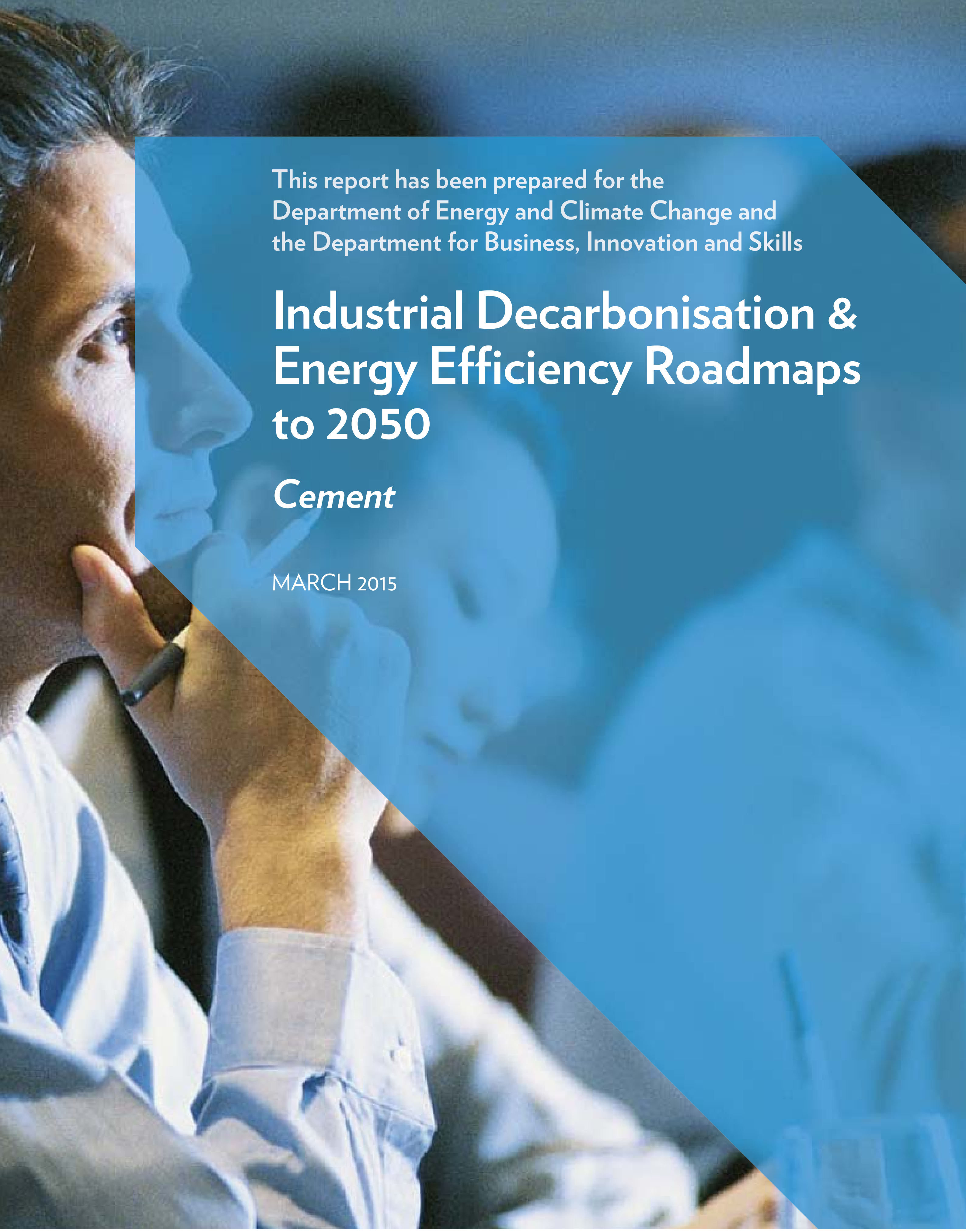

This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills

Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Cement

MARCH 2015

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DNV·GL

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ACRONYMS

ADOP	Adoption Rate
APP	Applicability
BAT	Best Available Technology
BAU	Business as usual
capex	Capital Expenditure
CC	Carbon Capture
CCA	Climate Change Agreement
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CRCs	Carbon Reduction Commitments
EU ETS	European Emissions Trading System
MPA	Mineral Products Association
R&D	Research and Development
RD&D	Research Development and Demonstration
REA	Rapid Evidence Assessment
ROI	Return on Investment
SIC Codes	Standard Industrial Classification codes
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technology Readiness Level
UK PRTR	UK Pollutant Release and Transfer Register

1. EXECUTIVE SUMMARY

1.1 Introduction: What is the 'Decarbonisation and Energy Efficiency Roadmap' for the Cement Sector?

This report is a 'decarbonisation and energy efficiency roadmap' for the cement sector, one of a series of eight reports that assess the potential for a low-carbon future across the most energy intensive industrial sectors in the UK. It investigates how the industry could decarbonise and increase energy efficiency whilst remaining competitive.

Changes in the international economy and the need to decarbonise mean that UK businesses face increasing challenges, as well as new opportunities. The UK government is committed to moving to a low-carbon economy, including the most energy-intensive sectors. These sectors consume a considerable amount of energy but also play an essential role in delivering the UK's transition to a low-carbon economy, as well as in contributing to economic growth and rebalancing the economy.

The roadmap project aims were to:

- Improve understanding of the emissions abatement potential of individual industrial sectors, the relative costs of alternative abatement options and the related business environment including investment decisions, barriers and issues of competitiveness.
- Establish a shared evidence base to inform future policy and identify strategic conclusions and potential next steps to help deliver cost effective decarbonisation in the medium to long term (over the period from 2020 to 2050).

Each roadmap aims to present existing and new evidence, analysis and conclusions to inform subsequent measures with respect to issues such as industry leadership, industrial policy, decarbonisation and energy efficiency technologies, business investments, research, development and demonstration (RD&D) and skills.

This roadmap is the result of close collaboration between industry, academics and government (Department of Energy and Climate Change (DECC) and Department for Business, Innovation and Skills (BIS)), which has been facilitated and delivered by independent consultants Parsons Brinckerhoff and DNV GL; the authors of the reports.

1.2 Developing the Cement Sector Roadmap

The development of the cement sector roadmap consisted of three main phases:

1. Collection of evidence relating to technical options and business-related enablers and barriers for decarbonisation. Evidence was collected via a literature review, analysis of publicly available data, interviews, workshops and a survey of cement manufacturing companies. Validation of evidence and early development of the decarbonisation potential took place during an initial workshop.
2. Development of decarbonisation 'pathways' to 2050 to identify and investigate an illustrative technology mix for a range of emissions reduction levels. Draft results were validated at a second workshop.
3. Interpretation and analysis of the technical and business-related evidence to draw conclusions and identify potential next steps. These example actions, informed by the evidence and analysis, aim to assist with overcoming barriers to delivery of technologies within the decarbonisation and energy efficiency pathways while maintaining competitiveness.

A sector team comprising representatives from the cement industry and its trade association (the Minerals Product Association (MPA), the Government and Imperial College) acted as a steering group as well as contributing evidence and reviewing draft project outputs. It should be noted that the findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. Where possible we have tried to include alternative findings or viewpoints, but this has not always been possible; this needs to be taken into account when reading this report.

1.3 Sector Findings

The cement-making process can be divided into two basic steps. Firstly, clinker is made in a kiln, which heats raw materials such as limestone with small quantities of other materials to 1,450°C using fossil and non-fossil fuels. During this process, the CO_2 is disassociated from the limestone allowing the calcium oxide to react with alumina, silica and iron minerals; this aspect of clinker production is known as calcination. Secondly, clinker is ground with gypsum and other materials to produce cement powder. The cement sector produced 8.6 million tonnes of cement in 2013, the vast majority being used to make concrete.

The chemical decomposition of limestone (calcination) gives rise to approximately 60-65% of total CO_2 emissions. The remainder of emissions arise from combustion of fossil fuel and non-biomass waste fuel and indirect emissions from electricity consumption. Total emissions for eight energy intensive sectors are shown in Table 1.

SECTOR	TOTAL ANNUAL CARBON EMISSIONS 2012 (MILLION TONNES CO_2)
Iron and Steel[1]	22.8
Chemicals	18.4
Oil Refining	16.3
Food and Drink	9.5
Cement[2]	**7.5**
Pulp and Paper	3.3
Glass	2.2
Ceramic	1.3

Table 1: Energy intensive industry total direct and indirect carbon emissions in 2012 (data sources include CCA data, EU ETS and NAEI)

[1] For the iron and steel sector, the reference year used is 2013. This was chosen due to the large production increase from the re-commissioning of SSI Teesside steelworks in 2012.
[2] For the cement sector, the 2012 actual production levels where adversely affected by the recession. Therefore we have assumed production of 10 mtonne (rather than the actual production in 2012) and normalised emissions to this production level.

Cement is an energy intensive sector; energy is one of the largest operational costs in cement making. In 2012 it was estimated to emit 7 million tonnes/year of CO_2, with a further 0.37 million tonnes CO_2/year emitted in electricity production for use within the sector.

The companies operating within the cement sector are predominantly owned by international businesses headquartered outside of the UK. UK cement revenues were £426 million in 2012 (ONS, 2013).

The sector has been consolidating over a long period of time and the recession has further exacerbated this trend. In addition, an increasing market share is being taken by imports. However, there has been an upturn in production since the economy returned to growth.

1.4 Enablers and Barriers for Decarbonisation in the cement sector

In this report, we look at 'enablers', 'barriers' and 'technical options' for decarbonisation of the cement sector. Enablers for decarbonisation and, in particular, decarbonisation and energy efficiency projects include the ability to overcome significant technical and economic complexity and business risk associated with available energy efficiency measures. For example, cement companies noted that they have pipelines of various energy reduction projects awaiting funding but all companies interviewed cautioned that the majority of ideas with high impacts and lower risks have already been deployed by the sector. Projects with multiple benefits (including decarbonisation and energy reduction) have a higher chance of success.

Companies reported that a stable and profitable business environment coupled with a steady, consistent and predictable regulatory environment would encourage further capital investment and innovation in the UK. Companies emphasised that UK climate change and energy regulations, taxes and incentives must enable companies to operate competitively relative to other countries in Europe and beyond.

Other key enablers identified by this research included collaboration on and identification of suitable funding for the development and demonstration of technologies with the potential to significantly reduce carbon such as carbon capture and recognition of whole-life impacts of concrete as a building material.

The main barriers to decarbonisation and energy efficiency often relate closely to the enablers as they provide different perspectives on the same issue. These include issues relating to business case development for projects, such as capital and resource availability, a requirement for short payback periods and production risks. This is compounded by the fact that many UK cement companies have already implemented significant energy efficiency projects (and, in doing so as a sector, reduced CO_2 emissions significantly since 1990, for example).

Short term barriers relate to the need for policy to support decarbonisation and energy efficiency in a way that enables industry to compete in its markets. For example, the Renewable Heat Incentive (RHI) and other renewable fuel systems increase biomass costs for the cement sector (the sector is not currently eligible for the RHI and is reportedly being outcompeted for some biomass fuels by other sectors).

1.5 Analysis of Decarbonisation Potential in the Cement Sector

A 'pathway' represents a particular selection and deployment of options from 2012 to 2050 chosen to achieve reductions falling into a specific carbon reduction band relative to a reference trend in which no options are deployed. Two further pathways with specific definitions were also created, assessing (i) what would happen if no particular additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech). These pathways include deployment of options comprising (i) incremental improvements to existing technology (ii) upgrades to utilise the best available technology and (iii) the application of significant process changes using technologies that have the potential to become commercially viable in the medium term.

The pathways created in the current trends scenario, the central of these three scenarios used in this study, are shown below in Figure 1.[3]

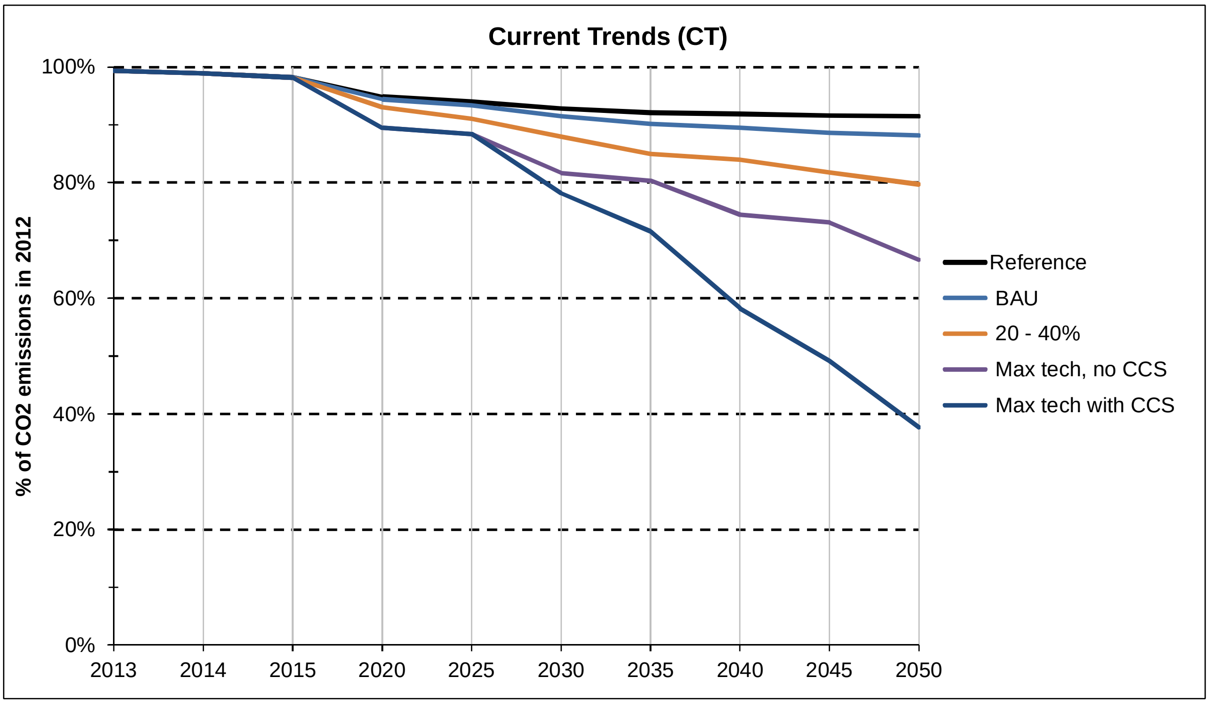

Figure 1: Overview of the different decarbonisation and energy efficiency pathways

Analysis of the costs of the pathways used order of magnitude estimates to add up the capital cost of each pathway. As an indication, the net present capital cost for the pathways, discounted at 3.5%, falls within an estimated range of £300 million[4] to £600 million[5]. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. Also, costs of operation, energy use, research, development, demonstration, civil works, modifications to plant and costs to other stakeholders are significant for some options, but not included here. The costs presented are for the study period and are adjusted to exclude residual value after 2050, thus a proportion of the costs of high capex items deployed close to 2050 is excluded. Great care must be taken in how these costs are interpreted. While implementation of some of the options within the pathways may reduce energy costs due to increased efficiency, the scale of the investments associated with the pathways must be considered by stakeholders when planning the next steps in the sector.

