use of more novel cements in concrete mixes.

Operations and use

A huge opportunity to reduce material consumption lies in simply maintaining buildings for their full design life. Building lifespans vary considerably between countries and applications.[412] Residential and office buildings are generally expected to last 100 years, while commercial buildings are often designed to last 50 years but on average are replaced after only 25.[413] Paradoxically, even as technical ability has increased, there has been a steady decline in the length of buildings' operational lifespans.[414]

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[406] Proverbs, D. G., Holt, G. D. and Cheok, H. Y. (2000), 'Construction industry problems: the views of UK construction directors', In: Akintoye A, (ed.), *16th Annual ARCOM Conference*, 6–8 September 2000, Glasgow Caledonian University. Association of Researchers in Construction Management, 1: pp. 73–81, http://www.arcom.ac.uk/-docs/proceedings/ar2000-073-081_Proverbs_Holt_and_Cheok.pdf (accessed 19 Oct. 2017).

[407] Rotman, D. (2013), 'How technology is destroying jobs', *MIT Technology Review*, 12 June 2013, https://www.technologyreview.com/s/515926/how-technology-is-destroying-jobs/ (accessed 19 Oct. 2017); Elliott, L. (2017), 'Millions of UK workers at risk of being replaced by robots, study says', *MIT Technology Review*, 24 March 2017, https://www.theguardian.com/technology/2017/mar/24/millions-uk-workers-risk-replaced-robots-study-warns (accessed 19 Oct. 2017).

[408] Grayson, W. (2015), 'With drones and driverless dozers, Komatsu to begin leasing automated construction fleets', *Equipment World*, 26 January 2015, https://www.equipmentworld.com/with-drones-and-driverless-dozers-komatsu-to-begin-leasing-automated-construction-fleets/ (accessed 12 Nov. 2016).

[409] Ikonen, J., Knutas, A., Haemailaeinen, H., Ihonen, M., Porras, J. and Kallonen, T. (2013), 'Use of embedded RFID tags in concrete element supply chains', *Journal of Information Technology in Construction*, 18: pp. 119–147, http://www.itcon.org/2013/7 (accessed 2 Feb. 2018).

[410] Converge (2018), *How it works*, https://www.converge.io/product (accessed 25 Feb. 2018).

[411] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.

[412] Celadyn, W. (2014), 'Durability of Buildings and Sustainable Architecture', *Technical Transactions Architecture*, 7–A: pp. 17–26, https://suw.biblos.pk.edu.pl/downloadResource&mId=1275984 (accessed 23 Feb. 2018).

[413] Ibid.

[414] Pomponi, F. and Moncaster, A. (2016), 'Circular economy for the built environment: A research framework', *Journal of Cleaner Production*, 143: pp. 710–718, doi: 10.1016/j.jclepro.2016.12.055 (accessed 10 Jun. 2017).

Connectivity, embedded sensors, intelligent machines and data analytics are enabling a host of changes in how buildings are managed, which can extend their useful lifetimes.[415] Drones and robots can provide maintenance and retrofitting services.[416] Sensors embedded throughout a building can deliver data to a central management system, reporting on structural integrity, energy use and operational health to raise issues as they crop up, such as the need to replace or refurbish a particular component.[417]

A huge opportunity to reduce material consumption lies in simply maintaining buildings for their full design life

BIM may allow facilities managers to be involved at an earlier stage of the building planning process, so that they can influence the design and construction. At the end of a project, the BIM model can be handed over to the facilities manager, tenants, service agents and maintenance personnel, giving them access to details on materials.[418] BIM can also ensure more accurate and timely maintenance or retrofit projects. Robotics companies are combining machine vision with BIM systems to retrofit insulation.[419]

However, insufficient durability is rarely the reason for replacing a building at least in industrialized countries. Other factors, typically financial, aesthetic and practical, drive most current demolition work.[420] In the UK, for example, new construction is exempt from VAT while reuse and adaptation are often regarded as riskier and less desirable options.[421]

The challenge of extending the life of buildings is, therefore, about making them more adaptable and flexible as well as more durable – along the lines of the 'long life, loose fit' design approach highlighted above. Through smart design and use of materials, a building core can deliver a high-performance, low-carbon structure that is flexible enough to accommodate future tastes and requirements.

The shift towards shared and multiple-use infrastructure, often facilitated by digital technologies,[422] could alter how many new buildings have to be built. During the 2016 Olympics in Rio de Janeiro, the online property-rental service Airbnb housed around 85,000 visitors in other peoples' homes. Without the service, the city would have needed to build another 257 hotels,[423] with roughly 3 million tonnes of concrete needed for the foundations alone.[424]

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[415] World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.

[416] Lavars, N. (2015), 'How drones are poised to build the cities of tomorrow', New Atlas, 2 March 2015, https://newatlas.com/drones-building-construction-industry/36306/ (accessed 19 Oct. 2017); Carr, D. (2015), 'A robotic solution to a retrofit conundrum', Building4Change, 9 June 2015, http://www.building4change.com/article.jsp?id=2653#.WeoGcFtSzcs (accessed 10 Oct. 2017).

[417] Somwanshi, S. and Gawalwad, B. (2015), 'Monitoring civil structures with a smart wireless sensor network', *International Journal of Engineering and Applied Sciences*, 2(3): pp. 34–38, ISSN: 2394-3661 (accessed 18 Oct. 2017); Spencer, B. F., Ruiz-Sandoval, M. and Kurata, N. (2004), 'Smart sensing technology: opportunities and challenges', *Structural Control Health Monitoring*, 11: pp. 349–368, doi: 10.1002/stc.48 (accessed 18 Oct. 2017).

[418] Azhar, Hein and Sketo (2014), 'Building Information Modeling (BIM)'.

[419] *Building Products* (undated), 'Futuristic robot helps deliver construction service', http://buildingproducts.co.uk/futuristic-robot-helps-deliver-construction-service/ (accessed 11 Dec. 2017).

[420] Bullen, P. and Love, P. (2009), 'Factors influencing the adaptive re-use of buildings', *Journal of Engineering, Design and Technology*, 9(1): pp. 32–46, doi: 10.1108/17260531111121459 (accessed 23 Feb. 2018).

[421] Gov.UK (2018), 'VAT for builders', https://www.gov.uk/vat-builders/new-homes (accessed 23 Feb. 2018).

[422] Ernst & Young (2015), *The rise of the sharing economy: The Indian landscape*, October 2015, http://www.ey.com/Publication/vwLUAssets/ey-the-rise-of-the-sharing-economy/$FILE/ey-the-rise-of-the-sharing-economy.pdf (accessed 20 Oct. 2017).

[423] World Economic Forum (2016), *Understanding the Sharing Economy*, http://www3.weforum.org/docs/WEF_Understanding_the_Sharing_Economy_report_2016.pdf (accessed 18 Oct. 2017); Lee, B. (2017), 'Are we on the cusp of a demand revolution?', Hoffmann Centre for Sustainable Resource Economy, 18 May 2017, https://hoffmanncentre.chathamhouse.org/article/are-we-on-the-cusp-of-a-demand-revolution/ (accessed 18 Oct. 2017).

[424] Authors' analysis based on estimate that 12,000 tonnes of concrete were needed for a hotel in Florida. Zaffiro-Kean, E. (2017), '24 million lbs. of concrete = 1 Daytona hotel foundation', *Daytona Beach News-Journal*, 24 August 2017, http://www.news-journalonline.com/news/20170824/24-million-lbs-of-concrete--1-daytona-hotel-foundation (accessed 18 Oct. 2017).

End of first life

Beyond how buildings and structures are designed, built and maintained, there are opportunities to better manage them when they reach the end of the initial useful lifespan envisaged in their design – as part of a broader shift to a circular economy. A circular economy is one 'in which products are recycled, repaired or reused rather than thrown away, and in which waste from one process becomes an input into other processes'.[425]

Reusing concrete has multiple benefits: it reduces construction costs, volumes of new cement used, and construction and demolition waste

Reusing concrete, for example, has multiple benefits: it reduces construction costs, volumes of new cement used, and construction and demolition waste.[426] There are different ways to reuse concrete. Reusing a whole frame in situ is increasingly common in the UK, and more carbon-efficient than removal of parts for use elsewhere.[427] Moreover, the use of parts of a building elsewhere is often limited to precast concrete and modular components such as panels or slabs, as opposed to concrete that is cast on site.[428] Precast concrete tends to be used in mass housing developments, where a large number of buildings need to be constructed in a short time at low cost.[429] Mature economies may have valuable reuse potential embedded in their existing housing stock.

There has been growing interest around concrete 'recycling'.[430] Concrete structures can be broken down into aggregate and mixed back into new concrete. This type of recovered concrete is mostly used for roadworks, a lower-quality application.[431] Such recycling can reduce the amount of virgin aggregate needed (and therefore the environmental costs of mining and transporting it), and it reduces the amount of waste materials in landfill. A large-scale renovation project in Paris recycled concrete from the building being renovated to achieve a 16 per cent reduction in the carbon intensity of the concrete aggregate used.[432] Crushed concrete aggregate also carbonates, absorbing CO_2. Optimizing this absorption by establishing global best practice for the demolition and storage of concrete could further reduce levels of embodied carbon.[433] More recently,

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[425] Preston, F. and Lehne, J. (2017), *A Wider Circle? The Circular Economy in Developing Countries*, Briefing, London: Royal Institute of International Affairs, https://www.chathamhouse.org/publication/wider-circle-circular-economy-developing-countries (accessed 16 Apr. 2018).

[426] Hradil, P., Talja, A., Wahlstroem, M., Huuhka, S., Lahnedisvu, J. and Pikkuvirta, J. (2014), *Re-use of structural elements: Environmentally efficient recovery of building components*, VTT Technical Research Centre of Finland Ltd, http://www.vtt.fi/inf/pdf/technology/2014/T200.pdf (accessed 23 Feb. 2018).

[427] Mineral Products Association The Concrete Centre (undated), 'Refurbishment, reuse and renewal', https://www.concretecentre.com/Performance-Sustainability-(1)/Material-Effieciency/Refurbishment,-reuse-and-renewal.aspx (accessed 27 Mar. 2018).

[428] Salama, W. (2017), 'Design of concrete buildings for disassembly: An explorative review', *International Journal of Sustainable Built Environment*, 6: pp. 617–635, doi: 10.1016/j.ijsbe.2017.03.005 (accessed 23 Feb. 2018); Huuhka, S., Kaasalainen, T., Hakanen, J. H. and Lahdensivu, J. (2015), 'Reusing concrete panels from buildings for building: Potential in Finnish 1970s mass housing', *Resources, Conservation and Recycling*, 101: pp. 105–121, doi: 10.1016/j.resconrec.2015.05.017 (accessed 28 Feb. 2018).

[429] Cement Manufacturers' Association (2015), 'Housing – Mass Housing and Technological Options', http://www.cmaindia.org/industry/housing---mass-housing-and-technological-options.html (accessed 10 May 2017).

[430] Fraile-Garcia, E., Ferreiro-Cabello, J., Lopez-Ochoa, L. M. and Lopez-Gonzalez, L. M. (2017), 'Study of the Technical Feasibility of Increasing the Amount of Recycled Concrete Waste Used in Ready-Mix Concrete Production', *Materials*, 10(7), doi: 10.3390/ma10070817 (accessed 23 Feb. 2018).

[431] Tabsh, S. W. and Abdelfatah, A. S. (2008), 'Influence of recycled concrete aggregates on strength properties of concrete', *Construction and Building Materials*. 23: pp. 1163–1167, doi: 10.1016/j.conbuildmat.2008.06.007 (accessed 10 Jul. 2017); Cembureau (2016), *Cement, concrete & the circular economy*, Brussels: European Cement Association, https://cembureau.eu/media/1229/9062_cembureau_cementconcretecirculareconomy_coprocessing_2016-09-01-04.pdf (accessed 23 Feb. 2018).

[432] UN Environment and International Energy Agency (2017), *Global Status Report 2017*.

