RILEM Technical Letters (2023) 8: 94-105
https://doi.org/10.21809/rilemtechlett.2023.163

Cement and concrete decarbonisation roadmaps – a meta-analysis within the context of the United Kingdom

Alastair T.M. Marsh[1]*, Thomas Dillon[1], Susan A. Bernal[1]

[1] School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom

Received: 01 June 2022 / Accepted: 11 October 2023 / Published online: 24 November 2023

Abstract

Decarbonisation is the most urgent issue facing the cement and concrete industries, with an aim to reach net-zero carbon dioxide emissions by 2050. In response to this, several decarbonisation roadmaps have been published in recent years, to explore routes for how different decarbonisation strategies can be used to achieve this aim. However, there is a lack of understanding around the similarities and differences between these roadmaps. In this study a meta-analysis of nine cement and concrete sector roadmaps was conducted, with a detailed focus on five roadmaps covering Europe emphasising their applicability within the context of the United Kingdom. Whilst there are some similarities amongst roadmaps in terms of the decarbonisation strategies which are consistently recommended, there are also key differences. Industry roadmaps oriented towards cement-based strategies, whilst non-industry roadmaps were more inclusive of concrete-based strategies. The significance of this study is to highlight the difficulties faced by policymakers and investors in choosing which strategies to prioritise, when there is still considerable uncertainty in the roadmap literature. Recommendations are made for a greater focus on consideration of the construction sector practices which provide more autonomy to practitioners to adopt and implement concrete-based strategies and dematerialisation in future iterations of industry roadmaps, and more research into the capital and operating costs of technological innovations.

Keywords: Cement; concrete; decarbonisation; technological roadmapping

1 Introduction

Increasing performance requirements and decarbonisation are the most urgent drivers of research and innovation in the cement and concrete sector – these have driven the development of several new technologies and strategies in recent years [1, 2]. 2050 is the year which most decarbonisation targets are set for, in line with the Paris Agreement's aim to achieve a climate neutral world by the middle of the century, and also in line with numerous individual countries' targets.

In order to help meet this challenge, several decarbonisation roadmaps have been published by - and for - the cement and concrete industries in recent years. The use of roadmaps is believed to have first began in US companies and organisations in the 1960s [3]. There are several different types of roadmaps, which can be categorised (such as in the taxonomies described by Kappel [4] and Phaal et al. [5]) on the basis of what their purpose is, who has produced them, and how they are presented. Across their diversity, there is a common ground in their broad aim to "*identify, evaluate, and select strategic alternatives that can be used to achieve a desired science and technology objective*" [6]. However, in practice, terminology can be fluid with roadmaps, route maps and pathways all used to describe similar documents about decarbonisation strategies [7].

Given the increasing numbers of decarbonisation roadmaps emerging for energy-intensive industries (including cement and concrete), recent research has conducted comparative analyses between roadmaps. Johnson et al. [7] conducted an analysis of 29 roadmaps across a range of heavy industries across 13 countries. The analysis focussed on the extent to which roadmaps covered aspects of technology, policy and finance. A common criticism was made at the techno-centric focus of roadmaps, especially the policy recommendations, which neglected broader, social aspects of sustainability. Whilst cement was included within the scope of the energy-intensive industries, there was no specific analysis of the cement sector. Gerres et al. [8] took a European geographic scope, emphasising cross-sectoral comparisons and the extent to which decarbonisation strategies are shared across sectors. Their key findings were that certain technologies and strategies (e.g. heat recovery, electrification) can be transferred across sectors, but breakthrough technologies (e.g. carbon capture and utilisation/storage, CCUS) are also necessary in order to deliver the scale of carbon mitigation required. Whilst cement was included within the scope of the energy-intensive industries, the sector-specific analysis was

*Corresponding authors: Alastair T.M. Marsh, e-mail: A.Marsh@leeds.ac.uk

relatively brief as the study focussed on cross-sectoral comparisons.

A strength of these previous studies is their cross-sectoral perspective. However, a consequent limitation of their breadth is that detailed analysis of the cement and concrete sectors' decarbonisation roadmaps remains unexplored. Furthermore, technical discussion has focussed at the cement plant level, with relatively little evaluation of the influence of downstream strategies in the concrete industry and construction sector. Given arguments about how some degree of dematerialisation will be unavoidable in the pursuit of sustainable development [9, 10], it is important to evaluate the extent to which roadmaps consider material demand reduction strategies.

The type of actor that has created a roadmap is a crucial, non-technical aspect that is sometimes overlooked. Roadmaps rely on interpreting existing data and making assumptions about the future, so they are always subjective to some degree [4]. The author(s) and commissioning institution(s) of a roadmap is therefore an important detail - previous research has highlighted trends and biases amongst different actors in the construction materials sector. Incumbent companies (and the industry associations which represent them) have been characterised as focussing on process innovations, rather than on product innovations [11] or more radical transformations [12]. Whilst roadmaps' content is largely technical, they involve partially subjective judgements on which strategies should be used to achieve decarbonisation – thus, they also fulfil a socio-political function. In their analysis of cement and concrete innovation in the Netherlands, Wesseling and Van der Vooren [13] argued that roadmaps are used by incumbent actors to lobby against policies which incentivise disruptive change, and instead, they are used to help maintain the status quo. The cement and concrete industry has a reputation as technologically conservative and risk-averse [14] – it is not well understood whether this reputation is also reflected in industry roadmaps' approaches to decarbonisation. Investigating the trends around decarbonisation strategies amongst industry and non-industry actors is therefore valuable, to help navigate the complexity and scale of the decarbonisation challenge.

Policymakers face questions around which strategies to support, and how to support them, in order to accelerate decarbonisation of the cement and concrete sector. But presently, policy recommendations lag behind technical recommendations in the literature [15]. Having numerous different roadmaps on cement and concrete decarbonisation can offer a useful diversity of perspectives; but such diversity in approaches and recommendations does not necessarily offer a clear direction for non-specialists. So far, no research has been carried out to assess the similarities and differences between roadmaps around which different decarbonisation strategies are recommended, and what their respective mitigation potential is. This study is hence expected to be useful for both policymakers and investors.

In this study, a semi-quantitative analysis was undertaken on nine decarbonisation roadmaps for the cement and concrete industry, with a more detailed comparison of decarbonisation potential of different individual strategies carried out on five of these roadmaps. The geographical focus was on Europe emphasising their applicability to the United Kingdom, and the study sought to answer the following questions:

1. What trends exist between actor type (i.e. industry/non-industry) and the range of strategies included in decarbonisation roadmaps?
2. What are the similarities and differences between roadmaps regarding the decarbonisation potential of individual strategies?