[3] Two versions of Max Tech are shown to illustrate the impact of carbon capture on the pathways
[4] For the BAU pathway in the current trends scenario
[5] For the Max Tech pathway in the current trends scenario

1.6 Conclusions and Key Technology Groups

The following conclusions have been drawn from the evidence and analysis:

Leadership, Organisation and Strategy

Leadership is important at company, sector, regional and UK government level. It links to all of the themes below. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis. The cement sector continues to illustrate good practice in relation to strategy, for example with publication of the 2050 greenhouse gas reduction strategy published by the MPA.

Business Case Barriers

The RD&D and commercial deployment of energy efficiency projects and major technologies requires significant upfront capital. Decisions to invest are impacted by a number of technical and economic factors such as policy costs and certainty, availability and access to internal finance and an evaluation of technical and commercial risks and returns. A range of options could be developed to overcome business case barriers including incentive-based policy and external project finance.

Future Energy Costs, Energy Supply Security, Market Structure and Competition

Some of the key technological options considered by the pathways, such as carbon capture (plus storage or use), will require significant capital costs and higher energy consumption and thus increase operating costs. This will reduce the overall cost-competitiveness of the sector compared to businesses overseas without measures to level the international playing field. For example, future action needs to address concerns on all components of the future electricity price relative to other regions.

Industrial Energy Policy Context

There are concerns in the industry that the long-term direction of energy and climate change policies and regulations in the UK may put at risk international competitiveness of the cement industry. Uncertainty (perceived or real) reduces investors' confidence and reduces the ability of the sector to justify the business case for major investments in energy efficiency and decarbonisation technologies. It is reported by the sector that the business case for investment needs to be very strong and to include risk identification and effective risk mitigation and control measures. Industry would encourage that policy should consider the right balance of incentives to encourage such investments.

Life-Cycle Accounting

The sector uses raw materials from, and provides its products to, other parts of the economy. There needs to be further development of the understanding the overall carbon impact of the entire product life-cycle. For example, by constructing buildings from concrete, which increases their thermal inertia, there can be significant long-term carbon benefit through reduced energy use and long-term durability. Recarbonisation of concrete (reabsorbing CO_2) could form part of this assessment. The sector is active in the communication of these messages but the recognition of whole life benefits in construction is very limited. Government and industry could do more to achieve this market acceptance.

Value Chain Collaboration

The value chain for the cement sector extends from feedstock supply (quarries and alternative feedstock sources) through cement manufacture, concrete production, procurement and specification of cement/concrete products by customers and their architects / engineers. Transportation of materials through the supply chain is an integral element. The carbon emissions of the cement sector are affected by the expectations of consumers, the business needs of builders and other industrial users of concrete products together with product standards and the requirements of building regulations. Collaboration across the value chain could enable products with lower lifecycle carbon emissions to be developed and adopted. The cement sector utilises waste materials from the power generation and iron and steel sectors as alternative feedstocks. Future actions should include maintaining strong dialogue to understand the future strategies in these sectors, the future availability of these materials with the aim of maximising synergies and benefits.

Research, Development and Demonstration

The research, development and demonstration (RD&D) of new technologies required to deliver decarbonisation is challenging for companies and government alone, for example due to lack of confidence from industry on a stable policy framework and technical challenges. This includes early research activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Technologies should be selected through a collaborative process. It should be noted that RD&D largely happens at a group global level rather than in the UK businesses, so groups will tend to put the effort into where the benefits are maximised on a group-wide level – hence government support for RD&D in the UK could potentially bring such projects to the UK rather than elsewhere.

People and Skills

New manpower resources with specialised skills and knowledge in energy and heat engineering are increasingly needed by the UK cement sector. Currently, key responsibilities of energy teams include ensuring compliance with existing regulation which diverts attention and effort from identification and implementation of energy efficiency activities.

The key technology groups that, in this investigation, make the largest contributions to sector decarbonisation or energy efficiency are as follows:

Electricity Grid Decarbonisation

Decarbonisation of electricity imported to cement sites could provide a significant contribution to the overall decarbonisation of the sector. Actions (mainly by government and utilities) will be required to ensure that this takes place while maintaining cost-competitiveness. The Government's reforms of the electricity market are already driving electricity grid decarbonisation and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Fuel and Feedstock Availability (Including Biomass)

The availability of low carbon fuels and feedstocks is a key issue for cement sector decarbonisation, given the important role biomass could play. This availability is affected by demand in the cement sector and other sectors and/or with other demand (for example, the use of biomass for electricity generation or in the non-manufacturing sector such as domestic heating). The challenges are to understand where the greatest decarbonisation potential can be achieved with a limited resource, as well as to maximise the availability of the resource (links to life-cycle carbon accounting).

Energy Efficiency and Heat Recovery Technology

There are opportunities to increase heat recovery in the cement sector, both to improve energy efficiency and to produce electric power. However, the payback periods of such projects are typically above the 2-3 year threshold defined by industrial companies in the sector. Alternative financing mechanisms to facilitate investment in energy efficiency projects could increase their implementation across the sector.

Carbon Capture

Individual cement plants are not considered to be of a sufficient scale to justify their own CO_2 pipeline and storage infrastructure. Collaboration both within the sector and externally is necessary to establish the networks, along with the availability of sources of funding appropriate to this type of shared infrastructure. The scale of CO_2 emissions from each site in the cement sector means that carbon capture and utilisation applications would need extensive technical breakthrough to be developed into large scale options for use of CO_2 in products with associated value (this is a key area of current and future research where significant development is needed). A future strategy for the development of a CO_2 transportation network should be considered with government taking a lead. This would enable industry to understand if and when there is likely to be access to a CO_2 pipeline from their site for storage or use and to then plan accordingly.

Next Steps

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The report has been compiled with the aim that is has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy.

2. INTRODUCTION, INCLUDING METHODOLOGY

2.1 Project Aims and Research Questions

2.1.1 Introduction

Changes in the international economy, coupled with the need to decarbonise, mean that UK businesses face increased competition as well as new opportunities. The government wants to enable UK businesses to compete and grow while moving to a low-carbon economy. The UK requires a low-carbon economy but currently includes industries that consume significant amounts of energy. These energy-intensive industries have an essential role to play in delivering the UK's transition to a low-carbon economy, as well contributing to economic growth and rebalancing the economy.

Overall, industry is responsible for nearly a quarter of the UK's total emissions (DECC, 2011)[6]. By 2050, the government expects industry to have delivered a proportionate share of emissions cuts, achieving reductions of up to 70% from 2009 levels (DECC, 2011). Nonetheless, the government recognises the risk of 'carbon leakage' and is committed to ensuring that energy-intensive industries are able to remain competitive during the transition to a low-carbon economy.

The Department of Energy and Climate Change (DECC) and the Department of Business, Innovation and Skills (BIS) have set up a joint project focusing on the eight industrial sectors which use the greatest amount of energy[7]. The project aims to improve the understanding of technical options available to sectors to reduce carbon emissions and increase energy efficiency while remaining competitive. This includes include investigating the costs involved, the related business environment, and how investment decisions are made in sector firms. This will provide the industry and government with a better understanding of the technical and economic abatement potential, set in the relevant business context, with the aim to agree measures that both the government and these industries can take to reduce emissions while maintaining sector competitiveness.

The project scope covers both direct emissions from sites within the sector and indirect emissions from the use of electricity at the sites but generated off site.

The different industrial sectors evaluated in this project are listed in Table 2:

Cement	Glass
Ceramics	Iron and Steel
Chemicals	Oil Refining
Food and Drink	Pulp and Paper

Table 2: Industrial sectors evaluated in this project

[6] It has also been estimated that 70% of industrial energy use is for heat generation (Source: Energy Consumption in the UK 2014: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk)
[7] The 'non-metallic minerals' sector has been divided into three sectors: glass, ceramics and cement.

This report addresses the cement sector.

2.1.2 Aims of the Project

The DECC 2011 Carbon Plan outlined the UK's plans to reduce greenhouse gas emissions and make the transition to a low-carbon economy while maintaining energy security and minimising negative economic impacts. This project aims to improve evidence on decarbonisation and energy efficiency for eight energy-intensive industry sectors, with the cement sector the subject of this report.

The project consortium of Parsons Brinckerhoff and DNV GL was appointed by DECC and BIS in 2013 to work with stakeholders, including Mineral Products Association (MPA), to establish a shared evidence base to support decarbonisation. The roadmap process consisted of three main phases:

i. Information and evidence gathering on existing technical options and potential breakthrough technologies, together with research to identify the social and business enablers and barriers to decarbonisation
ii. Development of sector decarbonisation and energy efficiency pathways
iii. Conclusions and identify potential next steps

A series of questions were posed by DECC and BIS as part of the project. These 'principal questions' guided the research undertaken and the conclusions of this report. The questions and the report section in which they are addressed are stated below:

1. What are the current emissions from each sector and how is energy used? - section 3.3
2. For each sector, what is the business environment, what are the business strategies of companies, and how does it impact on decisions to invest in decarbonisation? - section 3.4
3. How might the baseline level of energy and emissions in the sectors change over the period to 2050? - section Emission-Reduction Potential and Pathway Analysis – Principal Question 4 and 54.3
4. What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050? - section 4.4
5. What emissions pathways might each sector follow over the period to 2050 under different scenarios? - section 4.4
6. What next steps into the future might be required by industry, the government and others to overcome the barriers in order to achieve the pathways in each sector? - section 5

2.1.3 What is a Roadmap?

A 'roadmap', in the context of this research, is a mechanism to visualise future paths, the relationship between them and the required actions to achieve a certain goal. A technology roadmap is a plan that matches short-term and long-term goals with specific technology solutions to help meet those goals. Roadmaps for achieving policy objectives go beyond technology solutions into broader consideration of strategic planning, market demands, supplier capabilities, and regulatory and competitive information.

The roadmaps developed by this project investigate decarbonisation in various UK industries, including how much carbon abatement potential currently exists, what technologies will need to be implemented in order to extend that potential and how businesses will be affected. The roadmap aims to present existing and new evidence, analysis and conclusions as a 'consensual blueprint' to inform subsequent action with respect to issues such as future energy and manufacturing industrial strategy and policy, decarbonisation and energy efficiency business investments, research and development, and skills. The roadmaps consist of three components: evidence, pathways analysis and conclusions, as illustrated in Table 3. Each component is necessary to address the principal questions, and is briefly defined below.

INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050			
SOURCES OF EVIDENCE	INTERMEDIATE OUTPUTS	PATHWAYS	STRATEGIC CONCLUSIONS AND EXAMPLE ACTIONS
Literature	Validated emission data	Analysis of evidence to construct decarbonisation and energy efficiency pathways	Analysis of evidence and pathways to develop strategic conclusions and possible next steps to: • Overcome barriers and strengthen enablers • Implement pathways
Publicly available emissions data	Decarbonisation options and associated data		
Interviews, meetings and workshops with stakeholders	Energy efficiency options and associated data		
Government policy and analytical teams, trade associations, academics as part of engagement with the sector team	Enablers and barriers to decarbonisation and energy efficiency options and investment		

Table 3: Inputs and outputs for the industrial decarbonisation and energy efficiency roadmap to 2050

The views of contributing organisations

These reports were commissioned by DECC and BIS, and jointly authored by Parsons Brinckerhoff and DNV GL. The project was progressed using a collaborative process and while important contributions were provided by the sector, it should not be assumed that participating organisations (i.e. government, trade associations and their members and academic institutions) endorse all of the report's data, analysis and conclusions.

The findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. We have tried to include alternative findings or viewpoints, but this has not always been possible within the constraints of the project. This needs to be taken into account when reading this report.

2.2 Overall Methodology

The overall methodology is illustrated in Figure 2 and shows the different stages of the project. As can be seen, the stakeholders are engaged throughout the main phases of the project: evidence gathering, modelling/pathway development and finally drawing out the conclusions and potential next steps. A detailed description of the methodology can be found in appendix A.