[433] Mineral Products Association (2016), *Whole-life Carbon and Buildings: Concrete solutions for reducing embodied and operational CO_2*, https://www.concretecentre.com/Publications-Software/Publications/Whole-life-Carbon-and-Buildings.aspx (accessed 23 Feb. 2018).

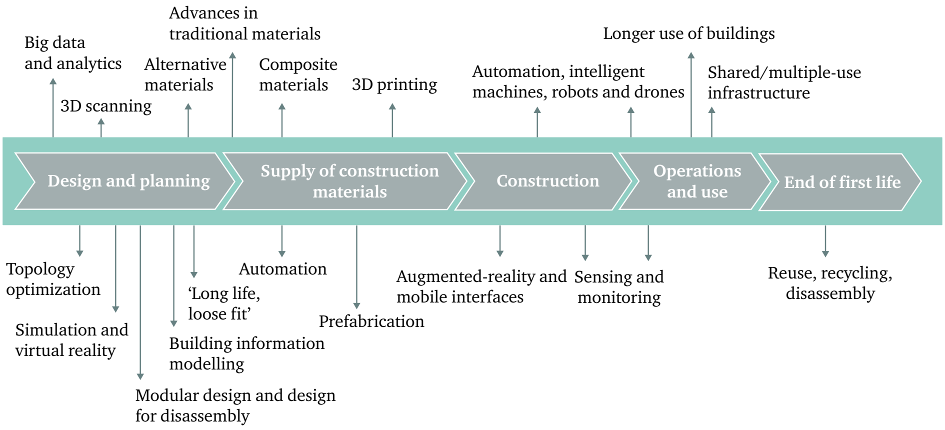
there has been excitement about 'smart crushers' that can crush and grind the cured cement elements of concrete, leaving sand and gravel intact.[434]

However, there are limits to the overall environmental benefits of recycling concrete. First, if the original concrete is of a low grade, this needs to be compensated for by mixing it with stronger cement. This would be the case for many buildings currently being demolished in China. Second, processing recycled concrete is more energy-intensive than processing virgin aggregate, as it requires decontamination.[435] Third, transporting recycled concrete adds to the potential environmental cost, so recycled concrete preferably needs to be sourced close to the construction site where it will be used (although electrified transport could address this problem). Finally, current levels of recycling are low, although they vary geographically (roughly 28 per cent of the UK aggregate market is supplied from secondary and recycled sources).[436] A plan to build a skyscraper out of recycled aggregate in Australia failed because not enough good-quality recycled aggregate could be found.[437]

4.3 Harnessing disruptive opportunities

Many doubt that the cement and concrete sector is susceptible to the kind of disruption that has been seen in many other parts of the economy over the past two decades. However, as this chapter has indicated, many opportunities are now opening up. Profound changes are under way that are putting new demands on the urban environment and creating new expectations of it. Especially in cities that are still rapidly growing, dramatic changes could emerge faster than currently anticipated. A suite of disruptive innovations is emerging in the sector that may transform the carbon content of buildings and structures, as well as the emissions produced over their lifetimes. Figure 27 summarizes these different areas of innovation along the value chain.

Figure 27: Disruptive innovation along the construction value chain



Source: Authors' own analysis.

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[434] De Ingenieur (2018), 'Smart Crusher Saves Concrete and CO_2', 5 Jun. 2018, https://www.deingenieur.nl/artikel/smart-crusher-saves-concrete-and-co2 (accessed 7 Jun. 2018).
[435] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[436] UK data for 2015, Mineral Products Association (undated), 'Aggregates', http://www.mineralproducts.org/prod_agg_recy01.htm (accessed 23 Feb. 2018); World Business Council for Sustainable Development (2009), *Recycling Concrete*, https://www.wbcsdcement.org/pdf/CSI-RecyclingConcrete-Summary.pdf (accessed 23 Feb. 2018).
[437] Internal workshop participant.

Managing trade-offs

Many of the options highlighted in this chapter are complementary. Emerging approaches to design – e.g. topology optimization – are facilitated by the availability of novel, high-strength and flexible materials.[438] 3D printing has opened up the range of shapes available to architects and engineers.[439] A shift towards prefabrication could help catalyse the move towards automation, as machines work best with standardized components and processes. In combination with modularity and prefabricated components, automation can already be applied to assembly and disassembly processes.[440] In addition, increased use of information technology such as radio tags on site could make automation more flexible: reducing the need to standardize component sizes if there is less risk of pieces being placed or installed incorrectly.[441]

In some cases, however, solutions might work against each other. The use of some composite materials reduces the potential for disassembly and recycling. The use of standardized components on which prefabrication often depends may conflict with the goal of improving material efficiency. Lowering embodied carbon could increase operational carbon, depending on the building material chosen. Stakeholders in the cement and concrete sector often emphasize that the high thermal mass of concrete can increase the energy efficiency of buildings; they query whether reducing concrete use would not raise operational emissions from heating and cooling.[442]

Digital tools such as BIM may have an important role to play in managing and balancing the factors that will inform these different decisions, especially as the best course of action will be highly site-, geography- and project-specific. In some cases, using precast concrete for a modular building that will be adapted and changed over the course of its life will make sense. In others, the emphasis might be on 'long life, loose fit', with a composite material core that is expected to remain in place and an outer shell that can be adapted.

Implications for the cement and concrete sector

While the focus of this chapter has been largely on lowering the carbon content of buildings and structures as well as their emissions over time, doing so can sometimes result in reduced concrete use. Table 6 summarizes the ways in which the disruptive changes described could have an impact on demand for concrete (and therefore cement).

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[438] Immsider (2016), 'Smart Materials: Neue Werkstoffe verändern das Design' [Smart materials: new materials are changing design], 11 October 2016, http://www.immsider.de/2016/10/smart-materials-new-materials-are-changing-the-design-world/?lang=en (accessed 2 Mar. 2017).

[439] Chalcraft, E. (2013), 'How 3D printing will change architecture and construction', Dezeen, 21 May 2013, https://www.dezeen.com/2013/05/21/3d-printing-architecture-print-shift/ (accessed 15 Jun. 2017); Winston, A. (2014), 'Arup unveils its first 3D-printed structural steel building components', Dezeen, 11 June 2014, https://www.dezeen.com/2014/06/11/arup-3d-printed-structural-steel-building-components/ (accessed 25 Feb. 2018).

[440] Neelamkavil, J. (2009), 'Automation in the prefab and modular construction industry', 26th International Symposium on Automation and Robotics in Construction (ISARC 2009), https://www.irbnet.de/daten/iconda/CIB14850.pdf (accessed 18 Oct. 2017).

[441] Moynihan and Allwood (2014), 'Utilization of structural steel in buildings'.

[442] Mineral Products Association (undated), 'Low-carbon: concrete is essential to deliver thermal mass and energy efficiency', https://www.concretecentre.com/This-Is-Concrete/Low-Carbon.aspx (accessed 23 Feb. 2018); Cembureau (undated), 'Downstream', 'The Role of Cement in the 2050 Low Carbon Economy', http://lowcarboneconomy.cembureau.eu/index.php?page=downstream-2 (accessed 23 Feb. 2018); European Concrete Platform ASBL (2007), *Concrete for energy-efficient buildings: The benefits of thermal mass*, Brussels: European Concrete Platform ASBL, https://www.theconcreteinitiative.eu/images/ECP_Documents/ConcreteForEnergyEfficientBuildings_EN.pdf (accessed 23 Feb. 2018).

Table 6: Potential effects of changes in the construction sector on demand for cement and concrete

Disruptive innovation/shift	Effect on demand for cement and concrete
Advanced concrete	*Unclear:* In theory, potentially less concrete will be needed in applications due to higher strength and other enhanced qualities. In practice, even in cases where high-strength concrete is used, more concrete is still applied than would be needed.
Composite materials	*Unclear:* It is too early to tell whether composites will reduce demand – and carbon mitigation will depend on the type of composite applied – but there are strong potential gains from certain types. More research is needed on nanocomposites.
Alternative materials	*Lower demand:* Shifting to alternative materials would decrease demand, but a degree of uncertainty exists about the scale of likely replacement given concerns about material availability and the properties of alternative materials and their suitability for different applications.
Smart and intelligent materials	*Unclear:* It is too early to tell whether smart materials will have an impact on the overall amount of concrete needed. Some smart concretes may increase demand, as they may allow concrete to be used in applications to which it was not previously suited.
Modular and prefabricated design and construction	*Lower demand:* Modular design and prefabricated/precast production has been shown to increase the efficiency of application, reduce waste and facilitate reuse of components.
Topology optimization	*Lower demand:* By definition, topology optimization should reduce demand for building materials, including concrete.
Building information modelling	*Unclear:* BIM could facilitate experimentation with novel cements and help the communication of decisions around reducing concrete use, but it largely acts as a facilitative tool for these activities.
Big data and analytics	*Unclear:* Although big data and analytics may help the industry to come up with optimized mixes and identify new compositions and nanocomposites, the likely impact on overall concrete use is still unclear.
Sensing and monitoring	*Unclear:* Sensing and monitoring may help to reduce concrete overuse in application and extend the useful lifetimes of buildings, thereby lowering demand, but it is still too early to tell.
Virtual reality, augmented reality and simulation	*Unclear:* Augmented reality, in particular, may help to improve efficiency in the application of concrete on site by providing workers with real-time information and guidance on the process, but it is still too early to tell whether this will be practical.
Automation and AI	*Unclear:* Although automation should increase efficiency and reduce wastage and errors in concrete application, the potential increase in productivity arising from increased automation could also lead to even more construction on a global scale, thereby increasing concrete demand.
3D scanning and printing	*Unclear:* 3D printing of buildings could increase material efficiency, but it is still too early to tell whether this will be a scalable opportunity beyond niche applications.
Shared/multiple-use infrastructure	*Lower demand:* Sharing buildings and widening their range of use should decrease the overall number of buildings needed, thereby reducing concrete demand.
Circular economy	*Lower demand:* An increased emphasis on reducing concrete use, and reusing and recycling concrete – including enhanced technical opportunities around recycling – should reduce demand for virgin cements and aggregates.

Source: Authors' own analysis, expanding on Buenfeld, N. (2016), 'Low-carbon innovation in cement and concrete', presentation given at a Chatham House roundtable on Low Carbon Innovation in Cement and Concrete, 12 May 2017.

In the cement and concrete sector, there is still a strong perception that most innovations are unlikely to significantly alter global concrete demand. Today, their effects are highly uncertain, and they can be expected to be context-dependent and to vary in scalability. Yet in many ways it would be surprising if the cement and concrete sector did not undergo major changes in the coming decades. Companies may wish to assess their readiness for these trends more systematically. Regardless of policy incentives related to climate change, broader trends in the built environment could prove highly disruptive. This points to the need for a wide range of stakeholders to think more carefully about disruption scenarios, and to test the assumptions used in cement modelling exercises.

Supporting low-carbon disruption

Like the cement and concrete sector, the construction sector is considered conservative and slow to change.[443] Although many of the solutions discussed above are already used in high-value construction projects, several barriers stand in the way of scaling them up.

The skills and training needed to roll out digital and other technologies are an important consideration.[444] In Europe, the construction sector is already suffering from a serious skills shortage and is struggling to deliver widespread training even on simple processes.[445] Given the size and age of the workforce, there is a question over how quickly innovative technologies can be widely adopted.

Moreover, there is likely to be resistance to some of the technological changes described above. For example, the social impacts from automation may slow down the construction sector's adoption of certain technologies, while concerns about a lack of individualization in housing developments and, in some locations, a poor image may present challenges to greater use of prefabricated components and buildings.[446]

Tailoring disruption to geographic contexts

It is beyond the scope of this report to examine in detail the policy frameworks and financial incentives needed to promote a sustainable, disruptive shift in the built environment. Key areas for consideration would include: changes to planning policies, and the financial structures around procurement, to encourage innovative approaches to design and procurement and adaptive reuse of existing structures; incentivizing the retention of existing structures where possible through, for example, tax reform; investment in training to address the digital skills gap; and the provision of de-risking mechanisms and financial support to encourage the use of new technologies and help to cover their cost.