2 Methods

2.1 Scope of study

Whilst the criteria for defining a roadmap are somewhat flexible [7], the scope of this study was limited to publications which were principally disseminated outside of academic journals (but not discounting academic authors per se). This restriction was used to limit the scope to roadmaps which were most likely to be read by (and hence influence) stakeholders within the value chain of the construction sector, policy and governmental audiences. In terms of geographical scope, it was chosen to focus on the cement and concrete sectors in Europe emphasising the United Kingdom. Out of the seven cement companies operating in the United Kingdom, five of these companies (operating 13 out of a total of 15 sites) are subsidiaries of multi-national parent companies with their headquarters and research and innovation facilities based in other countries, primarily in continental Europe (i.e. Heidelberg Cement, CRH, Imerys, Holcim) and other world regions (i.e. CEMEX) [16]. Therefore, it is relevant to give comparisons of United Kingdom roadmaps with roadmaps with a European and global scope, as decisions made around United Kingdom cement production and innovation have a strong international influence. Furthermore, the United Kingdom and Europe largely share alignment to the same set of standards defining cement and concrete specification (e.g. EN 197-1:2011 [17]). The same approach to geographical scope was used by Pamenter and Myers [18] to assess decarbonisation of cementitious materials in the United Kingdom and Europe. The scope was also limited to roadmaps available in English. In total, nine roadmaps were selected for analysis (Table 1), which covered a range of both geographic scope (i.e. United Kingdom, Europe and Global) and actor type (i.e. industry or non-industry) [19-27]. All were published within a 7 year window; with the exception of Roadmap H, the baseline years used to calculate emissions reductions were within an eight year window. All nine roadmaps were analysed to investigate trends linking actor type with material scope (Section 2.2.3) and specific strategies (Section 2.2.4); five of these roadmaps were analysed in more detail to compare the decarbonisation potential of individual strategies (Section 2.2.6).

Table 1: Details of the roadmaps used in this study. Intensity targets = metric of embodied CO_2 per mass of cementitious material; absolute targets = metric of absolute volumes of CO_2.

Code	Title	Commissioning institution	Regional scope	Publication year	Actor type	Target type	Baseline year
A	Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Cement [19]	Department for Business, Energy & Industrial Strategy	United Kingdom	2015	Non-industry	Absolute	2012
B	UK Concrete and Cement Industry Roadmap to Beyond Net Zero [20]	Mineral Products Association	United Kingdom	2020	Industry	Intensity	2018
C	Low carbon concrete routemap: setting the agenda for a path to net zero [21]	Low Carbon Concrete Group	United Kingdom	2022	Industry	n/a	n/a
D	A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050 [22]	European Climate Foundation	Europe	2018	Non-industry	Absolute	2015
E	Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry [23]	European Climate Foundation	Europe	2019	Non-industry	Absolute	2015
F	Cementing the European New Deal: Reaching Climate Neutrality Along the Cement and Concrete Value Chain [24]	The European Cement Association	Europe	2020	Industry	Intensity	2017 / 1990
G	Making Concrete Change: Innovation in Low-carbon Cement and Concrete [25]	Chatham House	Global	2018	Non-industry	n/a	n/a
H	Our Contribution Towards a Carbon Neutral World [26]	CEMEX	Global	2020	Industry	Absolute	1990
I	The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete [27]	Global Cement and Concrete Association	Global	2021	Industry	Absolute	2020

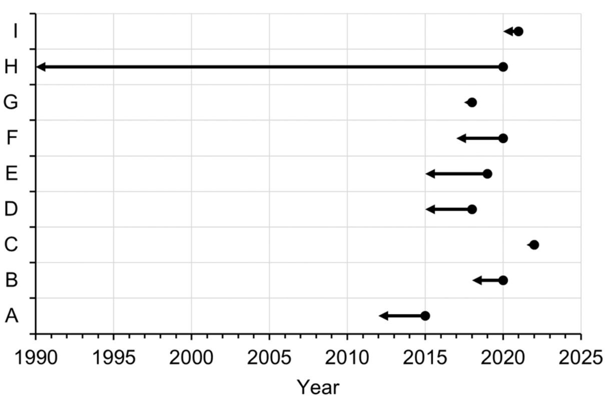

Figure 1: Overview showing the difference between publication year (circle) and base year (arrow) for each roadmap. Roadmaps C and G did not use a base year in their content.

2.2 Methods of analysis

The overall approach used was a semi-quantitative meta-analysis, based on categorising the roadmaps' key attributes. This approach has previously been used in studies on energy-intensive industries' roadmaps [7, 8], and so is appropriate to apply it to the cement and concrete sector. A brief summary of the analysis approach is given here, with detailed descriptions provided in the Supplementary Information.

2.2.1 Determining characteristics of the roadmaps

Actors were grouped as industry or non-industry, and assigned on the basis of the commissioning institution(s) and author(s) for each of the nine roadmaps. This is similar to the categorisation used by Johnson et al. [7], albeit it was decided to use a single category for non-industry actors due to the smaller number of roadmaps under consideration. The industry category included all private sector companies (e.g. consultancies), as well as trade associations and individual cement companies. Non-industry actors included governments, think tanks and other non-governmental organisations. Roadmaps are always subjective to some degree, as they rely on interpretation and prediction of existing data [4]. Therefore, categorisation between actor types is an important aspect of analysis to identify whether there are trends within, and between, industry and non-industry roadmaps.

2.2.2 Assigning material scope to decarbonisation strategies

A condensed list of sixteen distinct decarbonisation strategies was generated from the strategies described in the nine roadmaps, in a similar approach to Gerres et al. [8]. Each strategy was assigned as either a cement strategy or a concrete strategy (Table 2), on the basis of whether they applied primarily to cement or concrete. Full definitions and descriptions of the sixteen strategies are given in Supplementary Information Section S1.

Table 2: Classification of decarbonisation strategies into material scope categories of cement and concrete.

Material scope	Strategy
Cement	Clinker Replacement Alternative Binders Decarbonisation of Electricity Decarbonisation of Transport Carbon Capture and Utilisation/Storage (CCUS) Alternative Fuels Electrification Thermal Efficiency Improvements Re-carbonation Recycling of Concrete Fines
Concrete	Concrete Mix Design Optimisation Reduction of Over-specification Improved Design of Structural Elements Extended Building Lifetime Alternative Construction Materials Leveraged Thermal Mass

2.2.3 Determining material scope of the roadmaps

To make a semi-quantitative comparison around the level of detail in which different strategies were considered within the nine roadmaps, each strategy was assigned a weighting from 0 - 3 depending on its prominence within a given roadmap. This is similar to the approach used by Johnson et al. [7] to assess the level of detail of strategies in heavy industry decarbonisation roadmaps. These weightings were then used to determine whether each roadmap had a 'cement oriented' material scope (i.e. primarily focussed on cement strategies), or a 'cement and concrete oriented' material scope (i.e. an approximately even coverage of both cement and concrete strategies). Details of these weightings are given in Supplementary Information Section S2.

