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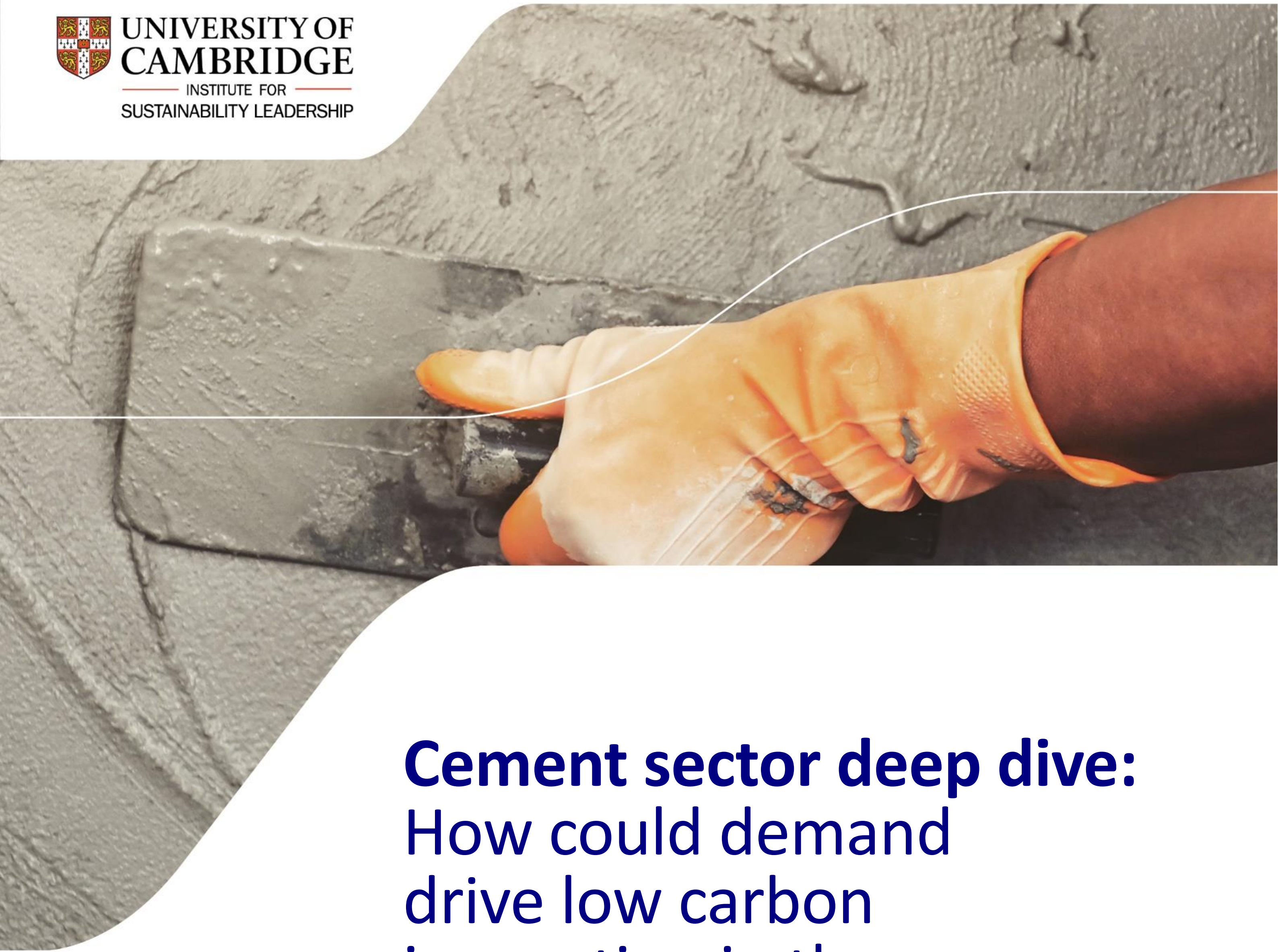
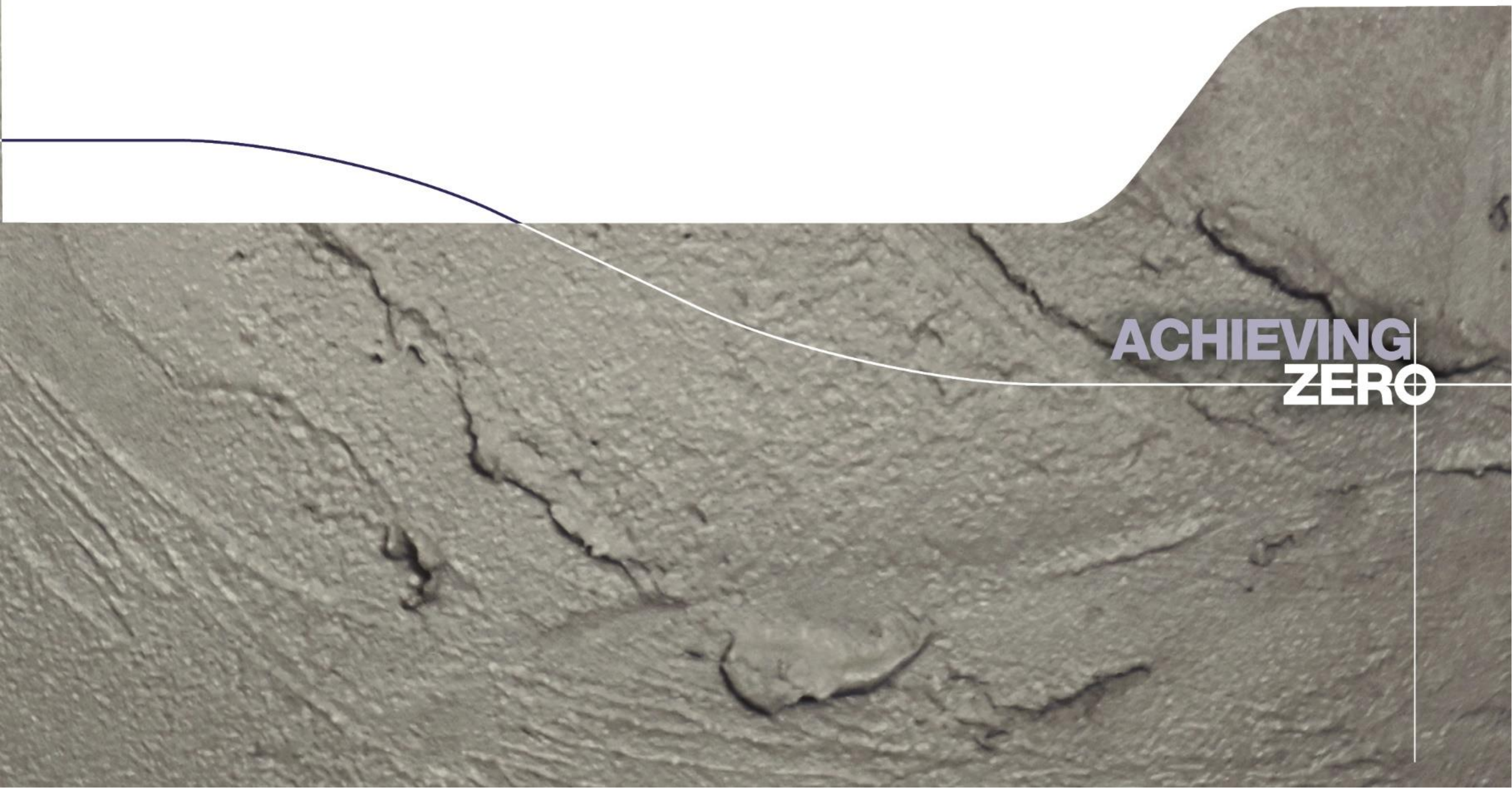