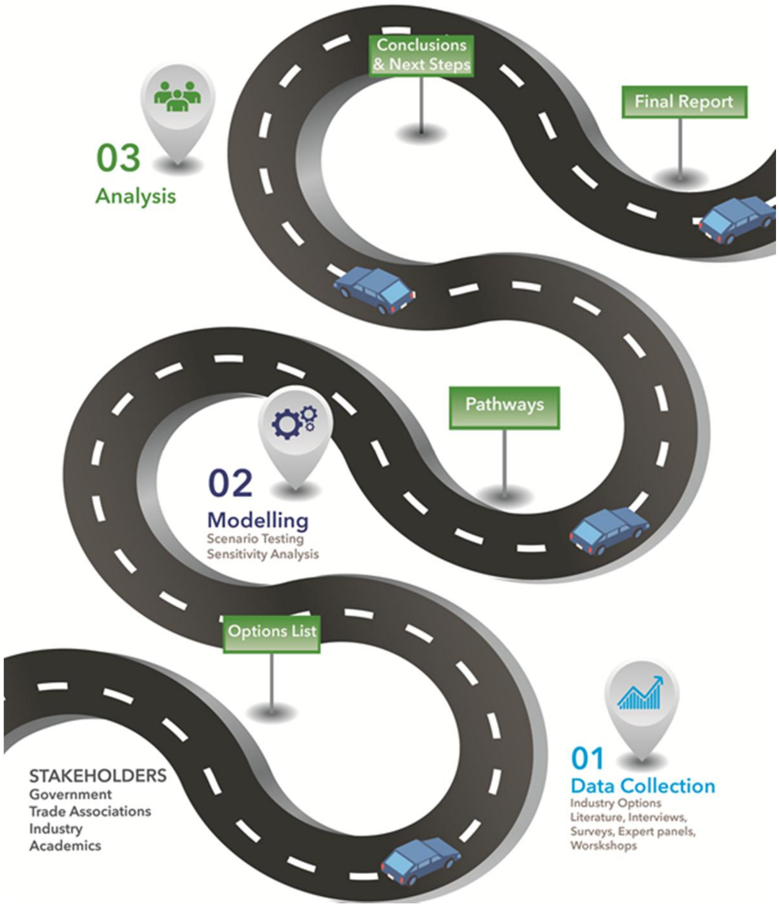

Figure 2: Roadmap methodology

Evidence was gathered for covering technical and social and business aspects from literature reviews, interviews and workshops with relevant stakeholders. These different sources of information allowed evidence triangulation to improve the overall research. The data was then used to develop a consolidated list of enablers and barriers for decarbonisation and a register of technical options for the industry. This was subsequently used to develop a set of decarbonisation and energy efficiency pathways to evaluate the decarbonisation potential of the UK cement sector and the main technical options required within each pathway.

Key to the overall roadmap methodology was engagement with all stakeholders, including with business and trade association representatives, academics and civil servants, to contribute to the evidence, validate its quality and interpret the analysis. We have worked closely with MPA, DECC and BIS to identify and involve the most appropriate people from the cement sector, relevant academics and other stakeholders, such as representatives from the financial sector.

2.2.1 Data Collection

Evidence Gathering

The data focused on technical, and social and business information, aiming to acquire evidence on:

- Decarbonisation options (i.e. technologies)

- Enablers and barriers to decarbonisation and energy efficiency
- Background to the sector
- Current state of the sector and possible future changes within the sector
- Business environment and markets
- Potential next steps

Such evidence was required to either answer the principal questions directly and/or to inform the development of pathways for 2050. Four methods of research were used in order to gather as much evidence as possible (and to triangulate the information) within a short timescale. These methods were:

- **Literature review:** A short, focused review of 39 documents published over the last 10 years. The documents were either related to energy efficiency and decarbonisation of the sector or to energy-intensive industries in general. This was not a thorough literature review or rapid evidence assessment (REA) but a desktop research exercise deemed sufficient by the project team[8] in its breadth and depth to capture the evidence required for the purpose of this project. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. This included the sector structure, recent history and context including consumption, demand patterns and emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation. Further details are provided in appendix A.
- **Interviews:** In liaison with MPA, DECC and BIS, seven face-to-face and telephone semi-structured interviews were carried out with MPA, CEMEX, Lafarge Tarmac, Hanson and Hope Construction Materials. The purpose of the interviews was to gain a deeper understanding of the principal questions, including how companies make investment decisions, how advanced technologies are financed, what a company's strategic priorities are and where climate change sits within this. The interviewees were interviewed using an Interview Protocol template, developed in liaison with DECC and BIS. This template was used to ensure consistency across interviews, fill gaps in the literature review, identify key success stories and extract key barriers to investment in low carbon technologies. The interview protocol can be found in appendix A. Interviewees were selected to maximise coverage across subsectors and emissions and also take into account company headquarters location, production processes and company size.
- **Workshops:** Two workshops were held with attendees identified in consultation with MPA, DECC and BIS. The first workshop focused on reviewing potential technological decarbonisation and energy efficiency options (that had been provisionally generated from the literature review) and discussing adoption rate, applicability, improvement potential, ease of implementation, capex, return on investment (ROI), savings potential and timeline for the different options. This was done through two breakout sessions: one focused on collecting more data and the other one on timelines under different scenarios. The second activity involved group discussions on enablers and barriers to energy efficiency and decarbonisation investment, and how to overcome them. The second workshop focused on reviewing the draft pathways and identifying potential actions for delivering them. The workshop participants included the relevant trade associations, large companies with the aim of achieving representation of key companies and/or subsectors and academics with expert knowledge of the sector, PB and DNV GL consultants, DECC and BIS project managers and senior civil servants. The average size of a workshop was 40 people.

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[8] DECC, BIS and the consultants of PB and DNV GL.

By using a range of information sources, the evidence could be triangulated to improve the overall research. Themes that were identified during the literature review were then used as a focus or a starting point during the interviews and workshops. The data from the literature was corroborated by comparing it with information from the interviews and workshops. Likewise, information gaps identified during the interviews and workshops were, where possible, populated using literature data. In addition, MPA collected data from its members that further helped to fill gaps and triangulate multiple data sources. It should be noted that the evidence-gathering exercise was subject to several limitations based upon the scale of activities that could be conducted within the time and resources available. Interview and survey samples were gathered through purposive and snowball sampling techniques in collaboration with trade associations, DECC and BIS experts. But due to time, sampling and resource constraints the samples may be limited in terms of their numbers and/or diversity. Where possible we have attempted to triangulate the findings to counter any bias in the sample, but in some areas this has not been possible. Some caution should therefore be used in interpreting the findings. The literature review, while not intended to be exhaustive, aimed to capture key documentation that applied to the UK. The criteria for identifying and selecting literature is detailed in appendix A. Interviewees included UK decision makers and technical specialists in the sector.

The different sources of evidence together with the associated outcomes are shown in Figure 3.

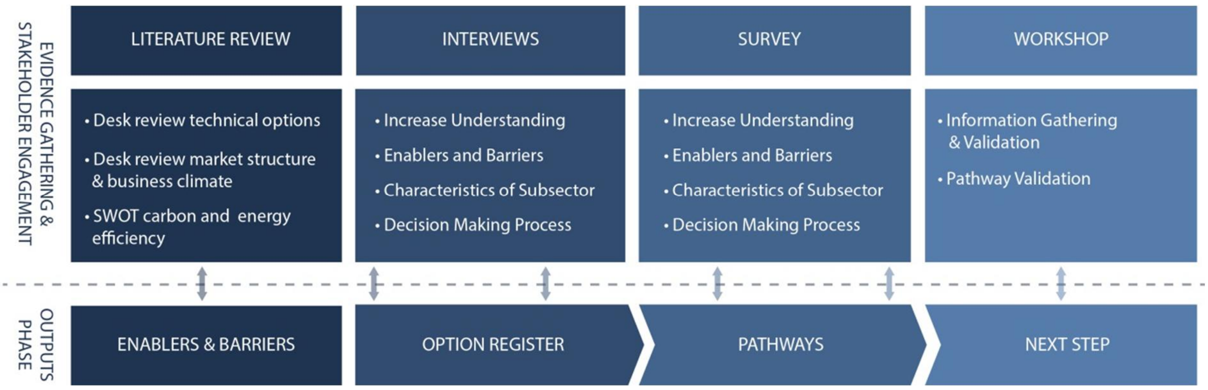

Figure 3: Evidence gathering process

The different sources of evidence were used to develop a consolidated list of enablers and barriers to for decarbonisation and energy efficiency, as well as a register of technical options for the cement sector. Evidence on adoption rate, applicability, improvement potential, ease of implementation, capex, ROI and reduction potential of all options (where available) was collected, together with information on strengths, weaknesses, opportunities and threats (SWOT). A SWOT analysis is a different lens to examine the enablers and barriers and reinforce conclusions and linkages between evidence sources. It identifies how internal strengths mitigate external threats and can be used to create new opportunities, and how new opportunities can help overcome weaknesses. By clustering the various possibilities, we identified key stories from the SWOT analysis which enabled us to describe the business and market story in which companies operate. Further information on the SWOT analysis is provided in appendix B. The SWOT analysis was used to further understand and validate the initial findings from the literature review and provided the basis for workshop and interview discussions and further helped to qualify the interview and workshop outcomes. Enablers and barriers were prioritised as a result of the outcomes and analysis of the evidence-gathering process and workshop scores.

This information was used to inform the development of a set of pathways to illustrate the decarbonisation potential of the cement sector in the UK. The summary and outcomes of this analysis are discussed in section 4.6.

The evidence-gathering process was supported by high levels of engagement with a wide range of stakeholders including industry members, trade association representatives, academics and staff from DECC and BIS.

The evidence-gathering exercise (see appendix A for details) was subject to inherent limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. There are only four operational cement manufacturing companies in the UK at present. All of the companies agreed to be interviewed, and interviewees included UK decision-makers and technical specialists in the sector. These interviews were conducted to provide greater depth and insight to the issues faced by companies.

The identification of relevant information and data was approached from a 'global' and UK viewpoint. The global outlook examined dominating technologies and process types, global production, CO_2 emissions (in the EU27) and the global outlook to 2050, including the implications for cement producers and consumers. The UK outlook examined the sector structure, recent history and context including consumption, demand patterns, emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation.

Evidence Analysis

The first stage in the analysis was to assess the strength of the evidence for the identification of the enablers and barriers. This was based on the source and strength of the evidence, and whether the findings were validated by more than one information source. The evidence was also analysed and interpreted using a variety of analytical techniques. SWOT analysis and system analysis were used to conduct the analysis of the business environment and the enablers and barriers (section 3.4.5); while concepts from storytelling and root cause analysis were used during the interviews with stakeholders. These different techniques are discussed in appendix B.

The options register of the technology options for decarbonisation was developed based on the literature review, interviews, the evidence gathering workshop and additional information provided by MPA and its members. The strengths, weaknesses, enablers and barriers of each option were taken into account to refine the options register, which was then used to build up the different pathways in the pathway model.

A second stage in the analysis was the classification of technological options and an assessment of their readiness.

Limitations of these findings

The scope of the study did not cover a full assessment of the overall innovation chain or of present landscape of policies and actors. Direct and indirect impacting policies, gaps in the current policy portfolio, and how future actions would fit into that portfolio (e.g. whether they would supplement or supplant existing policies) are not assessed in the report in any detail.

2.2.2 Pathways

The pathways analysis is an illustration of how the cement industry could potentially decarbonise from the base year 2012 to 2050. Together the set of pathways developed in the study help give a view of the range of technology mixes that the sector could deploy over coming decades. Each pathway consists of different technology options that are implemented over time at different levels. Each technology option included a number of key input parameters including CO_2 reduction, cost, fuel use change, applicability, current adoption (in the base year) and deployment (both rate and extent). A 'pathway' represents a particular selection and deployment of options from 2014[9] to 2050 chosen to achieve reductions falling into a specific decarbonisation band.

In this project, up to five pathways were developed, three of which were created to explore possible ways to deliver CO_2 emissions to different decarbonisation bands by 2050, as shown below:

- 20-40% CO_2 reduction pathway relative to the base year
- 40-60% CO_2 reduction pathway relative to the base year
- 60-80% CO_2 reduction pathway relative to the base year

Two further pathways - with specific definitions - were also created, assessing (i) what would happen if no additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech)[10].

The BAU pathway consisted of the continued deployment of technologies that are presently being deployed across the sector as each plant or site reaches the appropriate point to implement the technology. For the cement industry, two different Max Tech pathways were developed to test different configurations of options.

Pathways were developed in an iterative manual process and not through a mathematical optimisation process. This was done to facilitate the exploration of uncertain relationships that would be difficult to express analytically. This process started with data collected in the evidence gathering phase regarding the different decarbonisation options, current production levels and the current use of energy or CO_2 emissions of the sector. This data was then enriched through discussion with the sector team and in the first workshop. Logic reasoning (largely driven by option interaction), sector knowledge and technical expertise were applied when selecting technical options for the different pathways. These pathways were discussed by the sector team, modelled, and finally tested by the stakeholders participating in the second workshop. This feedback was then taken into account and final pathways were developed. All quantitative data and references are detailed in the options register and relevant worksheets of the model. The pathway model, which is available from DECC and BIS, is summarised in appendix A.

Scenario Testing

The different pathways developed have been tested under different scenarios (i.e. there are three different scenarios for each pathway). A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways.

For each pathway, the following three scenarios were tested (a detailed description of these scenarios is provided in appendix A):

[9] Model anticipates deployment from 2014 (assuming 2012 and 2013 are too early).
[10] Definitions are provided in the glossary.

- **Current trends**: This would represent a future world very similar to our world today with low continuous growth of the industry in the UK.
- **Challenging world**: This would represent a future world with a more challenging economic climate and where decarbonisation is not a priority and the industry is declining in the UK.
- **Collaborative growth**: This would represent a future world with a positive economic climate and where there is collaboration across the globe to decarbonise and where the industry has a higher growth rate in the UK.

In order to produce pathways for the same decarbonisation bands under the different scenarios, the deployment rate of the options varied according to the principals set out in the scenarios. For example, in order to achieve a specific decarbonisation band in 2050 in the collaborative growth scenario, options were typically deployed at a faster rate and to a higher degree as compared to the current trends scenario (provided this was considered to be consistent with the conditions set out in the scenarios).

Key Assumptions and Limitations

The pathway model was developed and used to estimate the impact on emissions and costs of alternative technology mixes and macro-economic scenarios. Modelled estimates of decarbonisation over the period (2013 to 2050) are presented as percentage reductions in emissions meaning the percentage difference between emissions in 2050 and emissions in the base year (2012). CO_2 emissions reductions and costs are reported compared to a future in which there was no further take up of decarbonisation options (referred to as the reference trend).

The model inputs and option deployments are based on literature review, interviews and stakeholder input at workshops and sector meetings. Parsons Brinckerhoff and DNV GL sector leads used these sources to inform judgements for these key parameters. Key input values (e.g. decarbonisation factors for options) are adapted from literature or directly from stakeholder views. If data values were still missing then values were estimated based on consultant team judgements. Decarbonisation inputs and pathways were reviewed and challenged at workshops. The uncertainties in this process are large given this level of judgement, however, uncertainties are not quantified. A range of sensitivity analysis was carried out including the development of alternative versions of the Max Tech pathway and also testing of different availabilities of biomass. Deployment of options at five-year intervals is generally restricted to 25% steps unless otherwise indicated. For example, an option cannot be incrementally deployed by 25% over ten years but has to deploy over five years and flat-line over the other five years.

