



Low Carbon Concrete Technologies (LCCT): Understanding and Implementation

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RESOURCE EFFICIENCY
IN CONSTRUCTION AND
THE BUILT ENVIRONMENT

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Executive Summary

Decarbonisation of the cement industry is necessary under the UK's Sixth Carbon Budget by 2040. Existing UK Roadmaps aim for net-zero in 2050 and rely heavily of technologies that are not commercially ready yet, such as Carbon Capture, Utilisation and Storage (CCUS).

It is accepted that there are existing technologies that can also be used to reduce emissions of the cement industry in the UK and yet many of these are not widely adopted. Systematic, top-down analysis of barriers to innovation in the UK construction industry have identified a number of issues that can be addressed to improve the uptake of innovations. However, no analysis to date looks at the particular barriers to each of the available Low Carbon Concrete Technologies (LCCTs) and quantifies the potential of these at a granular level across the lifecycle of cement and cementitious products.

This project uses existing literature to map the range of LCCTs across the cement and cementitious product lifecycle and quantify their upper bound potential emissions savings, compared to an OPC (Ordinary Portland Cement) baseline, and possible carbon savings if fully deployed in the UK cement and concrete industry.

To define the barriers to the uptake of each of these technologies, a Commercial Readiness Index (CRI) from the Australian Renewable Energy Agency (ARENA), is adapted to assess the LCCTs against nine indicators which represent the development areas required to achieve mainstream deployment. This index acknowledges the development gap between technology readiness (whether the technology performs technically in the real world) and mainstream deployment (whether the technology can capture significant market share), which is often overlooked when assessing technologies for industry uptake.

The analysis shows that upto 37% of current cement industry emissions can be mitigated, compared to an OPC baseline, through the use of technologies with a high level of commercial readiness, against a 100% OPC baseline. These technologies can be deployed at scale almost immediately, with policy encouraging or requiring their use, as deployment in the Architecture, Engineering and Construction (AEC) industry is best driven by changes to regulation.

Longer-term development of high-potential technologies across all lifecycle stages could unlock emissions reduction of up to 93%, compared to an OPC baseline, if these technologies prove to be viable at scale. Development should focus on those technologies with medium to high commercial readiness that can be used in combination with each other, rather than competing against other technologies. The technologies identified are spread across the full lifecycle of cement production, use and disposal, so their implementation is influenced by a range of stakeholder groups, rather than being the responsibility of just one actor.

Across the high-potential technologies, three barriers to wide-spread adoption were found to be common:

- | | |
|-------------------------------------|-----------------------------------------------------------------|
| 1. Regulation through Policy | Key Implementer: Government |
| 2. Industry Skills | Key Implementers: Industry Bodies, Educators |
| 3. Market Opportunities | Key Implementers: Market-leading Contractors and Clients |

By addressing these three areas as a priority, the industry can move a large number of high-potential technologies closer to commercial deployment. Specific mechanisms for addressing these barriers are discussed under three overarching recommendations:

1. **Introduction of policy that explicitly encourages or requires use of LCCTs**
2. **LCCTs education as part of industry training and certification**
3. **Creation of market-pull conditions for LCCTs**

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1 The need to reduce concrete emissions

It is widely accepted in academia and industry that the embodied carbon of buildings and infrastructure is increasingly important in the lifecycle emissions of such assets and therefore is a key part of achieving the UK's net zero targets (Hammond and Jones, 2011; Pomponi and Moncaster, 2016; Akbarnezhad and Xiao, 2017; Pomponi, De Wolf and Moncaster, 2018; Orr *et al.*, 2019).

Globally, concrete is the most consumed man-made material by weight and, as such, represents a large proportion of construction materials (Scrivener, John and Gartner, 2018). In the UK, the production of cement and concrete is responsible for around 1.5% of national greenhouse gas (GHG) emissions. Without including imported materials, the emissions attributed to manufacture of cement and articles of concrete, cement and plaster in the UK are around 8.5 Mt CO₂e/yr (Office for National Statistics, 2020). The UKGBC Low Carbon Concrete Routemap found that total cement and concrete carbon emissions, including all imports, in 2018 were approximately 13.5 MtCO₂e (Mulholland *et al.*, 2022). This project considers the emissions associated with domestic production and use of those products, as all of these emissions are within the control of the UK industry.

While there has been some focus by industry groups on reducing the emissions of the cement and concrete industry in the UK to date, such as the Mineral Products Association's (MPA) roadmap to Beyond Net Zero (Mineral Products Association, 2020b), much of the work is based on reaching a net-zero target in 2050. The UK government wrote into law the Sixth Carbon budget, The Carbon Budget Order 2021 No. 750, as recommended by the Climate Change Committee (CCC) and while the government has not yet explicitly accepted the underlying sector-specific targets of the CCC, this project considers these underlying targets to be the necessary standard of emissions reduction to reach for (Department for Business Energy & Industrial Strategy, 2021).

As a result, the UK cement and concrete industry is required to work towards net zero emissions by 2040 (Climate Change Committee, 2020), a whole decade earlier than existing roadmaps are defined for. This means that the industry needs to quickly mobilise existing emissions reduction potential and set out priorities for unlocking further potential through targeted development.

Cement and concrete is identified as a hard to decarbonise sector, as around 50% of the emissions arise from the fundamental chemical reaction required to create clinker (Mineral Products Association, 2020b) (called 'process' emissions), the main constituent of Ordinary Portland Cement (OPC), which accounts for the majority (~80%) of cement used in the UK (Mineral Products Association, 2019c). This means that emissions reductions techniques, such as alternative fuels and energy efficiency can only impact about half of the industry's emissions, requiring industry-specific solutions to be developed to address the rest.

This project aims to identify Low Carbon Concrete Technologies (LCCTs) that can be successfully implemented in the UK. Using a Commercial Readiness Index for identified LCCTs and the barriers preventing their implementation in the UK, the 'hierarchy' of barriers is identified along with means to overcome them. In this way, recommendations are made for unlocking the emissions reductions required for the cement industry in the UK to achieve net-zero in line with the UK's climate commitments.

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2 A review of previous studies

The current data availability on the UK cement and concrete industry is aggregated to a high level and further detail is fragmented, due to competition controls put in place by the Competition and Markets Authority (Competition and Markets Authority, 2016). As a result, the material flows of the industry are difficult to establish in detail and to date limited analysis has been undertaken. However, some industry patterns have been established.

For example, Hills et al. (Hills, Florin and Fennell, 2016) used data from the Getting the Numbers Right (GNR) initiative, which previously was run by the Concrete Sustainability Initiative, to show that in the UK large concrete producers tend to purchase high-clinker cement, typically CEM I, and then combine it with Supplementary Cementitious Materials (SCMs) at the concrete plant. Shanks et al. (Shanks *et al.*, 2019) have created a material flow for the industry, based on several key assumptions where data was not available. While this provides an understanding at a high-level of the proportion of cement used in different applications, it does not break the material flows down into such detail that can be used to reasonably establish the emissions-intensity of different groups and establish which LCCTs can be applied other than material efficiency.

With the understanding of sector emissions limited to a high-level, analysis to date on decarbonisation pathways has been similarly high-level, looking at groups of potential technologies and typically focussing on decarbonising existing manufacturing practices of OPC rather than at the whole lifecycle of cementitious products (Hills, Florin and Fennell, 2016; Mineral Products Association, 2019c).

Work completed by Pamentier et al. (Pamentier and Myers, 2021) is the most comprehensive lifecycle decarbonisation analysis for the UK cement sector, however, no formal assessment of the development stage and barriers to all of the technologies has been used, resulting again in high-level recommendations around groups of technologies.

From a bottom-up approach, there are a few analyses for the application of specific emissions reduction technologies to the UK cement sector. Hills et al. (Hills *et al.*, 2016) used a bottom-up approach to establish how Carbon Capture and Storage (CCS) could be used across UK cement plants, providing an understanding of the age and type of assets existing in the market today. This tests several industry assumptions, including those set out in the Mineral Products Association's (MPA) roadmap to Beyond Net Zero (Mineral Products Association, 2020b), that CCS can be applied to offset a large proportion of the industry's emissions. The MPA additionally looks at the application of alternative fuels to UK cement plants (Mineral Products Association, 2019c).

Beyond the UK, there is a significant body of research on the emissions reduction potential of numerous LCCTs. Many of these are well summarised by Scrivener et al. (Scrivener, John and Gartner, 2018), although this is not necessarily a complete list.

In addition to research and literature, there are several LCCT demonstration projects underway in the UK. This includes a trial of a plasma/hydrogen hybrid cement plant (Mineral Products Association, 2020a) and a number of trials of CCUS under development on other industrial plant (BEIS, 2020).

While some LCCTs are being supported by demonstration plants, the Innovation Readiness in UK Foundation Industries report (Enterprise Research Centre, 2021), identified the following key barriers to innovation across the foundation industries, including the cement industry:

- High entry barriers and associated very low levels of churn (the rate of change of industry assets).
- Under-developed management and leadership skills.
- Dispositions and mindsets resistant to innovation.

- Widespread reluctance to collaborate.
- Regulatory and other pressures to achieve profound reductions in carbon emissions.

While these barriers are all applicable to the uptake of LCCTs as a general set of new technologies and practices, they do not identify the readiness of specific LCCTs for application in the UK and the barriers which are holding back each LCCT.

Several other UK-focussed studies, such as (Barrett *et al.*, 2018; Koasidis *et al.*, 2020), also examine the systemic barriers to change that impede the uptake of emissions-reduction measures in the cement sector and wider heavy industry. Other analyses look at the impact that different technology types can have if implemented in the UK, such as the MPA 'Roadmap to Beyond Net Zero' (Mineral Products Association, 2020b).

However, these top-down and bottom-up analyses so far have failed to bridge the gap of where policy and investment effort should be focussed to start delivering the high impact, low barrier technologies through a consistent analysis framework across the lifecycle of cementitious materials in the UK.

To reach its targets, the UK needs to change by either dramatically reducing cement and concrete use or reducing the emissions intensity of these products. To understand how this can be achieved, it is necessary to assess the barriers of individual LCCTs and focus efforts to achieve the greatest impact to emissions reduction.

3 Technologies, emission abatement, and commercial readiness

3.1 Technology mapping

Technology mapping enables all LCCTs to be seen as a comprehensive set and the inter-dependencies of each to be better understood. By understanding where in the cementitious product lifecycle each LCCT sits, it is possible to investigate the stakeholders that can influence their implementation and propose how they can be combined in a holistic emissions reduction package. In response, this study identified 75 different technologies from across all life stages of cement and concrete production, which might be applied in the UK context.

3.1.1 Available technologies

A search of both academic and industry literature using terms ‘cement’ or ‘concrete’ combined with ‘emissions’ or ‘carbon’ or ‘sustainable’, resulted in a long list of technologies and their variants. These were classified in line with existing sectoral terminology where possible. The full list of technologies considered in this analysis is included in Appendix C.

While literature on specific technologies in some cases was detailed down to the chemical composition of a material, the technologies have been grouped to a level that indicates similar properties and material sources in order to produce a manageable list of technologies that is representative of those prominent in literature.

Where global resource limitations were highlighted in the literature, the technologies are included in the mapping exercise but not taken further in the analysis as their potential additional savings are considered to be negligible as the resource is practically fully utilised (Miller *et al.*, 2018). Details of these technologies and their limitations are listed in Table 1.

These technologies are not considered further for potential application in the UK construction industry as use of these in the UK would necessarily reduce their usage in other geographies. As such, developing their use in the UK would not reduce global emissions but rather shift high-carbon cement and concrete technologies to other regions, resulting in carbon leakage.

Table 1: LCCTs with global imitations identified in the literature

Technology	Limitation
Ground Granulated Blast-furnace Slag (GGBS)	Global suitable supply practically fully utilised (Scrivener, John and Gartner, 2018)
Coal Fly Ash	Dwindling supply due to energy decarbonisation (Scrivener, John and Gartner, 2018)
Silica Fume	Low global supply limits availability (Scrivener, John and Gartner, 2018)
Waste Glass	Competing uses limits global availability (Scrivener, John and Gartner, 2018)
Oil Shale Ash	Dwindling supply due to energy decarbonisation (Easac, 2007)
Calcium Carbide Residue	Low global supply limits availability (Dulaimi <i>et al.</i> , 2020)
Coal Bottom Ash	Dwindling supply due to energy decarbonisation (Abdullah <i>et al.</i> , 2019)
Rice Husk Ash	Low global supply limits availability (Scrivener, John and Gartner, 2018)
Volcanic Ash	Low global resource limits availability (Kupwade-Patil <i>et al.</i> , 2018)
Belite-Ye'elimite-Ferrite (BYF) Clinkers	Competing uses of bauxite limits global availability (Scrivener, John and Gartner, 2018)

3.1.2 Emissions reduction potential

The emissions reduction potential of each technology can be calculated as

$$P_T = \sum u_i a_i$$

Equation 1

Where P_T is the industry emissions reduction percentage possible through the full deployment of the technology, T . u_i is the percentage unit emissions reduction of the technology for product i and a_i is the percentage of the cement industry baseline emissions that the reduction technology can be applied to for product i .

Values for u_i are taken from literature as percentage savings and are listed in Appendix C. Where a range of values is found for u_i , the upper bound has been applied. This is likely to produce a higher potential saving than is possible as it is expected that literature studies calculate the unit savings of a technology compared to high-carbon materials (such as OPC). However, due to the complexity and number of variables in LCAs the presented percentage savings have been used in this analysis to provide an upper bound on the potential (i.e., potential savings compared to an OPC baseline).

The values for a_i are based on a material flow analysis conducted on data available for the UK cement and concrete industry for the year 2018. The data sources are as shown in Table 2 and the material flow analysis results are shown in Section **Error! Reference source not found.**

Granularity of material flow data for the UK is limited, resulting in a level of aggregation in determining where certain technologies would be applicable. As a result, some technologies are applied to a share of the market that may be larger than real-world outcomes. However, without further data, additional precision in the market share for each technology is not possible. This would be an important area for further study as a basis for any commercial decisions. For example, biocement has been applied to the full quantity of concrete blocks, however all UK concrete blocks may not be suitable for biocement technology, but without further granularity on the types of concrete blocks it is difficult to investigate this.

Table 2: UK Cement Industry Emissions Data Sources

Total Industry Emissions		Emissions Source		Channel of Sale		Product Market Share	
Source	Data type	Source	Data type	Source	Data type	Source	Data type
Environmental Accounts UK: 2020 (Office for National Statistics, 2020)	GHG Emissions (Total GHG) for manufacture of cement, and articles of concrete, cement and plaster in 2018. Residency basis. Absolute emissions values.	UK greenhouse gas emissions by Standard Industrial Classification (SIC) 1990-2018 (<i>Final UK greenhouse gas emissions national statistics - GOV.UK</i> , no date)	Cement industry emissions for 2018 split by Business (including fuel consumption), Industrial processes and Transport. Territorial basis. Absolute emissions values.	UK Cement Channel of Sale (Mineral Products Association, 2019a)	Cement sales for Ready Mix, Merchant, Products and Other. Residency basis. Absolute mass values.	Readymix Concrete Industry Statistics (European Ready Mixed Concrete Organisation, 2019)	UK RMC end-use 2018, split by Buildings, Infrastructure, Pavements, Concrete Roads and Other. Residency basis. Percentage values.
UK cement consumption (European Ready Mixed Concrete Organisation, 2019)	UK consumption, including imports for 2018. Residency basis. Absolute mass values.	UK Concrete and Cement Industry Roadmap (Mineral Products Association, 2020b)	Cement industry emissions for 2018 split by process emissions, fuel combustion and transport & electricity. Territorial			Monthly Statistics of Building Materials and Components - December 2019 (Department for Business Energy &	UK production of building materials, including concrete blocks and tiles. Territorial basis. Absolute volume values.

			basis. Absolute emissions values.			Industrial Strategy, 2019)	
UK cement production (Cembureau, 2019)	UK cement production for 2018. Territorial basis. Absolute mass values.					How much cement can we do without? (Shanks <i>et al.</i> , 2019)	UK estimated consumption of mortar and screed. Residency basis. Absolute mass values.

3.2 Assessment of Barriers

To define the barriers to the uptake of each of these technologies, an adapted Commercial Readiness Index (CRI) from the Australian Renewable Energy Agency (ARENA), is used to assess the LCCTs against 9 indicators which represent the development areas required to achieve mainstream deployment (Technology Readiness Levels).

3.2.1 Technology Readiness Level (TRL)

The Technology Readiness Level (TRL) system was developed for space industry and needs to be considered in terms of the operating environment of the technologies under consideration. Typically, this can be done at an industry level but a TRL for the construction industry has not been developed or adopted into common practice as in other industries such as weapons or energy. This may be due to the relatively low R&D spending in the cement and concrete industry (Lehne and Preston, 2018).

Some attempts at mapping particular construction technologies to TRLs have been developed and are used to inform the definitions for this project (Petrescu, Voordijk and Mihai, 2021). The proposed TRL definitions are based on the Horizon 2020 TRL framework (European Commission, 2014), which is particularly general and applicable in the European innovation context, and the NASA definitions which are more specific to the space industry and more clearly indicate the implications of each level (NASA, 1989).

Table 3: Definitions of Technology Readiness Levels for this project

Horizon 2020 TRL Definitions	Proposed TRL Definition for LCCT
TRL 1 – basic principles observed	TRL 1 – basic principles observed
TRL 2 – technology concept formulated	TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept	TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab	TRL 4 – technology validated in lab, such as through material characteristic testing
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	TRL 5 – technology validated in relevant environment, such as through element performance testing
TRL 6 – technology demonstrated in relevant environment¹ (industrially relevant environment in the case of key enabling technologies)	TRL 6 – system/product prototype demonstrated in relevant environment, such as in a simulated structure

¹ This differs from the NASA and ISO TRL definitions, which refer to system/subsystem demonstration at TRL 6

TRL 7 – system prototype demonstration in operational environment	TRL 7 – system/product prototype demonstration in operational environment, such as on-site test deployment
TRL 8 – system complete and qualified	TRL 8 – system/product complete and qualified, using on-site performance validation
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	TRL 9 – actual system proven in operational environment, such as in a real-world structure

Since the TRL scale is designed for technology deployment within an organisation, rather than commercial applications and open markets, TRL 9 is typically a small-scale commercial implementation and does not address market uptake and commercial scale-up of the technology.

Understanding the TRL of a technology is important in the planning of priorities and route maps. For example, literature shows that the cost of moving from one level to another increases exponentially through the scale, with costs up to TRL 7 representing only around 10% of the costs of getting a technology through to TRL 9 (Héder, 2017). As a result, the work required to get from TRL 8 to TRL 9 is typically more than the step between other levels and so a single TRL difference between technologies has varying implications along the scale.