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[443] Giesekam, Barrett and Taylor (2015), 'Construction sector views on low-carbon building materials'; World Economic Forum and the Boston Consulting Group (2016), *Shaping the Future of Construction*.
[444] McKinsey Global Institute (2017), *Reinventing Construction*.
[445] European Commission (undated), *European Construction Sector observatory: Improving the human capital basis*, https://ec.europa.eu/docsroom/documents/26206/attachments/1/translations/en/renditions/native (accessed 23 Feb. 2018); European Commission (2017), *European Construction Sector Observatory: Country profile Germany*, March 2017, https://ec.europa.eu/docsroom/documents/23744/attachments/1/translations/en/renditions/pdf (accessed 23 Feb. 2018).
[446] Gardiner, J. (2017), 'Can prefab homes solve UK's housing crisis?', *Guardian*, 26 January 2017, https://www.theguardian.com/sustainable-business/2017/jan/26/prefab-homes-uk-housing-crisis-modular-offsite-construction-manchester-liverpool-energy-efficiency (accessed 23 Feb. 2018).

As with policy encouragement for lower-carbon materials (see Section 3.4), it will be important to avoid being too prescriptive and to allow for mixing and matching the right technology solutions to fit the given context. Moreover, these policy frameworks should be tailored to the needs of different regions and to the specific potential for disruption in each of them. Eighty per cent of new construction in the period to 2060 is projected to be in non-OECD countries.[447] In some countries, growth will occur within a very short time frame: for example, 45 per cent of the projected increase in floor area in China by 2060 is expected to be completed by 2030.[448] By contrast, 65 per cent of the forecast building stock in OECD countries in 2060 is already standing today.[449]

As emphasized in Chapter 2, there are many regional differences in material supply chains. This affects the potential impact and penetration of new technologies. In the UK, for example, the ready-mixed-concrete industry uses automated supply, while in India 90 per cent of the concrete used is still bagged.[450]

This points to a need for different pathways to lowering the carbon content and impacts of the built environment in different regions.[451] Countries in which the majority of new construction is expected to happen – including China, India and Indonesia – should leverage the disruptive opportunities that are suited to developing a low-carbon building stock from scratch. These opportunities include lowering embodied carbon. Meanwhile, in more mature building sectors in Europe and North America, the focus should be on large-scale retrofitting of buildings and structures to lower their operational carbon, as well as on scaling up adaptive reuse and recycling of buildings at the end of first life.

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[447] International Energy Agency (2017), *Energy Technology Perspectives 2017,* p. 125.
[448] UN Environment and International Energy Agency (2017), *Global Status Report 2017*.
[449] International Energy Agency (2017), *Energy Technology Perspectives 2017*, p. 125.
[450] Scrivener, John and Gartner (2016), *Eco-efficient cements*.
[451] UN Environment and International Energy Agency (2017), *Global Status Report 2017*.

5. Conclusion and Recommendations

An ambitious vision for decarbonization of cement and concrete is not only a question of scaling up the use of low-carbon materials and putting the sector on a Paris-compatible pathway. It is also about meeting the vision set out in the SDGs: a more flexible, cleaner living environment for the 100 million people who are expected to move to cities over the next 10 years, and for the almost 4 billion people living in cities today.[452]

In the coming years, large quantities of concrete will continue to be used, and transforming how it is made to radically reduce the use of Portland cement is essential. As Section 3.3 explains, low-clinker and novel cements that release far fewer emissions in production are capable of matching the performance of Portland cement. Some already perform better than traditional cement in certain applications.

Today, these alternatives are rarely as cost-effective as Portland cement, and they face constraints in terms of raw material supply, resistance from customers and the difficulty of scaling up industry participation. The challenge is to overcome these barriers via a combination of policy mechanisms, enhanced collaboration, a concerted effort on disseminating best practice and targeted R&D. By creating the conditions for a race to the top, the sector could even become a low-carbon leader.

There is no simple formula or silver bullet. Moreover, while this paper focuses on the many exciting opportunities around clinker substitution and novel cements, greater action is also needed on energy efficiency, sustainable fuels and investments in CCS.

Yet it is entirely feasible that the cement and concrete sector can deliver the rapid decarbonization required to keep the rise in global temperature well below 2°C, and as close as possible to 1.5°C above pre-industrial levels. Current models indicate this can be achieved through incremental steps, and can rely to a significant extent on CCS technology. But other, more disruptive pathways could be accelerated by new business models, advances in material science, digital transformation and a revolution in the wider built environment.

Set for disruption?

Disruptive change in the cement and concrete sector could look quite different to what has been seen in other sectors. In the context of telecommunications or transport, the term ‘disruption’ is usually reserved for transformative changes that radically alter how people think, behave or do business, which often means rethinking from first principles. Such approaches are contrasted with ‘incremental’ or ‘sustaining’ innovations that simply improve existing products and processes.

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[452] Based on World Bank Data, 60 per cent of the world’s population in 2030 (8.5 billion) is projected to live in urban areas and 54.5 per cent (of 7.6 billion) is estimated to live in urban areas today. The World Bank (2017), *Urban Development*, http://www.worldbank.org/en/topic/urbandevelopment/overview#3 (accessed 19 Oct. 2017).

This understanding of disruption only goes so far in the context of a heavy-industry commodity business such as cement and concrete. The physical importance of construction materials is unlikely to diminish in the same way, for instance, that newspapers have been replaced by news websites. Moreover, a 'move fast and break things' approach without safeguards – an approach seen in some sectors, particularly the digital sphere – is far from desirable in the cement and concrete sector, given the importance of maintaining safety and structural performance.

The prospect of transformative shifts coming from within *the cement and concrete sector should be seen alongside new opportunities – or threats – coming from* outside *the sector*

Disruption in the cement and concrete sector will hinge on incremental and transformative solutions alike. On the one hand, smarter approaches are needed to deploy a plethora of already available technologies, while matching solutions to specific locations and the right set of policies to enable such solutions to be scaled up. These individually incremental gains could add up to a step-change in emissions reduction. On the other hand, a much greater push is needed to make tomorrow's transformative approaches, including the 'holy grail' of carbon-negative cements, commercially viable on a wide scale.

The prospect of transformative shifts coming from *within* the cement and concrete sector should be seen alongside new opportunities – or threats – coming from *outside* the sector. Innovations in connectivity, remote monitoring, predictive analytics, 3D printing and urban design are transforming traditional supply chains within the broader construction sector, with potentially large implications for concrete demand. Some of these technologies may seem to be over the horizon, but it is worth recalling how quickly the power sector changed once providers of renewable energy technologies such as solar and wind shifted from being niche players to disruptive competitors.

As these examples show, digital disruption and advances in manufacturing will play a critical role. Yet disruption in the sector is just as much about enabling people to enhance their skills, make better decisions and collaborate with others.

Geography matters

A global plan for cement sector decarbonization could be rooted in location-specific challenges and opportunities. The availability of a given material, the local climate and soil conditions, access to necessary finance and technology, and material/construction standards all vary across regions and determine the set of options available to cement and concrete producers. Connectivity between regions or cities matters too, not only in terms of infrastructure planning, but also for defining which construction materials can be economically traded.

This is about finding the optimal combination of technology, practice-related and policy solutions for a given location. For instance, while parts of Europe and the US are already feeling the effects of decreasing supplies of traditional clinker substitution materials, such as fly ash and blast furnace slag, China and India are currently producing huge volumes of these. 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.

Several studies suggest that calcined clays present a significant opportunity to increase clinker substitution around the world. These could have particular relevance for emerging and developing countries, especially in locations with existing stockpiles of suitable clays from ceramics industries, notably China and Brazil. Moreover, calcined clays are already being used in reconstruction efforts in Cuba, following damage from Hurricane Irma in 2017. This growing body of experience could lead to the widespread use of alternative materials to accelerate rebuilding after natural disasters.

Trade plays a small but significant and growing role in the availability of clinker substitutes, particularly for countries like Brazil where there is scarcity of key materials. Even within countries, transport is a significant factor. In China, there are underutilized supplies of fly ash in the west of the country, but a scarcity in the east. In Europe, a concentration of well-connected urban areas enhances the viability of concrete recycling.

The availability of construction materials is not just a question of cement and concrete. The viability and sustainability of potential bio-based substitutes for concrete, such as wood and hemp, also depend on local conditions. The environmental benefits could vary significantly, for example, between a well-managed Norwegian forest versus one in a country with weak forest governance.

Major regional infrastructure and connectivity initiatives may shape resource demand for a number of years. China has become a global enabler for infrastructure development through its overseas investments and its growing partnerships with countries involved in its Belt and Road Initiative. Ensuring that mega-initiatives such as these also create the right enabling environment for investment in sustainable infrastructure will require concerted efforts to collaborate and harmonize approaches at the global level.

High-performance building materials will be particularly important for enhancing resilience, including for flood defences and critical-infrastructure protection. Risks to infrastructure and cities posed by extreme weather events are especially serious for those places exposed to flood and hurricane damage, but also where residents need protection from extreme summer temperatures. Traditional concrete can come under strain when exposed to humidity and higher concentrations of atmospheric CO_2. While concrete is likely to remain important in applications where the environment is challenging, novel, smarter and more adaptable materials are also needed.

Raising policy ambition

Governments, especially in OECD countries and China, should consider giving a clear market signal by setting a target date for the achievement of net-zero carbon emissions in cement production and/or in the construction sector – recognizing that negative-emissions technologies may need to play a role.

A credible commitment by policymakers to decarbonize the sector could be a major driver of low-carbon innovation.[453] In the past, anticipation of a Copenhagen summit deal and expectations of further tightening of the EU ETS led to a surge in innovative activity in research and in industry efforts such as the Cement Sustainability Initiative. However, patenting activity soon faded in the absence of a strong agreement and the

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[453] Beyond Zero Emissions (2017), *Zero Carbon Industry Plan*.

lack of a high carbon price in most markets. Following the 2015 Paris Agreement, there is now a critical opportunity to recreate this momentum and to define a climate-compatible pathway for specific industrial sectors, including cement and concrete.

In many countries, governments are the largest procurers of construction products and services. (In the Netherlands, for example, public procurement has already helped increase demand for low-carbon cement.) Sub-national entities, cities, local authorities and housing corporations have a key role to play in exploring such approaches. A growing number of companies in various countries are also setting carbon-intensity targets for their construction projects. More generally, the major companies committed to 100 per cent renewable energy and electric vehicles could demonstrate further commitment to climate action by requiring the use of low-carbon materials in any buildings or infrastructure they choose to build.

Cement producers can reasonably expect that regulatory frameworks for reducing greenhouse gas emissions will come under greater scrutiny from civil society and governments

New product standards have long been seen as vital for shifting industry practices and stimulating demand for lower-carbon products, but in the short term these are unlikely to provide sufficient incentive to expand the markets for such products or build sustainable supply chains around them. Current standards, in particular for concrete, hold back the deployment of very-low-clinker cements. Yet it can take decades for a new standard to be approved – and even once this exists, it can take a long time for customers to accept a new type of cement. One recent report suggests that there is little prospect of an overhaul of European cement and concrete standards.[454] In the short to medium term, standards-setting bodies have a key role to play in developing the technologies needed to make more flexible approaches to standard-setting possible, such as accelerated durability testing.

The other widely cited policy approach is carbon pricing. Carbon prices could create the necessary incentive to scale up investment in early-stage low-carbon cements, but sufficiently high price levels are unlikely for at least the next few years in key markets such as the EU, China, India and the US. Moreover, carbon prices alone are unlikely to deliver enough investment in new approaches fast enough to generate the deployment rates needed. [455] Evidence from other sectors suggests that breakthroughs can be made through more innovation-led policymaking. One option that has not yet been fully explored is differentiated carbon pricing on the final product, i.e. consumers would be charged for the carbon embedded in the building materials they procure.

Policymakers will need to consider how to encourage a more open approach to data among existing and future market players. This is not straightforward given the vertical integration of the sector today. Several of the opportunities outlined in this report for digital technologies to unlock the potential of low-carbon innovations rely on access to data so that advanced analytics can play a role.