In this report, when we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO_2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO_2, are very low.

Assumptions in relation to the Max Tech pathway

Max Tech pathway: A combination of carbon abatement options and energy savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier or cheaper option is chosen or two alternative Max Tech pathways are developed.

The following assumptions apply:

1. Technology Readiness Level (TRL): process or technology at least demonstrated at a pilot scale today, even if that is in a different sector.
2. Other disruptive technology options that could make a significant difference but that are not mature enough for inclusion in the pathways are covered in the commentary.
3. Cost is not a constraint: it has been assumed that there are strong and growing financial incentives to decarbonise which mean that the cost of doing so is not generally a barrier.
4. Option deployment rate: the sector team followed the roadmap method process to develop and test option deployments in all pathways, including Max Tech. Hence, in each sector, rates at which the options can be deployed were considered as ‘highly ambitious but also reasonably foreseeable’.
5. Biomass: maximum penetration of biogenic material as fuel or feedstock assuming unlimited availability. Carbon intensity and sensitivities are included in each sector.
6. Carbon Capture (CC): All sectors have made individual (sector) assessments of the maximum possible potential by 2050 based on what is ‘highly ambitious but also reasonably foreseeable’. This assessment included the most suitable CO_2 capture technology or technologies for application in the sector, the existing location of the sites relative to each other and anticipated future CC infrastructure, the space constraints on sites, the potential viability of relocation, the scale of the potential CO_2 captured and potential viability of both CO_2 utilisation and CO_2 storage of the captured CO_2.
7. Electricity Grid: three decarbonisation grid trends were applied through the scenario analysis.

Option Interaction Calculation

The pathway model incorporated two methods of evaluating potential interaction of options. The first method reflected the assumption that all options interacted maximally and the second method reflected the assumption that the options did not interact. Neither of these cases was likely to be representative of reality; however the actual pathway trends would lie between the two. The two methods therefore provided a theoretical bound on the uncertainty of this type of interaction in results that was introduced by the choice of a top down modelling approach. Figures calculated based on the assumption of maximum interaction are presented exclusively in the report unless otherwise stated.

Cumulative Emissions

An important aspect of an emission pathway is the total emission resulting from it. The pathways presented in this report are not designed or compared on the basis of cumulative emissions over the course to 2050. Only end-targets are assessed e.g., it is possible for a pathway of lower 2050 emission to have larger cumulative emissions, and thus a greater impact on the global climate system. The exception to this is in the cost analysis section where total CO_2 abated under each pathway – as calculated by the model – is quoted.

Scope of Emissions Considered

Only emissions from production or manufacturing sites were included in scope (from combustion of fuels, process emissions and indirect emissions from imported electricity). Consumed and embedded emissions were outside the scope of this project.

Complexity of the Model

The model provided a simplified top down representation of the sector to which decarbonisation options were applied. It does not include any optimisation algorithm to automatically identify a least cost or optimal pathway.

Material Efficiency

Demand reduction through material efficiency was outside the scope of the quantitative analysis. It is included in the conclusions as material efficiency opportunities are considered to be significant in terms of the long-term reduction of industrial emissions: see for example Allwood et al. (2012) and the ongoing work of the UK INDEMAND Centre.

Base Year (2012)

The Climate Change Act established a legally binding target to reduce the UK's greenhouse gas (GHG) emissions by at least 80% below base year (1990) levels by 2050. DECC's 2011 Carbon Plan set out how the UK will achieve decarbonisation within the framework of the carbon budgets and policy objectives: to make the transition to a low-carbon economy while maintaining energy security and minimising costs to consumers. The Carbon Plan proposed that decarbonising the UK economy "could require a reduction in overall industry emissions of up to 70% by 2050" (against 2009 emissions).

In this project for the analytical work, we have set 2012 as the base year. This is the most recent dataset available to the project and was considered to be a suitable date to assess how sectors (as they currently are) can reduce emissions to 2050. This separates the illustrative pathways exercise from national targets, which are based on 1990 emissions.

2.2.3 Conclusions and Next Steps

The conclusions and potential next steps are drawn from the outcomes of the pathways modelling, the scenario testing and the potential actions to overcome barriers and enhance enablers that were identified together with stakeholders. The strategic conclusions can include high-level and/or longer term issues, or more specific, discrete example actions which can lead to tangible benefits. The potential next steps are presented in the context of eight strategic conclusions (or themes) and a number of key technology groups. The strategic conclusions or themes are:

- Strategy, leadership and organisation
- Business case barriers
- Future energy costs, energy supply security, market structure and competition
- Industrial energy policy context
- Life-cycle accounting
- Value chain collaboration
- Research, development and demonstration
- People and skills

The main technology groups as presented in section 5 are:

- Electricity grid decarbonisation
- Fuel and feedstock availability (including cementious substitution and biomass)
- Energy efficiency and heat recovery
- Clustering
- Carbon capture
- Sector-specific technologies

3. FINDINGS

3.1 Key Points

The UK cement industry has reduced absolute CO_2 emissions by 55 per cent between 1990 and 2011 (MPA, 2013). However, around half of this absolute reduction is a result of declining production, with the remainder resulting from decarbonisation and energy efficiency improvements.

The cement industry argues that increased competition from other countries with lower environmental regulations and energy costs is making it more challenging for UK cement companies to obtain internal funding due to a reduction in profits. Investments are going to other countries rather than the UK.

The UK cement sector has developed a decarbonisation roadmap, "MPA cement GHG Strategy: Roadmap to 2050" (MPA, 2013). It sets out a clear vision and qualitative objectives for increased research into decarbonisation and specific work streams on decarbonisation. This demonstrates that decarbonisation is becoming a more prominent issue for the sector.

The main enablers for decarbonisation for the cement sector are:

- Financial and Technological feasibility – if technology is proven and financially viable it is more likely to be deployed.
- Management and organisation – Pipeline of technological innovations to reduce energy and carbon emissions – ideas waiting for investment so the opportunity for energy improvements could potentially be implemented relatively quickly if funding is made available.
- Market and Economy - A stable and profitable business environment – this would encourage further capital investment and innovation in the UK.
- Legislation – A more stable, consistent and predictable regulatory environment – this would enable better long term planning and investment.
- Legislation - A level regulatory playing field – Reform of UK climate change and energy regulations, taxes and incentives to allow UK-based cement producers to be more cost competitive with both EU and global competitors.
- Market and Economy – Better recognition of whole-life impacts of cement and concrete as a building material to promote the use of concrete as a sustainable material.
- Innovation – Funding for the development and successful deployment of CCS/U would enable the sector to significantly reduce emissions.
- Innovation – Government funding and investment support for decarbonisation R&D activities and capex costs.
- Management and organisation – Agreed and achievable, sector-wide targets and carbon-reduction roadmaps.

The main barriers that hamper decarbonisation are:

- Financial – Requirement for short payback periods and high rates of return on energy efficiency projects.
- Financial – Lack of access to and competition for capital – internal competition for funds from cement plants outside UK.
- Operational – Longevity of current equipment and investment cycle. High capital costs for new plants or significant projects.

- Financial – Risk aversion – companies are wary of being locked in to the 'wrong' investment choices (in part due to high technology costs, long investment cycles and concerns over product quality impacts).
- Market and Economy/Legislation – Increasing competition of diversion of alternative fuels and biomasses. Specifically, the Renewable Heat Incentive increases biomass costs for the cement sector as it is not eligible.
- Organisational – Shortage of qualified engineers and specialists skills and knowledge.
- Legislation – Uneven EU and global playing field with overseas competition due to differences in climate change and energy policies and pricing.
- Legislation – EU ETS – Risk induced by future uncertainty (unknown future carbon prices, caps, proportion of allocations, etc.).
- Market and Economy – UK demand for cement is below 2007 levels and growth forecasting is difficult. Also at risk from low cost imports.
- Innovation – industry perception that the UK government is not backing CCS R&D as strongly as other countries.
- Innovation – CCS forms integral part of established sector roadmaps, but the technological feasibility or affordability is still highly uncertain.

Future UK cement production is projected to grow in the short term, as the economy recovers from the recent recession. However, longer term, production is uncertain, and will be linked to the future economic environment in the UK, EU and beyond. MPA has provided the following growth projections used in the analysis. Depending on the scenario, cement production is expected to grow by -0.5%, 0% and +0.5% for the challenging world, current trends and collaborative growth scenarios, respectively. An initial representative production figure of 10 mtpa is assumed (with emissions based on this production level), to eliminate short-term volatility in cement production resulting from the economic climate of recent years. The sector's growth is reliant on trends downstream in the construction sector and the level of competition from imports. Under current trends, for example, any increase in demand would be met from an increased level of imports.

The energy savings and decarbonisation opportunities for the cement sector distilled from the literature review, interviews and workshops can be classified into nine categories: Kiln Process Technology, Electrical Efficiency Improvements, Electricity from Waste Heat, cementitious Substitution, Alternative Raw Materials, Fuel Switching, Alternative cements, Carbon Capture and Oxygen Enrichment.

3.2 Cement Processes

Cement is a fine, soft powdery-type substance, mainly used to bind fine sand and coarse aggregates together in concrete. Cement is a hydraulic binder, meaning it hardens when water is added which acts as a glue to the concrete mixture. Cement is a key ingredient in both concrete and mortar and is always mixed with other materials before use:

- Cement mixed with water, sand and gravel forms concrete, which is what the vast majority of cement is used for
- Cement mixed with water, lime and sand forms mortar

From BS EN 197-1, there are 27 types of common cements that can be grouped into five general categories (CEM I Portland cement, CEM II Portland-composite cement, CEM III Blastfurnace cement, CEM IV Pozzolanic cement, and CEM V Composite cement) and three strength classes: ordinary, high and very high. The standard for common cements further specifies seven sulfate resisting common cements, three distinct low early-strength blast furnace cements and two sulfate resisting low early strength blast furnace cements. There are also a number of special cements, such as super sulphate-cement, very low-heat cement and calcium aluminate cement (CEMBUREAU, 2013).

Concrete is a mixture of cement, water, aggregates and, in some cases, small quantities of chemical admixtures. Aggregates make up approximately 60-75% of the mixture and cement and water make up the rest. Aggregates are usually inert coarse materials like gravel, crushed stone, sand or recycled concrete. The types of aggregate and cement selected depend on the application of the concrete. Thanks to the special binding properties of cement, concrete is a very resilient, durable material that can bear heavy loads and resist environmental extremes (CEMBUREAU, 2013).

The vast majority of cement is used to make concrete. For this reason, any roadmap must also take into account the final product, i.e. concrete. This is especially relevant because as more new cement types are developed, the amount of cement needed to make concrete could vary.

The cement-making process can be divided into two basic steps:

- Clinker (the main constituent of cement) is first made in a kiln, which heats raw materials such as limestone (calcium carbonate) with small quantities of other materials (e.g. clay) to 1,450°C. During this process, known as calcination, the calcium carbonate (limestone) is transformed into calcium oxide (lime), which then reacts with the other constituents from the raw material to form new minerals, collectively called clinker. This near-molten material is rapidly cooled to a temperature of 100-200°C.
- Clinker is then ground with gypsum and other materials to produce the grey powder known as cement.

A more detailed cement-making process has been described, in order, below and is illustrated in Figure 4.

Quarrying raw materials: Natural occurring calcareous deposits such as limestone, marl or chalk provide calcium carbonate ($CaCO_3$) and are extracted from quarries, often located close to the cement plant. Very small amounts of ‘corrective’ materials such as iron ore, bauxite, shale, clay or sand may be needed to provide extra iron oxide (Fe_2O_3), alumina (Al_2O_3) and silica (SiO_2) to adapt the chemical composition of the raw mix to the process and product requirements (IEA et al., 2009).

Crushing: The raw material is quarried and transported to the primary and secondary crushers and broken into 10cm large pieces (IEA et al., 2009).

Prehomogenization and raw meal grinding: takes place in which different raw materials are mixed to maintain the required chemical composition, and the crushed pieces are then milled together to produce ‘raw meal’. To ensure high cement quality, the chemistry of the raw materials and raw meal is very carefully monitored and controlled (IEA et al., 2009).

Preheating (assuming all plants have pre-heaters): is the next stage in cement production. The preheater is a series of vertical cyclones through which the raw meal is passed, coming into contact with swirling hot kiln exhaust gases moving in the opposite direction. In these cyclones, thermal energy is recovered from the hot flue gases, and the raw meal is preheated before it enters the kiln, so the necessary chemical reactions occur faster and more efficiently. Depending on the raw material moisture content, a kiln may have up to six stages of cyclones with increasing heat recovery with each extra stage (IEA et al., 2009).

Precalcining (assuming all plants have a pre-calciner): Calcination is the decomposition of limestone to lime. Part of the reaction takes place in the ‘precalciner’, a combustion chamber at the bottom of the preheater above the kiln, and part in the kiln. Here, the chemical decomposition of limestone typically emits 60-65% of total CO_2 emissions. Fuel combustion generates the rest; typically 65% of fuel is combusted in the precalciner (IEA et al., 2009).

Clinker production in the rotary kiln: The precalcined meal then enters the kiln. Fuel is fired directly into the kiln to reach material temperatures of up to 1,450°C. As the kiln rotates, about 3-5 times per minute, the material slides and tumbles down through progressively hotter zones towards the 2,000°C flame. The intense heat causes chemical and physical reactions that partially melt the meal into clinker (IEA et al., 2009). Typically 35% of fuel is combusted in the kiln.

Cooling and storing: From the kiln, the hot clinker falls onto a grate cooler where it is cooled by incoming air, the heated air is generally recovered for use as combustion air or for raw material drying, thereby minimising energy loss from the system. A typical cement plant will have clinker storage between clinker production and grinding. Clinker is commonly traded (IEA et al., 2009).