# **Cement sector deep dive:** How could demand drive low carbon innovation in the cement industry



ACHIEVING ZERO

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https://www.cisl.cam.ac.uk/resources/publications/market-driven-decarbonisation.

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# Contents

# 1. Introduction

In this sectoral deep dive, we explore the challenge of reducing carbon emissions from the UK cement industry. We start with a brief overview of the UK cement sector, the most common production methods and the cement industry value chain. We then outline the key decarbonisation pathways for the industry, examine how demand-led innovation could help support emissions reductions in the cement industry and discuss necessary demand-side policies that could facilitate low carbon innovation and upscaling of new solutions in this sector.

Cement is fundamental for building diverse structures, infrastructure, and transportation systems. It is one of the most widely used materials on a global scale and will remain a critical element for sustainable development and modern societies in the future. Due to urbanisation, infrastructure expansion, and population growth, the manufacturing of cement has been steadily growing – and will continue to grow (Schneider, 2019).

However, the concrete and cement industries contribute significantly to carbon dioxide emissions. At the global level, the carbon-intensive production methods used in the manufacturing of cement, which is the key component of concrete, generate 2.3 billion tons of $CO_2$ each year, accounting for about 7 per cent of global $CO_2$ emissions - roughly comparable to the annual emissions of India (Fennell et al., 2022). In 2020, the UK cement industry was responsible for 7.3 million tons of $CO_2$, approximately 1.5 per cent of total UK $CO_2$ emissions (MPA, 2020) and 9 per cent of the UK's manufacturing emissions (ONS, 2022). Most of these emissions, around 4.4 million tons, came from clinker production, 2.2 million tons from fuel combustion, and the rest from electricity use and transportation (MPA, 2020).

Decarbonising cement will play a significant role in helping the UK to achieve its Net Zero goals and beyond (MPA, 2022). However, there are several challenges to achieving this goal, which will require complete decarbonisation of all aspects of production, supply, and use. The industry cannot accomplish this alone and will need support from the government and significant changes across the wider construction, energy, and transportation sectors.

## 1.1 Overview of UK Cement Industry

In a broad sense, cement can be referred to as a substance that possesses adhesive and cohesive characteristics, enabling it to bind together mineral fragments into a compact whole (Neville, 2011). Concrete, which includes cement in it (cement contributes 10 per cent of concrete's mass, along with sand, aggregates and water), is a fundamental component of the construction industry and plays a crucial role in shaping the infrastructure of modern society. Construction, which makes up 6 per cent of the UK GDP (Rhodes, 2019), heavily relies on concrete to build the infrastructure we depend on, including clean water, sanitation, and energy (MPA 2020). Concrete is the second most used product globally after water, with demand expected to rise further by 2050 (IEA, 2018).

Over 95 per cent of concrete used in the UK is produced in the UK (MPA, 2020). This is common across all geographies, as concrete typically must be used within 2 hours of manufacture. The cement and concrete industries directly employ 74,000 people and indirectly support an additional 3.5 million jobs, primarily in the construction sector, while contributing around £18bn to the country's GDP (MPA, 2020).