The more physical a discipline, for example, those for which the operational environment is the physical world, the better suited it is to the application of TRLs (Héder, 2017). What the TRL scale does not address is what happens to a technology between being proven in the operational environment and mainstream market deployment. As discussed by Héder, this phase of development is captured in the Commercial Readiness Index, conceived and utilised by the Australian Renewable Energy Agency (ARENA) in 2015.

In this project, where TRL is expressed for one of the mapped technologies or processes, the maximum TRL level achieved to date is given. For example, where bioconcrete is addressed, the TRL is “Up to TRL 9” as some bioconcrete technologies have been proven in an operational environment. There are, no doubt, other bioconcrete technologies that have not reached such a level of development yet but since this would likely apply to all technologies, it is not deemed to be useful in the understanding of how to bring these technologies into mainstream deployment.

3.2.2 Commercial Readiness Index (CRI)

Investigation by Chatham House, (Lehne and Preston, 2018), has shown that cement and concrete innovations at high TRLs commonly fail to reach commercialisation. This clearly indicates that TRL9 is not the end goal for market penetration in the concrete and cement industry, as ARENA discovered in the renewable energy sector.

ARENA developed the CRI to address the pathway from TRL9 to bankability for renewable energy technologies. ARENA’s mandate to assist renewable energy technologies is intentionally broad and as such they have developed this framework to assist in their decision making to help understand and minimise the risks and barriers for technologies at each stage of development.

The CRI framework is designed to work in conjunction with the TRL framework, as illustrated in Figure 1.

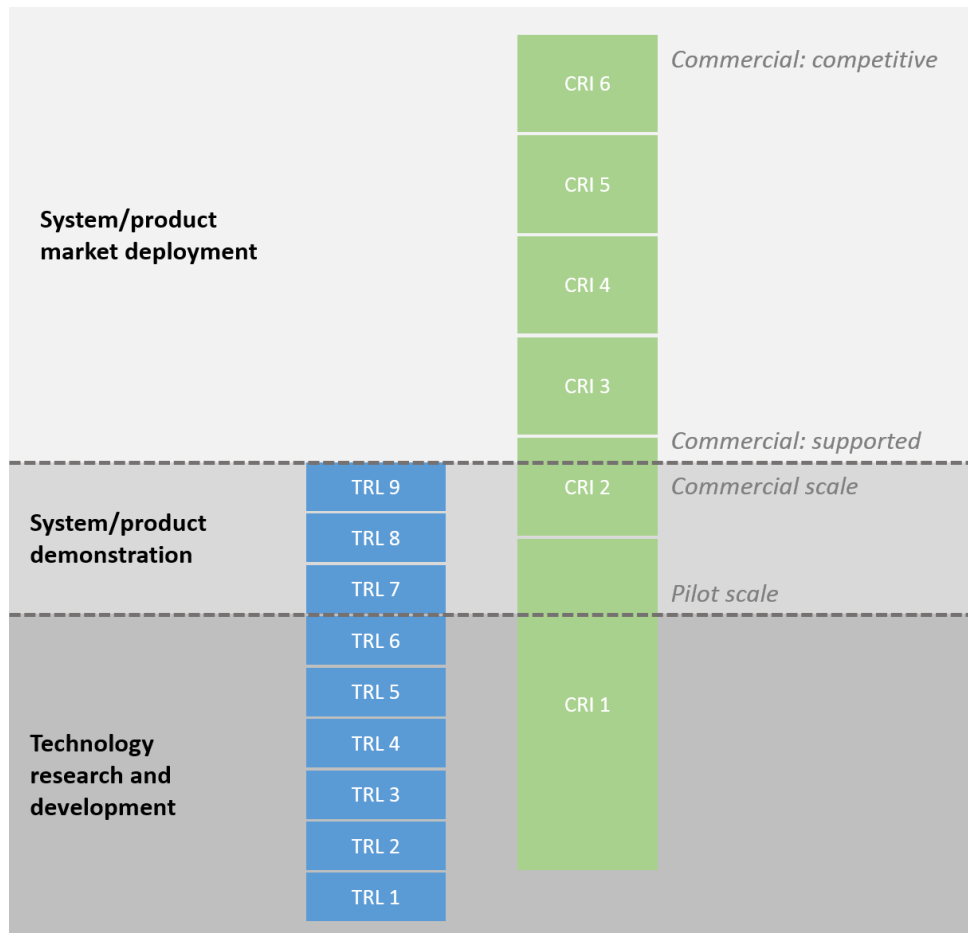


Figure 1: Assessment Framework for LCCT, reproduced from (Héder, 2017)

The ARENA index looks at the commercial performance of a system or product through eight different indicators, resulting in an overall 'score'. This system has been modified for use in other industries, but it has not been applied yet to construction technologies or to LCCT specifically.

Table 4 sets out the proposed use of the CRI for this project, using the same summary index tags as the ARENA framework but modifying the descriptions where necessary to address the differing commercial settings of the sectors. The CRI summary score is calculated as the modal value of the indicators.

Table 4: Proposed Commercial Readiness Index definitions

Commercial Readiness Index	Index Tag	Index Description
6	Mainstream Deployment	"Bankable" grade asset class driven by same criteria as other mature construction technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving decisions. Supplier capability, pricing and other typical market forces driving uptake.
5	Market Competition	Market competition driving widespread deployment in context of long-term regulatory settings. Competition emerging across all areas of supply chain.
4	Multiple Commercial Applications	Multiple commercial applications becoming evident locally although some still subsidised. Verifiable data on technical and cost performance in the public domain driving interest. Regulatory challenges being addressed in multiple jurisdictions.
3	Commercial Scale Up	Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publicly discoverable data driving emerging interest from end-user and regulatory sectors.
2	Commercial Trial (small scale)	Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	Hypothetical Commercial Proposition	Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

Giesekam et al. (Giesekam, Barrett and Taylor, 2016) show a summary of common barriers to innovation and uptake of sustainable materials in construction, which is used to ascertain indicators of success for the technologies considered in this analysis. This clearly highlights that while the technical performance of a technology is necessary, it is not sufficient to drive adoption of the technology itself. Their survey of UK construction professionals' views on several different low-embodied-carbon materials highlighted the following as important enablers for a technology's adoption; knowledge and skills, perceptions, proven technical performance, established standards and availability of materials. This is broadly supported by previous work on the mechanisms for diffusion of innovation more generally (Mahapatra and Gustavsson, 2009).

The indicators used to determine the CRI in this project are listed below. These have been adapted from the ARENA definitions to account for the complexity of the Architecture, Engineering and Construction (AEC) industry and the financial context of the development of new technologies in the industry. The definitions of the six levels for each of these indicators are set out in Appendix A.

- Regulation through Policy** – in the UK, construction regulations, such as Building Regulations and The Highways Act, determine what is and is not allowed in terms of building work for new and altered buildings. The aim of the regulation is to make buildings safe and accessible while limiting their environmental impact. Such legislation can make existing codes of practice mandatory in certain applications. At the very start of a technology's development, it is possible that it is not able to be used under existing UK regulations, particularly where the technology is entirely novel. The

other end of the scale is where technologies are actively encouraged or even required by regulations as part of a performance standard.

- **Regulation through Technical Standards** – alongside policies, technical standards are widely used in the UK as a compliance requirement for the construction regulations and to ensure performance of materials, elements and structures. Technical standards have a range of levels and governing bodies, with the highest level of standard for construction in the UK being harmonised technical rules, the ‘Eurocodes’, e.g., BS EN 1990 Eurocode 0 – Basis of structural design. When a technology is in its infancy, it is unlikely to have any standards associated with it, particularly if it is entirely novel. As a product develops and the body of evidence for it grows, it can aim to achieve different levels of inclusion in standards. The most widely accepted technologies in the UK are typically included in BS EN and BS standards.
- **Stakeholder Acceptance** – the AEC industry in the UK has a complex and fragmented structure, with many different stakeholders involved in each project. As a result, a single stakeholder can often struggle to take up a technology without the acceptance of other stakeholders. At early stages, a technology will not have achieved stakeholder acceptance with any parties. Through its development, a technology may target acceptance in certain stakeholder groups initially before being accepted by all stakeholders in general industry consensus.
- **Technical Performance** – in industry technical performance does not just relate to the analysis and testing required to achieve TRL9 (actual system proven in operational environment) but looks more broadly at the reliability of technology outcomes and the risks associated with implementation. At early stages, the technical performance has not been proven but as technologies reach TRL9, increasing bodies of technical performance data and industry use cases will provide certainty around the ability of the technology to meet performance requirements in a range of applications and environments.
- **Financial Proposition** – initially the financial proposition of a technology is unknown as production costs and market value are not yet available. Through development of the technology into products, definitive costs can be established, and scales of economy can be utilised to improve the cost performance. The highest level of financial proposition occurs when a technology has become cost-competitive with existing market alternatives, while offering additional value such as reduced carbon emissions.
- **Industry Supply Chain** – since the AEC industry is fragmented and has many supply chain participants, being able to get a technology from the raw materials provider through to the end client involves the integration of many parts. Initially, the technology will not have a supply chain and will be being created on a lab scale. By initiating small scale production, through to full commercialisation, all parts of the supply chain must be engaged to achieve a route to market. The highest level of supply chain development occurs when there are several competitive suppliers at each stage of the supply chain, creating a robust system.
- **Industry Skills** – with many stakeholders involved in AEC projects, it is important that the skills needed in each group to correctly implement a technology are available. This relies on the development of knowledge and experience using a new technology. At an early stage, only the technology producer will have any knowledge or skills regarding the technology. As development progresses, skills will be disseminated through early adopters of the technology before becoming common industry knowledge. Due to the complexity of the AEC sector, having one highly skilled stakeholder group is typically not sufficient to achieve market penetration.

- **Market Opportunities** – there must be a market opportunity for a technology for it to reach commercialisation. As the technology is being tested, the market opportunity is usually hypothetical, with an understanding of what market the technology may target. As the technology is developed into products, the market need will be scoped out to understand the potential size of the market. The highest level of market opportunity is when the technology can be produced at scale and compete with existing alternatives due to demand-pull, rather than technology-push drivers.
- **Company Maturity** – where a new technology is being developed by a new company, the company maturity is at the lowest level. As the technology is developed, or adopted by larger companies, the company's performance record and market share with the technology grows to the point where the technology is being provided by industry-leading companies with strong track-records.

By determining the level of each indicator relating to the high-potential technologies and processes, it is possible to determine which areas of development are holding a technology back and where effort should be concentrated and progress the commercial readiness of each technology and process.

While the indicators have equal weighting in calculating the CRI summary score, it is worth noting that some indicators may be more important in decision making than others. For example, a study by ARUP in 2012 showed that cost is the key priority when selecting materials with personal knowledge and experience being very influential as well (World Business Council for Sustainable Development and ARUP, 2012). This suggests that some indicators may present stronger barriers than others if lagging behind the modal value.

4 Creating baselines for the UK concrete industry

To calculate the emissions-reduction potential of each technology and process, it is important to first understand the current state of the UK concrete industry. For this project, a breakdown of the industry emissions is required in order to ascertain how much of the industry emissions a technology can be applied to.

Since the data available on the industry is fragmented, a combination of data sources is required to obtain an overall picture. The most recent year of available data is 2018 and so this is used as the baseline year. It is assumed for this mapping exercise that the amount of cement in the final products is proportional to the share of industry emissions they represent as further detail is not publicly available.

Based on industry and governmental data, an understanding of the components and uses of concrete and cement in the UK has been produced. This is based on data from ERMCO, The National Office of Statistics and the MPA (Mineral Products Association, 2018, 2020b; European Ready Mixed Concrete Organisation, 2019; Office for National Statistics, 2020, 2021). The data types and sources are summarised in Table 2.

Where territorial or mass absolute values were required to be used, these were converted into percentages and applied to the residency emissions total. Where volume data was required to be used, these were converted into cement mass values using Environmental Product Declarations (EPDs).

The emissions sources in Table 2 are adapted to be consistently on a residency basis, meaning that they account for all cement consumed in the UK, including imports. This is visualised as a Sankey diagram, shown in Figure 2.

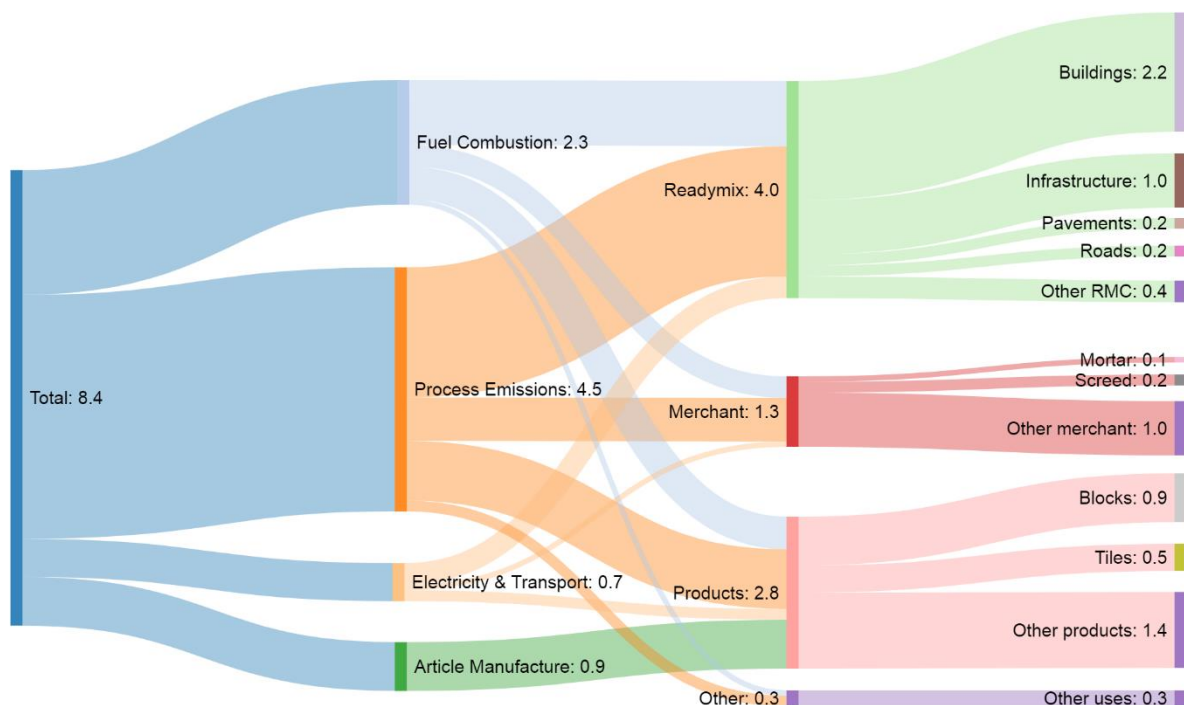


Figure 2: Breakdown of UK cement sector emissions by varying categories. Each column totals 8.4Mt CO₂e, the total industry emissions.

As unit emissions intensities of each product type are not readily available at a UK average level, unit savings for each LCCT are applied as the literature percentage savings possible to the share of UK emissions as set out in Figure 2. While the basis of calculation of these savings is not always consistent, it is assumed that these savings represent the maximum savings possible, such as compared to OPC-based products, and therefore provide an upper bound.

Further work to disaggregate the applicability of LCCTs in the UK industry and determine absolute savings potential against UK product average emissions intensities, would increase the accuracy of the savings potential of the LCCTs.

5 Assessing the mitigation potential of LCCT

5.1 LCCTs through the cementitious lifecycle

There are a plethora of technologies and processes that may be able to reduce the emissions of the concrete industry in the UK. To understand the variety of these potential emissions-reduction options, and their applicability to the UK construction industry, a literature review has been undertaken.

Based on a review of the existing literature around low-carbon cement and concrete technologies, a summary mapping of the existing and emerging technologies has been carried out. The technologies are categorised based on the lifecycle stage at which they are applied. The lifecycle stages used in the mapping exercise are shown in Figure 3.

As highlighted in Habert et al. (Habert *et al.*, 2020), there are different stakeholders responsible for the emissions reduction actions across the lifecycle and, without engagement with all stakeholders, significant emissions reductions will be extremely difficult to achieve. Figure 3 indicates the main stakeholders that can undertake or influence the use of LCCTs at each stage.

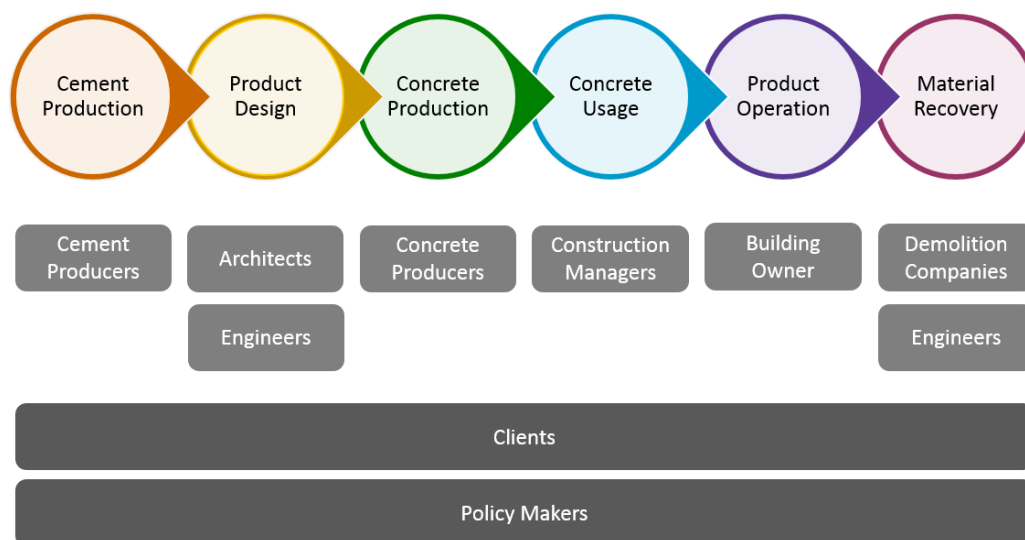


Figure 3: The lifecycle stages of concrete products and key stakeholders with LCCT influence, adapted from (Habert *et al.*, 2020).

The full map of LCCTs that can result in industry emissions reductions is shown in Figure 4. In total, 75 different technologies and processes were identified at the level of detail of this analysis. A number of the technologies have been identified in the literature as having global limitations to their application. These technologies are listed in Table 1 with the relevant limitation.