Cement grinding: the cooled clinker and gypsum mixture is ground into a grey powder, CEM I, CEM II, CEM III, CEM IV or ground with other mineral components and additives to make blended cement. All cement types contain around 4-5% gypsum to control the setting time of the product. Traditionally, ball mills have been used for grinding (IEA et al., 2009).

Blending: If significant amounts of slag, fly ash, limestone or other materials are used to replace clinker, the product is called "a factory made composite cement or blended cement". [6] These composite and blended cements can be made at the site that produced the clinker but they can also be produced remotely at grinding and blending, or just blending, sites. These blending sites typically consume CEM I to produce other cement types e.g. CEM II or CEM III. In contrast to the kiln sites these blending sites often only consume electricity.

Storing in the cement silo: the final product is homogenised and stored in cement silos and dispatched from there to either a packing station (for bagged cement) or to a silo truck for despatch to customers (IEA et al., 2009).

There are older, much less efficient technologies for the production of cement. One example is the wet kiln into which the raw material is fed as slurry and not as powder (dry kiln) (IEA et al., 2009).

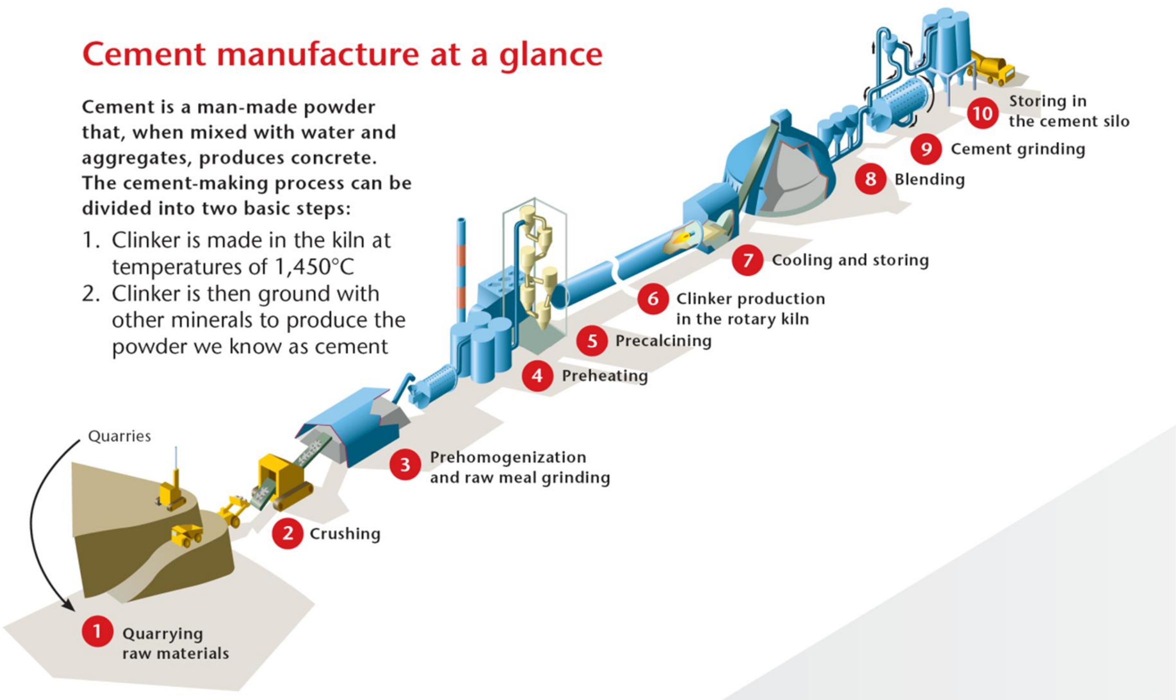

Figure 4: The cement making process (IEA et al., 2009)

3.3 Current Emissions and Energy Use - Principal Question 1

This section covers the findings in response to principal question 1: 'What are the current emissions from each sector and how is energy used?' It focuses on technologies that are currently used in the sector, the emissions associated with the activities, the heat and power demand of cement plants and the fuels that are used to deliver this energy and the lifespan of equipment and key timings for replacement or rebuild.

3.3.1 Evolution of emission reductions

In 2011, the EU (EU27 and Turkey) cement Industry accounted for 7.6% of total global cement production. China was responsible for 57.3% and India for 6.2% (CEMBUREAU, 2013). European companies use by far the highest quantity of alternative fuels in cement production, with 8.7% of these fuels originating from biomass waste and 25.6% from other waste in 2011 – this tendency is increasing steadily (CEMBUREAU, 2013). In 2011, the European cement Industry used over 7 million tonnes of alternative fuels, a six fold increase compared to 1990 – this translates into a reduction the equivalent of 17 million tonnes of CO_2 (CEMBUREAU, 2013). Over the past 20 years, the European cement industry has reduced CO_2 emissions per tonne of cement from 719 kg in 1990 to 660 kg in 2010, translating into a reduction of 40 million tonnes of absolute European CO_2 emissions from 1990 levels (CEMBUREAU, 2013). Three of the five world's largest global cement producers are headquartered in the EU28 (CEMBUREAU, 2013). It has been estimated that by 2050, alternative fuels will provide 60% of kiln energy, including 40% biomass in the sector (CEMBUREAU, 2013).

3.3.2 Emissions

In 2009 the global cement sector published a 2050 Technology Roadmap under the auspices of the international Energy Agency (IEA) and the World Business Council for Sustainable development (WBCSD) cement Sustainability Initiative (CSI). As the first global sector to outline its contribution to GHG abatement and mitigation the CSI Roadmap paved the way for technological development in the sector (MPA, 2013).

On a global scale, in 2012, 638 kg of CO_2 were produced per tonne of cementitious product[11]. Compared to 761 kg of CO_2 per tonne of cementitious being produced in 1990, this represents a reduction of 16% - as shown in Figure 5 (CSI, 2012).

For the UK the CO_2 emissions in 2013 from cement production totalled 6.0 million tonnes of CO_2 for a production of 11.6 million tonnes of cement. Direct emissions originate largely from fossil fuel combustion and raw material degradation in the kiln (process emissions), and indirect emissions from electricity from the grid, with the kiln accounting for about three quarters of all energy use in a typical UK cement plant. The predominant fuels used include coal and petroleum coke. Fossil fuels accounted for 60% of combustion fuel use in 2012, down from 94% in 1998 (MPA, 2013). As such, the cement sector has already taken considerable early action in decarbonising its fuel demand by switching to waste derived and biomass fuels.

[11] Comprise the glue that holds concrete together. These materials include traditional Portland cement, fly ash, ground granulated blastfurnace slage (GGBS), limestone fines and silica fume.

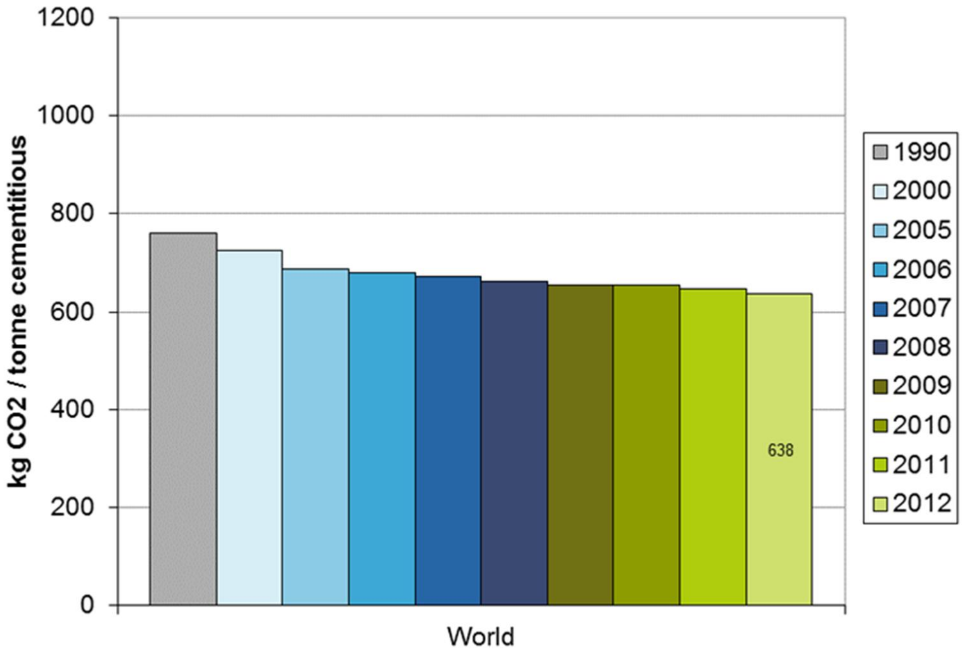

Figure 5: Average gross CO_2 emissions per tonne (cementitious) (all GNR participants – World) (CSI, 2012)

According to the MPA (MPA, 2013), progress to date in the UK cement industry to produce Portland cement has resulted in a partial decoupling of the sector's economic growth from environmental impact. As shown in Figure 6 below, the industry has reduced absolute CO_2 emissions by 56 per cent between 1990 (13,363,615 CO_2 tonnes emitted) and 2013 (5,971,693 CO_2 tonnes emitted), outstripping the UK economy as a whole. However, from inspection of the UK cement production figures over this period, it can be observed that around half of this absolute reduction is a result of declining production, with the remainder resulting from decarbonisation and energy efficiency improvements.

The British Cement Association (BCA) 2005 Carbon Strategy focused on short, medium and long term objectives. The short-term targets were focused on delivery by 2010. These were:

- A target of 15 per cent Alternative Waste Derived Fuel use by 2010 (MPA, 2013).
- Growing cementitious additions to 8 per cent by 2010 (MPA, 2013).
- Research Carbon Capture and Storage (MPA, 2013).

BCA is now part of MPA and MPA cement members[12] have made progress against these targets following investment in new kiln technology, fuel switching and improving product combinations. In 2010, approximately 8 million tonnes of CO_2 were emitted in the production of cement (MPA, 2013).

[12] CEMEX UK, Hanson cement, Lafarge Tarmac. Associate members include Kerneos and Quinn cement

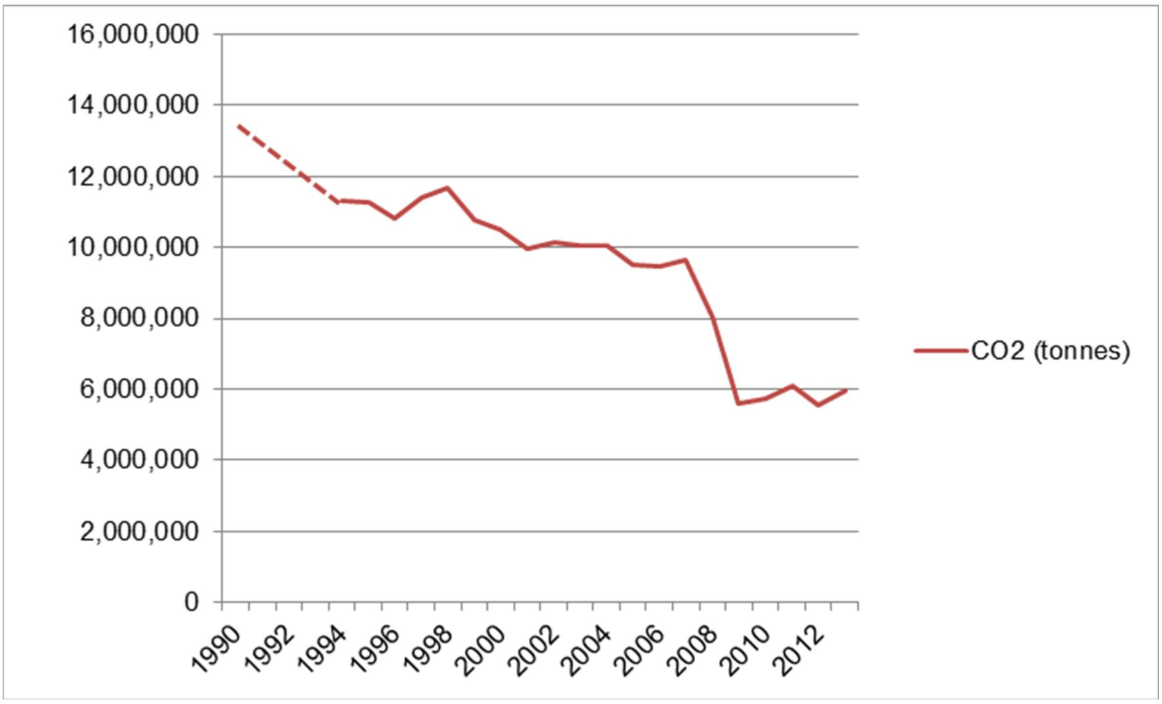

Figure 6 Annual CO_2 emissions from UK cement production

3.3.3 Heat and Power Demand

The average power consumption for cement manufacturing per tonne of cement in 2012 has been measured as being 110 kWh/t of cement (CSI, 2012).

The cement industry is energy-intensive, mainly because of the fuel requirements of kilns. Wet processes and long dry kilns tend to use more energy, the former because of the extra drying requirement. Kiln energy efficiency has increased substantially since the 1960s as long-dry and old wet kiln processes have been replaced. While this has levelled off since 1990, the commissioning of new kilns in the last few years is expected to restart this progress (EA, 2005).

According to MPA, the UK cement production includes two semi-dry and one semi-wet kiln, with the rest comprising of a dry process.

3.3.4 Fuels Used

In the UK cement sector, the predominant fuels used include coal and petroleum coke. Fossil fuels accounted for 60% of combustion fuel use in 2012, down from 94% in 1998. As such, the cement sector has already taken considerable early action in decarbonising its fuel demand by switching to waste derived and biomass fuels (House of Commons, 2013).