2.2.4 Determining existence of trends between strategies and actor type

To investigate the existence of any trends between actor type and the promotion of particular decarbonisation strategies, the average of the weightings for each strategy (as described in Section 2.2.3) from roadmaps of each Actor Type were calculated. These average weightings were then used to determine whether each strategy was favoured by industry roadmaps, favoured by non-industry roadmaps, or not favoured by either actor type. Details of these average weightings are given in Supplementary Information Section S3.

2.2.5 Determining Technology and Market Readiness Level (TMRL) range for each strategy

To compare the decarbonisation strategies, Technology and Market Readiness Level (TMRL) was used as a semi-quantitative measure of technological maturity. The Readiness Level scale developed by the International Energy Agency's ETP Clean Energy Technology Guide [28] was adopted for this study – this is compatible with conventional Technology Readiness Level scales from 1 to 9, but adds two extra levels of 10 and 11 to describe market readiness. This scale was used, as the highly time-sensitive nature of achieving decarbonisation by 2050 makes market readiness (beyond technology readiness) a critical factor to consider. The TMRL of each strategy was adopted from the ETP Clean Technology Guide [28] if available, and if not, was determined using information collated from the nine roadmaps and supplemented with other sources. These values are based on the best available information that is publicly accessible – due to the nuances between neighbouring levels, these values should be considered as indicative, rather than definitive. Some strategies were assigned a range of TMRLs, reflecting the diversity of technological maturity for different technologies in development within that strategy. Full details and descriptions of the TMRLs are given in Supplementary Information Section S4.

2.2.6 Determining carbon reduction potential for each strategy

From the values given in each roadmap, estimates were made for the anticipated carbon reduction to concrete production in 2050 from each roadmap, in a similar approach to Gerres et al. [8]. In order to achieve a fair comparison between roadmaps of the same regional scope, only the roadmaps which covered the United Kingdom or Europe, and contained quantitative mitigation estimates, were used. Five roadmaps (A, B, D, E, F) out of the nine roadmaps met these criteria, and were therefore used in this analysis. These estimated mitigation values are intended to be indicative and semi-quantitative - this is due to the differences in methodological approach, presentation of data and base year (Figure 1) between the roadmaps. Detailed workings for these carbon reduction potential values are given in Supplementary Information Section S5.

3 General characteristics of the roadmaps

The majority of the roadmaps used a base year within 3 years previous to the publication year (Figure 1). The choice of base year for emissions reduction targets is important, as the choice of an earlier year can give an impression of exaggerated progress [29]. The notable exception is Roadmap H, which used 1990 as a base year. 1990 is an influential year, as both the International Energy Agency and the European Commission use it as a base year. Each choice of base year presents pros and cons. Using the most recent year (for which data is available) gives the clearest evaluation of performance in upcoming years, but also causes difficulties for comparison since base years will vary between different roadmaps. Using 1990 aligns with established approaches, but can give a false impression of progress. For example, the majority (30% out of a 40% total) of the carbon reductions in Europe from 1990-2015 were attributed to a slump in demand for cement following the economic crisis of 2008 [22]. A compromise may be for roadmaps to present estimated mitigation relative to both a 1990 base year and a base year of the most recent year (as was partially done in Roadmap D). However, this additional information may risk making the roadmaps too complicated to interpret effectively.

In terms of target year, all roadmaps considered a principal target year of 2050, with some (Roadmaps C and H) also considering nearer term target years of 2030 or 2035. 2050 is a universal target year given that the Intergovernmental Panel on Climate Change (IPCC) has recommended that to stay below 1.5°C of warming, net zero GHG emissions must be achieved by 2050 [30]. Whilst there is evidence to suggest that long-term targets (such as to 2050) are more effective for reducing emissions compared to short-term targets alone, a combination of both is proposed as best [31]. Moreover, to stay within 1.5°C of warming it is recommended to reduce global greenhouse gas emissions by 45% (relative to a 2010 base year) by 2030 [30]. Therefore, future iterations of roadmaps could benefit from adopting nearer-term targets (i.e. for a 2030) in addition to the ultimate goal of net zero for 2050.

In terms of the type of target used, intensity targets use a metric of embodied CO_2 per mass of cementitious material, whereas absolute targets use a metric of absolute volumes of CO_2 [32]. Five roadmaps used absolute targets and three roadmaps used intensity targets (Table 1). Out of the industry roadmaps, two used intensity targets (Roadmaps B and F) and two used absolute targets (Roadmaps H and I). Intensity targets are recommended for the cement industry by the Sectoral Decarbonisation Approach [33], adopted by the Science-Based Targets Initiative (SBTI) [32]. However, SBTI recommend that absolute-based targets are more appropriate for companies which produce concrete (but not cement) and construction companies which use cementitious products [34]. Moreover, the use of absolute targets is associated with more successful emissions reductions compared to the use of intensity targets [31]. For roadmaps that cover both the cement and concrete sector, it is therefore not straightforward what the most appropriate target type is. Whilst a joined-up approach is vital from a life cycle perspective, it does not necessarily align with reporting conventions for individual companies who only operate over a part of cement and concrete's life cycle - this illustrates the socio-technical challenges in producing roadmaps for the cement and concrete sector.

4 Influence of actor type on roadmap scope

The roadmaps analysed in this study included both industry and non-industry actors, for regional scales spanning the United Kingdom, Europe and worldwide. Comparing the material scope of the roadmaps (Figure 2), the majority of non-industry actors' roadmaps had a 'cement and concrete oriented' scope, whereas the majority of industry actors' roadmaps had a 'cement oriented' scope.

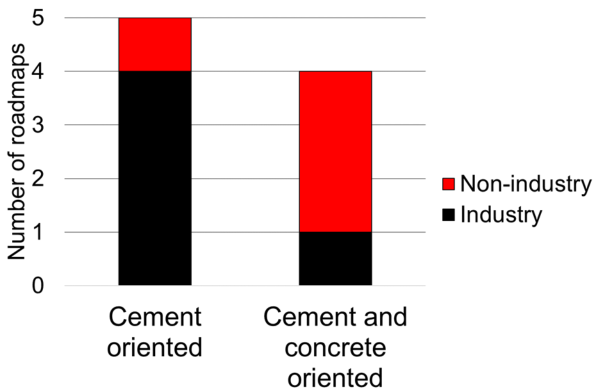

Figure 2: The distribution between material scope and actor type, for the roadmaps analysed.