Cement producers can reasonably expect that regulatory frameworks for reducing greenhouse gas emissions will come under greater scrutiny from civil society and governments, and that growing demand for cleaner air will continue to shape public opinion and policy. As confidence grows around the decarbonization of the energy sector and electric vehicles, other industrial sectors may be next in line. Some companies are better placed than others to move fast on decarbonization, or to profit from opportunities

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[454] Wuennenberg and Casier (2018), *Low-Carbon Innovation For Sustainable Infrastructure*.
[455] International Energy Agency (2017), *Energy Technology Perspectives 2017*.

to move up the value chain. The launch of the Global Cement and Concrete Association in 2018 appears to represent a potential new coalition of the willing.

Box 4: A multi-track, multi-level approach

Given the different sectors and groups of actors involved, policymakers might want to adopt a multi-track, multi-level approach. In the context of focused deployment support for low- and alternative-clinker cements, this might look like the following:

Two tracks
1. Implementing and scaling up the use of available technologies and practices.
2. Identifying and developing the next generation of technologies.

Three levels
1. Working with cement producers and academic institutions to:

- Identify and develop alternative binders and novel cements;
- Evolve and improve existing low-clinker binders and alternative binders;
- Identify new sources for clinker substitutes and develop new blends based on these; and
- Market and deploy lower-carbon cements.

2. Working with concrete producers to:

- Disseminate best practice in mixing lower-carbon concretes; and
- Scale up use of carbonation-cured concretes.

3. Working with clients, architects, structural engineers and contractors to:

- Disseminate best practices in working with lower-carbon cement;
- Build demand for lower-carbon cements;
- Scale up material efficiency strategies to optimize the use of building materials; and
- Explore how innovations in the broader built environment will affect upstream sectors.

Enhancing cooperation

Sharing experience and knowledge within and across industries, as well as between different regions around the world, should be encouraged and facilitated. International alignment on embodied-carbon targets and measurement for building materials is important as countries increasingly rely on imported materials. Policies directed solely at domestic material producers are unlikely to achieve sufficient reductions in embodied emissions.

The EU can play a powerful role in sharing lessons from its own attempts to shape innovation in heavy industries. Not only are many of the largest cement producers with the greatest R&D capacity headquartered in Europe, but the EU has also been behind some of the most advanced attempts to develop innovation pathways through its ETS. Exchanging knowledge with other countries and regions, such as China, that might hope to promote low-carbon cements through carbon-pricing schemes will be key. Moreover, a shift to using performance-based standards in Europe would be particularly effective, given that European cement and concrete standards are often followed elsewhere.[456]

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[456] Internal workshop participant.

Cities will play a critical role in delivering these decarbonization strategies, but today they rarely have access to all the necessary policy levers or the capacity for implementation. Cooperation between cities, including on shared lessons on the future of the built environment, will be important. Rapid shifts could be delivered through pilot schemes, smart public procurement, and incentives and regulations encouraging the use of waste materials in cements. Cities can work together to build the market for low-carbon cements through C40-type initiatives – a network of the world's largest cities committed to addressing climate change – and city pledges.

To be effective and truly disruptive, cooperation will need to bring together new combinations of market actors capturing cross-sector opportunities and addressing cross-cutting challenges in the built environment. Long-term planning can be aided by innovative institutional arrangements to engage a new set of actors at national and regional levels and within different sectors. Existing initiatives, such as the National Infrastructure Commission in the UK,[457] which acts as an independent body, collecting evidence and engaging stakeholders throughout the country, may play an important role in providing a long-term vision for the built environment.

Recommendations

If we are to achieve deep cuts in greenhouse gas emissions in line with the Paris Agreement, there can be no sectoral exceptions. The cement and concrete sector has to change. There are many potential pathways to lower emissions, and not all are likely to succeed. But as this report argues, there are clear approaches that can help create the conditions for the adoption of low-carbon materials and for private-sector leadership. The nature of the necessary interventions will, of course, differ across geographies and national settings.

1. Growing the market for low-carbon building materials

Carbon-neutral or -negative construction will need to become the norm everywhere by around 2030.[458] For this to be achieved, there needs to be a rapid increase in the use of building materials with zero or negative embodied emissions in the next few years.

Many governments in major economies have big plans for investment in infrastructure. Perhaps the most significant is China's Belt and Road Initiative, which by some estimates will increase demand for cement by 162 million tonnes annually by 2020.[459] Provisional assessments of President Donald Trump's infrastructure plan for the US suggest it would require approximately 30 million tonnes of cement per year up to 2021.[460] A major road-building initiative in India is projected to require 4 million tonnes per year over a five-year period.[461]

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[457] UK Government (2017), 'National Infrastructure Commission', https://www.nic.org.uk/ (accessed 19 Oct. 2017).
[458] Röckstrom et al. (2017), 'A roadmap for rapid decarbonization', pp. 1269–1271.
[459] Samruk Kazyna (2018), *Belt & Road Updates 2018 "Expansion continues"*, January 2018, https://www.sk.kz/upload/iblock/898/8982ade4e1075b33189e5044b01ff98e.pdf (accessed 6 Mar. 2018).
[460] Balaraman, K. (2017), 'Industry is ready to pour concrete – and release emissions', Climatewire, 22 March 2017, https://www.eenews.net/stories/1060051842 (accessed 6 Mar. 2018).
[461] Jethmalani, H. (2018), 'Bharatmala project may not be a game changer for cement demand', livemint, http://www.livemint.com/Money/72K1MdIz3qnAAhRdon9tbM/Bharatmala-project-may-not-be-a-game-changer-for-cement-dema.html (accessed 6 Mar. 2018).

It would be a game-changer if such megaprojects specified the use of lower-carbon cements or alternative products for a large share of their construction. There are many examples of governments already setting ambitious requirements. In the UK, the concrete for London's Crossrail project must have a minimum cement-replacement content of 50 per cent. Since 2015, the United Arab Emirates has required all major infrastructure projects to use cements that contain at least 60 per cent blast furnace slag or fly ash. Multilateral development banks will have a vital role to play in encouraging or requiring such approaches in the projects they help finance.

Yet while major infrastructure projects are well suited to the introduction of novel products, another test is whether governments start to commit to ambitious sustainability targets for social housing or even all new buildings, which would likely trigger profound changes in market structure.

The ultimate goal here should be material and technology neutrality at the building or city scale. This would guide consumers to choose not only more sustainable solutions but also the most appropriate option for any given project, while allowing suppliers to innovate to meet those demands. Policies and regulations should encourage a shift towards functional or performance-based specifications, rather than prescribing or forbidding the use of a particular material.

In the meantime, targets for embodied carbon in construction materials could be introduced with little risk of carbon leakage,[462] helping to align incentives and responsibility for net-zero-emissions construction along the value chain. This matters because concrete often accounts for a small share of the total cost of construction projects, and the end-users in construction may be better able to absorb the costs of mitigation.

Key recommendations

- **Mainstream embodied carbon.** An international standards committee should convene expert stakeholders, construction firms, architects and structural engineers to establish an industry-wide methodology for measuring embodied carbon, as well as a process for gathering and sharing data on buildings and materials. This methodology would need to be granular enough to capture supply-chain-specific aspects. Governments should mandate the measurement of embodied carbon across projects. They should provide information sources, training and support for contractors and engineers who might be asked to carry out these assessments. Metrics on embodied carbon should be integrated into sustainability-rating codes.

- **Introduce CO_2 footprint labelling for construction materials.** Material suppliers should establish labelling schemes indicating their carbon credentials. The introduction of reliable and certified CO_2-footprint marking of materials (down to zero CO_2 emissions per tonne) would help to make it attractive for users to pay a premium for CO_2-neutral building materials. Policymakers should also explore setting a maximum threshold for the embodied carbon allowed in the construction of low-risk, non-structural applications such as house slabs and non-load partition walls.

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[462] Defined as a situation in which, for reasons or costs related to climate policies, businesses transfer production to other countries with less stringent emissions regulations.

- **Promote a whole-life-cycle approach to low-carbon public procurement.** Governments should restructure the typical tender route for building materials on large public projects so that it integrates embodied-carbon measures and end-of-first-life considerations in addition to the operational phase emissions usually considered, with bidders required to calculate the embodied carbon of the materials they are supplying. Governments could set maximum embodied-carbon levels in public tenders, specify minimum cement-replacement levels for large infrastructure projects, or implement scoring systems that strongly favour low-carbon proposals. Public agencies and companies should seek to specify a service rather than a product, encouraging a shift towards less resource-intensive business models. Policymakers should also work with insurers to ensure that clients who specify novel materials are not constrained by unnecessarily high insurance rates.

- **Secure commitments from major concrete-consuming companies.** Firms with significant influence over construction decisions or with major capital investments in construction should set ambitious carbon-intensity targets for major projects and engage with construction companies, design teams, contractors and material suppliers to encourage them to find the lowest-carbon, most viable options for a given project. Construction companies and material suppliers should collaborate on training to encourage design teams and contractors to familiarize themselves with novel materials, so that designers/contractors can in turn recommend them to clients or specify them when ordering from material suppliers.

2. Building the supply chain for net-zero emissions materials

As demand for low-carbon materials is ramped up, a host of changes will be needed in material supply chains. Governments will need to find ways to incentivize investment in distribution networks for clinker substitutes, and in the additional processing equipment and storage infrastructure that may be required to scale up the provision of lower-carbon cements. Incentives to use clinker substitutes and novel cements will need to be accompanied by best-practice dissemination and support to make the use of innovative products viable. The use of waste materials and other cement additives, for instance, requires specialist knowledge and equipment that are often lacking in emerging markets.

Key recommendations

- **Build capacity and diffuse best practice in emerging markets.** Developed countries should establish partnerships with emerging markets to facilitate knowledge-sharing between material-research labs and construction and engineering companies to encourage best practice on low-clinker and novel cement, and around more efficient cement use more broadly. Such partnerships could also enhance access to the equipment and chemical admixtures needed to optimize concrete design; dedicated specialists could be deployed to key plants in regional clusters, as well as to smaller mixing and batching plants in each area.

- **Gather data on material availability in different regions.** Major importing countries could work with large suppliers to improve data on the availability of clinker substitutes, such as fly ash and blast furnace slag, in different regions.

This could be done as part of the Cement Sustainability Initiative's Getting the Numbers Right database and would enhance stakeholders' ability to track the availability of materials in different regions over time, providing insight into the possibility of importing from different locations and visibility of when shortages are likely to occur and where.

- **Improve incentives to recover and process waste materials and use them in cement and concrete.** National and local governments could use tools such as landfill taxes and other restrictions to encourage coal and steel companies to (a) find markets for their waste products and (b) invest in equipment for collecting, processing and storing their waste products.
- **Encourage the reprocessing of waste from old disposal sites.** Regulations for the storage and disposal of secondary materials could include incentives to screen, test and process materials from ash fields, slag stocks and bauxite waste to increase supplies in the short term, while also addressing significant environmental challenges. These supplies can be huge in scale, but their quality is variable and they are not always located conveniently relative to cement and concrete production sites.
- **Optimize the efficiency of cement use in concrete.** Cement producers will need to invest in additional equipment to use alternative clinkers and scale up the use of clinker substitutes. This includes pre-processing equipment such as specialized grinding machinery and calciners, as well as additional silos.

3. Expanding the portfolio of low-carbon cements

Technologies take a long time to get from laboratory to market in many sectors, but low-carbon cements seem to face particular challenges in bridging this 'valley of death'. A considerable push is required to get the next generation of low-carbon cements out of the lab and into the market.

Given the huge scale of cement production, it is not sustainable to provide long-term subsidies for low-carbon alternatives. Instead, the goal should be to identify a suite of materials, technologies and approaches that have the potential to rapidly become more cost-effective once deployed at scale, and to focus support for innovation in these areas.

Not all novel approaches will succeed, but those that do may well have significant decarbonization potential. As well as additional funding for R&D and demonstration, new models of cooperation around innovation between companies and across borders will be important.