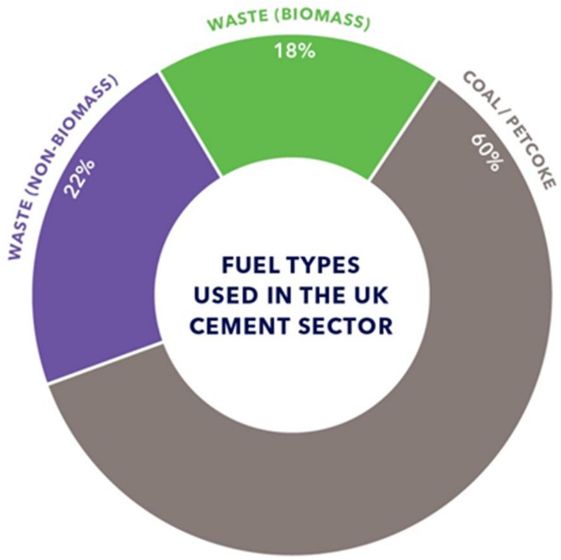

Figure 7: Fuels used in the calcination and clinker production process in the UK cement sector (DECC, 2014)

Currently, solid fuels constitute the large majority of fuel consumption, with coal on its own accounting for more than half of all fuel on an energy basis. The cement sector is a large consumer of waste fuels, some of which are renewable or have a renewable component. The ability of the cement sector to combust a large proportion of waste fuel derives from the alkaline environment, very high temperature and long processing times of the clinkering process, whereby harmful species are broken down.

Burning a large proportion of waste fuels has been accompanied by significant investments in the industry to comply with the Waste Incineration Directive.

The final mineral product also allows the ash from a wide range of combustion products to be absorbed. Overall, about 40% of fuel input is in the form of waste fuels and the sector association estimates that about 18% of fuel input is biomass derived. This figure will be sensitive to the proportion of SRF that is biogenic. The composition of SRF may be deliberately altered through fortification with plastic material in order to raise the calorific value of the fuel. This will tend to depress the proportion of SRF that may be defined as biomass derived.

Overall, SRF combusted in the cement sector has a non-biogenic content of about 40%. According to the MPA, the SRF burned in the cement sector has a CO_2e factor of about 0.14kg CO_2e/kWh. Currently an estimated 18% of the fuel input for the generation of direct heat is estimated to be biomass derived (DECC, 2014).

3.3.5 Lifespan of Equipment and Key Timings

The production of cement clinker in cement plant takes place in kilns that are constructed to continuously produce large quantities of cement clinker over operational lifespans of 30-40 years according to MPA, after which they may undergo a partial rebuild. Typically, modifications and partial rebuilds are more frequent than completely new build. Since the kiln is the dominant energy centre in the plant it represents by far the greatest opportunity for decarbonisation of the cement making process and is therefore determinative in setting the lifespan of the plants.

CO_2 abatement opportunities will have to avoid interrupting production and associated down-time and production losses: renovating kilns and introducing decarbonising technologies hence has to wait for planned kiln replacement. The implementation of opportunities requiring retrofit will either have to wait until planned shut-down periods or during unplanned down-time and lost production.

In conclusion, cement plants operate continuously and have long life cycles of at least 30 years and often considerably longer. Not all decarbonisation measures need to be delayed until major rebuild but can be implemented on operating sites, but opportunities to finance large-scale disruptive technologies are at specific times, with 1 or 2 opportunities per site prior to 2050. The specific refurbishment dates for each kiln have not been identified because this information is commercially confidential; however, these dates are planned well in advance by the companies, so they can make plans to implement major decarbonisation opportunities at these times.

3.4 Business Environment - Principal Question 2

This section provides an assessment of the range of questions under principal question 2: 'For each sector, what is the business environment, what are the business strategies of companies, and how do these have an impact on decisions to invest in decarbonisation?'

3.4.1 Market Structure

The UK cement industry is a mature market, with high capital intensity requirements. It is a highly concentrated (i.e. small number of manufacturing sites) and regulated industry. It is dependent on trends in downstream construction and public sectors in particular. Total turnover for the manufacture of cement in the UK was £426 million in 2012 (Office for National Statistics, 2014). Market share data is only available from 2012 which at that time showed that Lafarge had 37% of the market share, CEMEX 21%, Hanson 19%, and Tarmac 10%. Lafarge and Tarmac subsequently formed a joint venture company Lafarge Tarmac, but as a result the company was required to divest part of its cement and concrete business to form a new, separate competitor called Hope Construction Materials who are the smallest of the four cement companies currently manufacturing in the UK (Global Cement, 2013).

Domestic cement production tonnage was 8.6m in 2013 which represents a 3% increase on 2012 (7.95m) (MPA, 2014). However, while demand is currently forecast to increase, market demand remains volatile since the 2007 financial crash and the UK cement sector has experienced significant consolidation since then. UK domestic cement demand is still approximately 30% lower than it was in 2007 (11.9m tonnes) (MPA, 2014). However, despite the reduction of UK production, imports have risen steadily over the last ten years and now represent approximately 12-14% of all cement purchased in the UK (MPA, 2014).

Key drivers for growth include demand from building and construction. The public sector and government have a large market influence over the cement sector as one of the key drivers of construction of homes, public buildings and infrastructure. Cement (concrete) structures can last over 100 years and concrete is widely reused at end of life as a raw aggregate material, although it is infrequently recycled into new cement according to UK cement companies who stated that the logistical, financial and energy implications of collecting and transporting old concrete back to cement factories does not usually make this option viable.

Production figures from the MPA, shown in Table 4: Sector production growth data (MPA, 2014)

Table 4 and Figure 8 below, were provided showing production for recent years and the MPA's annual growth forecast. As all companies in every industrial sector are subject to competition law the industry is subject to particularly tight competition rules, the discussion of revenues, prices and projected revenues is a highly sensitive subject. Therefore the MPA and companies speak in terms of production volumes. However, the most recent ONS data on cement sector revenues indicated sector revenues of £431m in 2012, down from £623m in 2008 and £753m in 2010 (Office for National Statistics, 2014).The MPA cautions that it does not have full confidence in these figures - although it does provide an approximate outlook.

UK cement companies do not comment on any projected production, revenue or growth for their own organisation due to Competition Law although have all expressed general optimism that there will be at least some limited growth over the next few years as the UK economy continues to strengthen. However, the UK is a mature market for construction. There will always be a certain amount of 'maintenance' of the existing building stock, e.g. replacing old buildings with new, infrastructure improvements, etc. The UK cement sector indicated that only a truly thriving UK economy with above forecast growth rates along with a more expansive house building programme or the delivery of a national infrastructure programme would stimulate significant growth for their sector.

	Annual UK cement production (2013)	Annual Growth in Production 2012-13	Forecast Growth in Production
cement	8.6Mt	3.1%	2014: +4/+6% 2015: +4/+6% 2016: +2/+4%

Table 4: Sector production growth data (MPA, 2014)

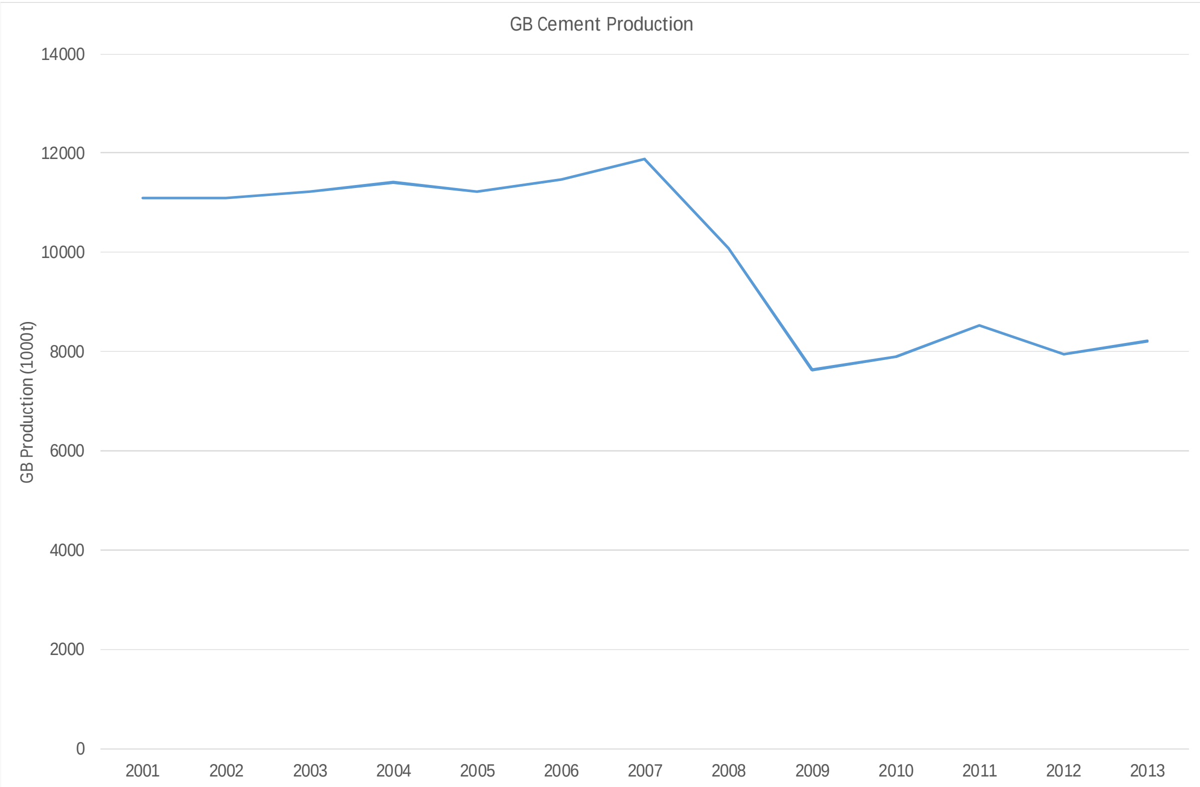

Figure 8: Annual CO_2 emissions from UK cement production (MPA, 2014)

3.4.2 Business Strategies

Decarbonisation Strategies

The MPA, the EU, the World Business Council for Sustainable Development and the International Energy Agency have developed 2050 decarbonisation roadmaps which indicates that decarbonisation is becoming a more prominent issue for the sector on a national (MPA), continental (EU) and global level (World Business Council for Sustainable Development and the International Energy Agency). The interviews with UK cement companies showed that **all four UK companies have carbon or energy reduction targets and decision making processes in place in relation to energy reduction and carbon.** When asked whether workshop participants were concerned about the impact of energy efficiency on their business strategies, all respondents replied that they were. When asked whether they were concerned about decarbonisation and its impact on their business strategies, all indicated it was a strong concern. The interviews confirmed that energy efficiency is prioritised as it creates an opportunity to lower costs. **However, the need for the sector to significantly reduce carbon emissions was recognised as essential by all interviewees**. Management commitment to decarbonise and address climate change was seen as an enabler as often the decarbonisation journey is challenging and requires management buy-in. **All UK companies expressed the view that decarbonisation is an important strategic priority for their senior management.**

Energy efficiency helps reduce companies' operational costs through reducing exposure to fluctuating and increasing energy prices – the two main energy uses are electricity for plant equipment and fuels such as coal for direct firing of cement kilns. Higher electricity prices are driving efforts to reduce electricity consumption, but as efficiency savings become more difficult higher electricity prices become more of a burden and less an opportunity.

UK energy prices were discussed in the workshops as possibly contributing to an uneven competitive playing field against European competitors. However, there are different views on this, for example a recent publication of Agora Energiewende (2014), illustrates that the comparison of electricity wholesale prices between sectors and countries is a difficult task. Moreover, a recent communication from the European Commission on energy prices and costs in Europe shows that UK electricity prices for industry are very similar to the average EU-27 prices, although certain countries (like Bulgaria and Finland) show significantly lower prices (European Commission, 2014).

"While numerous European companies have complained of market distortion due to regulatory favouritism for Germany's energy-intensive industries, caution must be exercised when attempting to directly compare industrial end-use prices between countries and sectors. Because firms in different regions and sectors vary considerably in the extent to which they pay wholesale market prices or receive tax exemptions and levy reductions, comparing prices between sectors and countries is a difficult task. The heterogeneity of the situation is not fully and transparently captured by European statistics." (Agora Energiewende, 2014)

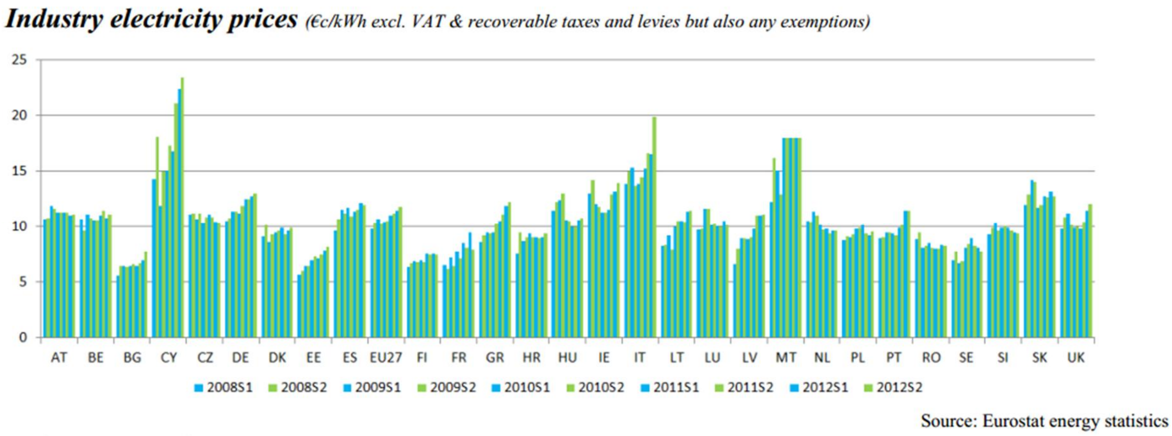

Figure 9: Industry electricity prices in EU member states and the average in EU-27 2008-2012 (European Commission, 2012)

The UK cement industry was a first mover in utilising alternative fuels and biomass to replace fossil fuels such as coal and petcoke. Much of the initial move towards such alternative fuels (e.g. tyres, meat and bone meal, processes sewage pellets, wood chips, waste and refuse-derived fuels, etc.) was driven by cheap and abundant availability of alternative fuels. This made them financially attractive compared with fossil fuels, but increasing competition for alternative fuels has raised prices of such fuels and is now proving problematic for the sector. **Currently fuel switching to alternative fuels represents a key element of all UK cement companies' decarbonisation strategies and roadmaps – interviews indicated that their ambition for**

switching to alternative fuels ranges from 60-80% of total raw fuel use at all cement plants. Switching beyond 80% is not seen as technically feasible in most existing plants due to the need for consistent heat patterns to ensure product quality.