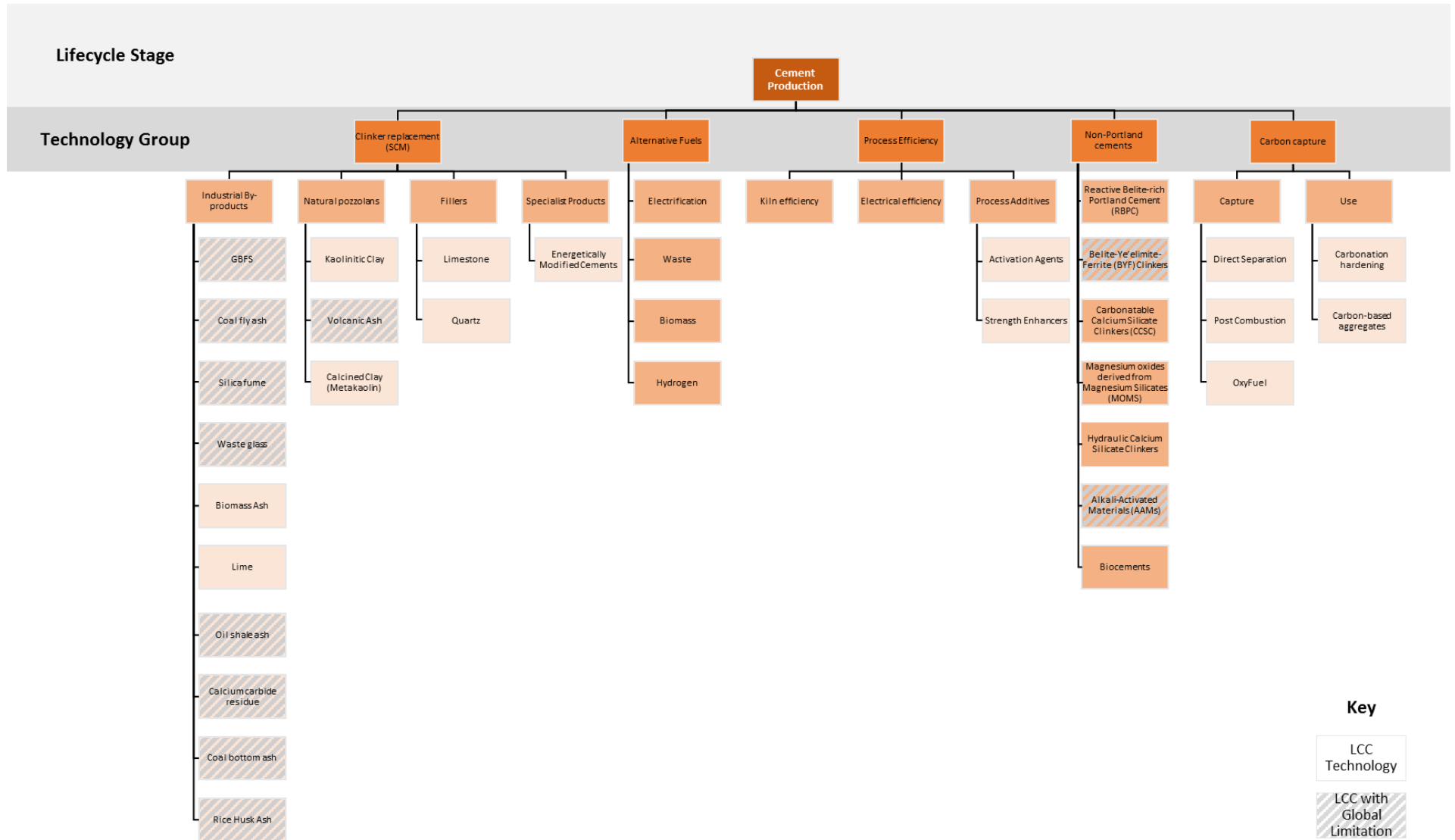


Figure 4: Map of low carbon concrete technologies and processes, arranged by lifecycle stage

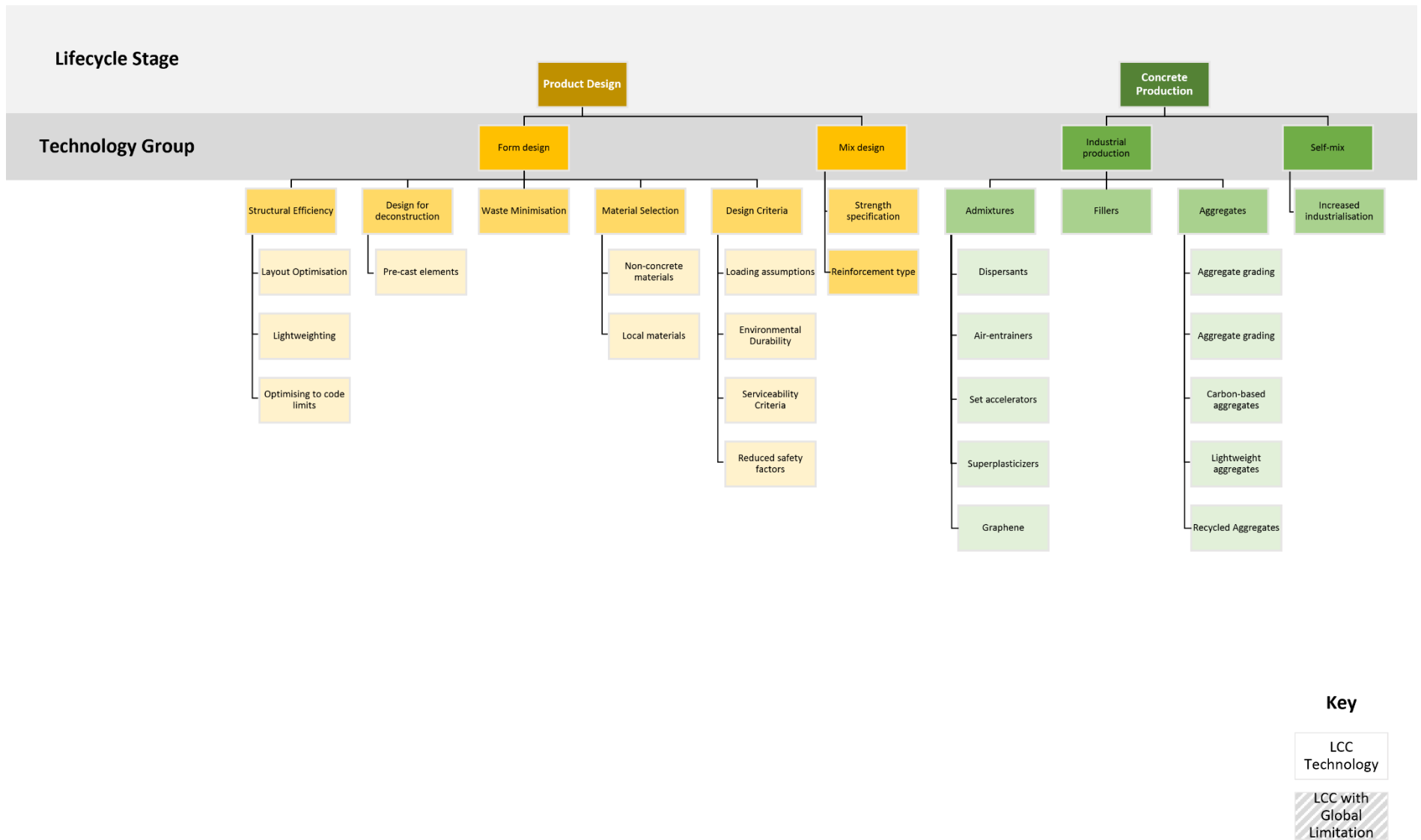


Figure 5: Map of low carbon concrete technologies and processes, arranged by lifecycle stage

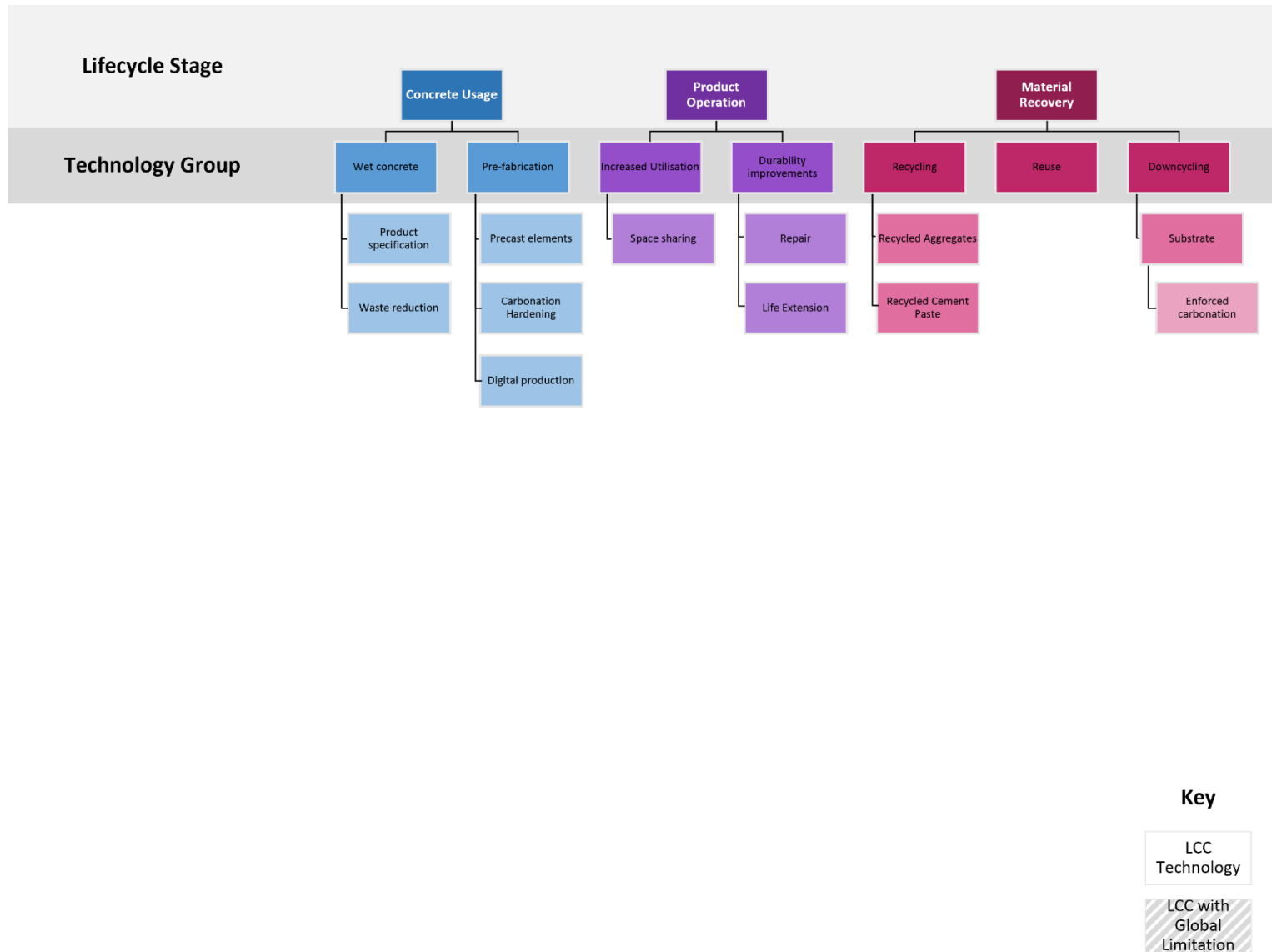


Figure 6: Map of low carbon concrete technologies and processes, arranged by lifecycle stage

5.2 UK Industry Potential

With an understanding of the LCCTs available throughout the lifecycle, it is important to filter the full list of technologies for those that can unlock the most additional carbon savings relative to Business As Usual (BAU).

The technologies are assessed for their potential emissions reductions in the UK cement and concrete sector, using available data from literature and industry. The calculations are intended to provide an upper bound on the potential savings (i.e., compared to an OPC baseline), to enable low-impact technologies to be ruled out from industry priorities. There are several technologies that could not be quantified based on the existing literature. These technologies, Process Additives, Increased Environmental Durability, Serviceability Criteria Assumptions, Safety Factor Assumptions, Smart Concrete Management, Self-mix contents, Increased Structure Utilisation and Life extension, are not included in Figure 7. These all warrant further investigation as to their potential contribution to reducing emissions of the sector.

Technologies which indicate a high potential should be assessed in further detail to ascertain more accurate emissions reductions forecasts as data available on the end uses of concrete and cementitious products in the UK is highly aggregated.

The upper bound potential emissions reductions (i.e., compared to an OPC baseline) for the studied technologies (where data was available), are plotted in Figure 7.

The detailed tables setting out the description, applicable product categories and potential savings of each technology and process, both on a per unit and industry-wide scale, are include in Appendix C.

LCCTs with a potential industry saving greater than 10% of UK cement and concrete related GHG emissions are considered to be high potential as their development and uptake could result in significant savings for the industry. This threshold is used to exclude technologies which are unlikely to result in significant industry emissions reductions. Based on the potential savings identified for each technology and process in this analysis, 18 technologies with a potential industry emissions reduction of 10% or more are taken forward.

It is important to note that the potential savings of all technologies are not additive as several of the technologies could not be fully deployed simultaneously. However, it is possible to ascertain certain combinations of technologies which are additive or complementary and could be pursued to reach deep decarbonisation of the sector. In this way, the emissions reduction potential of technology combinations can be estimated by combining the potential of technologies from different columns as

$$P_C \cong 1 - ((1 - P_{Ti}) \times (1 - P_{Tj}) \times \dots \times (1 - P_{Tn}))$$

Equation 2

Where P_c is the upper bound potential industry emissions reduction of the combination (i.e., compared to an OPC baseline), P_{Ti} is the upper bound potential industry emissions reduction of technology i (i.e., compared to an OPC baseline), and i to n represent the technologies included in the combination. The use of technology combinations is discussed in Section 1.

Potential Savings in UK cement industry CO₂e emissions

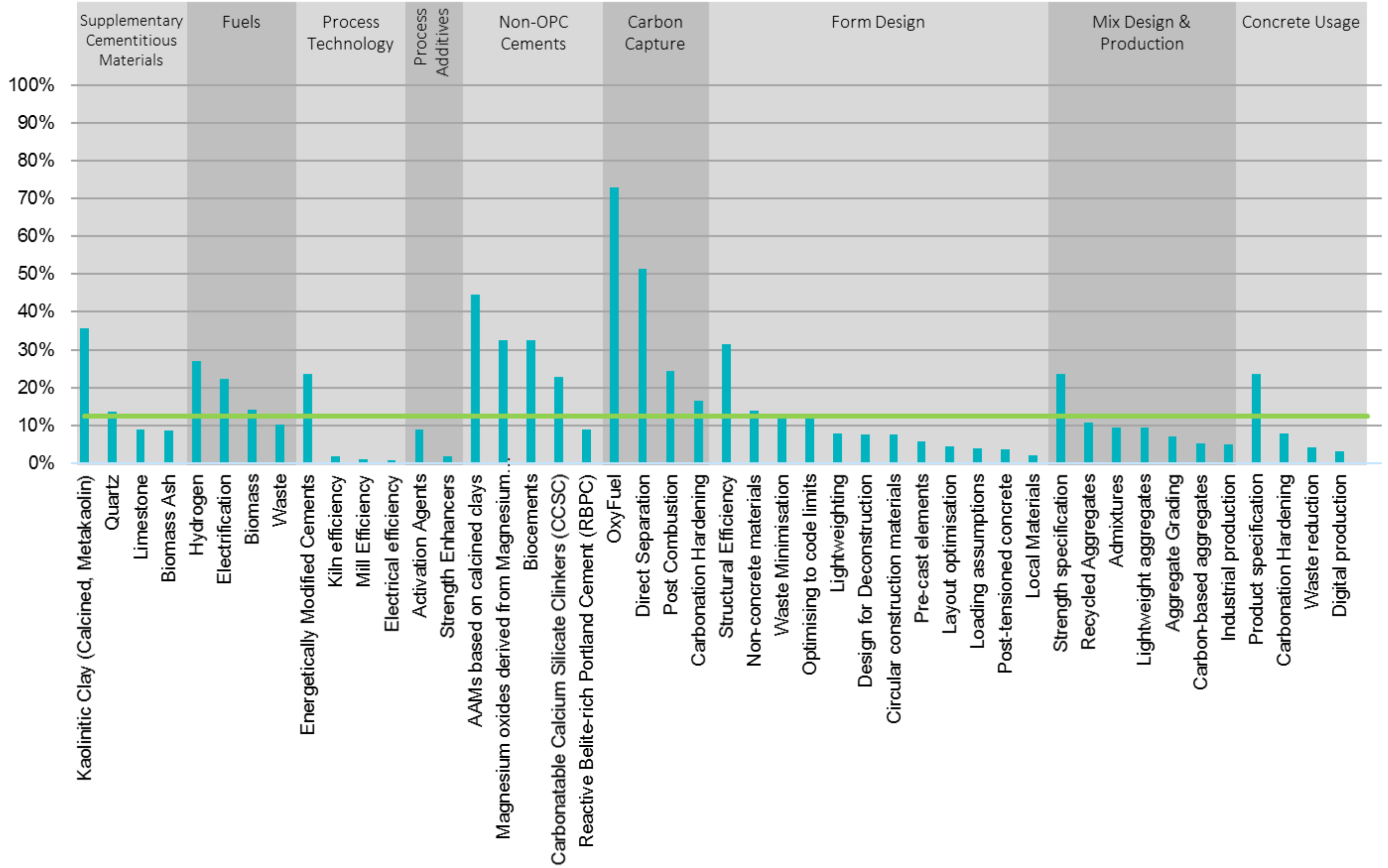


Figure 7: Potential emissions reductions available in the UK through the widespread use of the technologies studied. Technologies are arranged in order of UK potential savings within their mapping category.

6 Barriers to implementation of LCCT in UK industry

To list technologies and processes that could be used to reduce emissions of the cementitious products of the UK does not automatically lead to a clear way forward for the industry. Some high-potential technologies and processes are deployable today, so understanding why they have not achieved widespread adoption is key for defining how the industry can unlock these potential emissions reductions.

A recent report into innovation in the UK's foundation industries (Enterprise Research Centre, 2021) identified the following as structural barriers to innovation:

- *High entry barriers and associated very low levels of churn.*
- *Under-developed management and leadership skills.*
- *Dispositions and mindsets resistant to innovation.*
- *Widespread reluctance to collaborate.*
- *Regulatory and other pressures to achieve profound reductions in carbon emissions.*

However, at an individual technology level, there are other factors at play as explored in this section. To identify the key barriers which restricted implementation of the high-potential technologies and processes, a modified Commercial Readiness Index is adopted. This framework uses nine indicators to categorise the necessary steps for a technology that has reached TRL7, or higher, to achieve market adoption.