Key recommendations

- **Develop demonstration projects.** Large-scale demonstration projects are needed to build confidence in novel products and engage stakeholders along the supply chain. Initiatives should involve a broad group of universities, construction companies, engineering firms, regulatory authorities, asset owners and industry stakeholders. As part of these efforts, novel financing mechanisms could be explored, such as investing in accelerators or incubators to stimulate innovation capacity within the sector and enhance private financial participation in R&D projects.

- **Expand R&D capacity in the sector.** Industry stakeholders, governments and research funds such as the EU's Horizon 2020 should focus efforts on basic materials such as cement and concrete. In particular, belite ye'elimite-ferrite (BYF) clinkers, carbonatable calcium silicate clinkers (CCSC) and magnesium-based cements require further research support. Engineering courses should include novel cements and low-carbon considerations in their syllabuses.
- **Explore new models for cooperative innovation.** Governments should create new avenues for cooperation both among cement producers and along supply chains to promote the development and diffusion of novel products. The current reluctance of cement producers to collaborate is born out of previous experiences with antitrust legislation and uncertainty over the application of competition law. Governments, cement producers and actors in the broader supply chain should work together to identify 'pre-competitive areas' – in which companies work together to tackle systemic issues, and in which collaboration could be encouraged through, for example, stakeholder advice platforms. At the more ambitious end of the scale, governments could consider creating patent pools or cross-licensing schemes to encourage innovation and mass diffusion of relevant novel-cement technologies.[463]
- **Support and expand joint R&D at the international level.** Governments and research funds should support and enhance capacity for joint R&D on lower-carbon cements at the international level, including by expanding Mission Innovation – a commitment to invest in R&D for energy – to have a remit for low-carbon construction materials. National standards institutes should collaborate on testing facilities. Universities could lead work to establish accelerated laboratory endurance tests to validate new materials and bring these options to scale.
- **Build diagnostic tools.** Material-science laboratories should work with technology and construction companies to develop effective diagnostic tools and field-based detection tools for assessing the strength and durability of concrete. Policymakers, insurers and local authorities should stipulate the use of in situ testing, data collection and data dissemination for major projects using novel products.

4. Harnessing digital disruption

The digital revolution will not remove all the physical and economic challenges of decarbonizing cement and concrete, but it can make a dramatic difference – whether via optimizing supply chains, enhancing collaboration, or providing workers in all relevant fields with the data needed to make economically viable and technically appropriate decisions on low-carbon materials. Digital tools, for instance, will play a key role in building the market for novel cement and concrete products by addressing misinformation, enhancing collaboration, disseminating best practice and reducing asymmetries in access to relevant information at different points along the value chain. These tools are especially important for growth markets such as China, India and countries in sub-Saharan Africa.

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[463] Lee, Iliev and Preston (2009), *Who Owns Our Low Carbon Future?*.

Industrial sectors also offer some of the most promising near-term opportunities for using machine learning to increase profit margins and reduce emissions. Today, the application of AI in industrial and commercial applications is primarily focused on optimizing logistical operations in the high-tech, relatively controlled environment of industrial plants, or on identifying promising new materials. But many of the recommendations in this report depend on decisions being made based on factors ranging from material availability to expectations of material performance in specific contexts. Machine learning is well suited to this challenge. Where it is not yet capable of producing fully fledged autonomous decisions, it could still have powerful applications in the sector: for instance, by providing a clear set of decisions for workers to select from, drawing on a wealth of historical and real-time data.

Key recommendations

- **Design digital tools for disseminating best practice.** Material-science labs, cement companies and engineering firms should work with leading technology firms and internet platform providers to design open-source, user-friendly and affordable digital tools to disseminate best-practice guidelines on how to optimize concrete mixes for locally available materials and given applications.
- **Develop platforms for coordination along the value chain.** Enhancements to existing digital tools, such as BIM, could help ensure the integration and engagement of all key players along material and construction supply chains. However, this depends heavily on the use of appropriate and effective mechanisms for data sharing.
- **Safeguard beneficial applications of AI in industrial sectors.** A major push is needed by industry stakeholders and technology pioneers to explore the beneficial uses of machine learning and wider AI in terms of meeting the challenge of deep decarbonization in industrial sectors. Such an initiative could be convened by the Partnership on AI – a technology industry consortium focused on establishing best practices for AI systems – including leading firms in cement and concrete, steel, chemicals and other heavy industries.
- **Support open and inclusive innovation.** Governments should work with universities to host open innovation platforms for exploring the potential for digital technologies to transform processes in the built environment. Innovation partners should work together to 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 and blends. Governments should also provide training to address the digital-skills shortage in the construction sector and cement and concrete sector, also with a view to retaining the number and improving the quality of jobs in each sector.
- **Establish a vision for a digital future.** Cement companies should assess their readiness for disruptive trends more systematically and with a wider range of stakeholders. The Cement Sustainability Initiative or the Global Cement and Concrete Association could convene a group of cement companies, construction companies and technology providers to take part in scenario analyses, to test the assumptions used in current modelling exercises and to map out a digital future for the sector.

5. Developing partnerships for climate-compatible pathways

Several of the solutions proposed above depend on well-coordinated international efforts, whether on research, best-practice dissemination or procurement. The cement and concrete sector encompasses multiple types of actor, different country contexts and different private-sector interests. Coordinating these and orienting them towards a net-zero-emissions pathway will be key.

Key recommendations

- **Set sectoral targets.** Governments should set sectoral targets, including for cement, in their mid-century, low-carbon development strategies for meeting commitments under the UN Framework Convention on Climate Change (UNFCCC), and should include heavy-industry sectors in their Nationally Determined Contributions. Canada's mid-century strategy, for example, projects a 93 per cent reduction (on 2015 levels) in emissions from cement and lime by 2050.

- **Secure G20 commitments.** At the international level, a taskforce should be established under the G20 to agree on international commitments for a net-zero-carbon, resilient built environment. This should be linked with the Global Infrastructure Connectivity Alliance, the G20's work around energy and climate change, and the Financial Stability Board's taskforce on climate-related financial disclosures.

- **Set science-based targets.** Major cement and construction companies should set science-based targets (SBTs) as soon as possible and work together to achieve them. These should be 'feasible by design' in that they factor in what is commercially viable and technically realistic, but must also be in line with the Paris Agreement. Setting these targets would signal companies' commitment to addressing climate risk to investors, policymakers, customers and employees. SBTs will not be a perfect representation of reality, but they utilize a set of tools and methods that could be used by firms to rally support for practical but ambitious emissions reduction goals, which could then be rolled out throughout the firms in question, and in partnership with suppliers and customers.

- **Facilitate leadership from pioneer cities.** Cities should work together to build the market for low-carbon cements and construction products by aligning their goals via the C40, ICLEI-Local Governments for Sustainability and Urban Leadership Council. This could include collective city pledges and developing common principles for what a low-carbon, clean-air and climate-resilient city should look like, as well as agreeing guidelines and flexible standards to inform decisions along the supply chain from planning, design and construction through to operations and end-of-first-life.

- **Mobilize a coalition for a circular built environment.** This coalition would bring together policymakers, academics and industry stakeholders to test the viability of circular approaches along the construction value chain – from material efficiency in design to better use of secondary materials – and explore policy measures to promote these. It would provide a platform for interdisciplinary research on the role of buildings in a circular economy and vice versa, and explore in greater detail the links between the fast-evolving technological trends and societal challenges explored in Chapter 4. Building on the work of existing initiatives, such as the Buildings as Material Banks project focused on construction and demolition waste, it would work to bridge knowledge gaps in this area, demonstrate the business case for circular approaches and raise awareness among built-environment stakeholders.

- **Scale up finance for a sustainable built environment**. Governments and multilateral development banks involved in large multilateral infrastructure projects, such as those associated with China's Belt and Road Initiative, should establish a set of sustainability criteria for projects and structures, including targets for maximum embodied-carbon content and the operational carbon of the structures involved.

Appendix 1: Table of Subcategory Definitions

Table 7: Low-carbon innovations in clinker substitution and binders

Categories	Subcategories	Description
Clinker-lowering technologies		
Supplementary cementitious materials (SCMs)	Gypsum (calcium sulphate)	Gypsum is a soft sulphate material required to control how cement hardens. Gypsum is added to clinker, totalling 3–5 per cent of the mix, to form OPC.
	Limestone	Ground limestone can be blended with clinker to reduce the final clinker content of cement. Although it is usually regarded as a filler, it is also reactive.
	Calcined shale	Clay shale, a fine-grained sedimentary rock formed of clay minerals, can be used as an SCM when calcined.[i]
	Calcined clay/ metakaolin	Clays, in particular those containing kaolinite, can be used as an SCM when calcined.[ii] Metakaolin is a type of calcined clay.[iii]
	Volcanic rocks	Rocks of volcanic origin, particularly pyroclastic materials resulting from explosive eruptions, exhibit pozzolanic behaviour with minimal processing.[iv]
	Fly ash	A coal combustion product composed of fine particles that are carried out of the boiler by flue gases in power plants.[v]
	Granulated blast furnace slag (GBFS)	Molten iron slags are by-products of iron- and steel-making that have been quenched in water or steam to produce a sand-like granular product. This is then ground for mixing into cement.[vi]
	Silica fume	An ultrafine powder collected from the production of silicon and ferrosilicon alloy. Due to its expense, it is mostly used in high-performance concrete.
	Rice hull/ husk ash	Rice husk is a waste product from rice production, which, if burnt under controlled conditions, can result in a highly reactive pozzolan.[vii]
	Waste glass	Recycled glass ground into a fine powder.[viii]
	Waste	Any form of waste products (agricultural or industrial waste).
	Industrial sludge	A semi-solid slurry produced from waste water from industrial processes.
Chemical admixtures		Materials and chemicals mixed into cement and concrete to alter their performance.[ix]

Alternative-clinker technologies		
Activated binders	Geopolymers	Geopolymers typically require an alkaline activation and networking element to bind pozzolanic materials in a polymer formation. This does not include alkali-activated binders, which do not form polymeric connected structures.
	Alkali-activated binders	Synthetic alkali aluminosilicate materials produced from the reaction of a solid aluminosilicate (e.g. natural pozzolans, including clays and volcanic rock; or artificial pozzolans, including fly ash and GBFS) with a highly concentrated aqueous alkali hydroxide or silicate solution.[x] This category also encompasses many of the geopolymer-classified patents, as geopolymer cements require alkali activation at the start of the process.
	Alkali-activated calcined clays	Geopolymers based on calcined clays as the solid aluminosilicate. This category covers patents in the dataset that use alkali-activated clays to activate non-traditional binders within cement composition.
Alternative-clinker cements	Belite-rich Portland cement clinkers	Clinkers based on belite rather than alite, produced with the same process as OPC but with lower limestone content and lower calcination temperature. Less fuel for heating is needed, and CO_2 emissions from calcination are reduced.[xi]
	Belitic clinkers containing ye'elimite or calcium sulphoaluminate (CSA)	Clinkers based on belite containing ye'elimite or calcium sulphoaluminate, produced with the same process as OPC but with less limestone and more aluminum as raw materials. This lowers the sintering temperatures required and the energy requirements for grinding.
	Belite ye'elimite-ferrite (BYF or BCSA) clinker	Clinkers based on belite, ye'elimite and ferrite. These are produced with the same process as OPC and lower the sintering temperature and energy requirements for grinding. BYF clinkers are a subset of CSA clinkers, the main distinction being the ferrite element.
	Low-carbonate clinkers with pre-hydrated calcium silicates	Binders based on hydraulic calcium hydro silicates with a low calcium share. Carbonates are calcined before processing. Raw materials include marl, limestone, natural sand, slags, glass and fly ash.[xii]
	Carbonatable calcium silicate clinkers (CCSC)	Low-lime calcium silicates (e.g. wollastonite) made for carbonation curing instead of hydration. These can be made in the same kilns as OPC using practically the same raw materials as OPC. A lower burning temperature is required. This category includes cements containing formed Ca-silicates before the final hardening step, with the Ca-silicates present in the starting mixture. It also includes cements based on calcium silicate-forming mixtures not containing lime or lime-producing ingredients (e.g. waterglass-based mixtures heated with a calcium salt).
	Magnesium-based clinkers	Clinkers based on magnesium oxide, generally produced by calcinating natural magnesite, a process that is highly carbon-intensive. These clinkers could potentially be made using ultramafic rocks instead of limestone, which could result in a truly carbon-negative solution.[xiii]

Notes:

[i] Seraj, S., Cano, R., Ferron, R. P. and Juenger, M. C. G. (2015), 'Calcined Shale as Low Cost Supplementary Cementitious Material', in Scrivener, K. and Favier, A. (eds) (2015), *Calcined Clays for Sustainable* Concrete, Dordrecht: Springer, https://link.springer.com/chapter/10.1007/978-94-017-9939-3_66 (accessed 11 Mar. 2017).
[ii] Scrivener, John and Gartner (2016), *Eco-efficient cements*; Sakai and Noguchi (2012), *The Sustainable Use of Concrete*.
[iii] National Precast Concrete Association (2017), 'SCMs in Concrete: Natural Pozzolans', 22 September 2017, http://precast.org/2017/09/scms-concrete-natural-pozzolans/ (accessed 20 Oct. 2017).