## 1.2 The UK cement decarbonisation challenge

The emissions from the cement industry are a result of both chemical reactions during the production of cement and energy resources. In the past 200 years, the model of producing cement has changed little, and emissions cuts have been achieved primarily through energy efficiency improvements and a reduction in the use of clinker. In 1990, cement was made almost exclusively of clinker, with other ingredients accounting for less than one per cent of its content. Since then, the share of clinker in cement has been reduced to around 75 per cent, with some national variation (Globally ~72 per cent, EU and UK ~75 per cent, US ~89 per cent) (GCCA, 2019). Supplementary cementitious materials (SCMs), which are near-zero carbon (eg fly ash & blast furnace slag from steel production), make up the remainder.

The process of cement production starts with extracting raw materials, such as limestone, clay, sand, and iron ore, from quarries or mines. Cement production primarily involves grinding the raw materials and blending them in specific proportions. The resulting mixture is then subjected to high temperatures of up to approximately 1450 °C in a large rotary kiln. During this process, the material undergoes sintering and partial fusion, which forms clumps of material known as clinker. After the clinker has been cooled, it is finely ground to a powder and combined with gypsum to create Portland cement, which is used extensively worldwide (Neville, 2011). Mixing and grinding raw materials for cement production can be carried out in either in water or dry. These processes are referred to as the 'wet' and 'dry' methods. The specific techniques employed during cement manufacture are also influenced by the moisture content and hardness of the raw materials used.

In the cement production process, there are two main sources of $CO_2$ emissions. The first is the chemical reaction that occurs during the production of clinker, primarily due to the combustion of fossil fuels, such as coal and natural gas, to heat the kiln during the production process (GCCA 2020). The second source of emissions is primarily due to the calcination of limestone during the production of clinker. The use of energy accounts for approximately 35-40 per cent of clinker's $CO_2$ emissions, with the remainder being released primarily from the chemical reactions which occur when the limestone is heated (Shanks et al., 2019; McKinsey & Co, 2020).

Creating concrete involves mixing Portland cement (10-15 per cent) and water (15-20 per cent) to form a paste. This paste is combined with aggregates (65-75 per cent), which may consist of crushed stone, sand, and gravel. As the cement and water in the paste react with the aggregates, they harden to create a solid and robust mass that bears similarity to natural rock (Pamenter and Myers, 2021). Cement is a constituent material in the mixture that creates concrete and is primarily utilised as the binding material that holds the aggregates together when forming concrete. Although cement makes up a relatively small percentage of the overall mixture, it is almost solely accountable for the $CO_2$ emissions that occur during the manufacturing process (McKinsey & Co, 2020).

Clinker is a vital component in cement production, and its usage directly correlates with the $CO_2$ emissions generated during cement manufacturing. This is due to both the combustion of fuels and the decomposition of limestone during the clinker production process. The emissions intensity of cement production has increased since 2015 at an average rate of 1.6 per cent per annum worldwide, largely due to increasing clinker-to-cement ratio globally (IEA, 2022). The clinker-to-cement ratio is projected to decrease by 1.0 per cent annually, according to the IEA Net Zero Scenario (IEA, 2021b). This decrease is attributed to the increased utilisation of blended cement and clinker substitutes.

In the long term, clinker replacements made from commonly available materials, such as calcinated clay in combination with limestone, will become increasingly important. This is due to decreased availability of industrial by-products, currently used as alternatives, such as fly ash from coal power plants and ground granulated blast furnace slag from the steel sector, as other sectors decarbonise.

# 2. Cement industry decarbonisation strategies and progress

Decarbonising the cement industry cannot be achieved by a single solution; instead, every stage in the value chain must reduce its carbon footprint for the UK to reach its decarbonisation targets. To achieve the necessary carbon reduction targets by 2050, more innovative solutions, like new technologies and alternative building materials, will be needed (McKinsey & Co, 2020). Potential strategies for lowering carbon emissions in the cement sector include increasing the energy efficiency of the cement production process, switching to lower carbon fuels, improving material efficiency by reducing the clinker-to-cement ratio and implementing carbon capture and utilisation or sequestration technologies (Rumayor et al., 2022). Each of these strategies has some important benefits as well as limitations, meaning that to effectively reduce GHG emissions and develop effective mitigation strategies in the cement industry, all potential carbon reduction levers need to be exploited fully across all stages of the production process. This entails focusing on the supply chain flows at each step of the process, including considering resource depletion, and implementing integrated approaches to optimise resource utilisation.

Currently, there are few efforts to develop low-emission technologies in the cement and concrete sector, and there is a lack of specific policies with clear technology roadmaps. So far, efforts have focused primarily on reducing the use of fossil fuels by using alternative fuel sources: almost half of the fuel demand in the cement industry has been replaced with waste alternatives, which helps reduce waste and the need for landfill and incineration facilities (BEIS, 2017). However, most carbon emissions come from manufacturing cement rather than energy use. To address this issue, the UK cement and concrete industry has been gradually reducing the amount of clinker used in construction, as it is the active ingredient that produces carbon emissions (see Ecocem case study below).

In the current context, significant obstacles to achieving deep decarbonisation in the cement industry remain. Without a clear signal from carbon pricing, there is little motivation to make changes that will not provide immediate economic benefits. Alternative materials may not be readily available in the quantities required. Additionally, those involved in construction, such as architects, engineers, contractors, and clients, are often hesitant to adopt new building materials, a challenge that is not helped by product standards that are slow to respond to technological advances (see Ecocem case study below). Implementing new practices also requires retraining for millions of workers who use concrete in urban areas, making it a critical factor to consider (Chatham House, 2018).