The indicators used for this project are shown in Section 3.2.2. The full definitions of the indicator levels are listed in Appendix A.

6.1 High-potential technologies

The technologies identified to have an upper bound for UK cement and concrete industry emissions reduction potential (i.e., compared to an OPC baseline) of 10% or higher are referred to as high-potential technologies. The resulting technology readiness map is shown in Figure 8. Assessments of each technology against the individual indicators are provided in Appendix D.

Figure 8 is set out such that each column is mutually exclusive. That is that any technology on the map can be combined to full deployment with a technology from another column, but not a technology within its own column. In this way, the emissions reduction potential of technology combinations can be estimated by combining the potential of technologies from different columns as

$$P_C \cong 1 - ((1 - P_{Ti}) \times (1 - P_{Tj}) \times \dots \times (1 - P_{Tn}))$$

Equation 2

The use of technology combinations is discussed in Section 1.

Mapping the technologies in this way clearly shows that the majority of high-potential LCCTs are in the cement production life-cycle stage, with form design presenting the next largest group of high-potential LCCTs.

In addition, several technologies are at a CRI level of 6, suggesting they are ready for mainstream implementation. These technologies should be the focus of efforts for immediate emissions reductions in the industry and as such their remaining barriers should be addressed as a matter of urgency.

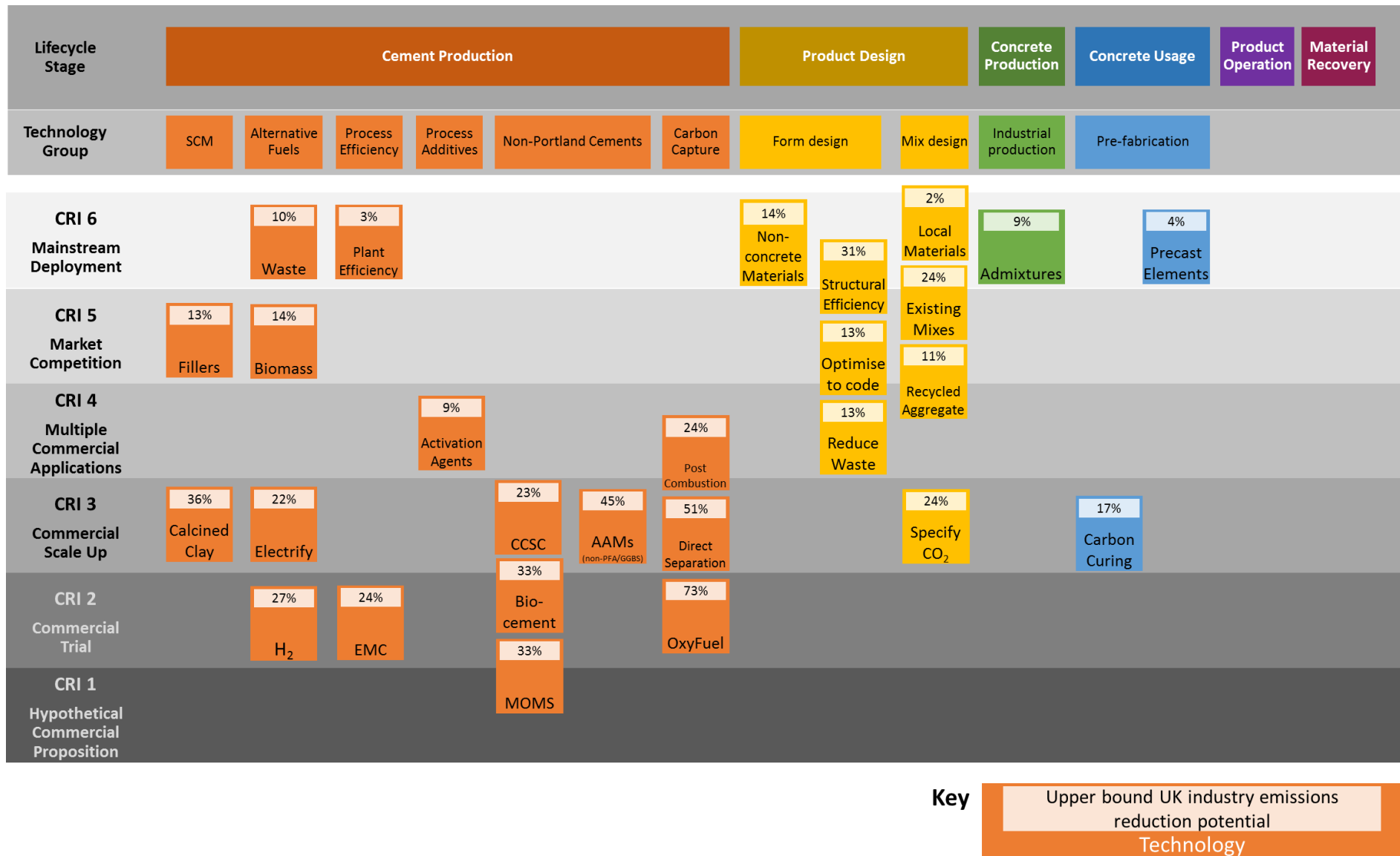


Figure 8: Low Carbon Concrete Technologies mapped by Commercial Readiness Index and upper bound UK industry emissions reduction potential. The technologies included in this map have either an upper bound UK industry potential emissions reduction of over 10% of total UK industry emissions or are assessed as having the highest level of commercial readiness (CRI 6 -Mainstream Deployment). Upper bound potentials have been calculated assuming full deployment of the technology, using the potential saving of the technology compared to an OPC baseline and the upper bound of savings found in literature. Real world applications of these technologies are likely to result in smaller emissions reductions. Given the interplay between different admixtures, all admixtures are considered under one LCCT going forward, as assessed in Cheung et al. (2018).

6.2 Lagging Indicators: All Technologies

All technologies with quantified upper bound emissions potential reduction (from Figure 7), were assessed for their lagging indicators, based on publicly available information, and are included in Appendix D. These indicators are those that have a level lower than the modal value for the technology, as illustrated in Figure 9. The summary of lagging indicators across all assessed technologies are shown in Figure 10.

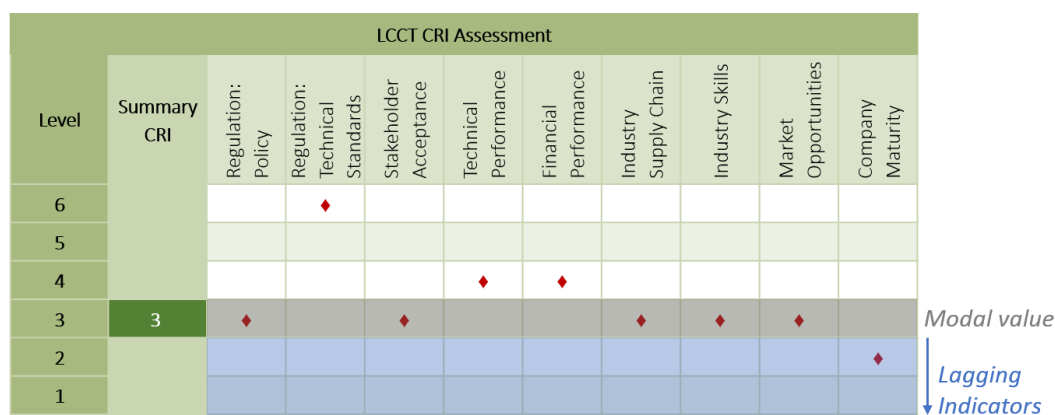


Figure 9: Illustration of lagging indicator definition using example LCCT CRI Assessment

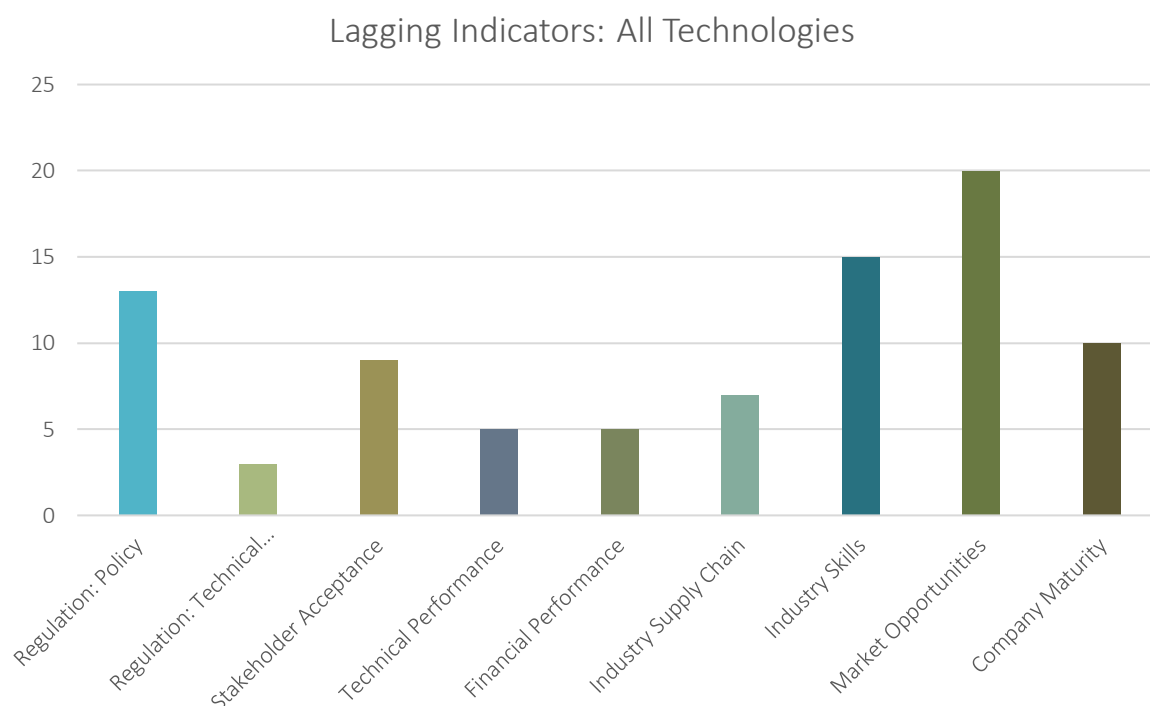


Figure 10: Frequency of lagging indicators for all technologies

When considering all of the assessed LCCTs (from Figure 7), the three lagging indicators that are most common are Regulation through Policy, Industry Skills and Market Opportunities. This implies there are three key areas that can be targeted in order to increase the uptake of LCCTs in the UK:

1. Industry Skills

Require education around LCCTs as part of industry training and certification. As Health and Safety training has been incorporated into industry certifications and internal organisational requirements, similarly education around LCCTs and their application could be incorporated into the formal training of individuals.

2. Regulation: Policy

Develop policy that explicitly encourages or requires the use of LCCTs in relevant applications. A precedent for this type of policy can be seen in the energy performance requirements for new buildings and as quantifying embodied carbon becomes increasingly advanced, similar measures could be implemented for concrete usage.

3. Market Opportunities

Create market-pull conditions for LCCTs to expand opportunities beyond technology-push channels. Market leaders wield significant power in changing industry attitudes and creating large-scale demand for certain technologies and projects. By uniformly adopting LCCTs across all applicable projects, market leaders at all stages of the cementitious lifecycle can develop market opportunities and accelerate penetration of LCCTs.

The mechanisms by which these could be implemented are discussed in Section 1.

6.3 Lagging Indicators: High-readiness technologies

Looking more specifically at the technologies with a CRI of 6, the distribution of lagging indicators is different, as shown in Figure 11.

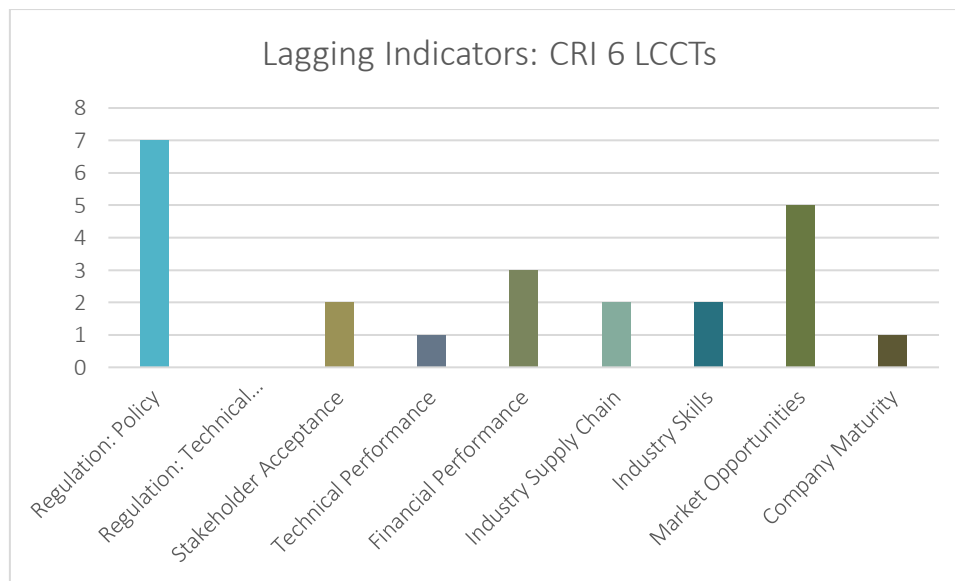


Figure 11: Lagging CRI indicators for LCCTs with a summery score of 6

These technologies, with the highest level of commercial readiness, have clear alignment that Regulation through Policy is a barrier. This is primarily showing that policy is not explicitly encouraging or requiring LCCTs to be used in relevant applications. This can be evidenced by the lack of embodied carbon considerations and requirements in existing AEC industry policy in the UK.

Other than policy, financial performance (both reliability and level of cost), industry skills and market opportunities are common lagging indicators for the high-readiness technologies. Here financial performance is different to the overall picture of lagging indicators, suggesting that the availability of cost data and multiple products using these high-readiness technologies are limiting their uptake to some extent.

However, as cost reductions and reliability can typically be achieved through scale of production and market competition, it is not surprising that financial performance can be a follower of mainstream implementation in some cases.

7 Priorities and Opportunities for deploying LCCT in the UK

7.1 Top LCCTs

The analysis of LCCTs' potential emissions savings across the lifecycle of cementitious products has shown the following to be the top 10 LCCTs, based on their potential industry savings being over 25%. Each technology's upper bound individual potential savings (i.e., compared to an OPC baseline), P_T , and the CRI summary level, CRI, is also indicated.

1. **OxyFuel Carbon Capture** (P_T 73%, CRI 2)
2. **Direct Separation Carbon Capture** (P_T 51%, CRI 3)
3. **AAMs (non-PFA/GGBS)** (P_T 45%, CRI 3)
4. **Calcined Clay SCM** (P_T 36%, CRI 3)
5. **MOMS** (P_T 33%, CRI 2)
6. **Biocements** (P_T 33%, CRI 2)
7. **Structural Efficiency** (P_T 31%, CRI 5)
8. **Hydrogen as Fuel** (P_T 27%, CRI 2)
9. **Post Combustion Carbon Capture** (P_T 24%, CRI 3)
10. **Existing Mixes** - (P_T 24%, CRI 5)

While this illustrates which technologies individual organisations may wish to pursue, these cannot all be deployed to their full potential simultaneously. For example, the industry cannot fully deploy both OxyFuel and Direct Separation carbon capture. Therefore, this list of potential savings is not additive.

7.2 Technology Combinations

To understand the industry-wide approach to implementation of LCCTs, the technologies must be considered in combinations. The method for calculating the combination potentials is according to Equation 2.

Providing a lower bound for the potential savings at maximum deployment of a technology, and thus a technology combination, involves applying an average UK cement replacement factor of 20% compared to the upper bound baseline of OPC. In this way, where material replacement is being considered, the lower bound for unit emissions reduction is given as $(1.25u_i - 0.25)$. Note this does not apply for technologies that work on material efficiency, carbon capture or fuel combustion.

7.2.1 Market-ready combination

An obvious starting point for short-term emissions reduction in the AEC industry is to combine the CRI 6 technologies into a 'market-ready' package. This combination would include:

- | | |
|-----------------------------------------------------------------|--------------------------------------------------|
| 1. Waste as Fuel - (P_T 10%, CRI 6) | 4. Local Materials - (P_T 2%, CRI 6) |
| 2. Kiln & Electrical Efficiency - (P_T 3%, CRI 6) | 5. Admixtures - (P_T 19%, CRI 6) |
| 3. Non-concrete Materials - (P_T 15%, CRI 6) | 6. Pre-cast elements - (P_T 6%, CRI 6) |

Using Equation 2, we can estimate that the upper bound combined UK industry emissions reduction potential (i.e., compared to an OPC baseline) of these technologies is 37%. The lower bound (i.e., compared to an average UK mix baseline) is 21%. The difference is because the admixtures technology impacts the material constituents of the concrete, whereas the other technologies impact the amount of concrete or the production emissions of OPC. This clearly shows that significant emissions reductions in the AEC sector can be implemented almost immediately. The primary barrier to the mainstream implementation of these

technologies is shown to be regulation through policy, suggesting that LCCT-forward policy could unlock these emissions. Of course, market leaders are capable of catalysing such uptake without the ‘stick’ of policy, but typically this is viewed as a risky large-scale change to make for an organisation in a low-margin industry, as illustrated in the ERC Foundation Industries report (Enterprise Research Centre, 2021).

7.2.2 Maximum potential combination

An alternative approach would be to create a combination of the highest-potential mutually exclusive technologies, regardless of their CRI. Applying a filter of technologies with a minimum potential of 20% and selecting the highest-potential technology to each of the mutually exclusive groups, the following technologies are included:

- | | |
|------------------------------------------------------------------------|----------------------------------------------------------------|
| 1. Calcined Clay SCM - (P _T 36%, CRI 3) | 5. Non-PFA/GGBS AAMs - (P _T 45%, CRI 3) |
| 2. Hydrogen as Fuel - (P _T 27%, CRI 2) | 6. OxyFuel Carbon Capture - (P _T 73%, CRI 2) |
| 3. Energetically Modified Cements - (P _T 24%, CRI 2) | 7. Structural Efficiency - (P _T 31%, CRI 5) |
| 4. Biocement - (P _T 33%, CRI 2) | 8. Existing Mixes - (P _T 24%, CRI 5) |

This high-potential combination has an approximate upper bound UK industry emissions reduction potential of 98% compared to an OPC baseline. The lower bound (compared to a UK average mix baseline) for this combination, at maximum deployment, is 93%, due to the large number of high potential technologies selected here.