Increasing demand for sustainable building materials resulting from voluntary agreements, regulations, and for public housing is also increasing the importance of decarbonisation to cement manufacturers although some companies expressed concern that the government is not promoting sustainable building standards and certifications strongly enough. One example cited was the recent scrapping of the Code for Sustainable Homes.

Cement companies are interested in decarbonisation from the lifecycle perspective and are promoting the thermal properties of concrete that can significantly reduce energy use throughout the lifetime of a building. Cement companies also stressed that the re-carbonisation properties of cement and concrete during their lifetime, and particularly when broken down and reused, are not being appropriately recognised or accounted for at present. Cement companies have a further interest in the issue of climate change as the sector considers its product to be vital in the construction of UK low-carbon infrastructure such as nuclear and wind power installations as well as being important for climate change adaptation measures such as flood and coastal defences.

All of the companies interviewed had climate change strategies in place. All interviewees also had decarbonisation targets in place at group level and site level energy efficiency targets or KPIs that are closely monitored. Energy efficiency is not a new issue for them it was reported that cement companies have been investing in energy efficiency and are reaching a 'peak' of what is achievable in terms of efficiency. While there are opportunities to invest in options like biomass fuel where availability, policy and economics allow, further equipment investments are only likely to yield incremental energy savings and decarbonisation. This is because companies feel they have already implemented the majority of innovations that are considered to actually make a significant difference or are affordable by offering a suitable ROI.

Building new plants and kilns is seen as the critical point at which any major step changes can occur. The current generation of kilns, however, is relatively new with most being built or modified within the last 15 years as the sector switched from wet process kilns to significantly more energy efficient dry kilns. Plants and kilns have a typical lifespan of 30 to 50 years so it is likely there will be only one more generation of kilns between now and 2050. While all companies indicated that it was standard practice to incorporate the most efficient, cutting-edge technology available when a new plant is built, they had reservations that there were any new significant carbon-reducing technological solutions on the horizon other than CCS/CCU. As a result the focus of UK cement companies in recent years and at present is on fuel switching to biomass and alternative fuels where possible – along with making incremental plant equipment improvements where commercially viable.

All UK cement companies are interested in CCS/U, but all expressed the view that it was not currently an affordable option for them to pursue without external support. The industry is risk-averse due to high capital costs, low revenue margins and fear of being 'locked into' investment mistakes due the long life cycle of plants and equipment. As a result no UK company is currently willing to be the 'first mover' on piloting CCS/U as the risk is deemed too great and in any case it is currently extremely unlikely that any of the UK companies would be able to gain management or shareholder buy-in due to the excessive costs of CCS/U.

The industry consensus expressed by all four UK cement producers and the MPA in the sector workshops is that a typical scale cement plant costs £250-300m to build. This cost would double with the inclusion of CCS/U as would the physical size of the plant itself. However, the UK cement sector expressed interest in working on CCS/U with suitable government support and with cross-sector collaboration.

Ultimately all UK companies indicated that without CCS/U then the sector would not be able to reach the target of reducing sector emissions by 80% by 2050. This is due to the unavoidable calcination process by which cement clinker is made and which represents almost half of the total emissions footprint of UK-produced cement.

3.4.3 Decision-Making Processes

Decision making processes vary by company and the most important factor in regards to the level of authority of investment expenditure includes size of the company and ownership structure. For large multinational companies there are decision-making hierarchies and expenditure thresholds that UK based leaders must abide by or seek additional approval from the Group if the project is above this level of expenditure. **While UK decision-makers have significant autonomy over smaller investment decisions (e.g. >£250k), investments that may run into the millions of pounds typically require Group approval.**

Project managers must come up with the business case for projects and payback criteria under three years must usually be met in order for the project to move forward. Longer paybacks of four to five years are accepted by some companies if the project has additional production benefits beyond energy savings and decarbonisation or could hold strategic value to the company. The longest payback period mentioned as having been accepted by any company for even a strategic project with energy/carbon-reducing co-benefits was 7 years. **All companies interviewed used commercial and productivity criteria to inform their decision making as well as calculations on energy savings and decarbonisation.** Projects are usually carefully monitored to assess subsequent performance improvements and all companies have good data management systems in place. **All companies also have a pipeline of future projects (e.g. plant energy efficiency projects) that they are interested in implementing depending on available capital and feasibility study outcomes.** However, companies cautioned that there were no more step change projects waiting to be implemented [other than CCS/U] such as the step change in energy savings due to switching UK kilns from wet processing to dry processing over the last 15 years. All but one of the UK's kilns are now dry process kilns while the sole remaining semi - wet process kiln has remained as such as the majority of raw materials used for cement clinker manufacture are transported as a slurry via a 92km pipeline.

The cost of energy is as much, if not more of a driver to reduce energy (with reducing carbon as a positive additional benefit). **This means that decisions to reduce energy are often driven more from concerns over cost than based on carbon concerns.** This approach also initially applied to alternative fuels which from the 1990s were attractive to cement companies as they represented a cheap source of direct firing fuel compared with fossil fuels rather than because they represented a decarbonisation. However, all UK cement companies currently recognise that alternative fuels and biomass constitute a highly significant element of their on-going decarbonisation activities.

Overall, the main factor that have implications for the adoption of disruptive advanced technologies are availability of capital to invest, competition for internal funds with other parts of the business or priorities, commercial risks, potential impact on production, potential impact on product quality, ROI and cost savings. Climate change policies are considered as part of the decision-making process yet an attractive ROI and payback remain highly important.

3.4.4 Financing Investments

Companies are less likely to finance investments in decarbonisation if the payback period is greater than three years and 1-2 year payback projects would be much more likely to be approved. Workshop participants also categorised this as significant and all interviewees indicated payback was one of the most significant barriers to implementing new projects. Another key barrier to financing disruptive technologies is the availability of capital, mainly due to competition for internal funds in multinational companies and other projects more closely related to the core business.

There were experiences of companies having applied for external funding through government grant and schemes, but said that academic applicants such as universities were much more experienced with locating and applying for such funding and therefore they were usually unsuccessful in this approach. They also questioned whether the money might be better spent by companies and their internal experts rather than by academic institutions. **The workshops and interviews indicated that third party financing would be a good way to overcome paybacks over 3 years, but that not much activity had taken place in this regard.** Typically the companies prefer to source capital internally through established channels if possible. One company had investigated funding via the Green Investment Bank but found that the required returns were not dissimilar from usual market rates and therefore not useful for their needs.

Workshop participants indicated that there may be an opportunity to collaborate and share the costs of demonstration projects – particularly on CCS/U. However, concerns regarding the impact on competitiveness and competition law requirements would need to be addressed first.

Linked to payback is the fact that cement plants operate continuously and have long life cycles around 30 to 40 years. This means there are limited opportunities to finance large scale disruptive technologies prior to 2050.

3.4.5 Enablers and Barriers

One of the outcomes of the analysis of the sector is a list of the most prevalent enablers and barriers for decarbonisation. The enablers and barriers have been identified through a number of different research methods, namely literature review, interviews and workshops. Triangulating data has been of utmost importance. Seen below are details of the enablers and barriers that have not only been triangulated with regards to research methods, but were also selected at the workshops as the most important enablers and barriers.

Table 5 and Table 6 below indicate the most prevalent enablers and barriers across literature and interviews, as well as the perceived level of impact to decarbonisation as assessed by workshop participants. Although the number of times an enabler or barrier was referenced or highlighted could provide some guidance as to the strength of sentiment towards a particular enabler or barrier, the discussions during workshops and interviews provided a greater understanding as to the detail and context behind each enabler and barrier.

- There were over 20 documents reviewed as part of the social and business literature review. The number in the literature column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of sources that discuss it.
- There were seven telephone and face-to-face semi-structured interviews in total. The number in the interview column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of interviewees that discussed it.
- The workshop column shows the impact level of the enabler and barrier as discussed and agreed by the evidence-gathering workshop group
- The numbers on the left-hand side do not present a ranking but provide an easy point of reference to the order of analysis

These enablers and barriers are illustrated throughout the text with supporting quotes and citations from interviews, workshops and literature. Further depth and interpretation is provided in the following paragraphs:

[Top Enablers]

#	Category	Enablers	Prevalence of occurrence		Level of impact
			Literature	Interviews	Workshop
1	Financial and Technology	Technological and financial feasibility	1	5	4
2	Management and	Pipeline of technological innovations	-	5	4
3	Market and Economy	A stable and profitable business environment	2	3	4
4	Legislation	A more stable, consistent and predictable regulatory environment	2	6	4
5	Legislation	Level playing field	3	5	4
6	Market and Economy	Better recognition of whole-life impacts of cement and concrete as a building material.	2	5	3
7	Innovation	Funding for the development and successful deployment of CCS/U	3	6	4
8	Innovation	Government funding and investment	4	3	3
9	Management and	Agreed and achievable, sector-wide targets and carbon-reduction roadmaps	1	3	3

Table 5: Top enablers

The first enabler - **Technological and financial feasibility** - was identified from all sources and particularly during the workshops. This supported the concept that projects that are already technically feasible, that typically have a payback period of less than 3 years and are linked to other operational improvements have a better chance of obtaining funding. Investments in advanced technologies have a higher likelihood of being approved if they help the companies to improve in areas such as their market share, capacity, product quality, HSE performance, productivity and/or save costs and/or meet new regulations.

The second enabler - **Pipeline of technological innovations -** is that this sector has a strong pipeline of smaller projects waiting to be implemented. For example, the use of automation technology and environmental (energy efficiency and emissions reduction) technologies are widespread in cement manufacturing. This means that further opportunities for energy improvement could potentially be implemented relatively quickly if funding was available. However, it should be noted that many of the 'lower hanging fruit' technologies with lower payback periods and/or high energy savings have already been implemented by the sector.

Technical and operations managers have made the following statements about ROI and pipeline of projects:

"*If a project had a return of a year then it would be instantly signed off"*

"We have a range of projects, but they have to hit specific hurdle rates to receive capital. More incremental decarbonisation opportunities are delivered as part of the daily operation of plants."

"There are some projects that if they are just based on energy then they are hard to justify, but some of them we can point to ways they improve the quality of the product or enhance throughput – i.e. looking at the wider context to further justify the cost"

"We do have many projects we are always putting forward – a healthy pipeline of projects over the next five years including some big ones. We'll have to see if they become viable financially"

"Each project is weighed against each other to determine which offers the best value and returns. If selected then it'll go into a detailed costing and feasibility study (at that point we're investing a bit of

money to get this study done). We have a team of engineers with projects they'll work on each year."

The third enabler - **A stable and profitable business environment -** is that a stable and profitable UK business environment would encourage further capital investment and innovation in the UK. The importance of this can be understood in the context of the market structure section. There are a range of enablers and barriers that impact upon the sector's ability to compete and grow, such as product demand and competition from overseas. The cement companies indicated that only a truly thriving UK economy with above forecast growth rates combined with a more expansive house building programme or the delivery of a national infrastructure programme would stimulate significant growth for their sector.

MPA 2009 states that: "*Growth in the construction sector will provide a platform for investment in new products. Without construction sector growth UK assets will continue to decline and will place the UK vulnerable to imports when demand returns*"

Boston Consulting Group 2008 found that: "*Based on the expected cost of production in the EU assuming the carbon cost of CO_2 versus the cost of producing in non-ETS countries, clinker and cement production in the EU is not competitive without free allowances allocation. As a result, the 'wise businessman' will prefer to relocate production to more competitive countries*."

This is supported by statements from senior level decision-maker interviewees:

"*A stable and buoyant cement market would be the biggest enabler! So if we have higher consumption we'll have excess capital to invest in more improvements"*

"Cement consumption in the UK per capita is the lowest in Europe. So we're not spending enough on construction or we're using different materials."

"There is a need for long term growth to enable more investment. We need delivery of government infrastructure pipeline..."

Legislation related to enablers four and five - **A more stable, consistent and predictable regulatory environment** and a **Level playing field -** describe how a stable, consistent and predictable regulatory environment would enable better long term planning and investment and specifically how reform of UK climate change and energy regulations, taxes and incentives would allow UK-based cement producers to be more cost competitive. This is also described as a barrier in the next section.

Boston Consulting Group found that (to reduce carbon and remain competitive cement companies require):
"*− A consistent and predictable legal framework which allows for long-term investment planning and integrates economic, environmental and social considerations within a coordinated and consistent industrial policy at European level*
− Climate change and energy legislation that is characterised by a legal framework where parameters are fixed long-term, and continued security of supply is guaranteed with competitive energy prices, in a unified European market.."

Senior level decision-maker interviewees stated:

"A big barrier is regulatory risk and uncertainty – at both UK and EU level (especially at EU level) and the degree of interference into emissions markets is a big problem. Phase 3 was only a few months old before the whole debate on backloading began and now we're working on Phase 4. Our timetables are much longer than these phases so constant interference results in much more cost for us to address."

The sixth enabler - **Better recognition of whole-life impacts of cement and concrete as a building material -** is regulatory promotion of thermal properties of concrete in buildings to reduce building energy use during lifetime. Cement companies are interested in decarbonisation from the lifecycle perspective and state that the re-carbonisation properties of concrete structures during their lifetime, and particularly when broken down and reused, are not being appropriately recognised at present. In addition, cement and concrete are very durable and are utilised for low-carbon infrastructure such as wind farms as well as flood defences.

The impact of whole life costings has been recognised in literature:

CEMBUREAU (2009) found that: "*Some national design codes and standards place undue emphasis on minimising embodied impacts and energy use of products, whilst little or no attention is paid to the whole-life performance of buildings. The benefits of heavyweight materials used in construction works should be recognised in existing and future legislation, such as the Energy Performance of Buildings Directive (EPBD). In addition, national compliance tools for assessing both energy consumption and sustainable performance of buildings need to be amended to take due account of thermal mass and climate change."*

Senior level decision-maker interviewees stated:

"*There is a drive to reduce carbon which is not just based on compliance costs – it's also to do with overall company sustainability strategy including enhancing our product attractiveness to clients.. The UK definitely has much higher demand for low-carbon building materials – this is a driver from the government who want to lead on climate change."*

"We explain the carbon profile of our product to our customers if they want to understand the impacts. In future the industry could include full life cycle benefits (of concrete) and sell these benefits to clients"

"We also need to look more at the impact in buildings and where we improve their carbon performance over lifetime"

"Cement is essential for carbon savings down the line in terms of its use, not just manufacture."