If the UK fails to invest seriously in decarbonising the cement and concrete industries, it will lose the opportunity to lead the market in low-emission manufacturing technologies and solutions. To achieve zero emissions by 2050, the cement sector needs to gradually phase out carbon-intensive production methods and replace them with low-emission technologies. Although improving energy efficiency can help in the short term, a more significant change is needed. The sector will depend on key low-emission technologies, but the focus should be on replacing clinker with the use of supplementary cementitious materials. Below, we describe and discuss the decarbonisation pathways most prominent in the UK discourse.

## 2.1 Carbon capture and storage (CCS)

The UK government has outlined CCUS and electrification pathways as part of the Industrial Decarbonisation Strategy (2021). CCUS has the potential to reduce emissions in cement plants, and substantial research has taken place in the past few years to enhance reagent and membrane capture methods at a pilot scale. Currently, experiments are being conducted to explore how to better concentrate $CO_2$ in the gas stream, thus improving the effectiveness and affordability of carbon capture.

However, it is worth noting that CCUS is a novel technology not yet available at an industrial scale, meaning that relying on it to deliver future emissions reductions can be risky. The International Energy Agency (2020, pp. 18), which has proposed a cement decarbonisation roadmap where CCUS contributes to the reduction of $CO_2$ emissions by 48 per cent by 2050, has noted that “the story of CCUS has largely been one of unmet expectations.” Even if CCUS is as successful as hoped, cement decarbonisation roadmaps show that it will remain an expensive solution and unable to eliminate all (or even most) emissions from cement production. In the UK, the estimates regarding CCUS availability and adoption in the official strategy documents may be overly optimistic, considering the absence of consistent, long-term policy, institutional and regulatory frameworks and explicit plans for multi-year funding for CCUS implementation (Cembureau, 2020; GCCA, 2020).

The length and cost of shutdown periods for installing different (CCUS) technologies in the cement industry will ultimately determine which are competitive in the market. One way to reduce the time and expense associated with CCUS deployment could be to design cement plants to be "carbon-capture ready" from the beginning, even if CCUS is not currently viable in the cement sector. While the use of CCUS in the cement industry is unlikely to be available before 2035, it is important to consider the challenges that the industry will face, such as retrofitting and ensuring compatibility between cement plants and capture plants, to reduce their complexity in the long term (Hills et al., 2016). Therefore, we should consider other options besides CCUS to achieve net-zero compatible emission reductions in the cement industry.

## 2.2 Electrification

The UK Industrial Decarbonisation Strategy aims to reduce greenhouse gas emissions from industrial processes by promoting electrification as a key strategy (BEIS, 2021). The plan emphasises the use of renewable energy sources to generate electricity for industrial processes and the electrification of heat and transport in the industry. The cement industry can leverage electrification to reduce its carbon footprint by utilizing electricity (instead of fossil gas) for the heat in the production processes. However, this will reduce emissions significantly only if the electricity is entirely generated from renewable or other low carbon sources, such as nuclear.

Various technologies, like plasma generators and microwave energy, are being explored to electrify cement production. However, these technologies are still in the early stages of development and have only been tested in laboratory settings (TRL 3). A pilot plant that employs plasma technology is currently under investigation (9) to advance these technologies further (Somers, 2022).

The electrification of the cement industry presents comparable challenges to CCUS, particularly in using electric kilns. Although electric kilns have been prototyped and deployed in the industry recently (Katajisto, 2022), their widespread deployment is limited. The cement industry demands high levels of energy, making it essential to invest heavily in infrastructure to meet the increased power demand in the process of electrification.

## 2.3 Resource and energy efficiency

The UK 2021 Industrial Decarbonisation Strategy suggest that considerable $CO_2$ emissions reductions (in the region of about 15 Mt per annum) could be achieved from resource efficiency, energy efficiency and material substitution across the different industries covered by the strategy, including cement. The exact estimates for the emissions reduction potential through these routes, however, may need to be approached with caution as they are not broken down by sector and suggest substantial improvements until 2030, after which they plateau.

Some existing research indicates that operational changes in the cement industry can reduce emissions without the need for significant capital investment, mainly through consistently improving fuel metrics to best-observed levels, as well as reducing the excess air ratio to industry-standard levels, which has shown the potential to reduce fuel consumption by up to 7 per cent, and fuel derived $CO_2$ emissions by up to 12 per cent (Summerbell, 2017). Furthermore, the 'Next Manufacturing Revolution' (NMR) by Lavery et al. (2013) suggests that the UK industries, on average, could reduce GHG emissions by at least 4.5 per cent per annum through utilisation of management strategies to do more with less.

## 2.4 Replacing cement clinker with alternatives

By reducing the percentage of clinker needed to produce cement, the sector will reduce emissions at source, thus reducing levels of carbon emissions that would require CCUS.

Two key approaches can deliver substantial additional reductions in global $CO_2$ emissions related to cement and concrete, minimising the risks associated with the technological pathways of CCUS and electrification over the next 20 to 30 years. The first involves using low carbon supplements, such as supplementary cementitious materials (SCMs), to partially replace Portland cement clinker. The second approach involves using Portland Cement clinker more efficiently in the production of mortars and concrete (United Nations Environment Programme, 2017).

Option 1: Using supplementary cementitious materials (SCMs), to partially replace Portland cement clinker As clinker is the primary contributor to $CO_2$ emissions in the cement industry, even a one per cent reduction in the clinker factor can lead to a reduction of 8-9 kg $CO_2$/tn of cement (Miller et al., 2021). Many of the SCMs currently used in the cement industry as partial replacements for clinker or as partial replacements for cement in concrete mixtures are by-products of other (often emission-intensive) industries, such as fly ash from coal-fired power plants (Juenger, Snellings, and Bernal 2019).