However, it must be noted that several of these technologies have low levels of commercial readiness and it is not known when, or even if, they will be viable at scale. For example, biocement is currently produced commercially only by a single company at a small scale. As a result, while the total upper bound emissions reduction potential is 99%, the work and expenditure required to unlock these potential savings will be significantly higher than the market-ready combination as more development is required to test whether these technologies can be brought to mainstream deployment. Therefore, there is a low likelihood of this level of reduction being possible in the real-world using this mix of technologies, and we consider this to be an upper theoretical bound only.

7.2.3 Optimised combination

Pragmatically, the preferable path to decarbonisation of the cement and concrete sector will be to use the most commercially ready technologies that result in an almost complete decarbonisation of the sector. If we take the most commercially ready technology from each mutually exclusive group, the resulting combination includes:

- | | |
|-------------------------------------------------------------------------|----------------------------------------------------------------|
| 1. Fillers - (P _T 13%, CRI 5) | 8. Non-concrete materials - (P _T 14%, CRI 6) |
| 2. Waste as Fuel - (P _T 10%, CRI 6) | 9. Structural Efficiency - (P _T 31%, CRI 5) |
| 3. Kiln & Electrical Efficiency - (P _T 3%, CRI 6) | 10. Existing Mixes - (P _T 24%, CRI 5) |
| 4. Activation Agents - (P _T 9%, CRI 4) | 11. Aggregate Grading - (P _T 7%, CRI 5) |
| 5. CCSC - (P _T 23%, CRI 3) | 12. Admixtures - (P _T 19%, CRI 6) |
| 6. AAMs (non-PFA/GGBS) (P _T 45%, CRI 3) | 13. Carbon Curing - (P _T 17%, CRI 3) |
| 7. Post Combustion Carbon Capture - (P _T 24%, CRI 3) | 14. Pre-cast elements - (P _T 4%, CRI 6) |

This combination has an approximate combined upper bound UK industry emissions reduction potential of 93% (i.e., compared to an OPC baseline). The lower bound emissions savings for full deployment of this combination is 68% (i.e., compared to a UK average mix baseline). This presents a wide range of LCCTs that can be implemented by a wide range of stakeholders in the AEC industry, resulting in significant savings at

full deployment. This opens several avenues to achieve emissions reductions, rather than relying on a singular technology to do most of the work.

Of course, assuming full deployment of any technology is optimistic and further granularity on the uses of cement and concrete in the UK industry would allow a more detailed analysis of where each technology is applicable. This is likely to reduce the real-world potential of the technologies and so further work into the recommended technologies should be undertaken to support any commercial decisions.

Since this high-readiness combination includes all the CRI 6 technologies, it is recommended that this combination of 14 technologies drives the planning of further work to increase the implementation of LCCTs.

7.3 Identified Key Barriers to LCCTs

Based on the Commercial Readiness Index framework of indicators, several barriers were found to be common to a significant proportion of technologies, as presented in Section 6.2. In response to these common barriers, this section sets out recommendations for unlocking commercial readiness improvements in a wide spread of technologies by tackling the common barriers.

Further work that could inform refinement of these recommendations would be a review of international barriers to LCCTs and measures undertaken to date to overcome these. Evidence of successful measures that have led to increased use of LCCTs abroad could help to shape or prioritise the implementation of these recommendations in the UK.

7.3.1 Policy that explicitly encourages or requires the use of LCCTs

If we consider the recommended combination of LCCTs against the lifecycle stages of cementitious products, we can see where policy interventions may be most useful. This staging of the combination is illustrated in Figure 12.

Giesekam et al. (Giesekam, Barrett and Taylor, 2016) concluded that regulation is a powerful way to get the industry to act on environmental concerns as being prepared for regulatory change is a valuable differentiator in the market. This is likely to be necessary where additional cost will be required to implement LCCTs as it brings a value to the technology that is not related to the cost.

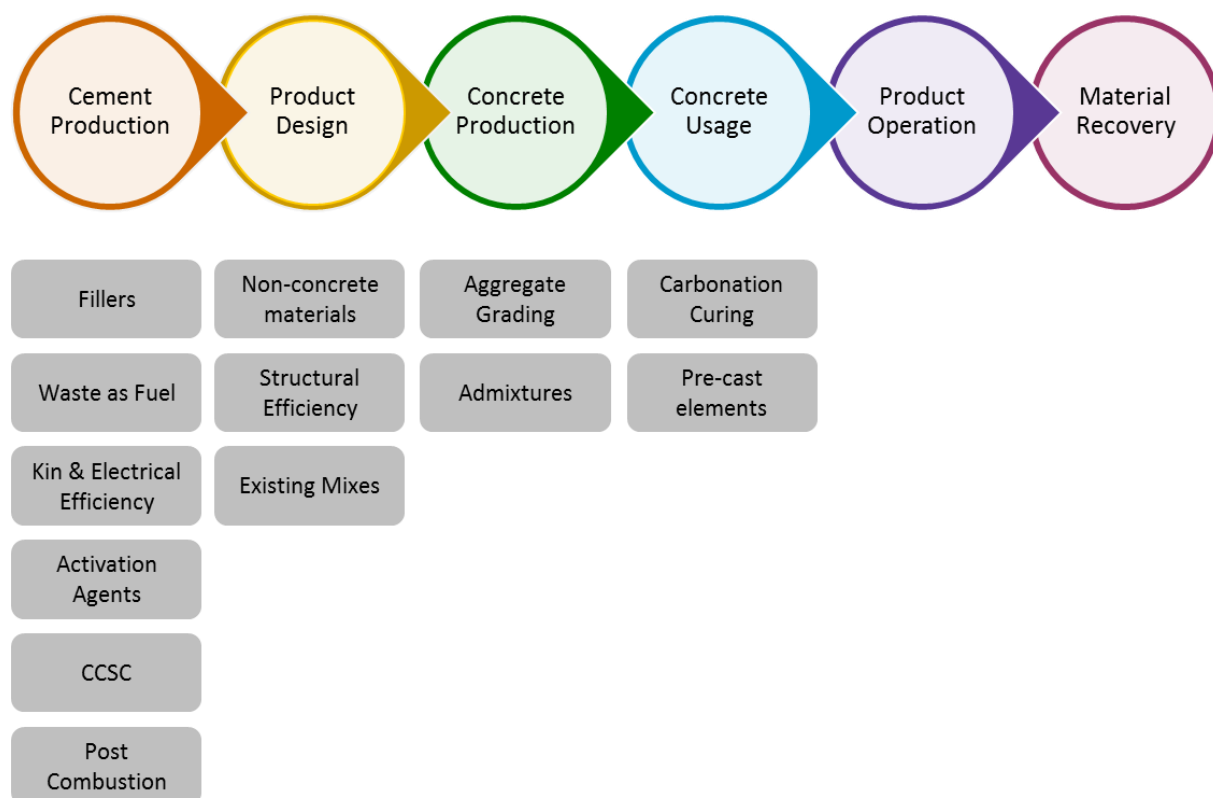


Figure 12: Life-cycle spread of the optimised LCCT Combination

As Figure 12 clearly indicates, the largest number of recommended LCCTs fall under the cement production stage. This can be helpful in terms of implementing policy as cement production as an industry in the UK has a relatively small number of producers, with 13 existing cement plants in the UK. Possible policy interventions at this stage are addressed below.

7.3.1.1 Maximum carbon emissions from combustion per unit of cement output

This would enable either energy efficiency or fuel replacement to be used to achieve required levels of emissions reduction. It would also incentivise the use of fillers with lower process emissions than OPC clinker at the cement production stage as this would reduce the energy required per tonne of cement.

Encouraging the use of fillers and other SCMs at the cement production stage is important as it shifts the industry norm away from making concrete with OPC, focussing the emissions reductions of concrete on the 13 cement plants, rather than the numerous concrete producers and cement users.

7.3.1.2 Funding of non-Portland cement production

As per the recommended combination, funding of new cement production should focus on CCSC for pre-cast products and elements, and calcinated clays for all cement uses. One issue that the cement industry faces is around competition and recent proceedings have found some concrete industry companies to be in breach of competition standards (Competition and Markets Authority, 2020; Competition and Markets Authority and Enser, 2021). By enabling new entrants to the market that bring new low-carbon cement and cementitious products, policy can support the implementation of non-Portland cements in the relevant market sectors while addressing competition issues through reducing the market share of existing large organisations and increasing the diversity of product offerings.

This additional injection of competition could also draw existing cement producers into developing their own low carbon products based around these technologies.

7.3.1.3 Demonstration of Post-combustion CCUS

There is significant existing policy support for the development of CCUS across the UK heavy industries. However, with cement plants being largely dispersed in remote locations, the coordination of cost-effective infrastructure for transportation of captured carbon places cement plants further down the list of priority implementations. This suggests that the cement sector will not be the basis for early CCUS trials.

However, CCUS is not required in the immediate short-term to meet the UK's targets as there are other commercially ready technologies that can be disseminated in less time while CCUS implementation is developed in a coordinated manner across UK industry.

7.3.1.4 Inclusion of embodied carbon in building and infrastructure regulation

Later lifecycle stages are not so easily targeted through policy intervention due to the dispersed and multi-stakeholder nature of the industry. However, overarching policy such as including embodied carbon requirements in building and infrastructure regulation could be used to encourage LCCTs as a whole. Such umbrella policies would increase demand for LCCTs, enabling greater scales of production and unlock cost reductions.

Much as buildings now have energy performance requirements and ratings, a similar system could be used for embodied carbon, or indeed whole-life carbon, in order to holistically address the environmental impact of new buildings. For this to be effective, a standardised approach to calculating whole-life carbon of buildings and other structures would need to be devised by the regulating body. This could be adapted from several existing industry tools.

Such policies can be developed from existing voluntary industry schemes. For example, the Institute of Structural Engineers has produced a guide titled 'How to Calculate Embodied Carbon' (GIBBONS and ORR, 2020), which could be adopted as an industry standard for mandatory embodied carbon calculations. This could be supported in implementation by the Institute of Structural Engineers' guide 'Design for Zero' (Orr *et al.*, 2021).

In addition, the inclusion of embodied carbon data in standards, such as the National Structural Concrete Specification, would help to bring embodied carbon into common usage, build understanding and make its inclusion in decision making easy through accessibility of data.

7.3.2 LCCTs education as part of industry training and certification

Industrial skills is a common barrier to LCCT market deployment, so it is important that this is addressed in a rigorous manner. It has been shown by other research into construction innovation that the perceived risk of new technologies plays an important role in decision making. However, these technologies are often new to the individual or organisation, rather than new to the industry. For example, there are many blended cements specified in the harmonised standards (BS EN 197) and BS 8500 for use in structures, however, many practitioners are not familiar with their use, as few are produced in the UK. Therefore, there is a perceived additional risk around using them over ‘common’ cements.

If industry can be educated around the correct techniques for implementing LCCTs in their profession, particularly focussed on those in the recommended combination, the perceived risk around using the LCCTs can be reduced to known risks and suitable mitigations, as with ‘common’ technologies.

7.3.2.1 Messaging around LCCTs

Understanding the requirement, intention and potential of LCCTs is inconsistent in the AEC industry. While many individuals and organisations acknowledge the need to reduce emissions globally, what constitutes ‘low-carbon’ is not widely agreed. As low-carbon or similar labels are often used as a point of value in a transaction, such as offering a developer a ‘low-carbon’ structural system, it seems appropriate that such labels should have some sort of formal definition or certification.

“Our aim is to ensure concrete is recognised as the sustainable building material of choice for today’s needs” - (GCCA)

“Concrete is a low carbon, local and responsibly sourced material and is widely used throughout the construction industry” - (The Concrete Centre)

“Concrete is a low carbon material.” - (MPA)

This is clearly evidenced in the mixed messaging of a number of major cement and concrete industry bodies that label concrete as a low-carbon or sustainable material, due to it having lower carbon emission per kg than other materials, while also setting out pathways to reduce the carbon intensity of the product (Global Cement and Concrete Association, no date; The Concrete Centre, no date; Mineral Products Association, 2019b). This is a flawed message as it does not include the functional unit and, where it does, weight is not an appropriate functional unit for comparing cement and concrete are used to other materials.

For example, a functional unit such as m² of created floorspace for buildings would be more appropriate as the same weight of material is not used in each type of structural system. An analysis of 219 different structural frames has shown that the distributions of whole-life embodied carbon per unit floor area for timber, reinforced concrete and steel overlap (Pomponi, 2021).

In addition, referring to concrete in general as ‘low-carbon’ suggests that all existing concrete is low-carbon and therefore reduces the sense of urgency around reducing the associated emissions.

A definition for ‘low-carbon’ that is dynamic to market uptake of LCCTs has been proposed by the Green Construction Board and this could be used as a basis for advertising standards of products.

7.3.2.2 Chartership Requirements

Many roles in the AEC industry have a professional body through which an individual can achieve professional chartership such as RIBA, ICE, IStructE and RICS. These qualifications require the individual to prove competency in several areas of expertise relevant to their role. It could be pioneered by these professional bodies that knowledge of, or experience with, LCCTs relevant to their profession are required for chartership. This would increase the level of knowledge in the existing professional population.

In addition to those gaining chartership in their early career, chartership often requires Continued Professional Development (CPD) to be undertaken by the individual. Professional bodies could require topics concerning LCCTs as requisite to a wider fraction of the professional population.

7.3.2.3 Apprenticeships and higher-education in LCCT usage

In addition to the existing professional population, those entering the sector should be equipped with the skills and knowledge to implement LCCTs where relevant. Requiring such topics to be included for course accreditation would quickly increase the industry skills as all generations of professionals would have basic knowledge of the key LCCTs relevant to their profession.

Initiating knowledge and understanding of LCCTs during formal education reduces the burden of training on industry and establishes new norms in the upcoming workforce. This provides a foundation for long-term LCCT penetration and will complement in-work educational initiatives.

As LCCTs are developing quickly, there can also be a benefit to 'first-principles' education, which addresses how to implement 'new' technologies through risk management, rather than addressing the characteristics of specific technologies. This can also be used to educate individuals about how 'alternative' methods to meeting regulation can be used, such as design by testing, which opens up the possibility of using LCCTs before they have been through the lengthy process of being included in international standards.

7.3.3 Creation of market-pull conditions for LCCTs

To address the market opportunities barrier, demand for LCCTs can be created in a number of ways. As already addressed in the policy discussion, requiring or encouraging use of LCCTs in building and infrastructure regulation would create demand for LCCTs and unlock economies of scale for the industry.

From the other side, large organisations can be sufficient to create demand that unlocks scales of economy while also using it to differentiate from competitors.

7.3.3.1 Market-leaders setting embodied carbon targets

To establish meaningful adoption of LCCTs, the key overarching metric should be based on embodied carbon of materials. This could be in the form of major contractors committing to using a cap on the amount of OPC per tonne of concrete, or developers establishing a target for embodied carbon per m² floorspace created.

Precedent for such voluntary ambition exists through industry groups that have formed to formally recognise the climate emergency, such as UK Contractors Declare Climate and Biodiversity Emergency. These groups set principles for how the member organisations should behave to address the climate emergency. Often these are statements of intention, rather than measurable or specific actions and as such could be expanded.

The financial implications of organisations setting embodied carbon targets for their outputs should be considered on an organisational basis and further work around the cost of LCCTs in this holistic approach is required.

7.3.3.2 Procurement policies

The UK government is the largest construction client in the country and as such have significant market pull. This could be used through the setting of procurement policy relating to embodied carbon to establish strong market opportunities for LCCTs. In addition, these procurement policies could be set as a standard or template for other organisations and thus create further market pull.

7.4 Industry Perceptions

While analysis using a formal framework can provide a view on the state of different LCCTs, their adoption into industry also depends on industry's perception of them. Perceived barriers may not align with actual barriers and are primarily overcome with education and knowledge sharing.

7.4.1 Industry Opinion Survey

To calibrate the lagging indicators with industry experience, a short survey on the high-potential technologies was undertaken. This covered the technologies which have a savings potential of 10% or greater, and those with a CRI of 6.

Participants were asked to identify those of the CRI indicators that they consider to be the key barriers to each technology. There was also an option to indicate that the participant did not know what the barriers are for each technology.

Due to the time constraints of the project, it was only possible to obtain 17 responses to the survey. This is not deemed to be a representative sample of the industry and as such the survey results are not used for analysis of barriers but rather to corroborate findings in Section 1.

The survey is reproduced in Appendix B.

7.4.2 Industry Survey Insights

In total, 17 AEC industry professionals responded to the survey. These individuals identified with the roles as shown in Figure 13, with some individuals identifying with multiple roles. As previously stated, this was not considered to be a representative sample of the industry and as such the results are only used to provide a few insights to how industry opinions may compare to the CRI analysis.

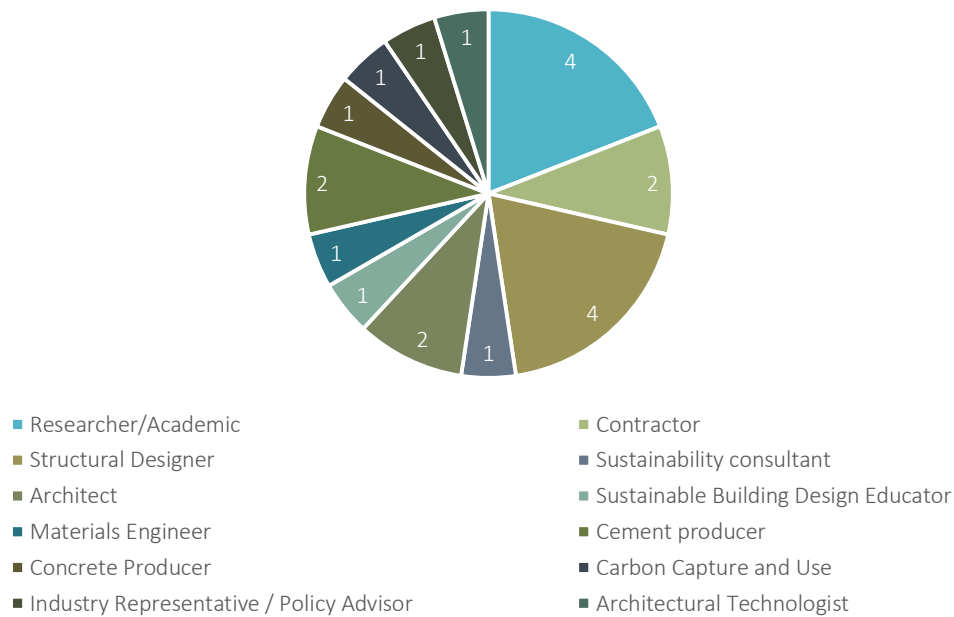


Figure 13: Survey participant roles

Of the participants, around half were involved in the product design phase of the cementitious lifecycle, representing roles of Architect, Structural Designer and Researcher/Academic. The rest of the participants covered the full cementitious lifecycle, with one or two participants with experience in each stage.