[iv] Snellings, R., Mertens, G. and Elsen, J. (2012), 'Supplementary Cementitious Materials', *Reviews in Mineralogy and Geochemistry,* May 2012, https://www.researchgate.net/figure/259357577_fig4_Figure-4-Global-distribution-of-volcanic-rocks-grey-areas-and-deposits-of-reported (accessed 3 Jul. 2017).

[v] Thomas, M. (2007), *Optimizing the Use of Fly Ash in Concrete*, Portland Cement Association, http://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-concrete.pdf (accessed 3 Jul. 2017).

[vi] National Slag Association (2013), 'Blast Furnace Slag', http://www.nationalslag.org/blast-furnace-slag (accessed 3 Jul. 2017).

[vii] Abood Habeeb, G. and Bin Mahmud, H. (2010), 'Study on properties of rice husk ash and its use as cement replacement material', *Materials Research,* 13(2): pp. 185–190, doi: 10.1590/S1516-14392010000200011 (accessed 3 Jul. 2017).

[viii] Federico, L. (2013), *Waste Glass - A Supplementary Cementitious Material,* https://macsphere.mcmaster.ca/bitstream/11375/13455/1/fulltext.pdf (accessed 3 Jul. 2017); Ellen MacArthur Foundation (2016), *The Circular Economy and the Promise of Glass in Concrete,* Case Study, October 2016, https://www.ellenmacarthurfoundation.org/assets/downloads/circular-economy/The-Circular-Economy-and-the-Promise-of-Glass-in-Concrete.pdf (accessed 28 Feb. 2018).

[ix] Portland Cement Association (2017), 'Chemical Admixtures'.

[x] Duxson, P., Fernandez-Jimenez, A., Provis, J. L., Lukey, G. C., Palomo, A. and van Devener, J. S. J. (2007), 'Geopolymer technology: the current state of the art', *Journal of Material Science,* 42: pp. 2917–2933, doi: 10.1007/s10853-006-0637-z (accessed 3 Jul. 2017).

[xi] Scrivener, John and Gartner (2016), *Eco-efficient cements.*

[xii] Stemmermann, P., Beuchle, G., Garbev, K. and Schweike, U. (2010), *Celitement – A new sustainable hydraulic binder based on calcium hydrosilicates,* http://www.celitement.de/fileadmin/user_upload/Downloads/2010-11-16_Celitement_a_new_sustainable_hydraulic_binder_based_on_calciumhydrosilicates.pdf (accessed 26 Apr. 2018).

[xiii] Scrivener, John and Gartner (2016), *Eco-efficient cements.*

Appendix 2: Methodology for Patent Landscaping

Below is a description of the steps taken for the patent-landscaping exercise, the results of which are presented in Chapter 2.

Dataset-generation methodology

In the first stage, Chatham House and CambridgeIP mapped out the relevant technology areas that contribute to emissions mitigation from cement and concrete production. This was supplemented by a survey of the broader intellectual property landscape for cement and concrete to build up a set of keyword descriptors and classification systems, including Cooperative Patent Classification (CPC) and International Patent Classification (IPC) systems, for the different technology areas.

On the basis of expert interviews, stakeholder engagement and desktop research, the scope of the patent analysis was narrowed to: **products and processes to do with lowering or entirely replacing the Portland clinker content of cement and concrete.** Once this focus area was chosen, CambridgeIP built a comprehensive Boolean search algorithm based on a combination of keyword descriptors and targeted CPC- and IPC-based searches. Boolean search algorithms are a commonly used patent search method. To demonstrate, a very simple example of a search for belitic clinkers might be: (belite OR ‘dicalcium silicate’ OR Ca_2SiO_4) AND (clinker OR cement).

Searches were performed for title, abstract and claims across all available patent databases. The patent dataset was compiled from LexisNexis’s TotalPatent database.[464] Patent searches were conducted in the first quarter of 2017 (see Table 8 for an overview of the subsequent filtering and quality control steps taken).

Table 8: Overview of patent dataset creation

Process stage	Detail	Dataset size
Dataset 1	Keyword descriptors and IPC/CPC codes are combined through iterative development into a search algorithm that collects relevant patent documents into a broadly focused inclusive dataset.	19,225
Dataset 2	The dataset then has all patent family duplicates temporarily removed to enable manual expert review and data cleaning. Name normalization is undertaken to account for assignee and inventor name variations throughout the dataset so as to standardize publication ownership.	2,170
Dataset 3	A semi-automated manual expert review of this family-collapsed dataset filters out any false positives collected by the broad search algorithm through combinations of title, abstract and claim keywords, classification codes and assignee filtering. Relevance for remaining documents is confirmed through random sampling.	1,571
Dataset 4	The final expert-reviewed dataset is re-supplemented with all relevant family members to create the final dataset, including all relevant patent documents.	4,577

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[464] LexisNexis (2017), TotalPatent database, http://www.lexisnexis.co.uk/en-uk/products/total-patents.page (accessed 30 Oct. 2017).

Using CPC and IPC codes

CPC- and IPC-based searches use CPC and IPC codes assigned by the patent examiner to find patents. For example, technologies relating to climate-change mitigation in the context of cement production might be assigned the CPC code Y02P40/10.

Although these codes act as a helpful guide for defining the technology space, there are reasons to believe that CPC- and IPC-based searches may be imperfect. Especially in the case of CPC codes, not all historical patents have been manually assessed and so some may be missing from this dataset.[465] For new patents, the CPC codes will be assigned directly within the examination procedure and so will be more accurate. Moreover, there are likely to be innovations that lie outside the definition used for a given code but that contribute in some way to the outcome in question. For example, Y02P40/10 codes are application-based rather than directly technology-based, which results in a fuzzier overlap with older classification systems and between technology subsystems. Even with a highly specific CPC code, it is difficult to distinguish between different technology systems. We therefore see CPC- and IPC-based searches as insufficient on their own, but as a valuable complement to Boolean searches

In technology areas that did not fall within the specific search focus – such as alternative fuel use or CCS, as in figures 9 and 10 in Chapter 2 – we used CPC and IPC codes to get a general sense of the intellectual property landscape while recognizing that this was likely to underestimate overall patent numbers within those technology areas.

Disaggregation of technology subcategories

Existing expert research[466] indicated the presence of important technology subcategories within the focus search area. We therefore further disaggregated the dataset into more focused subcategories so as to analyse patterns within these as well. For each technology subsystem, sets of keywords most likely to be used by patents within the subsectors were developed (e.g. for waste glass, these would include 'waste glass', 'glass', 'recycled glass' and 'recycled glass powder'). Searches for these keywords were performed within title, abstract and claims, and combined with CPC and IPC classification codes to filter the dataset into category groupings.

These groupings were reviewed manually to determine whether any systematic false positives were encroaching upon the categories as a result of alternative uses for keywords, or as a result of records being captured under classification codes for non-relevant applications. These records were then filtered and removed from that category designation.

After multiple iterations of this approach, clean categories were developed, grouping related technologies together. During the category review process, further subdivisions providing greater granularity were sometimes recognized, resulting in further separations within the original planned categories. The full set of technologies included within this focus area is mapped out in Appendix 1.

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[465] Whitman, K. (2012), 'Ready or Not, the Cooperative Patent Classification Has Arrived!', Intellogist blog, 12 July 2012, https://intellogist.wordpress.com/2012/07/12/ready-or-not-the-cooperative-patent-classification-has-arrived/ (accessed 12 Oct. 2017).

[466] We followed the technology categories used in two publications in particular: Scrivener, John and Gartner (2016), *Eco-efficient cements*; European Cement Research Academy and Cement Sustainability Initiative (2017), *CSI/ECRA-Technology Papers 2017*.

Limitations

Patent landscaping has several limitations, which were not fully addressed owing to resource constraints among other factors. These limitations include the following:

- There is a lag of up to 18 months in the publication of patent applications by various patent offices. Recent changes in the landscape may not be captured by the analysis.
- The searches were performed in English. This should capture the majority of relevant patents and patent families. However, owing to language differences, some patents are likely to have been missed and false positives may have cropped up due to mistranslations.
- The cement industry sees many mergers and acquisitions. Following an acquisition, the patent names are frequently not reassigned. Assignee names may not always capture these changes.
- Some relevant technologies may have been missed in the focus search area and in the technology subcategorization. Moreover, the boundaries of the technology spaces shift over time, so there may be some newer areas of innovation that were not identified.
- Smaller patent portfolios may, on occasion, play a more significant role than is suggested by the patent rankings. Some of the important disruptive technology and innovation may come from SMEs and individual innovators. These tend to file a small number of patents due to limited resources, and therefore may not be picked up in analysis of key players based on total numbers of patents held.

Appendix 3: Key Companies and Innovations

Box 5: Novacem

In 2005, Novacem, a company spun out of Imperial College London, announced the development of a 'carbon-negative cement'. The magnesium-based cement, produced without limestone, absorbed CO_2 during the concrete-curing stage, creating an overall carbon advantage over regular OPC.[467] Novacem received investments from the innovation arm of Imperial College London, the Royal Society Enterprise Fund, the London Technology Fund and several cement, construction and engineering companies, such as Lafarge, Laing O'Rourke, Rio Tinto and WSP.

In 2012, Novacem sold its intellectual property to Calix, an Australian technology company, and dissolved shortly thereafter. Despite the early promise and the financial support it was able to attract, the company failed to raise sufficient funds to continue research and production. Nikolaos Vlasopoulos, the former head scientist at Novacem, has speculated that the financial crisis of 2008 created a difficult climate in which to attract investors.[468] Information and news about Calix's acquisition of Novacem's technology have been sparse since the sale, although Calix has continued working on its own contributions in low-carbon cement processes, taking part in Project Leilac, an EU Horizon 2020 project focused on CCS. As of 2014, Calix was 'still working on Magnesia-based niche applications'.[469] Research into patent families once held by Novacem indicates that many have now lapsed, due to lack of continuation of fees, or have been withdrawn.

Box 6: LafargeHolcim

Among major cement producers, LafargeHolcim (formed from the 2015 merger of France's Lafarge and Switzerland's Holcim) is generally considered to be one of the more innovative players. Its investment in Novacem, its partnership with Solidia Technologies and its work on improving building energy efficiency are seen as indicative of the company's commitment to low-carbon innovation in the sector.