Considering the individual decarbonisation strategies included in each roadmap - four strategies were favoured by all actors, and six other strategies were not heavily favoured by either industry or non-industry actors (Table 3). In contrast, four strategies were favoured by industry actors and two strategies were favoured by non-industry actors (Table 3).

Table 3: Summary of trends identified between strategies and actor type. * denotes strategies which were included within all the roadmaps.

Strategies favoured for consideration within roadmaps by:		
***All* actors / *No* trend**	***Industry* actors**	***Non-industry* actors**
Clinker replacement* Alternative binders* Carbon capture and utilisation/storage (CCUS)* Alternative fuels* Thermal efficiency improvements Improved design of structural elements Extended building life Decarbonisation of electricity Recycling of concrete fines Concrete mix design optimisation	Decarbonisation of transport Electrification Re-carbonation Leveraged thermal mass	Reduction of over-specification Alternative building materials

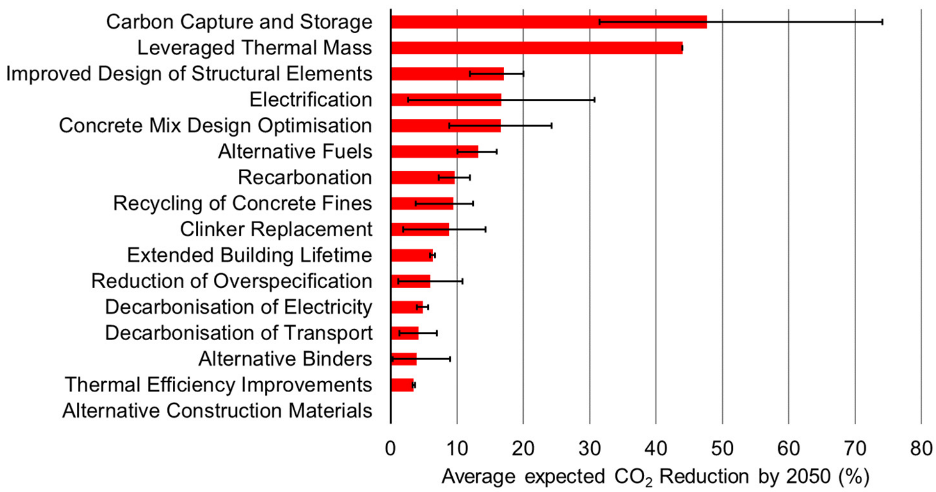

Figure 3: The average expected CO_2 reduction by 2050 for each strategy. Whisker bars are used here to show the minimum and maximum values for each strategy across the roadmaps analysed[a].

The trends described in Table 3 broadly agree with previous research [11] – that incumbent industry actors and their trade associations have historically preferred to focus on process innovations (i.e. electrification, alternative fuels, thermal efficiency improvements, CCUS), rather than product innovations. However, this analysis shows industry actors do advocate some product innovations (i.e. clinker replacement, alternative binders) in addition to process innovations.

The industry roadmaps generally showed an orientation towards cement strategies (Figure 2). Cement dominates the embodied carbon of concrete, despite being the minority component by mass; at the same time, the volume of concrete used in construction, and the volume of cement used in a concrete mix, together determine the demand for how much cement is used. Given the complexity of how different factors can influence absolute emissions, it is helpful to look at the orientation towards different strategies from a socio-technical perspective, and examine the role of emissions reporting. Whilst many terminologies exist for reporting emissions [35], the GHG Protocol terminology of Scope 1, 2 and 3 emissions is widely accepted among companies [36]. For a company that principally produces cement: Scope 1 emissions correspond to direct emissions associated with cement production (e.g. combustion of fuels, process emissions); Scope 2 emissions correspond to indirect emissions arising from purchased electricity; and, Scope 3 emissions correspond to other indirect emissions arising from both upstream activities (e.g. transport and distribution) and downstream activities (e.g. concrete made by other companies from the cement produced) [34]. In comparison, for a concrete company that does not produce its own cement, the production emissions of the purchased cement would classify as Scope 3 upstream emissions. This distinction is important, as historically, there has been a lesser focus on Scope 3 emissions reporting [35], and guidance for the cement sector is more straightforward for reporting Scope 1

[a] The absence of a whisker bar for “Leveraged Thermal Mass” is used to show that an estimate for decarbonisation potential was found in only one of the roadmaps analysed (Roadmap B) – hence there was no minimum-maximum range.

and 2 emissions [34]. These differences in emissions reporting do not feature strongly in a purely scientific perspective; however, from a socio-technical perspective, a greater emphasis on Scope 1 and 2 emissions in companies' emissions reporting may help explain the general orientation towards cement strategies in industry roadmaps.

For strategies that do not sit within existing business models (i.e. reduction of over-specification, alternative building materials), a general trend was observed – they were relatively neglected by industry roadmaps, and favoured by non-industry roadmaps. This trend could be interpreted from an economic perspective as incumbent firms being unwilling to engage with radical strategies in order to uphold existing business models and maintain market share [12], due to the derived complexities associated with departing from prescriptive design standards and its associated risk, and the consequent difficulties in complying with insurance companies' requirements. From a technical perspective there is conservatism to new approaches [14]. In reality, it is expected that both technical and economic considerations will influence the orientation of industry roadmaps.

5 Decarbonisation potential of individual strategies

Comparison of the decarbonisation potential of various strategies was carried out for the five roadmaps which covered Europe and the United Kingdom, and contained quantitative estimates for strategies' decarbonisation potential. This yielded a large range of values, with an order of magnitude difference between some strategies (Figure 3).

It is useful to compare these values against similar emissions reduction estimates, also for the European and United Kingdom context, from the study of Pamenter and Myers [18]. In their study, the five strategies with highest decarbonisation potential were alternative binders (<28%), electrification (23%), CCUS (21%), clinker replacement (<21%), and reduction of overspecification (<13%). Only two of these (CCUS and electrification) match the top five from Figure 3. Whilst some strategies have similar values for decarbonisation potential between the two studies (e.g. electrification, decarbonisation of electricity), the majority differ by >10%. The extent of the differences between the two studies is not surprising – as the authors observed, there is a great diversity in the literature in terms of scope, method, assumptions and reproducibility [18]. Nonetheless, this highlights how estimating the decarbonisation potential of different strategies, even those which are technologically and commercially mature, has inherent uncertainty.