One of the most common responses to being asked what the key barriers are to each of the high-potential LCCTs was 'Don't Know'. This clearly indicates the low level of awareness around LCCTs and their state in the market. On average, each respondent responded 'Don't Know' to 7 of the 31 technologies. The least well understood technologies were in the cement production lifecycle, which may reflect that the respondents typically did not have experience of this lifecycle stage.

The most common barriers identified by the respondents were Supply Chain, Industry Skills and Technical Standards, as shown in Figure 14. However, most of the indicators were identified a similar number of times, with only Policy and Market Opportunities receiving a noticeably low number of selections. This may be due to the fact that typically policy and market opportunities do not stop an individual from using a LCCT but are more related to their ability to reach mainstream deployment.

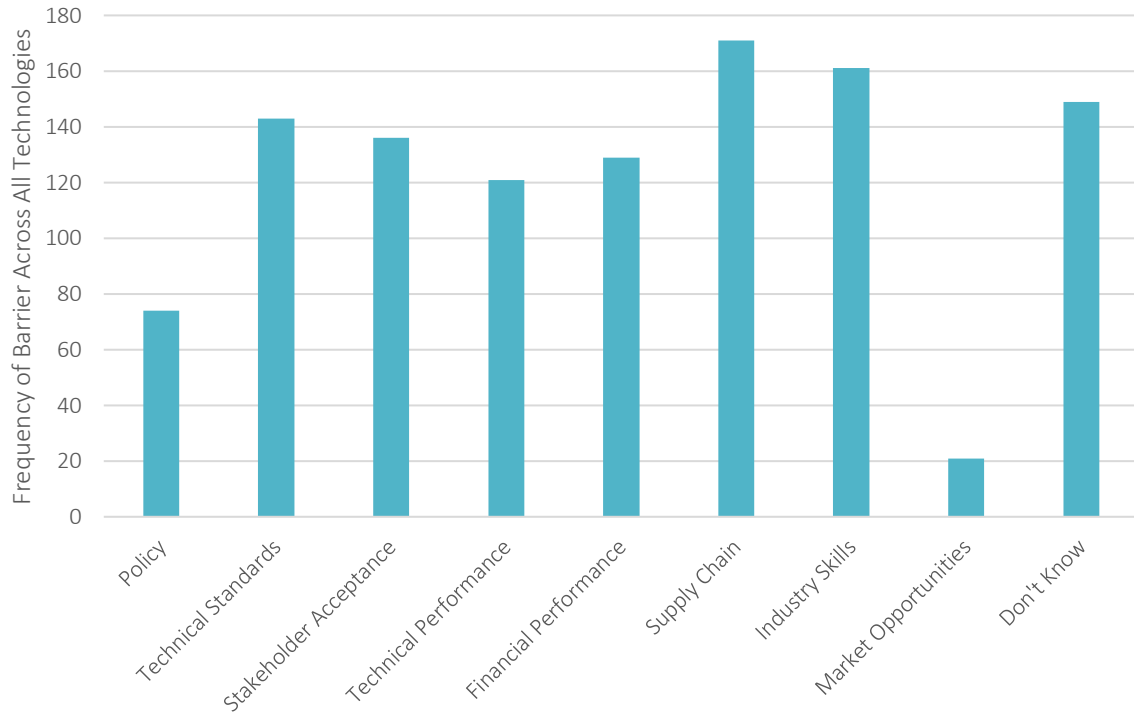


Figure 14: Survey Barrier Frequencies

Further work could ask a representative sample of industry experts to contribute to CRI assessments for the LCCTs relevant to their area of expertise. This would be a more directly comparable dataset to the barriers analysis conducted in this project.

8 Conclusion

Based on the need for the UK cement industry to decarbonise by 2040, as demonstrated by the CCC and according to the Sixth Carbon Budget, and the Architecture, Engineering and Construction (AEC) Industry's slow-changing nature, this project has looked at the industry emissions reduction potential and commercial readiness of Low Carbon Concrete Technologies (LCCTs) across the cementitious lifecycle.

By determining LCCTs that can be fully deployed in combination, three key technology combinations were identified:

1. Market-ready combination – 37% emissions reduction potential (upper bound)

This combination applies only technologies that have achieved the highest level of commercial readiness and therefore represents the emissions reduction potential of existing technologies. This indicates that high levels of emissions reduction are possible with minimal technical development but significant behavioural change.

2. Maximum-potential combination – 99% emissions reduction potential (upper bound)

This combination is comprised of the highest-potential technologies that are mutually deployable but require varying levels of commercial development. As such, this combination will require significant funding and time to be achieved and as such does not present a path of least resistance but of highest possible reward. Due to the low level of commercial readiness of several of these technologies, it is unlikely that the upper bound estimate for emissions reduction could be realised.

3. Optimised combination – 93% emissions reduction potential (upper bound)

This combination utilises the most commercially ready technology from each of the mutually-deployable groups. In this way it includes all of the technologies from the market-ready combination and then includes the technologies that can be fully deployed in addition with the least requirement for commercial development. Since this could achieve an upper bound of 88% emissions reduction potential with lower commercial development requirements than the maximum-potential combination, this is considered to be the optimised combination. Considering the emissions reduction the UK has achieved to date against an OPC baseline, the lower bound estimate of 68% emissions reduction potential is likely to be more realistic.

Through assessing the commercial readiness of the technologies, using a modified Commercial Readiness Index, three key barriers were identified with several recommended actions to address these barriers.

A. Regulation through Policy

Develop policy that explicitly encourages or requires the use of LCCTs in relevant applications. A precedent for this type of policy can be seen in the energy performance requirements for new buildings and as quantifying embodied carbon becomes increasingly advanced, similar measures could be implemented for concrete usage. Specific recommended actions include:

- (i). Set maximum carbon emissions from combustion per unit of cement output
- (ii). Fund non-Portland cement production
- (iii). Demonstrate Post-combustion CCUS
- (iv). Include embodied carbon in building and infrastructure regulation

B. Industry Skills

Require education around LCCTs as part of industry training and certification. As Health and Safety training has been incorporated into industry certifications and internal organisational requirements, similarly education around LCCTs and their application could be incorporated into the formal training of individuals. Specific recommended actions include:

- (i). Clear messaging around LCCTs, including definitions
- (ii). Chartership requirements for LCCT knowledge
- (iii). Apprenticeships and higher-education to include LCCT usage

C. Market Opportunities

Create market-pull conditions for LCCTs to expand opportunities beyond technology-push channels. Market leaders wield significant power in changing industry attitudes and creating large-scale demand for certain technologies and projects. By uniformly adopting LCCTs across all applicable projects, market leaders at all stages of the cementitious lifecycle can develop market opportunities and accelerate penetration of LCCTs. Specific recommended actions include:

- (i). Market-leaders setting embodied carbon targets
- (ii). Procurement policies that favour LCCTs

These actions sit across most lifecycle stages of cementitious materials and products and as such can be implemented by a range of stakeholders. This ensures that responsibility for decarbonising the sector does not rest with a single stakeholder group but requires cooperation between stakeholder groups to achieve meaningful outcomes.

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10 Appendix A

Indicator: Regulatory Environment: Policy		
Level	6	Existing policy encourages or requires use of the technology in certain applications, directly driving uptake.
	5	Construction regulations explicitly allow for use of the technology in the majority of relevant applications.
	4	Construction regulations explicitly allow for use of the technology but only in limited applications.
	3	Precedent exists for use of technology to meet regulations by alternative routes, such as design by testing
	2	Regulation does not explicitly allow for use of technology but alternative routes, such as design by testing, available for use of technology
	1	Current regulation does not allow for use of this product in AEC industry

Indicator: Regulatory Environment: Technical Standards		
Level	6	The technology is included in international standards, such as material certification schemes, and codes of practice, such as the Eurocode, enabling widespread use.
	5	The technology is included in national standards, such as BS standards, enabling common use within the UK.
	4	The technology has initial externally verified standards, such as PAS or BSI Flex standards, supporting further market uptake.
	3	Producer-specific standards and codes are available to early adopters to assist in implementation.
	2	Performance data allows for development of initial codes of practice and technical standards to be developed within the developing organisation.
	1	No standards exist for the technology, even within the developing organisation.

Indicator: Stakeholder Acceptance		
Level	6	All stakeholder groups in the industry have a consensus acceptance of the technology as a viable option for use in the majority of relevant applications.
	5	Acceptance in established industry groups and companies is achieved in some stakeholder groups, addressing any major misconceptions in the industry.
	4	All stakeholder groups have pockets of acceptance, with numerous examples of implementation available.
	3	Early adopters establish pockets of stakeholder acceptance through flagship projects. Initial industry-wide perceptions develop in some stakeholder groups.
	2	Stakeholder support or opposition is tested through individual interactions and the development of value proposition.
	1	Stakeholder support or opposition is hypothetical due to highly limited exposure of the technology to external parties.

Indicator: Technical Performance		
Level	6	Technical performance data widely verified through approved industry practices, enabling direct comparisons between the technology and alternatives.
	5	Multiple datasets discoverable on projects operating in range of operating environments. Performance evaluation methodology and warranties/insurances widely available. Performance expectations based on experience from wide range of sources.
	4	Performance evaluation methodology and warranties/insurances becoming available. High confidence in expected performance.
	3	Performance forecasts based on extrapolation from similar applications or similar technologies.
	2	Performance forecasts based on simulation models referenced to evidence from research & development or pilot scale demonstration in operational environment.
	1	Performance forecasts based on product/process provider modelling.

Indicator: Financial Performance		
Level	6	System cost sufficiently reliable and competitive to drive mainstream uptake. Cost detail widely published and accepted for multiple similar applications.

	5	Price and value proposition clear and attractive with open access to cost trends and projections based on actual project data from wide range of applications.
	4	Key cost elements of executed projects available to industry. Project implementation costs variable depending on suppliers selected. Cost drivers are understood with roadmaps in place to bring costs to being market competitive.
	3	Cost data based on projections from single implementation of product/process. Key cost drivers are understood enabling understanding of long-term prospects of technology.
	2	Key costs based on projections with data from similar technologies/applications available to verify.
	1	Cost data (if available) based on projections and forecasts with little or no prior data to substantiate.

Indicator: Supply Chain		
Level	6	Multiple alternative sources available, creating robust supply chains. Location and cost differentiation are a key selection factor.
	5	Specialisation occurring along supply chain with established end-to-end supply chains available to new users of the technology.
	4	Limited supply options proven. Organisations establishing reputation for delivering projects using technology.
	3	Project by project approach to establishing supply chain across AEC industry. Project teams typically with limited prior experience driven by a technology proponent.
	2	Supply chain not available or not willing to participate for many key components. Project team typically designing and procuring multiple elements to own specification.
	1	Supply chain not established with key elements from specialist source on ad hoc basis, often under technology proponent specification.

Indicator: Industry Skills		
Level	6	Individuals and organisations with skills in the implementation of the technology are commonplace and continuous improvement becomes differentiator.
	5	Industry groups and organisations provide skills development platform and knowledge sharing for new technology users.
	4	Some organisations in each of the stakeholder groups possess the skills to implement technology, with skills development typically through project experience with previous adopters.
	3	Limited number of organisations external to technology developer disseminate skills internally to deploy these on multiple projects as early adopters.
	2	Developer works directly with early adopter to provide skills required for implementation.
	1	Skills limited to technology/process developer.

Indicator: Market Opportunities		
Level	6	Market demand driving scale of production and new entrants to market. External factors may slow down or accelerate ongoing deployment.
	5	Market driving the supply-side investment process with little or no concessional policy support. External factors may slow down or accelerate ongoing deployment. Market opportunities clear and understood.
	4	Market demand primary driver of the investment case with clarity on market segments and industry supply chain and/or market channels to deliver. Funding gaps between net present value of revenue and cost understood, with target segment customers a key stakeholder in the investment decision process. Some concessional policy support may be required to drive uptake if technology-push still main driver.
	3	Focus moving from proving commercial performance to optimising supply cost and revenue structures. Detailed market research to understand the size, interest and readiness of the market available.
	2	Commercial trial has identified initial target market segment for a trial with goal of proving that the technology can operate reliably, even if still uneconomic. Market research has been done to enable proponents to estimate the market size locally and internationally. The commercial trial seeks to balance the absolute cost of the trial with the scale required to demonstrate basic commercial performance.
	1	Investment case for commercial trials supported by evidence of peer reviewed business plans with verifiable cost and revenue estimates, market size and early channel to market identified. Key risks identified both within and external to the proponent's sphere of control.

Indicator: Company Maturity		
Level	6	Leading proponents are major, public companies with large balance sheets. Management capability is no longer a consideration for most projects, as proponents have strong track records.
	5	Leading proponents of technology have significant balance sheets and wide management experience in LCCT and delivery of product/process.
	4	Established construction industry players starting to provide technology. Balance sheets and the influence of new entrant product/process proponents increasing.
	3	New industry bodies established to represent technology or technology explicitly recognised by relevant existing bodies. Industry bodies positively represent technology to external stakeholders. Industry still driven by product/process proponents.
	2	Technology developed either within or with the support of an established industry provider.
	1	Technology being developed by new market entrant. Management capability is dependent on individual proponents.

11 Appendix B

Low Carbon Concrete Technologies: Barriers to UK Implementation

This survey is part of the Low Carbon Concrete Technologies (LCCT): Understanding and Implementation project, funded by an EPSRC IAA Impact Starter Grant, and is being conducted by Aurelia Hibbert, under the supervision of Michal Drewniok and Jon Cullen, at the University of Cambridge.

The project aims to identify Low Carbon Concrete Technologies that can be successfully implemented in the UK. A Commercial Readiness Index (CRI) is used to assess the identified LCCTs and the barriers preventing their mainstream implementation in the UK. The 'hierarchy' of barriers will be identified along with means to overcome them. In this way, recommendations will be made for unlocking the emissions reductions required for the cement industry in the UK to achieve net-zero in line with the UK's climate commitments.

The survey has been designed to assess how industry views the barriers to implementation of low carbon concrete technologies in the UK. The survey is completely anonymous and can be completed by anyone involved in the building design process. Results will be used in the project report and academic publications.

The survey should take approximately 15 minutes to complete and any responses will be greatly appreciated.

***Required**

1. What is your role? *

Tick all that apply.

- Architect
- Cement producer
- Client
- Concrete producer
- Construction Manager
- Contractor
- Demolition Contractor
- Industry Representative / Policy Advisor
- Researcher/Academic
- Structural Designer

Other: _____

2. What lifecycle stages of cementitious materials are you primarily directly involved in? *

Tick all that apply.

- Cement Production
- Building/Product/Element Design
- Concrete Production
- On-site Concrete Usage
- Off-site Concrete Usage
- Product Operation (incl. Repairs and Maintenance)
- Material Recovery

Other: _____

**Barriers to
Technology
Implementation
in the UK -
Background**

ACTION:

Please indicate the key barriers (listed as rows) that you believe are holding back implementation of each technology or practice in the UK (listed as columns). You can select multiple barriers for each technology, if you wish.

BACKGROUND:

Investigation by Chatham House, (Lehne and Preston, 2018), has shown that cement and concrete innovations commonly fail to reach commercialisation. This clearly indicates that Technology Readiness Level 9 (TRL9 as defined by NASA) is not the end goal for market penetration in the concrete and cement industry, as the Australian Renewable Energy Agency (ARENA) discovered in the renewable energy sector.

ARENA developed the Commercial Readiness Index (CRI) to address the pathway from TRL9 to bankability for renewable energy technologies. They have developed this framework to assist in their decision making to help understand and minimise the risks and barriers for technologies at each stage of development. This has been adapted for this project to take into account the context of the UK Architecture, Engineering and Construction (AEC) sector.

The 29 technologies below have been identified as having a high emissions reduction potential and/or a high commercial readiness and are not an exhaustive list of all LCCTs. They are grouped into similar roles they play in the cement and concrete lifecycle, in order to provide some clarity around how they are expected to be implemented. These groups are as follows:

1. Supplementary Cementitious Materials
2. Alternative Fuels
3. Cement Process Alterations
4. Non-portland Cements
5. Carbon Capture
6. Material Efficiency
7. Concrete Mix Design
8. Pre-fabricated Products

Eight indicators have been identified that can present significant barriers to the implementation of each Low Carbon Concrete Technology (LCCT):

- A. Policy - the inclusion of the technology in policy such as building regulations or the Highways Act
- B. Technical Standards - the inclusion of the technology in technical standards such as Eurocodes
- C. Stakeholder Acceptance - the perception of the technology by industry
- D. Technical Performance - the ability of the technology to perform in real-world applications
- E. Financial Performance - the reliability and level of cost of the technology
- F. Supply Chain - the availability of the technology or product in the UK through established supply chains
- G. Industry Skills - the ability of individuals in the industry to implement the technology on a project
- H. Market Opportunities - the volume of applications in which the technology could be adopted

In this part we would like to identify the key barriers connected with each LCCT that you believe are holding back implementation of each technology or practice in the UK.

1. Supplementary Cementitious Materials

Calcined Clay - Kaolinitic clay is an abundant natural material. When heated to high temperatures, also known as being calcined, it becomes a reactive cementitious material sometimes referred to as metakaolin or calcined clay.

Biomass Ash - Biomass ash is a by-product of processes that burn biomass as a fuel. A common source of biomass ash is biomass power plants.

Fillers (Limestone/Quartz) - Limestone and quartz are naturally occurring materials and can be used in powdered form to replace a proportion of Ordinary Portland Cement (OPC).

3. Key Barriers to Supplementary Cementitious Materials

Tick all that apply.

	Calcined Clay	Biomass Ash	Fillers (Limestone/Quartz)
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

2. Alternative Fuels

Biomass - Biomass such as fast-growing energy crops and waste from the agricultural sector can be used as a fuel to produce process heat for cement and concrete production.

Waste - Waste as a fuel uses waste that would otherwise be disposed of in landfill to provide process heat. Waste is already used to some extent in the cement industry to provide process heat.

Electrification - Using electricity to provide process heat can reduce the use of fossil fuels in cement and concrete production.

Hydrogen - Various processes can be used to separate hydrogen from water and other compounds to produce pure hydrogen. This can be used as a fuel to produce process heat.

4. Key Barriers to Alternative Fuels

Tick all that apply.