Beyond partnerships with and investment in other firms, LafargeHolcim has looked to develop its own low-carbon cement products. In 2003, what was then Lafarge started researching belite-rich clinker. This ultimately culminated in Project Aether, a public–private project aimed at the industrial deployment of lower-carbon Aether cements.[470] Aether, a new form of BYF (beliteye'elimite-ferrite) clinker, has a lower limestone content than conventional OPC and requires a lower production temperature.[471] In 2010, Lafarge, along with the consortium behind Project Aether, received €2.3 million from the EU's LIFE environmental programme to fund industrial trials. These indicated that Aether

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[467] Evans, S. M. (2008), 'Novacem – carbon negative cement to transform the construction industry', presentation, Imperial College London, 15 October 2008, http://www3.imperial.ac.uk/pls/portallive/docs/1/50161701.PDF (accessed 10 Oct. 2017).
[468] Majcher, K. (2015), 'What Happened to Green Concrete?', *MIT Technology Review*, 19 March 2015, https://www.technologyreview.com/s/535646/what-happened-to-green-concrete/ (accessed 12 Mar. 2017).
[469] Dewald and Achternbosch (2015), 'Why more sustainable cements failed so far?'.
[470] Aether (undated), *Aether Lower Carbon Cements*.
[471] Ibid.

emits between 20 per cent and 30 per cent less CO_2 in production than OPC cement while maintaining a high compressive strength.[472]

Despite renewed funding from the EU, continued rounds of testing and the fact that Lafarge announced it would start marketing the product in 2014,[473] Aether cement has not progressed past the R&D stage. The main reason is that it is still too expensive, due to the cost of raw materials, to compete with OPC. A European standard for the use of BYF clinkers is currently being drafted.

Box 7: Solidia Technologies

Based in the US, Solidia Technologies has received a lot of attention within the industry.[474] It has attracted investments from companies such as French multinationals Total and Air Liquide;[475] several venture capitalist firms, including Kleiner Perkins Caufield Byers; and LafargeHolcim, which has partnered with Solidia in an attempt to scale up the commercialization of Solidia's technology. The company also recently received investment from the Oil and Gas Climate Initiative, a CEO-led group of 10 oil and gas companies.[476] Compared to other SMEs in the sector, Solidia has also received a remarkable amount of public-sector support: the US Environmental Protection Agency, the US Department of Transport and the EU's LIFE Programme have all supported the company.

Solidia's cement uses the same raw materials as OPC, but its binder is produced at lower temperatures and contains lower levels of lime-containing calcium silicate, reducing CO_2 emissions from cement production by 30 per cent. Additionally, it cures its cement with CO_2 rather than water, sequestering around 240 kg of CO_2 for every tonne of cement that goes into its concrete.[477] Solidia cement has been tested in pilot and industrial-scale projects.

Despite its partnerships and support, and low-scale deployment in Japan, Canada and the US, Solidia's innovations still have a long way to go before they are likely to see widespread market deployment. The company has started to partner with regulatory agencies in the US to come up with updated validation and testing methodologies.[478] One of the key challenges is the fact that the CO_2-curing process currently still relies on a more controlled setting than can often be provided in a ready-mixed-concrete plant, limiting application and use of Solidia's product to precast concrete.[479]

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[473] Imbabi, Carrigan and McKenna (2012), 'Trends and developments in green cement and concrete technology'.

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Box 8: Taiheiyo Cement Corporation

Taiheiyo Cement Corporation has been developing 'eco-cements' in which large amounts of limestone are replaced with ash or other waste materials, ultimately reducing the amount of CO_2 released from the limestone during processing. The Japanese company has included ash treatment in its operations since the mid-1990s[480] and has established at least five fly-ash-washing plants in coordination with local-government disposal facilities.[481] This contrasts with its overall high emissions intensity relative to other cement companies, and the fact that it has one of the lowest emissions reduction targets in the sector.[482]

The company's push towards a lower-carbon cement system can be seen in the context of a broader national push towards sustainability. The Japanese Cement Association highlights the 'Fourth Basic Environment Plan', adopted by the government, which defined a sustainable society as a 'low-carbon society' and a 'sound material-cycle society' as a framework for developing more alternative and eco-friendly ways to produce cement.[483] In response to a call to action by the Keidanren (the Japanese Business Federation, consisting of more than 1,000 companies), the Japanese Cement Association mandated a voluntary action plan to 'redu[ce] the average energy consumption for cement production over the period FY 2008–2012'.[484] Eco-cement was standardized in 2002 as a 'constituent material' by the Japanese Society of Civil Engineers.[485] The usage of fly ash in cements also reflects a broader emphasis on recycling. High-density living and low land space have made several recycling activities (from those involving household waste to industrial waste processing) more attractive for businesses and individuals.[486]

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Table 4

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Appendix 5: Actions Needed in Different Countries/Regions

China

The scale of its market, the materials it has available locally and its role as an innovator give it a unique position to bring new, low-carbon cement and concrete technologies to maturity.

Although consumption is slowing, **China will continue to be the largest cement consumer globally** in the short term. Rapid urbanization is driving continued expansion of the construction sector – particularly in the western parts of the country as economic growth in coastal regions stabilizes.

The **cement market is maturing fast**, with rapid consolidation and industrialization being promoted by the central government. Cement standards and supervision have been improved, leading to efficiency gains. China already has a clinker ratio of 0.57, and this is expected to further decrease to 0.55 by 2060. However, China lags behind Europe on the use of alternative fuels.

China is also a **major hub for innovation**. Chinese companies and institutions make up the majority of patent assignees in our dataset. China is one of the few markets in which belite clinkers have been used in large infrastructure projects. It could also be a leader in digital disruption in the construction sector, with digital technologies already transforming a number of other sectors in the country. Chinese contractors spend almost three times as much as European contractors on R&D.

The **Chinese government** is a major procurer of construction materials and services, both domestically and overseas, through its Belt and Road Initiative. Approximately 20 per cent of all construction spending goes to public-works projects. The main market players include a large number of collective and state-owned companies.

The **impacts of climate change** on China are likely to be higher than for most countries in the northern hemisphere. Projections suggest an increase in flooding in southern provinces and water scarcity in northern provinces, with major knock-on effects for the construction sector both in terms of what needs to be built and what can be built.

Material availability

China has:

- High short-term availability of fly ash and blast furnace slag;
- Large stockpiles of bauxite waste;
- An abundant volume of clays appropriate for calcining; but
- Limited availability of timber for construction.

Key priorities for China could include:

- Scaling up clinker substitution with fly ash and blast furnace slag and the use of sustainable alternative fuels through targeted regulation, investment in distribution infrastructure and best-practice dissemination. This is especially needed in western parts of the country, where resources are currently underutilized and construction is on the rise.
- Holding large-scale demonstration projects and pilots for clinker substitution using calcined clays from clay stockpiles to establish the potential of this technology, integrating stakeholders along the supply chain.
- Building on experience using belite clinkers in major infrastructure projects, to support the use of novel cements and concretes in smaller projects by sharing lessons and best practice with construction firms and material suppliers.
- Establishing technology cooperation agreements on low-carbon cement and concrete with Belt and Road participant countries and establishing targets for use of lower-carbon building materials in infrastructure projects funded as part of the Belt and Road Initiative.
- As part of market consolidation, supporting more mature firms in adopting the best available technology and in applying and disseminating best practice on lower-carbon cement and concrete production throughout the sector.
- Setting public procurement standards on the use of BIM, and establishing a focused technology partnership with the UK to share lessons on best-practice BIM implementation.

Europe

With the majority of major multinational cement producers headquartered in the region, and with a long track record of policy action on cement sustainability and ambitious target-setting on the built environment, Europe is a key agenda-setter for the global market.

Overcapacity in the European cement sector and **a highly industrialized market** mean that existing kiln facilities are capable of meeting future demand for cement. European cement producers are some of the most advanced in terms of their use of alternative fuels, benefiting from advantageous regulatory support, but are behind India and China on energy efficiency.

Europe has a fairly **established housing stock**, with the majority of housing in many regions stemming from the reconstruction period (1946–70) that followed the Second World War. Although Europe's building floor area is not expected to rise as much as in other regions, poor housing conditions in a number of European countries suggest that existing stocks could benefit from retrofit measures.

Europe has a **history of progressive policies** and market interest in establishing a more sustainable construction sector. It has the highest number of zero-carbon buildings. In France and Austria, zero-energy and positive-energy houses represent a growing share of new construction. Public procurement has been a key policy lever in the region.

Europe has **strong agenda-setting power** in the sector. The largest multinational cement-producing companies are headquartered in Europe, and the region's standards and building codes are often followed in other locations. It also has a strong track record on policy and regulation in the cement sector.

The **construction workforce in Europe is ageing**, and the sector is already facing a serious skills shortage. These factors risk slowing down digital disruption and the efficiency gains that this might otherwise bring.

Material availability

Europe has:

- Limited supplies of good-quality fly ash and blast furnace slag;
- Stockpiles of waste fly ash and blast furnace slag; and
- Abundant supplies of volcanic rocks and ash in parts of Greece and Italy.

Key priorities for the EU, European governments and/or other stakeholders could include:

- Addressing overcapacity by phasing out old and inefficient cement production infrastructure.
- Setting 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 different construction and demolition waste streams.
- Building 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. These should build on the Level(s) guidelines and indicators for office and residential buildings currently being tested.
- Increasing public funding for R&D and financial support for incubation facilities and demonstration projects with novel and low-clinker cements, specifically exploring the scale-up potential for volcanic rocks and ash in southern Europe. This could draw on the new innovation fund to support the deployment of breakthrough technologies as part of the EU ETS.
- Providing training to address the digital skills gap in the construction, cement and concrete sectors – with a view both to retaining and improving the quality of jobs, and to co-developing and building up the stack of digital tools needed in the construction and material-supply value chains.
- Communicating long-term infrastructure plans and policies that set low-carbon and climate-resilient priorities for public procurement.

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.

India is already the world's **second-biggest cement market**. With the country's rapid urbanization and urgent infrastructure needs, this consumption is set to increase. The floor area in India is expected to double by 2035. Accommodating a growing low-income urban population will require rapidly scalable collective housing, water, sewage, transport and social-service solutions.

These trends and needs suggest **a substantial number of new cement plants will be built**. These will replace older, less-efficient plants and contribute to the sector's energy efficiency, which, according to the data available, is already higher than in Europe, the US and China. India is also expected to reach an ambitious clinker ratio of 0.50 by 2060.

The government has enacted a number of policies that focus on **energy efficiency in buildings**. Commercial buildings have been included in the Perform, Achieve and Trade programme – a market-based energy efficiency certificate trading scheme. India's agreed Nationally Determined Contribution (NDC) under its Paris Agreement commitments was one of the few to recognize the potential that buildings play in helping a country achieve emissions reduction targets.

With 30 per cent of GDP spent on **public procurement**, the public sector could be a key driver of consumption of lower-carbon building materials. Reducing corruption and enhancing transparency and competitiveness are key challenges to overcome.

India is in a strong position to **capitalize on digital disruption** in the construction sector, as information and communication technology systems evolve. However, India does not crop up as a major patent hub in our dataset.

Across India, cities and infrastructure must already regularly contend with **climate-related disasters**, including floods and droughts. There is a growing need for high-performance buildings and construction, and for provisions to be made for climate resilience in urban planning.

Material availability

India has:

- High fly-ash and granulated-slag availability in the short to medium term;
- Large deposits of bauxite waste; and
- A shortage of gypsum.

Key priorities for India could include:

- Developing an industrial policy to expand indigenous innovation capacities around low-carbon construction processes and products. Establishing a focused technological partnership for the cement industry between companies, universities, research institutes and government to specifically address the issue of research, development and deployment of lower-carbon building materials.

- Supporting firms in promoting more industrial use of cements, in concert with growth and consolidation in the sector. Firms also need to be given support in acquiring the best available technology, best practice and experience.
- Scaling up the use of fly ash and blast furnace slag, currently underutilized in many Indian states. This could be promoted through best-practice dissemination and training, better access to data on local material availability, and reductions in VAT on high-blend cements and concretes. In the longer term, preparing for the phasing out of coal by exploring the use of alternative clinker substitutes such as calcined clays.
- Developing climate-resilient infrastructure and city plans. Establishing a city-level working group to share examples of best practice in climate-resilient urban planning, design and construction processes from different cities. The working group could also encourage joint scenario and investment planning exercises between cities on how to respond to long-term environmental trends.
- Establishing a national framework for sustainable or green public procurement for construction. This could consist of providing training, tools and technical knowledge to procurers, in order to professionalize and enhance existing processes and to make clear and verifiable information on the environmental footprint and performance of products and services in the construction sector available so that these indicators are mainstreamed.