Reducing clinker content in cement through the use of alternative materials such SCMs and fillers (eg crushed limestone) remains largely unexploited. However, it has proven potential to reduce emissions from cement production by up to 70 per cent (see Ecocem case study). Currently, SCMs only make up 15 per cent of cement production, but there is room for growth to increase this figure to 30-50 per cent and promote the use of SCMs to decrease the amount of clinker (Habert, et al., 2020).

SCMs are already being used widely in concrete manufacturing, where they offer a feasible solution to partially substitute Portland cement (Lothenbach et al., 2011). They can be incorporated into concrete by blending them with cement or adding them separately in the concrete mixer. As a result, SCMs can enhance the sustainability of construction materials by reducing the clinker content.

The benefits of using SCMs in cement or concrete manufacturing are economic and environmental. From an economic perspective, they can be deployed with minimal economic investment and negligible disturbance to operations because modifications required to the production facilities are limited. SMCs are also attractive from an environmental perspective: as industrial by-products, they can be resourced without any adverse environmental impacts. Using these by-products as construction materials is also an appealing alternative to disposal methods like landfills (Miller, 2018; Panesar and Zhang, 2020; Miller et al., 2021).

However, the fact that some SCMs have emissions associated with their production can create complications in allocating these emissions between their production and final use. The potential for using more SCMs in cement production may also be constrained by cost-effective transportation logistics, as SCMs are often not available locally and need to be transported over long distances, sometimes across the globe. In the future, the availability of the SCMs that are currently used most widely may be constrained by the need to phase out the industrial production processes that currently produce these materials as by-products, such as coal power plants. To address this challenge, efforts are being directed to develop new and more sustainable sources of SCMs.

### Case study 1: Ecocem – Reducing cement emissions through the reduced use of clinker

Conventional cement relies heavily on the use of clinker in a manufacturing process that produces ~600 kg of $CO_2$ per tonne of cement, of which clinker is responsible for ~95 per cent of the carbon footprint. Reducing the amount of clinker needed to produce a tonne of cement through the use of alternative materials such as supplementary cementing materials (SCMs) and fillers (eg crushed limestone) could reduce $CO_2$ emissions from cement production to ~170 kg – an greater than 70 per cent instant reduction in cement's carbon footprint. However, these options remain largely unexploited despite their potential.

Historically, the scalability of low carbon cements has been a challenge. However, recent advances in cement technologies have made it possible to develop cement that has a significantly lower clinker content and instead consists of ~70 per cent of SCMs and inert fillers, without compromising the quality of the product (UNEP, 2017). These technological advances would allow low carbon cement technologies to be produced at a scale that meets the demands of the concrete and construction sectors in the UK.

Ternary cement, developed by Ecocem, is one example of a new generation, low carbon cement. It is made of a blend that has a clinker content of 20–25 per cent, combined with SCMs (eg slag, fly ash, clays, accounting for 25–35 per cent of the content) and fillers (40–55 per cent of the content). By comparison, the average European and British cement contains ~75–77 per cent clinker. This advanced cement technology has been proven to work efficiently with concrete and achieve the workability and performance standards required. It can be produced, with fairly minor changes to existing production plants, by maximising the use of cementitious / filler technologies that are already widely utilised in the cement sector. As a result, transitioning a plant to produce low clinker, high SCM and filler cement instead of traditional cement is more immediate, cheaper, less disruptive and less energy intensive than the deployment of CCUS technology.

The new cement technology will:

- Reduce $CO_2$ emissions by over 70 per cent, which will generate financial savings through the avoidance of costly $CO_2$ credits (European Commission, 2023d; John et al., 2018) and substantially reduce the scale of CCUS required.
- Lower energy use: thermal energy demand is reduced by ~75 per cent and electrical energy by ~30 per cent.
- Reduce water demand in concrete manufacturing by ~35 per cent per cubic metre, which is important especially in water-stressed regions.
- Reduce toxic emissions (sulphur dioxide, nitric oxide) in line with $CO_2$ reductions.

However, current UK policy framework does not sufficiently support innovation in the cement industry or the scaling up of new low carbon cement technologies. The following changes are needed:

- Policies should support near-term solutions, which can significantly reduce cement carbon emissions, including solutions that enable a reduction in cement's clinker content. Focusing on CCUS as *de facto* core decarbonisation technology for cement is not sustainable when alternative low carbon technologies, which produce less $CO_2$ in the first instance, are much cheaper, speedier to deploy, and less energy intensive and disruptive to current operations.
- The process of changing standards needs to be faster and more responsive to technological change. Current standards for cement / concrete are no longer fit for purpose. Performance-based standards would be more technology neutral and incentivise innovation. Some countries are moving faster than others in this regard.

- Urgent public funding is required to accelerate the industrialisation of low carbon cement technologies. Policymakers need to level the playing field and increase their expertise in these technologies so that pilot / demonstration projects, first-mover industrial facilities, etc can be developed.

Option 2: Using Portland Cement clinker more efficiently in the production of mortars and concrete
Efficiency utilisation of using cement clinker in concrete manufacturing can also lead to reduced emissions. Both concrete and mortars have the potential for comparable reductions in $CO_2$ emissions. Optimisation of the mix of different material inputs can result in substantial improvements in concrete's eco-efficiency (the $CO_2$ emissions in relation to the concrete's ability to withstand compressive stress), with the best practices being able to achieve up to four times better eco-efficiency compared to the worst practices. To achieve this, careful optimisation of particle packing in both the coarse and fine components of the cementitious materials, along with the use of dispersants and fillers, can lower clinker content without compromising product performance. Some studies indicate that the using SCM could also enhance the performance of concrete at high-temperature due to its pozzolanic properties and super micro-filling capacity (Saboo et al., 2019).