Whilst the mitigation potential of all strategies has an unavoidable degree of uncertainty, the magnitude of uncertainty is far higher for some than for others. These uncertainties have three main causes:

1. Uncertainty over the effectiveness of immature technologies (e.g. CCUS). There is also a lack of reliable data for end-of-life technologies (e.g. recycling of concrete fines) [18].
2. Dependencies on other industrial systems. For example, the mitigation potential of electrification depends on the carbon factor of grid electricity (Scope 2 emissions), a factor which is largely outside of the direct control of cement and concrete producers.
3. Uncertainty in modelling the extent of market penetration for different strategies in the future. This applies both to upstream strategies in cement production (e.g. CCUS) as well as downstream strategies in concrete production (e.g. concrete mix design optimisation), structural design (e.g. improved design of structural elements) and service life management (extending building lifetime). Gerres et al. [8] identified the extent of market penetration as a key factor of uncertainty for a range of other energy-intensive industries.

Another key aspect of individual decarbonisation strategies is their TMRL. In order to achieve net zero carbon dioxide emissions (or as close as possible) by 2050, innovations need to be able to be deployed at scale before 2050, and preferably as soon as possible. Numerical values for estimated mitigation potential and TMRL are listed in Table 4; descriptions of how these values were obtained are given in detail in Supplementary Information sections S4 and S5. Comparing plots of mitigation potential against TMRL (Figure 4), the concrete strateies typically had a higher TMRL than the cement strategies.

Clinker substitution is one of the most widely endorsed strategies, both for its efficacy and TMRL. Its estimated mitigation potential - in relation to other strategies in Figure 3 - might therefore seem surprisingly low. Roadmaps D and E assumed a clinker factor of 0.6 in 2050, relative to a European average of 0.73 - 0.74 for a baseline year of 2015. These estimates represent a reduction of 0.13 in average clinker factor by 2050 – this is a modest but nonetheless important improvement. Whilst lower clinker factors are possible for some applications, an average of 0.6 is a plausible target that agrees with other sources [37]. The progress already achieved in reducing average clinker factor explains the relatively low estimated mitigation potential of the clinker substitution decarbonisation strategy.

Amongst the other strategies, two were reported to have substantially higher mitigation potential than the rest: CCUS and leveraged thermal mass.

CCUS is the individual strategy with both the highest mitigation potential, and the highest uncertainty in mitigation potential (a range of 31.5 – 71.4%). The range of different technologies under development [38, 39] is reflected in the wide range of TMRL values (4 - 8). An extremely rapid rate of technological development and market adoption will be required for CCUS to meet these estimates. The four large-scale CCUS projects currently under development or operation, reported by Plaza et al. [40], span a range of capture rates of 0.1 – 2 Mt.CO_2/year. And yet in 2050, Roadmap I [27] estimates a global capture rate from CCUS of 1370 Mt.CO_2/year. This represents a scale-up in capture capacity of 2 to 3 orders of magnitude, over less than two decades. This is not only extremely ambitious, but also represents an unprecedented scale of coordinated action in the cement sector. Even if technological development proceeds unhindered, there are many practical issues which may threaten this ambition. These include: the limitations and difficulties in retrofitting existing plants [38, 40], associated capital and operating costs [41], and, compatibility, availability and reliability of CCUS infrastructure [2, 42]. The prominence of CCUS in industry roadmaps indicates significant industrial support - yet considering the evidence available so far, reliance on CCUS as the single largest mitigation strategy represents a major risk to achieving 2050 decarbonisation targets.

Leveraged thermal mass is given a high mitigation potential (44.0%) by Roadmap B, but is not included in the other four roadmaps. The design of buildings with high thermal mass is a well-established design strategy for reducing operational carbon, by achieving passive regulation of indoor temperature. However, its inclusion as a decarbonisation strategy for the cement and concrete industry is controversial. Operational emissions in buildings are classified as Scope 3 indirect emissions for the cement and concrete industry, and its use in design is not within the control of cement and concrete producers. Furthermore, the design of buildings that achieve high thermal mass (by the use of concrete) necessitates the use of greater volumes of concrete, and hence results in higher embodied carbon [43]. This strategy would then seem to be in direct conflict with the strategy of "improved design of structural elements". It has been argued that (in some scenarios) the operational carbon savings over a building's lifetime outweigh the higher embodied carbon [43]; however, the balance of such carbon costs and savings depends on numerous factors (inc. climate, heating method) [44]. For these reasons, and its inclusion in only one roadmap, leveraged thermal mass is an outlier amongst cement and concrete decarbonisation strategies.

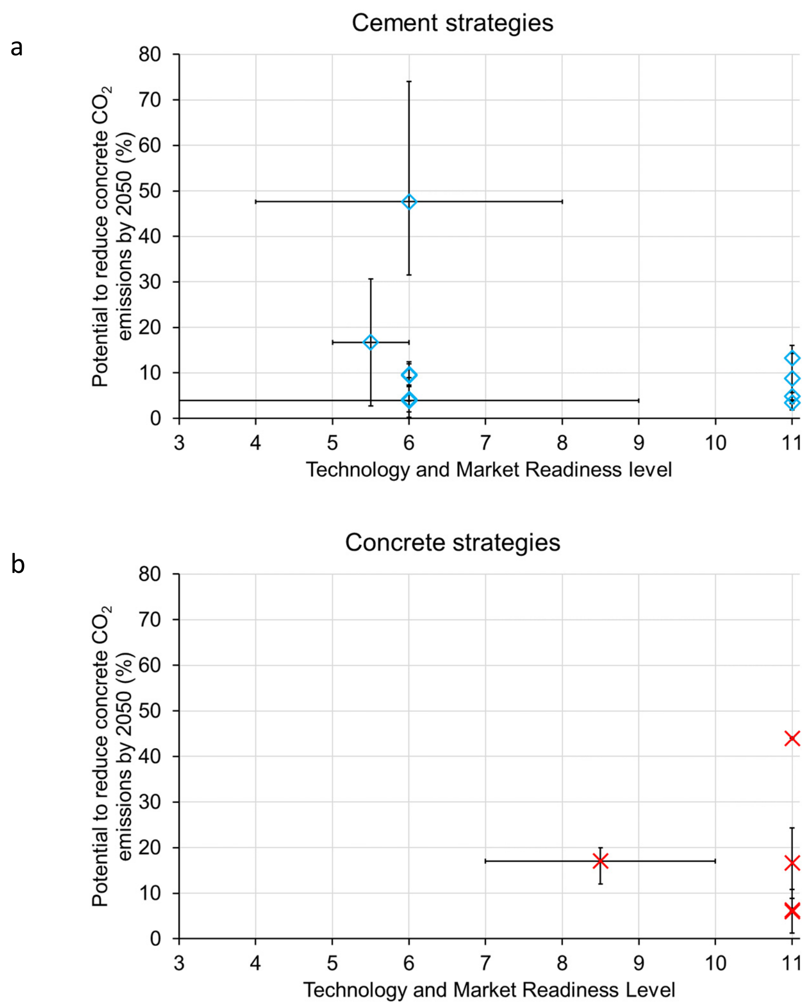

Figure 4: Plots showing the range of values across the strategies for average expected decarbonisation and TMRL, grouped by material scope: a = cement; b = concrete. Whisker bars in y-axis correspond to minimum and maximum value estimates; whisker bars in x-axis correspond to assessed range of TMRL levels for each strategy.