	Biomass	Waste	Electrification	Hydrogen
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

3. Cement Process Alterations

Kiln Efficiency - Pyro-processing of raw materials in the cement kiln is the major energy consumption process of cement production. Kiln efficiency is a measure of how much fuel is required to produce a tonne of cement.

Electrical Efficiency - Electricity typically drives a number of auxiliary processes and functions at a cement plant. The efficiency is a measure of how much electricity is required to produce a tonne of cement.

Activation Agents - Activation agents are added to blended cements in order to increase the reactivity of the cement, enabling a higher fraction of SCM and thus reducing the clinker factor. Activation agents can have many different chemical formulations.

5. Key Barriers to Cement Process Alterations

Tick all that apply.

	Kiln Efficiency	Electrical Efficiency	Activation Agents
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

4. Non-portland Cements

Carbonatable Calcium Silicate Cements (CCSC) - CCSC can be produced in traditional cement kilns using limestone and silica. These clinkers are not sufficiently reactive to harden by hydration but are designed for carbonation hardening. This restricts their use to pre-cast concrete and cementitious products.

Biocement - Bio-cements are produced by specialised bacteria which secrete cementitious materials in mimicry of natural systems such as coral reefs.

LC3 (Limestone Calcined Clay Cement) - LC3 utilises the interactive properties of metakaolin and limestone to produce a material with a higher reactivity than the sum of its parts.

AAMs not using Pulverised Fly Ash (PFA) or Ground Granulated Blast-furnace Slag (GGBS) - AAMs can be made from aluminosilicates from both industrial waste and natural resources, other than those already largely utilised in the cement industry (i.e., PFA and GGBS).

Magnesium Oxides derived from Magnesium Silicates (MOMS) - MOMS clinkers are produced from ultramafic rocks, which contain magnesium oxides in compounds without CO₂. As a result, there are no emissions from the calcination reaction of the raw materials. Atmospheric carbon is then absorbed during the hardening of the binder, unlocking potential for a truly carbon negative cementitious material.

6. Key Barriers to Non-portland cements

Tick all that apply.

	Carbonatable Calcium Silicate Cements (CCSC)	Biocement	LC3 (Limestone Calcined Clay)	AAMs (not using Fly Ash or GGBS)	MOMS (Magnesium oxides derived from Magnesium Silicates)
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

5. Carbon Capture

Direct Separation - Direct separation carbon capture is achieved by indirectly heating the raw materials for calcining, in order to produce the CO₂ from the calcination reaction of the limestone as a pure exhaust gas, rather than being mixed in with the fuel exhaust gases as would typically occur. This enables a pure stream of CO₂ to be captured without further purifying or scrubbing of the exhaust gasses.

Post-combustion - Post-combustion carbon capture separates the CO₂ in the flue gases of a combustion process (such as in coal power plants or where fossil fuels are burnt for process heat) in order to capture the CO₂ as a pure gas. This is typically achieved through a chemical separation process. The higher the CO₂ content of the flue gas, the less energy required to achieve the separation, typically.

OxyFuel - OxyFuel carbon capture burns carbon-based fuels with pure oxygen, rather than air, in order to produce a flue gas with a high CO₂ content. This enables capture of the CO₂ and a relatively simple purification process compared to typical combustion flue gases.

7. Key Barriers to Carbon Capture

Tick all that apply.

	Direct Separation	Post-Combustion	OxyFuel
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

6. Material Efficiency

Use of non-concrete materials (such as timber) - The use of non-concrete materials can reduce overall demand for cement, where it is possible to provide the same service with another material. For example, it is possible to use timber floor elements in buildings instead of concrete slabs, while providing the same structural performance. Not all concrete or cement usage can be displaced in this way and the availability and suitability of alternative materials needs to be considered on a systematic scale.

Design for waste reduction - Designing structures with consideration for the available quantities and sizes of components in order to reduce waste from off-cuts and excess.

Optimising structural efficiency - The codes of practice, typically Eurocodes in the UK, demonstrate good practice for the design of structures. However, designers often do not design to code limits and instead prefer to include additional strength than the codes require. The codes are fundamentally designed so that following them is safe and by including additional strength results in more material being used than is actually required for the structure to be safely delivered.

Lightweighting of concrete slabs - Lightweighting is the practice of reducing the amount of material required to deliver a structure by placing the material only where it is needed.

8. Key Barriers to Material Efficiency

Tick all that apply.

	Use of non-concrete materials (such as timber)	Design for waste reduction	Optimising structures to code limits	Lightweighting of concrete slabs
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

7. Concrete Mix Design

Existing low-carbon blended cements - There are many low-carbon blended cements specified in existing industry standards such as the Eurocodes. These are not typically used or produced in the UK compared to Ordinary Portland Cement (OPC).

Specifying concrete by embodied carbon - Concrete is typically specified by minimum strength requirements which does not specify the components of the concrete. It would be possible to specify a maximum embodied carbon in addition to a minimum strength in order to procure a low-carbon concrete.

Optimised aggregate grading - Aggregate grading refers to the distribution of particle sizes in an aggregate mix for concrete. Optimised aggregate grading can increase the strength of a concrete mix, allowing the reduction of cement content to achieve a certain strength.

Super-plasticisers - Super-plasticisers improve the rheology of concretes at low water content, which enables the reduction of binder content.

Air-entrainers - Air-entrainers reduce the density of concrete while maintaining other properties. This reduces the weight of a structure and therefore the strength requirements for withstanding self-weight loads.

Set accelerators - Set accelerators can be added to low-reactivity cements (several low-carbon cements are low-reactivity) and as such enables the use of low-reactivity low-carbon cements without impacting construction timelines.

Dispersants - dispersants can be used to improve the rheology of concrete by breaking up clumps of cement paste and therefore reduce the binder content required to achieve a given strength. Common dispersants include sulfonated naphthalene formaldehyde condensate (SNFC and sulfonated melamine formaldehyde condensate (SMFC), among others.

9. Key Barriers to Concrete Mix Design

Tick all that apply.

	Existing low-carbon blended cements	Specifying concrete by carbon intensity	Optimised aggregate grading	Super-plasticiser	Air-entrainer	Set accelerator	Dispersant
Policy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

8. Pre-fabricated Products

Pre-cast structural elements - these elements can be used instead of in-situ cast concrete. Pre-cast elements can be produced with a higher quality due to the level of control available in the manufacturing environment. This can reduce the waste from the construction process and enable alternative cements to be used as the environment can be controlled for curing.

Carbonation curing - The use of carbon dioxide to increase the speed of curing of pre-cast elements and products. This can be used as a form of carbon sequestration.

10. Key Barriers to Pre-fabricated Products

Tick all that apply.

	Pre-cast structural elements	Carbonation curing
Policy	<input type="checkbox"/>	<input type="checkbox"/>
Technical Standards	<input type="checkbox"/>	<input type="checkbox"/>
Stakeholder Acceptance	<input type="checkbox"/>	<input type="checkbox"/>
Technical Performance	<input type="checkbox"/>	<input type="checkbox"/>
Financial Performance	<input type="checkbox"/>	<input type="checkbox"/>
Supply Chain	<input type="checkbox"/>	<input type="checkbox"/>
Industry Skills	<input type="checkbox"/>	<input type="checkbox"/>
Market Opportunities	<input type="checkbox"/>	<input type="checkbox"/>
Don't Know	<input type="checkbox"/>	<input type="checkbox"/>

11. Do you have any further comments regarding the barriers to implementation of LCCT in the UK? If so, please provide these below.

Further Information

if you would be willing to discuss this topic in more detail, in a one-to-one interview, please contact Aurelia Hibbert (afh36@cam.ac.uk).

12. If you would like to be informed of the project results, reports and/or publications, please provide your email address below. This data will only be used to contact you regarding this project.

Thank you for your participation

re.c.be

RESOURCE EFFICIENCY
IN CONSTRUCTION AND
THE BUILT ENVIRONMENT

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12 Appendix C

12.1 Cement Production Technologies and Processes

12.1.1 Clinker Replacement (SCM)

12.1.1.1 Industrial By-products

Biomass Ash			
Description: Biomass ash is a by-product of processes that burn biomass as a fuel. A common source of biomass ash is biomass power plants. These burn fast-growing plants and organic waste, such as bagasse from agriculture, in order to produce electricity. Biomass ash can be used as a SCM in concrete to reduce the use of Portland cement in the final product. This addition of biomass ash can occur at the cement blending phase or the concrete production phase.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Upto 1 Mt produced by biomass power plants in the UK in 2050 (Bastien, 2020)	All cement	20% by mass replacement of OPC for structural uses, upto 40% for non-structural (Tosti <i>et al.</i> , 2018, 2021),	9% (Limited by biomass ash availability)
	89%		

12.1.1.2 Natural pozzolans

....

12.1.1.2.1 Kaolinitic Clay (Calcined)

Kaolinitic Clay			
Description: Kaolinitic clay is an abundant natural material. When heated to high temperatures, also known as being calcined, it becomes a reactive cementitious material sometimes referred to as Calcined Clay or calcined clay. Calcined Clay can be used to replace OPC in blended cements or can be added at the concrete production stage to reduce the use of OPC.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Reserves in current production sites in UK exceed 50 years of current consumption (2.2 Mt/year)(The Kaolin and Ball Clay Association, no date). There are other significant reserves in the UK.	All cement	Can replace OPC upto 50% by weight without compromising mechanical properties, resulting in ~40% emissions reduction(Mwiti, Karanja and Muthengia, 2018; Scrivener, John and Gartner, 2018)	36%
	89%		

12.1.1.3 Fillers

....

12.1.1.3.1 Limestone

Limestone			
Description: Limestone is a naturally occurring material and is the main input material of OPC. It can be used in powdered form to replace a proportion of OPC, which reduces emissions by avoiding the calcination of the limestone which is added 'raw' into the blended cement, or at the concrete production stage.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Limestone is naturally abundant in the UK, with around 67Mt extracted annually (<i>Material flows Domestic Extraction- Non-metallic minerals - Limestone and gypsum- Thousand tonnes - Office for National Statistics, no date</i>)	All cement 89%	Limestone can replace upto 15% of OPC (Tennis, Thomas and Weiss, 2011)	9%

12.1.1.3.2 Quartz

Quartz			
Description:			
UK Availability	Product Applicability	Unit Potential	Industry Potential
	All cement 89%	~20% reduction at 20% replacement rate, depends on w/b ratio and has strength impacts (~10% reduction for structural)	14%

12.1.1.4 Specialist Products

....

12.1.1.4.1 LC3

LC3			
Description: LC3 is a SCM which utilises the interactive properties of Calcined Clay and limestone to produce a material with a higher reactivity than the sum of its parts. This enables a higher percentage of OPC to be replaced in cement and concrete.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Abundant raw materials (kaolinitic clay and limestone)	All cement 89%	35% emissions reduction compared to OPC (Pillai <i>et al.</i> , 2019)	29%

12.1.2 Alternative Fuels

...

12.1.2.1 Electrification

Electrification			
Description: Using electricity to provide process heat can reduce the use of fossil fuels in cement and concrete production.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Renewable electricity can be built or contracted on a site-by-site basis	All cement	25% according to UK feasibility (Mineral Products Association, 2019c)	22%
	89%		

12.1.2.2 Waste

Waste			
Description: Waste as a fuel uses waste that would otherwise be disposed of in landfill to provide process heat. Waste is already used to some extent in the cement industry to provide process heat, some of which is biomass waste. Other forms of waste, such as tyres, can also be used.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
UK waste expectation	Fuel combustion	38%, if current waste mix used to replace all non-waste fuel	10%
	27%		

12.1.2.3 Biomass

Biomass			
Description: Biomass such as fast-growing energy crops and waste from the agricultural sector can be used as a fuel to produce process heat for cement and concrete production. Waste biomass in the UK is almost fully utilised and so increasing the amount of biomass used in cement and concrete production would likely result in demand for virgin biomass (e.g., energy crops).			
UK Availability	Product Applicability	Unit Potential	Industry Potential
UK biomass projection of 140 TWh domestic potential (around 50% of total industry energy consumption) (Freeman, Harry and Kmietowicz, 2018; Department for Business Energy & Industrial Strategy, 2020)	All cement	16% reduction if using 70% biomass (Mineral Products Association, 2019c)	14%
	89%		

12.1.2.4 Hydrogen

Hydrogen			
Description: Hydrogen is not naturally occurring in a pure state and is most commonly found in the form of water (H ₂ O). Various processes can be used to separate hydrogen from water and other compounds to produce pure hydrogen. This can be used as a fuel to produce process heat.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
	Fuel combustion		27%

Feasible UK production upto 700TWh/yr in 2050 (Royal Society, 2018)	27%	100% fuel decarbonisation where zero-emissions hydrogen is used	
---------------------------------------------------------------------	-----	-----------------------------------------------------------------	--

12.1.3 Process Technology

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12.1.3.1 Solar-thermal calcination

Kiln Efficiency			
Description: Solar-thermal calcination uses renewable energy to produce process heat in a specialised cement kiln. This reduces the need to burn fuels for the process.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
Insufficient solar irradiation in the UK to be viable	All cement	48% emissions reduction (Tomatis <i>et al.</i> , 2020)	0%
	89%		

12.1.3.2 Kiln efficiency

Kiln Efficiency			
Description: Pyro-processing of raw materials in the cement kiln is the major energy consumption process of cement production. As a result, the efficiency of cement kilns has been the focus of a lot of development in the industry as a cost-saving technique through reducing fuel consumption. The UK has primarily adopted dry processing, which is significantly more efficient than wet processing. As a result, remaining efficiency gains in cement kilns are regarded as being incremental gains only in the UK (Pamenter and Myers, 2021).			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	All cement	2% emissions reduction (Pamenter and Myers, 2021)	2%
	89%		

12.1.3.3 Electrical efficiency

Electrical Efficiency			
Description: Electricity typically drives a number of auxiliary processes and functions at a cement plant. By reducing electricity consumption, emissions can be reduced where electricity is not produced from 100% renewable energy sources.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	All cement	1% (Pamenter and Myers, 2021)	1%
	89%		

12.1.4 Process Additives

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12.1.4.1.1 Activation Agents

Activation Agents			
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Description: Activation agents are added to blended cements in order to increase the reactivity of the cement, enabling a higher fraction of SCM and thus reducing the clinker factor. Activation agents can have many different chemical formulations.

UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	All cement	Upto 14% strength increase shown in some cases, assume 10% reduction in cement content	9%
	89%		

12.1.4.1.2 Strength Enhancers

Strength Enhancers

Description: Strength enhancers are additives included at the milling stage of cement production. They help to control the particle size distribution, water input and other characteristics of the milling process and output. They can increase mill productivity and the reactivity of the resulting cement, reducing the cement content required to meet performance requirements.

UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	All cement	2% strength increase enabling 2% cement content reduction (CHRYSO and Guillot, 2020)	2%
	89%		

12.1.5 Non-Portland cements

12.1.5.1 Reactive Belite-rich Portland Cement (RBPC)

Reactive Belite-rich Portland Cement (RBPC)

Description: RBPC is produced through reducing the proportion of limestone in OPC production. By reducing the limestone that is calcined, the carbon emissions from the calcination reaction are reduced. These cements typically demonstrate slower strength gain than OPC.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Abundant, same as OPC materials	All cement	10% (Scrivener, John and Gartner, 2018)	9%
	89%		

12.1.5.2 Carbonatable Calcium Silicate Clinkers (CCSC)

Carbonatable Calcium Silicate Clinkers (CCSC)

Description: CCSC can be produced in traditional cement kilns using limestone and silica. These clinkers are not sufficiently reactive to harden by hydration but are designed for Carbon Curing. This restricts their use to pre-cast concrete and cementitious products. There is potential to use the kiln flue-gases as the source of CO₂ for the hardening process.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Limestone abundant, silica production ~ 5Mt/yr	Pre-cast products	70% (Meyer, Sahu and Dunster, 2019)	23%
	33%		

12.1.5.3 Magnesium oxides derived from Magnesium Silicates (MOMS)

Magnesium oxides derived from Magnesium Silicates (MOMS)

Description: MOMS clinkers are produced from ultramafic rocks, which contain magnesium oxides in compounds without CO₂. As a result, there are no emissions from the calcination reaction of the raw materials. Atmospheric carbon is then absorbed during the hardening of the binder, unlocking potential for a truly carbon negative cementitious material. However, industrial processes for MOMS are only in early development at present.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Some deposits in UK with additional global availability	Pre-cast products	100% + (Scrivener, John and Gartner, 2018)	33%
	33%		

12.1.5.4 Non-PFA/GGBS Alkali-Activated Materials (AAMs)

Non-PFA/GGBS Alkali-Activated Materials (AAMs)

Description: AAMs can be made from aluminosilicates from both industrial waste and natural resources, other than those already largely utilised in the cement industry (i.e., PFA and GGBS). Several aluminosilicate precursors have been investigated, including calcined clays, biomass ashes and red mud. Calcined clays are anticipated to be the most viable at scale due to their availability and the low energy requirements of their calcination. However, water glass, which is typically used as their activator, has an energy and emissions intensive production process at present.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Various including calcined clays, which are abundant	All cement	Around 50% using AAMs based on calcined clays	45%
	89%		

12.1.5.5 Bio-cements

Bio-cements

Description: Bio-cements are produced by specialised bacteria which secrete cementitious materials in mimicry of natural systems such as coral reefs. At present, these systems are in production for precast products, where the bacteria secrete the cementitious material between aggregates. However, development of ready-mix bio-concretes is underway.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Proprietary technology	Currently Precast	66%-100% for blocks Unknown for RMC	33%
	Ready-mix potential 33% (possibly upto 89%)		

12.1.5.6 Energetically Modified Cements

Energetically Modified Cements

Description: Energetically modified cements are blended cements of OPC and fillers, which undergo a specialised high-intensity grinding process in order to increase the mechanical properties of the resulting cement compared to traditionally-blended cements with the same components.