## 2.5 Demand reduction and improved circularity

Reducing demand and implementing circular economy practices can reduce emissions from the manufacturing of both cement and concrete, primarily by reducing the demand for concrete. This can be achieved through multiple avenues, including using (smaller quantities of) high-quality concretes, implementing efficient design strategies, substituting concrete with other materials, reducing waste on construction sites, and increasing the reuse and recycling of concrete and its material components (Allwood, Cullen, and Milford 2010; Chatham House, 2018).

These demand-reduction strategies are crucial levers to achieve net-zero emissions in the sector (Chatham House, 2018). For example, using high-strength concrete grades can enhance efficiency and potentially decrease the overall amount of materials needed (United Nations Environment Programme, 2017). Strategies such as design optimisation and the use of prefabrication techniques in construction (ie the use of ready-mixed concrete instead of site-mixed concrete) can lead to reduced waste on job sites and associated material saving, cutting GHG emissions by as much as 50 per cent (Miller et al., 2021; Dunant et al., 2021). However, when seeking to reduce cement and concrete use through improved material efficiency (to achieve the same task with less material), it is important to consider the various ways in which cement and concrete are used, including the differences between buildings and infrastructure, reinforced and unreinforced concrete, and how these factors may affect the implementation of circular economy principles (Marsh, Velenturf, and Bernal, 2022). The deployment of demand-side principles in practice will likely require the cooperation and motivation of many actors beyond the cement and concrete industry.

So far, efforts to implement a circular economy in the cement and concrete industry have focused primarily on individual materials and products rather than the entire system. However, adopting a systems-based approach is necessary to reduce carbon emissions in the UK cement industry and effectively implementing circular economy principles.

To decrease emissions in the cement industry as part of a circular economy, stakeholders can adopt three strategies:

1) Redesigning buildings and infrastructure to minimize the amount of material needed and, therefore, the amount that ends up in landfills;
2) optimizing production processes such as carbon-cured concrete and recycling building materials;
3) repurposing carbon generated during construction by either capturing and storing it or using it to create synthetic fuels (McKinsey & Co, 2021)

To effectively implement a circular economy, it is necessary to adopt demand-side strategies that promote the efficient use of cement and concrete in the built environment through the involvement of multiple stakeholders.

This can include material-efficient design techniques such as performance-based concrete design, the use of precast concrete components, post-tensioning, and avoiding overtly complex and material-intensive designs. Additionally, increased use of shared buildings and infrastructure, and the consolidation of urban functions, can contribute to reducing carbon emissions in the cement sector. Increasing the service life of buildings, reducing construction waste, reusing components, downcycling, and stockpiling demolition waste can also help align circular economy principles with the goal of deep decarbonisation in the sector (Watari et al., 2022).

# 3. How could demand drive low carbon innovation in the cement industry?

Demand-led decarbonisation pathways, which can stimulate a rise in market demand for specific products or services, are crucial to decrease emissions by reducing demand for high-carbon cement products and promoting the development of alternative options with lower embodied carbon content. Governments can encourage collaboration between consumers and producers to achieve net zero by implementing measures such as product standards, labelling schemes, and procurement policies to boost demand for low carbon products (CISL and Agora Energiewende, 2021; PA Consulting and BEIS, 2021).

To successfully reduce carbon emissions in the UK cement industry, it is essential to have strong demand-side strategies that reach all parts of the supply chain and industries that use large amounts of cement, including construction, transport, and manufacturing. These strategies will encourage the development of low carbon and efficient cement markets. To achieve this, it is necessary to establish a feedback loop between the various actors in the value chain that promotes sectorial decarbonisation. To do so, strategic innovation and policy mechanisms are required.

To decarbonise the cement industry, it will be necessary to make progress in reducing emissions through improved energy efficiency and technological innovation. Collaboration across the cement value chain will be important in achieving these goals. Although the challenges facing individual players in the industry are significant, those that take early action to address sustainability across the value chain to remain competitive in a global market (McKinsey & Co, 2022).

The UK has outlined significant low carbon technologies to reduce emissions from industry in the Industrial Decarbonisation Strategy (2021). However, when working towards a cement and concrete industry that is climate neutral, it is essential to have a comprehensive perspective. This would involve considering factors beyond the factory gates, including the infrastructure and the lifespan of the product. Utilising circularity and life-cycle approaches, and decarbonisation across the value-chain will be crucial in achieving carbon neutrality in the cement industry.

Reducing carbon emissions in the cement industry is currently a difficult challenge due to the lack of economic incentives for available $CO_2$ mitigation strategies. More impactful and holistic policy efforts are needed to address this issue (Rumayor et al., 2022). These could include:

- Focusing resources on policy interventions that increase the incentives for cement manufacturers to explore near term solutions to reduce carbon emissions from cement production, for example by reducing cement's clinker content. These solutions will also reduce future demand for CCUS (see Ecocem Case study). Focussing on CCUS as de facto core decarbonisation technology for cement is not sustainable when alternative methods, which produce less $CO_2$ in the first instance, could be much cheaper, speedier to deploy, less energy intensive, and less disruptive to current operations.
- Making it easier and faster to update product standards in response to the emergence of new, innovative, solutions. Current standards for cement and concrete are based on incumbent technologies that are emission intensive by design. Performance-based standards would be more technology neutral,

incentivising innovation and making it more feasible for downstream companies (such as the construction industry) to switch to new low carbon alternatives. Some countries are moving faster than others in this regard. A good example of this is the PERFDUB project in France, which aims to establish a performance-based methodology for ensuring the durability of concrete and create an operational and practical performance-based approach that can be adopted by all stakeholders involved in the construction industry. This will involve defining the "absolute" and "comparative" methods for justifying durability through gathering input and feedback from all stakeholders to identify and address gaps in the current framework. The goal is to create an operational and practical performance-based approach that can be adopted by all stakeholders in the construction industry (PERFDUB, 2015; Linger and Cussigh, 2018). The results of the PERFDUB project have been incorporated into the new concrete standard published at the end of 2022, creating opportunities for the use of innovative formulations within the new standard.