Table 4: Summary of values for each strategy, listing the estimated mitigation potential from each roadmap (A to F); the average, minimum and maximum values across roadmaps, and TMRL value.

	Strategy	Estimated CO_2 Reduction by 2050 (%)								TMRL
		A	B	D	E	F	Avg.	Min.	Max.	
Cement	Clinker Replacement	1.9	-	14.3	8.9	10.3	8.8	1.9	14.3	11
	Alternative Binders	-	-	9.0	0.3	2.4	3.9	0.3	9.0	3-9
	Decarbonisation of Electricity	-	4.0	-	5.7	5.0	4.9	4.0	5.7	11
	Decarbonisation of Transport	-	7.0	-	-	1.4	4.2	1.4	7.0	6
	Carbon Capture and Utilisation/Storage (CCUS)	31.5	61.0	31.7	74.1	39.9	47.6	31.5	74.1	4-8
	Alternative Fuels	14.2	16.0	12.7	-	10.1	13.3	10.1	16.0	11
	Electrification	-	-	-	30.7	2.7	16.7	2.7	30.7	5-6
	Thermal Efficiency Improvements	-	-	3.3	3.3	3.7	3.4	3.3	3.7	11
	Recarbonation	-	12.0	-	-	7.3	9.7	7.3	12.0	6
	Recycling of Concrete Fines	-		12.4	12.1	3.8	9.4	3.8	12.4	6
Concrete	Concrete Mix Design Optimisation	-	-	8.9	24.3	-	16.6	8.9	24.3	11
	Reduction of Overspecification	-	-	1.2	10.8	-	6.0	1.2	10.8	11
	Improved Design of Structural Elements	-	-	12.0	19.1	20.0	17.0	12.0	20.0	7-10
	Extended Building Lifetime	-	-	6.0	6.7	-	6.4	6.0	6.7	11
	Alternative Construction Materials	-	-	-	-	-	-	-	-	8-11
	Leveraged Thermal Mass	-	44.0	-	-	-	44.0	44.0	44.0	11

In line with the overall aim of achieving net zero cement and concrete industries by 2050 (and setting aside financial considerations), it is logical to prioritise the adoption of strategies which are ready to be deployed at scale (i.e. TMRL ≥ 9), and can make a substantial contribution to decarbonisation (a threshold of >10% carbon reduction is used here). The 'modified Eisenhower Matrix' in Table 5 groups the individual strategies on this basis, with the following groupings:

1. High priority strategies
   a. >10% carbon reduction potential, TMRL ≥ 9
2. Medium priority strategies
   a. >10% carbon reduction potential, TMRL < 9
   b. <10% carbon reduction potential, TMRL ≥ 9
3. Low priority strategies
   a. <10% carbon reduction potential, TMRL < 9

The high priority strategies (top-left quadrant) are approximately equally favoured by both industry and non-industry roadmaps. The exception is "Leveraged thermal mass", which is only included in one industry roadmap (Roadmap B) – whilst this meets the criteria for a high priority strategy as used here, there are several concerns as described in Section 5. Alternative binders include a range of different technologies with different TMRL - its TMRL range spans above and below the threshold value of 9. For this reason, alternative binders have been presented in Table 5 as two sub-groups – one sub-group for those with TMRL < 9 (inc. magnesia-based cements) and another sub-group for those with TMRL ≥ 9 (inc. calcium sulfo-aluminate cements, alkali-activated cements).

Table 5: Modified Eisenhower Matrix, grouping strategies into adoption priority quadrants based on TMRL and emissions potential. Colour code: blue = cement scope; red = concrete scope. Symbol code: ‡ = favoured by industry, * = favoured by non-industry.

	Commercially available (TMRL ≥ 9)	***Not yet* commercially available (TMRL < 9)**
***Higher* emissions reduction potential by 2050 (>10%)**	High priority Clinker replacement Alternative fuels Concrete mix design optimisation Leveraged thermal mass	Medium priority Carbon capture and utilisation/storage Electrification ‡ Improved design of structural elements
***Lower* emissions reduction potential by 2050 (<10%)**	Medium priority Decarbonisation of electricity Thermal efficiency improvements Reduction of over-specification * Extended building life Alternative binders (TMRL ≥ 9)	Low priority Alternative binders (TMRL < 9) Decarbonisation of transport ‡ Recycling of concrete fines Re-carbonation ‡

Whilst four strategies have been classified as high priority, these alone will not be sufficient to achieve net zero – a range of other strategies will be essential too. This analysis was approached from the perspective of identifying which strategies can have a large decarbonisation impact, and deliver that impact quickly. One could also undertake a similar prioritisation exercise on these strategies with a different perspective – for example, to identify where future research can have most impact, or where investment in decarbonisation infrastructure is needed.

6 Limitations

This analysis is appropriate for the purpose of exploring similarities and differences between roadmaps; at the same time, it does have several limitations. As shown in Figure 1, the studied roadmaps were all published within a 7 year window. It is likely that some of these roadmaps do not reflect the current state of the art in some decarbonisation strategies, as innovation is moving very quickly. However, given that gathering information and making judgements on decarbonisation pathways is a human process, it cannot be automatically assumed that more recent roadmaps are necessarily more valuable than older roadmaps within the studied group. In terms of target year, the mitigation values taken from the roadmaps focus on decarbonisation by 2050. Whilst 2050 is an important decarbonisation milestone year, this is a relatively short time horizon in the development of cement and concrete technology. Other promising strategies which are not scalable by that time can still be valuable to invest in, albeit with a longer time horizon for maturity.