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.

The US has one of the largest **infrastructure investment deficits** – reflecting the gap between the infrastructure needed and financing available – in the G20. Inadequate investment in transport networks has left ageing roads, railways and waterways at risk of disruption. President Donald Trump initially promised a trillion-dollar boost to infrastructure spending. Plans announced in early 2018, however, lacked detail and suggest that the federal contribution will remain too low to turn this trend around.

The US is the **fourth-largest cement consumer** after China, India and the EU. The US lags behind other major producers in terms of energy efficiency and its clinker ratio, which was 0.86 in 2015. However, the latter may reflect a difference in industry practices – in the US, clinker substitutes tend to be blended with cement at the point of concrete production rather than blended into cement.

Some of the **world's largest technology and logistics companies** locate a bulk of their operations in the US. Walmart, Amazon, Alphabet and Apple are becoming major construction product and service consumers. A growing number of these companies are setting sustainability targets for their construction projects. Apple's new headquarters, for example, has unique concrete slabs that act as structural features as well as serving as part of the natural air-conditioning system for the building; during construction, efforts were made to recycle concrete rubble on site.

Some **US states and cities** are taking a lead on green construction. California has adopted an energy goal of net-zero emissions for all new residential construction by 2020 and all new commercial construction by 2030.

Sustainable-building **certification systems** such as the Leadership on Energy and Environmental Design (LEED) system and ENERGYSTAR have seen considerable uptake in the US. The construction industry views green construction as a business opportunity.

The US has been at the forefront of many of the **major digital disruptions** and business model shifts in recent years. This innovative and disruptive potential is reflected in the cement sector, with almost 10 per cent of patents in our dataset owned by US companies and academic institutions, the second-highest share after China.

Material availability

The US has:

- A shortage of fly ash and blast furnace slag in the medium to long term; and
- An abundant supply of volcanic rocks and ash in parts of the west coast states.

Key priorities for the US at the state and federal level could include:

- Providing education and advice to major corporate clients and those that advise them – i.e. to architects, engineers, contractors and sustainability consultants – on how material selection can affect the carbon footprint of their projects, and on the digital tools that can transform material-selection processes.
- Working 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; and to help build the stack of digital solutions needed to integrate real-time decision-making tools, supply chain optimization and lesson-sharing from experience with new materials and blends.
- Facilitating coordination among US cities on tendering for similar infrastructure projects to achieve the necessary scale for material suppliers to provide lower-carbon solutions. In 2017, a total of 402 US mayors committed to act in support of the goals set forth in the Paris Agreement. These commitments could be expanded to focus on the potential for emissions savings from climate-smart procurement and construction. Cities could partner up to share best practice for building design and construction.
- Supporting the trialling of volcanic rocks and ash as clinker substitutes at scale in California, capitalizing on local material availability and potential demand for lower-carbon concrete in the state.

Appendix 6: Low-carbon Cements – Barriers and Opportunities in Comparison to Conventional Portland Clinker

Technology	**Patent families**	**Examples**	**Phase**[i]	**CO_2 mitigation potential (% reduction vs. Portland clinker)**	Raw material availability	Costs	Energy demand	Water demand	Concrete properties	Applications	Standards
Low- Portland-clinker cements	934	LC3, CEMX, L3K, Ecocem	Commercialized	>70%[ii]	Limited fly ash and slag supplies globally in long term, but plentiful supplies in **China, Japan, India, South Africa** and **Australia** in short term.[iii] Plentiful supplies of limestone for use as a filler. Limited availability of silica fume globally.[iv] Clays widely available. Using calcined clays as a clinker substitute will be particularly viable in locations with stockpiles of clays associated with large ceramics industries, e.g. **China, Brazil** and **India**.[v] Natural pozzolans will be important in locations with volcanic activity, particularly **Greece, Italy, Indonesia** and the **US**.[vi]	Variable but can be lower with traditional SCMs. Decrease in operational costs of up to €3.1/t of cement with calcined clays. Retrofit costs: €8–12 million.[vii] Potentially higher with pre-processing if needed for calcined clays and natural pozzolans.	Generally results in decreased energy demand, but this varies by material. GBFS results in decrease in thermal energy of 1,590 MJ/t of cement, but a small increase in electric energy of up to 10 kWh/t of cement.[viii]	Varies depending on material. Water demand for fly ash, silica fume and calcined clays (when not using flash calcination) can be high, but using limestone as a filler can lower water demand.[ix]	Vary depending on material and proportion of clinker replaced. Many high-blend cements have low early-strength development but can achieve superior durability later on.	A wide range of applications. High-blend cements made with slag and fly ash have been used in structural and non-structural applications in many different contexts.[x]	High-blend cements using traditional SCMs are covered by European and US standards. Non-traditional SCMs are included in European standards, but are often excluded, not mentioned or allowed only with restriction in most exposure classes in European concrete standards.[xi]

Technology	**Patent families**	**Examples**	**Phase**[i]	**CO$_2$ mitigation potential (% reduction vs. Portland clinker)**	Raw material availability	Costs	Energy demand	Water demand	Concrete properties	Applications	Standards
Geopolymers and alkali-activated binders	418	banahCEM, Zeobond cement	Commercialized	>90%[xii]	Same as for low-Portland-clinker cements. Limited by current global production of sodium silicate, needed as an activator.[xiii] Waste glass could be used in place of sodium silicate as an activator.[xiv]	Cost-competitive in some contexts. In Australia, geopolymer cements are currently 10–15% more expensive than Portland cement.[xv]	Varies depending on energy input required for manufacturing the activator, e.g. Sodium silicate often requires a high energy input.[xvi]	Ceratech claims that its geopolymers use 50% less water.[xvii]	Can match the performance of Portland cement concrete. Historically, quality has varied depending on composition, but predictable performance is now claimed.[xviii]	A wide range of applications. Geopolymer cements have been used in major infrastructure and multi-storey buildings in Australia.[xix]	Not covered by standards. Geopolymer concrete standard being developed in Australia, but will likely take several years. Several organizations have recognized geopolymer concretes in their own standards.[xx]
Belite-rich Portland cements (BPC)	20		Commercialized	~10%[xxi]	High (same materials as traditional cement).[xxii]	Can be produced in conventional cement plants.[xxiii] Retrofit costs: €0–12 million. Increase in operational costs: €2–3.8/t of cement.[xxiv]	Varies, thermal energy demand can decrease by 150–200 MJ/t of clinker. Electric energy demand can increase by 20–40 kWh/t of cement.[xxv]	Less water needed for hydration.[xxvi]	Slower strength development than traditional cement, but expected to be more durable.[xxvii]	Limited to applications where low early-strength development is less of an issue, e.g. used in dams in China. Well suited to applications in hot climates.[xxviii]	Meets Chinese standards for Portland cements.[xxix]
Belitic clinkers containing ye'elimite (CSA)	33		Commercialized	~50%[xxx]	Limited bauxite supplies if high ye'elimite content is targeted, but more potential where bauxite waste is available, for example in large producing countries such as **Australia, China, Brazil, Malaysia** and **India**.[xxxi] Variable sulphur supplies.[xxxii]	Can be produced in conventional cement plants.[xxxiii] Higher raw material costs than for Portland cement.	30–50% less grinding energy required compared with OPC.[xxxiv]		Similar performance to Portland cement appears feasible. Concretes can show less carbonation and chloride migration resistance.[xxxv]	Mostly used in applications in China where the additional cost can be justified.[xxxvi]	Small number of compositions covered by existing Chinese CSA standards. European standard is being drafted.[xxxvii]

Technology	**Patent families**	**Examples**	**Phase**[i]	**CO_2 mitigation potential (% reduction vs. Portland clinker)**	Raw material availability	Costs	Energy demand	Water demand	Concrete properties	Applications	Standards
BYF clinker (also known as BCSA clinkers)	23	Aether	Demonstration	>20%[xxxviii]	Similar to CSA, however, BYF clinkers can have a lower ye'elimite content than CSA, meaning relatively abundant aluminium sources such as clays and coal ashes can be used in place of scarce concentrated aluminium sources such as bauxite. [xxxix]	Similar to CSA, however, BYF clinkers can have a lower ye'elimite content than CSA, meaning relatively cheap aluminium sources such as clays and coal ashes can be used in place of concentrated aluminium sources such as bauxite, which can be expensive.[xl]	Same as for CSA.		Data from EU's LIFE programme indicate similar strength development rate to OPC, better sulphate resistance and lower drying shrinkage. Other durability tests are still under way.[xli]	Only demonstrated in a limited number of applications, but in theory can be used for a very wide range of applications. Lower setting and hardening times mean that BYF clinker may have an advantage in precast concretes but can also be adapted for use in ready-mixed concrete applications.[xlii]	Same as for CSA.
Low-carbonate clinkers with pre-hydrated calcium silicates	8	Celitement	Demonstration	>50%[xliii]	High (same materials as traditional cement).	Roughly similar to costs for producing OPC clinker.[xliv] Similar raw material costs.	50% less energy required.[xlv] Potential increase in electricity needed for activation grinding.	Less water needed.[xlvi]	Similar performance to traditional cement. Strength development, final strength and hydration vary in the same range as for conventional cement. Increased reactivity over belite-rich Portland cement clinkers.[xlvii]	May be suitable for a wide variety of applications, but particularly for high-durability applications. [xlviii]	Not covered by existing standards.[xlix]

Technology	**Patent families**	**Examples**	**Phase**[i]	**CO_2 mitigation potential (% reduction vs. Portland clinker)**	Raw material availability	Costs	Energy demand	Water demand	Concrete properties	Applications	Standards
Carbonatable calcium silicate clinkers(CCSC)	15	Solidia, Calera	Pilot	>70%[l]	High (same materials as traditional cement).[li] Variable supply of pure CO_2.	Can be produced in conventional cement plants.[lii] Similar raw material costs to Portland cement.	Less grinding energy required.[liii]	Solidia claims around 80% less water is consumed.[liv]	Similar performance to traditional concretes is claimed.[lv]	Limited to precast applications for now. Not expected to be suitable for reinforced-concrete applications. Some on-site curing applications may be possible.[lvi]	Precast concretes can be sold under local technical approvals and do not necessarily require standardization at the national level. However, national standards are being sought.[lvii]
Magnesium-based cements	24	Novacem	Research	>100 %[lviii]	Plentiful but localized supply of basic magnesium silicates. Limited supply of natural magnesite.	Too early to assess, as no established manufacturing process.[lix]	Too early to assess, as no established manufacturing process but could in theory require less energy to produce.[lx]		Too early to assess. Very little information available on durability.[lxi]	Too early to assess.	

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Abbreviations and Acronyms

AI	artificial intelligence
B2DS	Beyond 2°C Scenario
BCSA	Belite sulphoaluminate clinker(s) (same as BYF)
BAT	best available technology
BIM	building information modelling
BPC	belite-rich Portland clinker(s)
BYF	belite ye'elimite-ferrite clinker
CCSC	carbonatable calcium silicate clinker(s)
CCS/U	carbon capture and storage/and utilization
CO_2	carbon dioxide
CSA	calcium sulphoaluminate clinker
CSI	Cement Sustainability Initiative
EPD	Environmental Product Declaration
EPO	European Patent Office
ETP	Energy Technology Perspectives
ETS	Emissions Trading System
GBFS	granulated blast furnace slag
GGBS	ground granulated blast furnace slag
GJ	gigajoule(s)
GNR	Getting the Numbers Right Dataset
GT	gigatonnes
IEA	International Energy Agency
MJ	megajoule(s)
MOMS	magnesium oxides derived from magnesium silicates
mt	million tonnes
OPC	Ordinary Portland Cement
RTS	Reference Technology Scenario
SBT	science-based target
SCM	supplementary cementitious material
SDG	Sustainable Development Goal
t	tonne(s)
VAT	value-added tax
WIPO	World Intellectual Property Organization
2DS	2°C Scenario

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