- Allocating public sector funding or fiscal incentives for companies that invest in the research and development (R&D) of low carbon technologies or processes across cement and concrete industry value chains (including construction companies that invest in improving material efficiency and circularity). It would be beneficial for policymakers and representatives across the cement industry value chain to have regular information exchanges, to keep policymakers informed of recent and upcoming innovations in this industry. Policymakers can play a crucial role in ensuring these can be developed with a manageable risk profile.

- Directing public sector funding to support the cost of compliance for small and medium-sized enterprises (SMEs) in cement and concrete industries and downstream value chains. Without financial support, these companies may struggle to implement labelling schemes and standards.

- Implementing government-funded conversion schemes, which provide grants, low-cost loans and government-backed insurance to companies that undertake innovation or deploy innovative solutions in their operations. These schemes could be combined with regulatory sandboxes (Ofgem, 2018), which allow innovative, cement-like products that meet the performance standards for cement to be tested in the market with real consumers. However, for this option to be viable, insurance schemes would be needed to de-risk the take-up of new materials among downstream consumers. Similar approaches could also support decarbonisation in other non-metallic minerals industries, such as ceramics.

- Incentivising (through financial and fiscal incentives) the utilisation of best practices, such as operational changes, which can reduce emissions without the need for large capital investment (Lavery et al., 2013). For example, digital tools can be utilised to share effective techniques for improving specific concrete mixtures using materials found in the area or to enable a worker at the construction site to easily access information on how certain SCM and admixture work together. Improved knowledge sharing will play a crucial role in making it easier to use innovative cement and higher blends in developing markets. Developing and offering tools for implementing best practices in the cement industry worldwide, such as global standards for decreasing clinker, demolishing, and storing concrete, could also contribute to decreasing levels of embodied carbon.

- Implementing regulations that hold retailers and property demolition companies responsible for recycling such products may be necessary, along with infrastructure and public sector services, to make recycling feasible for households and small businesses. Innovative business operations and models in waste management and recycling can also help enhance closed-loop material circularity in the steel sector and reduce the quantity of materials required to serve the same function over a period. Enhanced collaboration across value chains, including standardised embodied carbon content accounting and reporting, can support the circular economy in practice, such as using digital product passports that provide detailed information on the recyclability of components and materials used in each product.

- Implementing product standards to mandate a minimum level of environmental performance, such as embodied carbon emissions associated with the entire lifecycle of cement products. Product standards in the cement industry serve as a guideline to define minimum specifications for cement products to meet certain quality, safety, or environmental standards. Updating these standards periodically in line with technological innovation could help create demand for low carbon cement by encouraging consumers to opt for more sustainable products while discouraging the sale of high-carbon alternatives (Aldersgate Group, 2022). By setting minimum standards for the environmental and technical performance of cement products, including lower carbon emissions, reduced energy usage, or higher recycled content, product standards could encourage manufacturers to adopt more sustainable practices and develop new, advanced, low carbon cement technologies.

  Product standards that set limits on embodied carbon content could nudge consumers towards more sustainable products and disincentivise the sale of carbon intensive products, thus stimulating investment and innovation in low carbon materials by creating confidence about future demand. To be effective, these standards would need to be well-designed, mandatory, and tightened over time. By implementing mandatory product standards, the UK Government could ensure that industry is competing on a level playing field and that companies pushing further on reducing emissions are not put at a competitive disadvantage (Aldersgate Group, 2022). To avoid hindering innovation, emissions intensity standards should be technology neutral and focus on performance instead of using a particular technology or specific material inputs (CISL and Agora Energiewende, 2021).

- Implementing labelling schemes independently or in conjunction with product standards and other policy measures. Labelling could support decarbonisation by providing clear information about the carbon emissions of cement products, incentivising sustainable production, empowering consumers to make informed choices, and driving innovation in low carbon technologies. Such schemes have already been effectively applied to the operational emissions of various products, such as white goods. However, labelling schemes must balance accuracy and accessibility to avoid confusion among consumers. Using colour codes or scales can simplify messaging but may sacrifice scientific precision. Additionally, business-to-business transactions may require support to bridge knowledge gaps between purchasers and suppliers, such as Japan's Act on Promoting Green Purchasing (Japan Ministry of the Environment, 2016) and the Buy Clean California Act (Department of General Services Procurement Division, 2021).

  Labelling schemes could also contribute to sustainable development by encouraging responsible consumption practices and promoting the efficient use of resources and energy by providing information on the environmental impact of cement products. These labels could create an environment that favours transparency, ensuring that consumers are informed and recognise their responsibility to make decisions based on the information they have (Lambin and Thorlakson, 2018). To mandate the use of low carbon cement products in construction, building codes and standards can be introduced in conjunction with these schemes. Governments can create a market for low carbon alternatives and support their development by setting performance standards that incentivise their use.