Comparing the carbon mitigation potential of individual strategies is helpful for a comparative analysis of roadmaps (Section 5), but it is acknowledged this approach does not reflect reality as these values are not simply summative. For example, if demand reduction strategies for cementitious materials (e.g. reduction of overspecification) reduce the overall volume of cement produced, then upstream strategies (e.g. alternative binders) will have a smaller relative impact, compared to a scenario in which the same volume of cement is produced. For this reason, it is common for roadmaps to present a range of scenarios in which different sets of strategies are modelled in combination. For example, Roadmap D presented three scenarios which represented different approaches to decarbonisation: "Breakthrough technologies", "Efficient use and recycling", and "Structural optimisation and circular economy principles" [22].

Roadmaps relevant to Europe and particularly to the United Kingdom were used for the comparison of different strategies' decarbonisation potential in Section 5. Given that the United Kingdom is part of Europe, and the main European cement producers control the majority of the national market, this was deemed a valid comparison. Nonetheless, it is acknowledged that the European region covers a large geographical area, and incorporates countries with different resources and approaches to manufacturing and use of cement and concrete (e.g. pre-blending of supplementary cementitious materials in the cement factory or in the concrete mixing plant in particular). Looking beyond Europe and the United Kingdom, decarbonisation strategies require a different perspective in regions which have higher demand for new housing and infrastructure, e.g. Latin America [45].

A limitation of the roadmaps themselves is a lack of detailed consideration around the cost aspects of different strategies, both in terms of capital investment and operating cost. These aspects are starting to be considered in more detail, such as in the IPCC Sixth Assessment Report [46].

7 Concluding remarks

There was clear agreement across the roadmaps analysed in this study that there is no 'silver bullet' - combinations of different strategies are essential to achieve substantial decarbonisation by 2050. There was also agreement on a small number of strategies which were included in all the roadmaps, ranging from high TMRL (clinker replacement, alternative fuels) to lower TMRL (CCUS, alternative binders). At the same time, there were considerable differences in perspectives and recommendations between roadmaps. Industry roadmaps were oriented towards cement-based strategies, whereas non-industry roadmaps typically gave greater consideration to concrete-based strategies. There was a high degree of uncertainty in the estimated mitigation potential for some decarbonisation strategies, particularly CCUS and electrification.

In terms of recommendations, CCUS stood out as the strategy with the highest estimated mitigation potential, but also the highest uncertainty around what is feasible by 2050. Given the current trajectory of CCUS and its known limitations, the mitigation estimates for CCUS deserve further attention. Leveraged thermal mass is an outlier strategy included by only one roadmap – given its downstream nature and inherently high uncertainty, it is recommended to be excluded from future roadmaps. Given the strong net mitigation potential of concrete strategies, future iterations of industry roadmaps would benefit from incorporating more concrete-based strategies. The roadmaps tended to be strongly techno-centric in their outlook, in agreement with previous research [7]. A positive development in more recent roadmaps is a greater focus on using less concrete in structures as a way to use less cement. This line of thinking can evolve further, from a technical mindset of "*how can we build this structure with less concrete?*", towards a societal needs-based mindset of "*do we need to build a new structure at all?*". Future roadmaps should be more receptive to concepts of dematerialisation, beyond resource efficiency at the structural level. Decarbonisation is a time-critical challenge, yet there should be caution around neglecting other planetary boundaries aside atmospheric greenhouse gas concentrations.

For future research, there would be value in further meta-analysis of decarbonisation plans in the cement and concrete industry, such as the adoption of carbon reduction targets and reporting by individual companies. The next stage of detail for the roadmaps themselves would be to include more details of the costs and spatial aspects of different decarbonisation strategies. Whilst this level of detail would be unfeasible for global scale roadmaps, it could be achievable for individual countries or companies. In terms of enabling infrastructure, the costs involved in developing carbon storage infrastructure is a crucial yet relatively neglected consideration for CCUS adoption, which will require additional research.

Decarbonisation roadmaps for the cement and concrete sector point to a common destination: net zero (or near net zero) carbon emissions by 2050. Yet the approaches they use can be substantially different. In the near future it is likely that revised iterations of existing roadmaps will be published, along with new roadmaps from a range of different organisations. Keeping up with technological, economic and policy developments, as well as evaluating the range of different recommendations in a growing number of roadmaps, will be a continuous challenge.

Acknowledgements

This study was developed thanks to the support of The Engineering and Physical Science Research Council (EPSRC), though the fellowship grant EP/R001642/1 and the UKRI-ISCF Transforming Foundation Industries Network+ grant EP/V026402/1. Thanks are given to Prof. John Provis for valuable comments on an earlier draft of this article.

Authorship statement (CRediT)

AM: Conceptualization; Investigation; Supervision; Visualization; Writing – Original Draft Preparation. **TD:** Formal analysis; Investigation; Methodology; Writing – Original Draft Preparation. **SB:** Conceptualization; Funding Acquisition; Supervision; Writing – Review & Editing

Supplementary Information

The accompanying Supplementary Information files give a detailed description of the methodology and data used in this study. The data associated with paper are openly available from the University of Leeds Data Repository, at https://doi.org/10.5518/1430

References

[1] Schneider, M., The cement industry on the way to a low-carbon future. Cement and Concrete Research, 2019. 124: p. 105792. https://doi.org/10.1016/j.cemconres.2019.105792

[2] Habert, G., et al., Environmental impacts and decarbonization strategies in the cement and concrete industries. Nature Reviews Earth & Environment, 2020. 1(11): p. 559-573. https://doi.org/10.1038/s43017-020-0093-3

[3] Kerr, C. and R. Phaal, Technology roadmapping: Industrial roots, forgotten history and unknown origins. Technological Forecasting and Social Change, 2020. 155: p. 119967. https://doi.org/10.1016/j.techfore.2020.119967

[4] Kappel, T.A., Perspectives on roadmaps: how organizations talk about the future. Journal of Product Innovation Management, 2001. 18(1): p. 39-50. https://doi.org/10.1111/1540-5885.1810039

[5] Phaal, R., C.J.P. Farrukh, and D.R. Probert, Technology roadmapping-A planning framework for evolution and revolution. Technological Forecasting and Social Change, 2004. 71(1): p. 5-26. https://doi.org/10.1016/S0040-1625(03)00072-6

[6] Kostoff, R.N. and R.R. Schaller, Science and technology roadmaps. IEEE Transactions on Engineering Management, 2001. 48(2): p. 132-143. https://doi.org/10.1109/17.922473

[7] Johnson, O.W., et al., Toward Climate-Neutral Heavy Industry: An Analysis of Industry Transition Roadmaps. Applied Sciences, 2021. 11(12). https://doi.org/10.3390/app11125375

[8] Gerres, T., et al., A review of cross-sector decarbonisation potentials in the European energy intensive industry. Journal of Cleaner Production, 2019. 210: p. 585-601. https://doi.org/10.1016/j.jclepro.2018.11.036