UK Availability	Product Applicability	Unit Potential	Industry Potential
Same inputs as OPC with fillers	Non-structural cement	Upto 50% with fly-ash (Ronin, no date)	23%
	47%		

12.1.6 Carbon capture

12.1.6.1 Capture

12.1.6.1.1 Direct Separation

Direct Separation			
Description: Direct separation carbon capture is achieved by indirectly heating the raw materials for calcining, in order to produce the CO ₂ from the calcination reaction of the limestone as a pure exhaust gas, rather than being mixed in with the fuel exhaust gases as would typically occur. This enables a pure stream of CO ₂ to be captured without further purifying or scrubbing of the exhaust gasses. This technique does not address the emissions from the combustion of the fuel used to provide the process heat.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	Process emissions	95% of process emissions (Hills <i>et al.</i> , 2017)	51%
	54%		

12.1.6.1.2 Post Combustion

Post-combustion			
Description: Post-combustion carbon capture separates the CO ₂ in the flue gases of a combustion process (such as in coal power plants or where fossil fuels are burnt for process heat) in order to capture the CO ₂ as a pure gas. This is typically achieved through a chemical separation process. The higher the CO ₂ content of the flue gas, the less energy required to achieve the separation, typically. Where cement plants have a mixed combustion and calcination flue gas, the CO ₂ concentrations are relatively high for such a process.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	Fuel emissions	90% flue emissions (Cloete <i>et al.</i> , 2019)	24%
	27%		

12.1.6.1.3 OxyFuel

OxyFuel Carbon Capture			
Description: OxyFuel carbon capture burns carbon-based fuels with pure oxygen, rather than air, in order to produce a flue gas with a high CO ₂ content. This enables capture of the CO ₂ and a relatively simple purification process compared to typical combustion flue gases. In a cement plant, this flue gas could be combined with the calcination flue gas or captured separately.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	Fuel and process emissions	100% flue emissions (Plaza, Martínez and Rubiera, 2020)	73%
	81%		

12.1.6.2 Storage

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12.1.6.3 Use

12.1.6.3.1 Carbon Curing

Carbon Curing			
Description: Carbon Curing is the use of CO ₂ to cure precast concrete products. It results in high early strength gain compared to steam hardening, which is the usual method. Typically the process currently uses pure CO ₂ produced industrially, but there is potential for the flue gases from cement plants to be used for the process.			

UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	Pre-cast products	50% emissions reduction of resulting concrete (CarbonBuilt, 2020)	17%
	33%		

12.1.6.3.2 Carbon-based aggregates

Carbon-based Aggregates			
Description: Carbon-based aggregates are those made from reactive CO ₂ with other minerals. This is an emerging technology that can use waste materials from industrial processes and flue gases, or virgin materials and processed CO ₂ . Some processes are able to produce aggregates that are comparable to natural aggregates and can be used in most concrete applications.			
UK Availability	Product Applicability	Unit Potential	Industry Potential
N/A	Non-structural concrete	Carbon-negative aggregates resulting in 11% embodied carbon reduction in concrete (Carey, 2021)	5%
	100%		

12.2 Product Design

12.2.1 Form Design

12.2.1.1 Structural Efficiency

12.2.1.1.1 Layout optimisation

Layout Optimisation			
Description: The layout of a building can have a significant impact on the embodied carbon required to deliver the structure. Typically, the embodied carbon of a building can be reduced by reducing the spans of the building grid, as shown in			
Product Applicability	Unit Potential	Industry Potential	
Buildings	Upto 17% of building frame embodied carbon (Eleftheriadis <i>et al.</i> , 2018)	4%	
26%			

12.2.1.1.2 Lightweighting

Title			
Description: Lightweighting is the practice of reducing the amount of material required to deliver a structure by placing the material only where it is needed. This can be achieved in several ways such as through including voids in slabs and use of elements such as hollow-core flooring.			
Product Applicability	Unit Potential	Industry Potential	
Concrete Slabs	Upto 65% reduction in some cases (e.g., waffle slab vs flat slab) (Drewniok, Orr and Astle, 2020)	8%	
16%			

12.2.1.1.3 Optimising to code limits

Title			
Description: The codes of practice, typically Eurocodes in the UK, demonstrate good practice for the design of structures. However, designers often to do not design to code limits and instead prefer to			

include additional strength than the codes require. The codes are fundamentally designed so that following them is safe and by including additional strength results in more material being used than is actually required for the structure to be safely delivered.

Product Applicability	Unit Potential	Industry Potential
Structural applications 42%	Upto 30% due to underutilisation of structures (Dunant et al. (2021), Shanks et al. (2019), Orr (2011), communication with Ramboll)	13%

12.2.1.2 Design for Deconstruction

12.2.1.2.1 Pre-cast elements

Title		
Description: Pre-cast elements are typically well suited to DfD as they can be assembled on site with mechanical fixings, rather than being cast in-situ. They also can create material efficiencies by being produced in a controlled environment with higher quality and accuracy than can typically be achieved on site in the UK.		
Product Applicability	Unit Potential	Industry Potential
Structural applications 42%	15% reduction compared to in situ casting (Hao <i>et al.</i> , 2020)	6%

12.2.1.2.2 Circular construction materials

Title		
Description: Circular construction materials are those that can be, or have been, taken from one building and re-used in another. One key to enabling circular construction materials is understanding the environment and loading of a structural element throughout its service life or being able to test its characteristics non-destructively. Using these materials can reduce demand for virgin materials.		
Product Applicability	Unit Potential	Industry Potential
Structural applications 42%	18% (Xia, Ding and Xiao, 2020)	8%

12.2.1.2.3 Waste Minimisation

Title		
Description: By re-using or repurposing concrete elements, waste to landfill can be reduced.		
Product Applicability	Unit Potential	Industry Potential
Buildings and infrastructure 38%	33% from design decisions (Pdemanlboroacuk, 2015)	13%

12.2.1.3 Material Selection

12.2.1.3.1 Non-concrete materials

Title		
Description: The use of non-concrete materials can reduce overall demand for cement, where it is possible to provide the same service with another material. For example, it is possible to use timber floor elements in buildings instead of concrete slabs, while providing the same structural performance. Not all concrete or cement usage can be displaced in this way and the availability and suitability of alternative materials needs to be considered on a systematic scale.		

Product Applicability	Unit Potential	Industry Potential
Structural Applications	33% of Year 0 emissions (taken as embodied) (Gustavsson, Pingoud and Sathre, 2006)	14%
42%		

12.2.1.3.2 Local Materials

Title		
Description: The transportation of raw materials for cement and concrete is typically by road in the UK. This results in GHG emissions from the vehicles. Typically, raw materials for cement and concrete are sourced locally to the production point, which is local to the site of use. However, as more alternative materials and SCMs are introduced to the market, the transport emissions can increase if the materials are not available locally. It is possible in some cases for an imported low-carbon cement to have sufficient transport emissions to result in an overall carbon impact that is no lower than the local alternative material.		
Product Applicability	Unit Potential	Industry Potential
All products	2% of lifecycle emissions come from transport, these could be zero-emissions (Pamenter and Myers, 2021)	2%
100%		

12.2.1.4 Design Criteria

12.2.1.4.1 Loading assumptions

Title		
Description: Loading assumptions are applied during the design of a structure and determine the strength required for the structure to operate safely during its lifetime based on the expected loading on the structure. Many of these loading assumptions are provided in the codes of practice and are based on historical practice. It has been indicated by That these assumptions could be much larger than a structure is likely to ever experience during its lifetime and as such it is resulting in excess material being used to provide unnecessary strength in structures.		
Product Applicability	Unit Potential	Industry Potential
Buildings and Infrastructure RMC	10% emissions reduction if designed for 1/3 load. (Drewniok, Orr and Astle, 2020)	4%
38%		

12.2.2 Mix design

12.2.2.1 Strength specification

Title		
Description: When concrete is specified for a design, it is usually specified as a minimum characteristic strength. This does not prevent the concrete provider from increasing the strength of the concrete for their own assurance and usually concrete delivered to site is significantly stronger than required. This is usually achieved through the inclusion of additional cement and as such increases the embodied carbon of the structure compared to its designed embodied carbon.		
Product Applicability	Unit Potential	Industry Potential
Structural applications	50% since mean mix emissions for given strength around 2x current best practice (Damineli <i>et al.</i> , 2010)	24%
47%		

12.3 Concrete Production

12.3.1 Industrial production

12.3.1.1 Admixtures

Title		
Description:		
Product Applicability	Unit Potential	Industry Potential
All RMC 47%	enables clinker replacement of about 20% just admixtures, can use other mix design features to get 40% by weight	9%

12.3.1.2 Aggregate Grading

Title		
Description: Aggregate grading is the practice of using an optimised distribution of aggregate particle sizes in order to maximise the strength of a given concrete.		
Product Applicability	Unit Potential	Industry Potential
All RMC 47%	15% as strength can be increased by 15% allowing equivalent reduction in binder content (Haque and Tuhin, 2012)	7%

12.3.1.3 Carbon-based aggregates

See 12.1.6.3.2.

12.3.1.4 Lightweight aggregates

Title		
Description: Lightweight aggregates are manufactured to reduce the weight and increase the strength of the concrete which includes them. In this way, they can significantly reduce the self-weight of a structure, typically leading to reduced material quantities required, and the binder content required for a given strength.		
Product Applicability	Unit Potential	Industry Potential
All RMC 47%	20% based on 20% binder reduction possible (Kayali, 2008)	9%

12.3.1.5 Recycled Aggregates

Title		
Description: Aggregates can be retrieved from end-of-life concrete through a series of mechanical and chemical processes. These aggregates can then be reused in new concrete products.		
Product Applicability	Unit Potential	Industry Potential
All RMC 42%	Can increase emissions but can reduce by 5-25% when crushed concrete used in RAC, only suitable for less than 45 Mpa (Visintin, Xie and Bennett, 2020)	11%

12.3.2 Increased industrialisation

Title		
Description: Industrialisation shifts the use of merchant cement for self-mix concrete and other products towards centralised production. Centralised production enables a higher level of control over mixes and reduces wastage on-site.		
Product Applicability	Unit Potential	Industry Potential
Merchant cement	Upto 30% through waste reduction (SCRIVENER, 2016)	5%
17%		

12.4 Concrete Usage

12.4.1 Wet concrete

12.4.1.1 Product specification

See 12.2.2.1

12.4.1.2 Waste reduction

Title		
Description: By ensuring the correct amount on concrete is ordered and through smart management techniques, the amount of RMC that goes to waste can be reduced.		
Product Applicability	Unit Potential	Industry Potential
All RMC	9% if all waste can be eliminated	4%
47%		

12.4.2 Pre-fabrication

12.4.2.1 Precast elements

See 12.2.1.2.1

12.4.2.2 Carbon Curing

See **Error! Reference source not found.**

12.4.2.3 Digital production

Title		
Description: Digital production methods such as 3D printing of concrete are enabling increased precision manufacturing of pre-cast parts and even in-situ production. This can reduce the amount of material needed to achieve structural strength due to complex forms being possible.		
Product Applicability	Unit Potential	Industry Potential
Buildings	12% savings shown to be possible on walls, assumed able to apply to other building elements	3%
26%		

12.5 Product Operation

12.5.1 Increased Utilisation

12.5.2 Space sharing

Title		
Description: By increasing the utilisation, such as 'shift' uses of buildings, the demand for new buildings can be reduced, in turn reducing demand for cement.		
Product Applicability	Unit Potential	Industry Potential
Buildings	Not currently quantified	N/A
26%		

12.5.3 Durability improvements

Title		
Description: Increasing durability of concrete elements, through use of different mixes, can increase the lifetime of elements and reduce the concrete/cement required for repairs or replacements.		
Product Applicability	Unit Potential	Industry Potential
All cement and products	Not currently quantified	N/A
100%		

12.5.4 Life extension

Title		
Description: Increasing the design life and using life-extension techniques instead of demolition can reduce the life-cycle emissions of a structure.		
Product Applicability	Unit Potential	Industry Potential
All cement and products	Not currently quantified	N/A
100%		

12.6 Material Recovery

12.6.1 Recycling

12.6.1.1 Recycled aggregates

See 12.3.1.5

12.6.1.2 Recycled cement paste

Title		
Description: Processes are being developed that can extract cement paste from end-of-life concrete and prepare it for use in new concrete products.		
Product Applicability	Unit Potential	Industry Potential
All cement	Not yet quantified (Wang, Mu and Liu, 2018)	N/A
89%		

12.6.2 Reuse

12.6.2.1 Circular construction materials

See 12.2.1.2.2

12.6.3 Downcycling

12.6.3.1 Enforced carbonation

Title		
Description: Crushed end-of-life concrete can be exposed to atmospheric or captured CO ₂ in order to increase the carbonation of the material. This can be used to sequester CO ₂ .		
Product Applicability	Unit Potential	Industry Potential
All cement products	5.5% of lifecycle emissions (Kikuchi and Kuroda, 2011)	6%
100%		

13 Appendix D

Direct Separation Carbon Capture

Direct Separation Carbon Capture CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5										
4		◆				◆				
3	3			◆			◆		◆	◆
2					◆			◆		
1										

OxyFuel Carbon Capture

OxyFuel Carbon Capture CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5										
4		◆								
3				◆		◆				◆
2	2				◆		◆	◆	◆	
1										

Biomass Ash SCM

Biomass Ash SCM CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3			◆							
2	2	◆		◆	◆	◆	◆	◆	◆	◆
1										

Calcined Clay SCM

Calcined Clay SCM CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5										
4					◆	◆				
3	3	◆		◆			◆	◆	◆	
2										◆
1										

LC3 Cement

LC3 Cement CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆	◆				
3	3		◆	◆			◆		◆	
2		◆						◆		◆
1										

Electrification

Electrification CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3	3	◆	◆	◆		◆	◆			
2					◆			◆	◆	◆
1										

Hydrogen for Process Energy

Hydrogen CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3		◆			◆	◆				
2	2		◆	◆			◆	◆	◆	◆
1										

MOMS

MOMS CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3					◆					
2	2	◆	◆	◆		◆		◆		◆
1							◆		◆	

Post Combustion Carbon Capture

Post Combustion Carbon Capture CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5										
4		◆				◆				
3	3			◆	◆		◆			◆
2								◆	◆	
1										

Structural Efficiency

Structural Efficiency CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5	5	◆			◆	◆			◆	◆
4				◆			◆	◆		
3										
2										
1										

Lightweighting

Lightweighting CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5					◆	◆				◆
4	4	◆		◆			◆	◆		
3									◆	
2										
1										

Existing Low Carbon Blended Cements for Strength Specification

Existing Low Carbon Blended Cements CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5	5	◆			◆	◆	◆	◆		
4				◆					◆	◆
3										
2										
1										

Admixtures

Admixtures CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆	◆			◆		◆	◆
5		◆			◆	◆		◆		
4										
3										
2										
1										

Product specification by embodied carbon

Embodied Carbon Specification CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5					◆					
4						◆	◆	◆		
3		3	◆	◆	◆				◆	◆
2										
1										

Fillers

Fillers CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆				◆			
5	5	◆		◆	◆	◆		◆		◆
4										
3									◆	
2										
1										

Biomass Fuel

Biomass Fuel CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6		◆		◆	◆					◆
5	5		◆			◆	◆	◆	◆	
4										
3										
2										
1										

CCSC

CCSC Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆	◆	◆			
3	3	◆	◆	◆					◆	
2								◆		◆
1										

Biocement

Biocement CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆					
3			◆			◆	◆		◆	
2	2	◆		◆				◆		◆
1										

Optimising to Code Limits

Code Limits CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆		◆					
5		◆				◆		◆		
4	4			◆			◆			◆
3									◆	
2										
1										

Waste Minimisation

Waste Minimisation CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5	5	◆			◆	◆	◆	◆		◆
4				◆					◆	
3										
2										
1										

Non-concrete materials

Non-concrete materials CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆	◆	◆	◆	◆			◆
5		◆						◆	◆	
4										
3										
2										
1										

Carbon Curing

Carbon Curing CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆	◆				
3		3	◆	◆	◆			◆		
2									◆	◆
1										

Waste Fuel

Carbon Curing CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆		◆		◆	◆		◆
5		◆		◆		◆			◆	
4										
3										
2										
1										

Kiln Efficiency

Kiln Efficiency CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆	◆	◆	◆		◆		◆
5		◆					◆		◆	
4										
3										
2										
1										

Electrical Efficiency

Electrical Efficiency CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆	◆	◆	◆		◆		◆
5		◆					◆		◆	
4										
3										
2										
1										

Activation Agents

Activation Agents CRI Assessment											
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity	
6											
5							◆				
4		4			◆	◆	◆		◆	◆	
3			◆	◆						◆	
2											
1											

Strengths Enhancers

Strength Enhancers CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5							◆			
4	4			◆	◆	◆		◆		◆
3		◆	◆						◆	
2										
1										

Reactive Belite-rich Portland Cement (RBPC)

Reactive Belite-rich Portland Cement CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3		◆	◆		◆	◆				
2	2			◆			◆	◆	◆	◆
1										

Belite -Ye'elemite-Ferrite Clinkers (BYF)

BYF CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3					◆					
2		◆	◆			◆				
1	1			◆			◆	◆	◆	◆

Hydraulic CSC

Hydraulic CSC CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3										
2		◆			◆	◆				
1	1		◆	◆			◆	◆	◆	◆

Non-PFA/GGBS AAMs

Non-PFA/GGBS AAMs CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4						◆				
3	3	◆	◆	◆	◆		◆			
2								◆	◆	◆
1										

Carbon-based aggregates

Carbon-based Aggregates CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆	◆				
3		◆		◆			◆			
2	2		◆					◆	◆	◆
1										

Pre-cast elements

Pre-cast Elements CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆		◆	◆	◆	◆	◆	◆
5		◆		◆						
4										
3										
2										
1										

Circular Construction Elements

Circular Construction Elements CRI Assessment											
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity	
6											
5											
4											
3		3	◆		◆	◆	◆	◆	◆		◆
2				◆						◆	
1											

Local Materials

Local Materials CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6	6		◆	◆	◆		◆	◆		
5		◆				◆			◆	◆
4										
3										
2										
1										

Loading Assumptions

Loading Assumptions CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6			◆							
5		◆			◆	◆	◆		◆	◆
4				◆				◆		
3										
2										
1										

Aggregate grading

Aggregate Grading CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6							◆			◆
5	5	◆	◆		◆	◆				
4				◆				◆	◆	
3										
2										
1										

Digital Production

Digital Production CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4					◆					
3			◆			◆	◆			
2	2	◆		◆				◆	◆	◆
1										

Accelerated Carbonation

Accelerated Carbonation CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3	3		◆		◆	◆	◆	◆	◆	
2		◆		◆						◆
1										

Recycled Aggregates

Carbon Curing CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5			◆		◆	◆				◆
4	4			◆			◆	◆	◆	
3		◆								
2										
1										

Recycled Cement Paste

Carbon Curing CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3									◆	
2	2	◆	◆	◆	◆	◆				
1							◆	◆		◆

Energetically Modified Cements

Energetically Modified Cements CRI Assessment										
Level	Summary CRI	Regulation: Policy	Regulation: Technical Standards	Stakeholder Acceptance	Technical Performance	Financial Performance	Industry Supply Chain	Industry Skills	Market Opportunities	Company Maturity
6										
5										
4										
3					◆				◆	
2	2	◆	◆	◆		◆	◆	◆		◆
1										

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