- Introducing incentivisation programmes for adopting/purchasing low carbon technologies. Again, some countries have been moving faster than others in this regard. For example, the Netherlands' $CO_2$ performance ladder assists organisations, companies, and projects reduce their carbon emissions. By obtaining a certificate on the Ladder, organisations can gain a competitive advantage in their bids for tenders (OECD, 2016). Similarly, France's RE2020 programme seeks to enhance the energy efficiency and environmental performance of all new buildings through regulation that requires all new buildings built in the country after 2020 to be nearly zero-energy. The RE2020 guidelines cover the complete lifespan of the building and gradually decrease the acceptable emissions limit for new constructions over time (Agora Energiewende, 2022). France's example could serve as a model for the UK, highlighting the level of ambition required for a country with an economy a similar size to the UK's.

- Implementing guidelines and strategies for public and private sector organisations to align their procurement practices with their sustainability objectives and reduce their carbon emissions from cement. These policies could include mandatory of voluntary commitments to source products that are more environmentally sustainable than conventional offerings. Government procurement programs are significant purchasers of concrete for public infrastructure, including buildings, roads, and bridges. As such, government procurement policies can create a substantial market for low-emission materials, encouraging further innovation in the industry (Krupnick, 2020). However, private sector companies can also play an active role in creating demand for low-carbon cement, for example by participating in initiatives such as ConcreteZero, which is featured in the case study below.

### Case study 10: ConcreteZero – A demand-side business initiative

At present, a globally agreed standard for low emission concrete does not exist. However, such a definition needs to be developed to align the industry and to build the collective action that is needed to get the concrete industry to net zero. One key barrier to developing a shared definition is the lack of data on the level of carbon emissions associated with the concrete that is currently being used and produced. These data are needed to develop a good understanding of the embodied carbon emissions of concrete in a business-as-usual scenario against which progress could be measured.

International non-profit Climate Group's ConcreteZero campaign brings businesses together to create a market for sustainable concrete, and to drive greater transparency on carbon emissions across the concrete industry value chain. Members include major companies in the property and construction industries including Thornton Tomasetti, Lendlease Europe and Multiplex. The focus is concrete, which is a mix of materials, including cement. The embodied carbon content of concrete is determined by the ratio in which cement and other ingredients are added to the concrete mix. Therefore, focusing on concrete allows maximum flexibility in reducing the carbon emissions associated with its materials, as multiple processes can be addressed.

Businesses that join ConcreteZero commit to using 100 per cent net zero concrete by 2050, with two ambitious interim targets of using 30 per cent low emission concrete by 2025 and 50 per cent by 2030. They also sign up to a 'baseline' commitment to report the volume and carbon intensity of concrete consumption through a digital platform, which will allow data to be shared (anonymously) among members. The design of this platform is well under way and will provide a standardised methodology for benchmarking performance and recording the improvements members are making. It will allow more accurate targets to be set based on seasonal, geographical and structural use of concrete, while also enabling policymakers to set meaningful parameters for operation.

Solutions to reduce the embodied $CO_2$ of concrete exist within the UK, but they require early engagement and an innovative, collaborative approach from construction companies and concrete producers. Aspiration and collaboration through initiatives such as ConcreteZero are key to unlocking fledgling technologies that need uptake today to provide tomorrow's solutions.

# 4. Conclusions

For the cement industry to decarbonise, the demand for low carbon cement needs to increase. By 2030, it will be necessary for carbon-neutral or carbon-negative construction to become the standard. To make this happen, there must be a significant surge in construction materials with zero or negative embodied emissions soon (Chatham House, 2018; Röckstrom et al., 2017). Technologies such as CCUS will be unlikely to be implemented within this timeline.

Globally, the cement industry is the second-largest contributor to $CO_2$ emissions and the third-largest consumer of industrial energy. The demand for cement and concrete is rising due to population growth, urbanization, and infrastructure development needs, which puts more pressure on reducing the carbon footprint of cement production. Even if countries stick to their carbon mitigation commitments and energy efficiency targets, the cement sector's direct $CO_2$ emissions will increase by 4 per cent worldwide by 2050, with a projected 12 per cent growth in cement production during the same period (IEA, 2018). It is imperative that the widespread use of low carbon cement becomes the norm urgently. We cannot solely depend on technologies such as CCUS and electrification to provide us with potential emission reductions in the future.

Greater utilisation of supplementary cementitious materials (SCMs) is the most viable way, at the moment, to reduce emissions from cement production. Replacing a high portion of the clinker content in cement with other materials would have a greater impact than anticipated. The share of clinker needed can be further reduced in specific applications, leading to a potential decrease in $CO_2$ emissions of 70-90 per cent (Chatham House, 2018). To decarbonise cement production, investment in R&D is necessary to enhance the effectiveness of implementing SCM in cement production. This includes developing high-quality SCM technologies that can improve the robustness of SCM use in cement production. However, it is necessary to revisit regulatory requirements that may present a barrier to greater use of cement made from SCMs (CISL and Agora Energiewende, 2021).

In addition to changing the production process and material inputs for new cement, emission reductions can be achieved through the scaling up of circular business models and improved material efficiency. To this end, we need strategies to explore how innovations in the built environment will affect upstream sectors, including where material efficiency strategies in the cement industry have the potential to decrease the demand for cement by utilizing minimalist designs, increasing the lifespan of products, promoting reusability, and recycling while ensuring the control of contaminants (Allwood and Cullen, 2015; Bataille, 2019). This can be achieved through design strategies such as minimising material use from a life cycle greenhouse gas (GHG) intensity perspective, lengthening the life of structures to minimise re-build cycles, and making structures flexible for multiple potential end-uses.

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