[9] Kallis, G., Radical dematerialization and degrowth. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2017. 375(2095): p. 20160383. https://doi.org/10.1098/rsta.2016.0383

[10] Grubler, A., et al., A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy, 2018. 3(6): p. 515-527. https://doi.org/10.1038/s41560-018-0172-6

[11] Karttunen, E., et al., Toward environmental innovation in the cement industry: A multiple-case study of incumbents and new entrants. Journal of Cleaner Production, 2021. 314: p. 127981. https://doi.org/10.1016/j.jclepro.2021.127981

[12] Wesseling, J.H., et al., The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. Renewable and Sustainable Energy Reviews, 2017. 79: p. 1303-1313. https://doi.org/10.1016/j.rser.2017.05.156

[13] Wesseling, J.H. and A. Van der Vooren, Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands. Journal of Cleaner Production, 2017. 155: p. 114-124. https://doi.org/10.1016/j.jclepro.2016.08.115

[14] Dewald, U. and M. Achternbosch, Why more sustainable cements failed so far? Disruptive innovations and their barriers in a basic industry. Environmental Innovation and Societal Transitions, 2016. 19: p. 15-30. https://doi.org/10.1016/j.eist.2015.10.001

[15] Busch, P., et al., Literature review on policies to mitigate GHG emissions for cement and concrete. Resources, Conservation and Recycling, 2022. 182: p. 106278. https://doi.org/10.1016/j.resconrec.2022.106278

[16] Mineral Products Association. About Us. 2022 [cited 2023 04th April]; Available from: https://cement.mineralproducts.org/About-Us.aspx.

[17] BSI, BS EN 197-1:2011. Cement. Part 1: Composition, specifications and conformity criteria for common cements. 2011, BSI.

[18] Pamenter, S. and R.J. Myers, Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts. Journal of Industrial Ecology, 2021. 25(2): p. 359-376. https://doi.org/10.1111/jiec.13105

[19] WSP and DNV-GL, Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050: Cement. 2015, Department for Business, Innovation and Skills.

[20] MPA, UK Concrete and Cement Industry Roadmap to Beyond Net Zero. 2020, Mineral Products Association: London.

[21] Low Carbon Concrete Group and The Green Construction Board, Low carbon concrete routemap: setting the agenda for a path to net zero. 2022, Institute of Civil Engineers: London.

[22] Favier, A., et al., A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050. 2018, European Climate Foundation.

[23] Material Economics, Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry. 2019, University of Cambridge Institute for Sustainability Leadership: Cambridge.

[24] CEMBUREAU, Cementing the European Green Deal: reaching climate neutrality along the cement and concrete value chain by 2050. 2020.

[25] Lehne, J. and F. Preston, Making Concrete Change: Innovation in Low-carbon Cement and Concrete. 2018, Chatham House: London.

[26] CEMEX, Our contribution towards a carbon neutral world: CEMEX position on climate change. 2020.

[27] GCCA, GCCA Concrete Future - Roadmap to Net Zero. 2021, Global Cement and Concrete Association: London. p. 48.

[28] IEA. ETP Clean Energy Technology Guide. 2021 [cited 2022 18th May]; Available from: https://www.iea.org/articles/etp-clean-energy-technology-guide.

[29] Giesekam, J., et al., Science-Based Targets: On Target? Sustainability, 2021. 13(4). https://doi.org/10.3390/su13041657

[30] Rogelj, J., et al., Mitigation pathways compatible with 1.5°C in the context of sustainable development, in Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, V. Masson-

Delmotte, et al., Editors. 2018, Intergovernmental Panel on Climate Change. p. 93-174.

[31] Dahlmann, F., L. Branicki, and S. Brammer, Managing Carbon Aspirations: The Influence of Corporate Climate Change Targets on Environmental Performance. Journal of Business Ethics, 2019. 158(1): p. 1-24. https://doi.org/10.1007/s10551-017-3731-z

[32] Science Based Targets, Sectoral Decarbonization Approach (SDA): a method for setting corporate emission reduction targets in line with climate science. 2015.

[33] Krabbe, O., et al., Aligning corporate greenhouse-gas emissions targets with climate goals. Nature Climate Change, 2015. 5(12): p. 1057-1060. https://doi.org/10.1038/nclimate2770

[34] Science Based Targets, Cement Science Based Target Setting Guidance version 1.0. 2022.

[35] Hertwich, E.G. and R. Wood, The growing importance of scope 3 greenhouse gas emissions from industry. Environmental Research Letters, 2018. 13(10): p. 104013. https://doi.org/10.1088/1748-9326/aae19a

[36] WBCSD and WRI, The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. 2004: Geneva.

[37] UNEP, Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. 2016, United Nations Environment Programme: Paris.

[38] Hills, T., et al., Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting. Environmental Science & Technology, 2016. 50(1): p. 368-377. https://doi.org/10.1021/acs.est.5b03508

[39] Voldsund, M., et al., Comparison of Technologies for CO2 Capture from Cement Production-Part 1: Technical Evaluation. Energies, 2019. 12(3). https://doi.org/10.3390/en12030559

[40] Plaza, M.G., S. Martínez, and F. Rubiera, CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations. Energies, 2020. 13(21): p. 5692. https://doi.org/10.3390/en13215692

[41] Gardarsdottir, S.O., et al., Comparison of Technologies for CO2 Capture from Cement Production-Part 2: Cost Analysis. Energies, 2019. 12(3). https://doi.org/10.3390/en12030542

[42] Industry Tracker, Net Zero: In a Binder. Are cement companies ready to transition? 2022: London, U.K.

[43] Hacker, J.N., et al., Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. Energy and Buildings, 2008. 40(3): p. 375-384. https://doi.org/10.1016/j.enbuild.2007.03.005

[44] Dodoo, A., L. Gustavsson, and R. Sathre, Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building. Applied Energy, 2012. 92: p. 462-472. https://doi.org/10.1016/j.apenergy.2011.11.017

[45] Villagrán-Zaccardi, Y., et al., Overview of cement and concrete production in Latin America and the Caribbean with a focus on the goals of reaching carbon neutrality. RILEM Technical Letters, 2022. 7: p. 30-46. https://doi.org/10.21809/rilemtechlett.2022.155

[46] Bashmakov, I.A., L.J. Nilsson, A. Acquaye, C. Bataille, J.M. Cullen, S. de la Rue du Can, M. Fischedick, Y. Geng, K. Tanaka, Chapter 11 - Industry, in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, J.S. P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, Editor. 2022, Cambridge University Press: Cambridge, UK. https://doi.org/10.1017/9781009157926.013