Enablers seven and eight - **Funding for the development and successful deployment of CCS/U** and **Government funding and investment -** are concerned with gaining funding for the innovation and technologies needed to have a significant impact on decarbonisation in the cement sector. Enabler seven concerns gaining funding for the successful deployment of CCS/U. All UK companies indicated that without CCS/U then the sector would not be able to reduce emissions by 80% by 2050. However, the cement sector expressed interest in working on CCS/CCU with suitable government support and with cross-sector collaboration. Enabler eight concerns how to gain government funding and investment support for decarbonisation R&D activities and associated costs to facilitate collaboration and investment in this area.

The potential impact of CCS/U has been identified in literature:

DECC (2013) found that: *"Industrial CCS could be a key technology for the decarbonisation of industry sector, potentially allowing energy intensive industries to continue using fossil fuels while significantly reducing emissions. ESME (Energy System Modelling Environment) modelling suggests that a significant component of long-term industrial abatement potential lies in CCS technology. Industries which emit carbon from their manufacturing process itself (for example CO_2 emitted as a consequence of chemical reactions [e.g. cement]) are likely to need to implement CCS to decarbonise. Industries which are most likely to be suitable for CCS are iron and steel, cement, oil refining and chemicals. 29 Industrial facilities which are located close to other industries or power stations and storage sites are more likely to be able to implement CCS if they can share transport and storage infrastructure. Cement: Post-combustion capture technology using amines is considered most suitable for current cement production methods although research into Oxyfuel methods is also under* *way."*

IEAGHG (2013) found that: "*CCS will be required if cement manufacturers are to meet overall decarbonisation targets as efficiency savings have limitations. Most cement companies feel CCS is relevant to them, but only a third are willing to contribute to a pilot project due to high costs*"

CEMBUREAU found that: "*Carbon capture and storage is currently being researched by the cement industry. Although not proven on an industrial scale, research on carbon capture (post combustion and oxyfuel technologies) is being undertaken by the European cement Research Academy (ECRA) to identify the possibilities it has to offer.*"

The MPA and senior level decision-maker interviewees stated:

"*Low carbon cements are being developed by some of the companies globally, but the research is not happening in the UK itself"*

"There is some R&D going on in the sector at universities such as Sheffield, Birmingham and Imperial. However, UK R&D tends towards cement types and formulas rather than plant and equipment related research which tends to be done abroad. Some of the new cement/concrete formulas are based on lower carbon outcomes"

"With some funding for R&D, academic bodies tend to be much better than the cement companies at claiming this funding. However the funding would be very useful for the industry, but it all happens so quickly with so little visibility that the companies miss the opportunity to take some of this money. This money for R&D might be much better spent by the operators rather than academic and research bodies."

Enabler 10 - **Agreed and achievable, sector-wide targets and carbon-reduction roadmaps -** is that agreed and achievable, sector-wide targets and carbon-reduction roadmaps would assist sector in reducing emissions in coordinated manner. The MPA, the EU, the World Business Council for Sustainable Development and the International Energy Agency have developed 2050 decarbonisation roadmaps which indicates that decarbonisation is becoming a more prominent issue for the sector. During the workshop, many participants noted that they felt government were simply not particularly aware that this roadmapping work had already been completed and agreed to by the sector companies and if there was better awareness this could facilitate coordination and understanding of efforts and impacts.

MPA literature stated:

"*MPA cement launched its first Carbon Strategy in 2005. The short term period of action in the original strategy ended in 2010. Since then there has been a considerable effort by policy makers, NGO's and industry groups to map the necessary reductions in emissions to address the scientific imperative to minimize anthropogenic induced climate change. There has also been considerable research into low carbon pathways and carbon footprinting."*

Top Barriers

#	Category	Barriers	Prevalence of occurrence		Level of impact
			Literature	Interviews	Workshop
1	Financial	Short payback periods and high rates of return	1	4	3
2	Financial	Lack of access to and competition for capital	-	6	4
3	Operational	Longevity of current equipment and investment cycle	1	5	4
4	Financial	Risk aversion	2	5	8
5	Market and Economy/Legislation	Increasing competition of diversion of alternative fuels and biomasses	4	13	7
6	Organisational	Shortage of qualified engineers and specialist skills and knowledge	1	3	3
7	Legislation	Uneven EU and global playing field with overseas competition	7	11	11
8	Legislation	EU ETS – Risk induced by future uncertainty	2	5	4
9	Market and economy	UK demand for cement is below 2007 levels	5	5	5
10	Innovation	It is perceived by industry that the UK government is not backing CCS R&D as strongly as other countries	2	2	3
11	Innovation	Technological feasibility and affordability of CCS	1	4	3

Table 6: Top barriers

There are a number of barriers that if they were overcome could facilitate reduction in carbon emissions for the cement industry and have also been included as enablers above.

The first two barriers - **Short payback periods and high rates of return** and **Lack of access to and competition for capital -** are around financing in terms of the desire for return on investment and access to capital. As before, the literature review and interviews found that companies are less likely to finance investments in decarbonisation if the payback period is greater than three years and one to two year payback projects would be much more likely to be approved. All interviewees indicated payback was one of the most significant barriers to implementing new projects. Another key barrier to financing disruptive technologies is the availability of capital, mainly due to competition for internal funds in multinational companies and other projects felt to be more closely related to the core business.

Senior level decision-maker interviewees had the following comments on ROI and access to capital:

"*Payback periods are another industry barrier. Companies need to be able to pay back investments in 2-3 years rather than the 10+ years the government often wants companies to invest. A couple of companies have spoken with GIB, but the rates are mainly market rates so not a particularly cheap way to borrow"*

"There is capex competition with plants elsewhere around the world – projects and plants compete on cost savings, carbon savings and market opportunities."

"Internal competition for capex is a big barrier"

"There is also a lot of internal benchmarking within companies by different plants in different countries. They are competing with each other for investment. The recession has affected many

companies in the sector, not just in the UK. Financial investment has declined across the world so internal competition for capital investment is very strong."

"We are competing for capital within an international business. This is a barrier for us."

Barriers three and four - **Longevity of current equipment and investment cycle** and **Risk aversion -** are also related to financing and approach to return on investment for environmental projects. This is further affected by long plant life (longevity of current equipment) and investment cycle and a generally risk averse approach in the cement industry – companies are wary of being locked in to the 'wrong' investment choices (in part due to high technology costs, long investment cycles and concerns over product quality impact).

Technical manager interviewees stated

"*A cement plant will cost a minimum of £250m and will last 30 to 40 years. Therefore there is only really likely to be one more significant investment cycle between now and 2050"*

"We are very capital intensive with very long payback periods of, 30 to 40 years and 7 years to plan and build new plants."

"You see the really big step changes at the point of plant construction. Typical payback is 30-40 years. At the point of construction you install the best available technology at the time. Plants are highly integrated so it's not easy or cheap to replace parts of already built plants. More common is continuous improvements such as switching to different fuel types."

DECC (2013) notes that the "*cement sector suffers from risk-averse thinking - wary of risks to product quality or being locked in to 'wrong' investment choice*."

Barrier five - **Increasing competition of diversion of alternative fuels and biomasses -** is the increasing competition for of diversion of alternative fuels and biomasses. Specifically, the Renewable Heat Incentive system increases biomass costs for cement sector as the sector is not currently eligible for this. According to sector interviewees, the UK cement industry was a first mover in utilising alternative fuels and biomass to replace fossil fuels such as coal and petroleum coke (petcoke). This was initially financially attractive compared with fossil fuels, but increasing competition has led to rising costs of alternative fuels which is now proving problematic for the sector in terms of cost and security of supply. This issue was identified by all interviewees involved.

The challenge for the future will be to make sure that the biomass fuels remain available to cement manufacturers and are not simply diverted to other areas of the economy that are currently receiving incentive payments via, for example, the Renewable Heat Incentive (RHI) which are inaccessible to the cement operators. Consequently, there is a measurement issue when it comes to deciding whether policies such as the RHI are generating additional biomass heat or just moving the biomass heat consumption from those sectors that don't currently receive RHI to those that do.[32] If the latter, then the policy has no net benefit, and can actually be a disbenefit if it results in biomass being used in a less efficient manner as a result of distorting subsidies.

MPA (2009) states: "*Government policies currently inhibit the maximized use of Alternative Waste Derived Fuel in cement manufacture which results in a continued reliance upon fossil fuels. Other policies allow Alternative Waste Derived Fuel to be incinerated without a charge being placed on the resulting GHG emissions which means there is uneven treatment of the combustion of the same fuels in different applications. Current government policies to enhance the use of renewable heat are poorly focused and incentivise the use of biomass for some activities but not others, potentially creating a shift in biomass use from one sector to another without an overall environmental benefit. The current Renewable Heat Incentive creates an incentive to move biomass use from cement kilns to other* *potentially less efficient uses. This is an unwelcome intervention in the market by a poorly designed policy."*

Senior level decision-maker interviewees have stated:

"*RHI is a problem – 10 years ago we were the only company who bought some alternative fuels and now we can't afford them compared to other companies. Alternative fuelswere previously almost zero cost and now they have a similar price to coal. If you look at small scale biomass then RHI takes it all away from us as we can't get the incentive.*"

"*Security of supply is a worry – we need to know we can get a long term supply when investing in new alternative fuel equipment. One key question we now get asked when we do alternative fuel capex is "Do you have a contract in place to get this material for the long term?" Distortions such as RHI need to be removed from the marketRHI is not recognising that alternative fuel can be burned anywhere, why should one person get the advantage?"*

"The sector have been pushing the government to allow the cement sector to have energy incentives such as RHI. It is offering the incentives to other industries, but not the cement sector. So the cement sector will be priced out of purchasing fuels such as biomass fuels.…"

Barrier six - **Shortage of qualified engineers and specialist skills and knowledge** - this is a shortage for the cement sector specifically in terms of heat engineers. There are a number of contributory factors that are linked including competition from other sectors for a limited number of qualified staff; location of the cement plants and aging workforce. This was discussed by the interviewees and at the workshops.

DECC (2013) notes that the "*Cement sector suffers from a shortage of qualified staff (especially heat engineers) and aging of workforce.*"

Technical managers stated:

"*We struggle to attract top graduate talent compared with more glamorous sectors such as technology. There are concerns about a knowledge gap occurring when more people retire from the sector."*

"*We need specialised technical resources/skills. cement plant operators are highly skilled. If a kiln is down for a day this can cost £100,000. More complex tech needs greater skill. The reduction in the manufacturing in UK makes it difficult to find graduates wanting to come into sector. Smaller pool to recruit from. How can government help? We need an environment where heavy industry can flourish and make youngsters want to study and join the sector. Cement perception is not positive, but reality is it's very clean and technical work. Visitors are always surprised by the level of skill required to make cement! We need to promote positive side of industry."*

"The *sector is rurally-based. We generally attract local youth/students with well-paid apprenticeship. When we look for specialists such as environmental experts it can take a long time to attract the right person though."*

Barriers seven and eight - **Uneven EU and global playing field with overseas competition** and **EU ETS – Risk induced by future uncertainty -** are legislation related barriers that are also described in the enablers section. This is in terms of how a more even regulator playing field at both EU and global levels would enable UK cement producers to be more cost competitive with EU and global producers who are not subject to the same regulatory costs. This view was expressed by the MPA and all cement companies. In particular, reform of UK-specific climate change and energy regulations, taxes and incentives such as the UK's unilateral Carbon Price Floor and the CRC Energy Efficiency Scheme would allow UK-based cement producers to be more cost competitive at both an EU and global level.

At the EU level, all the companies interviewed and the MPA indicated that the EU Emissions Trading Scheme added not only greater costs compared with non-EU producers, but also problematic uncertainty over future carbon allowances and costs which hamper their ability to make long term investment decisions in the EU. The MPA noted that the current and projected future allowances for the cement sector were considered to be flawed as the impact of the 2008 recession - which temporarily lowered production in the EU and therefore total carbon emitted - was not taken into account and this resulted in lower than expected allowances being issued for the sector. The MPA and some of the other interviewees also commented that the EU ETS has led to some unintended consequences in that plants will lose their allowance altogether if their production falls below 50%. This has led to occasional gluts in unneeded supply in some markets such as Ireland and Spain as plants over-produce cement to ensure they retain their current emissions allowances. A further unintended consequence expressed by interviewees is that new cement plants typically take a few years to move their production up to 100% capacity after commencing operations and this means they risk being given an allowance that doesn't recognise their expected production levels in future years. The result of this being a general disincentive to invest in new, more energy-efficient plants and rather to persevere with older, less efficient plants as they may be cheaper to operate with their higher emissions allowances.

In addition, barrier nine - **UK demand for cement is below 2007 levels -** is that UK demand for cement is still well below 2007 levels and growth forecasting is difficult which impacts on investment decisions. The UK cement industry is argues that it is at risk from low cost imports, partly due to the UK's extensive coastline and high number of ports suitable for importing cement and then easily transporting it around the country.

Boston Consulting Group 2011 found: "*the high level of regulatory uncertainty in Europe discourages companies from making the investments required in order to improve the efficiency of cement plants and the lack of an appropriate legal framework deters companies from adopting structural adjustments*"

A senior level decision-maker interviewee stated "*EU ETS creates a difficulty. Every 5 years we get a level of free allocation, but this declines every year. We are vulnerable to carbon leakage as an industry and at some point leakage will start to take place – only the recession and a relatively low carbon price has prevented this so far. The next review is in 2019 and the decisions made are so absolutely critical that it's almost a case of go or no go for staying in the UK*."

Boston Consulting Group 2008 states that: "*EU ETS could make European cement manufacturers uncompetitive with global competitors / plants leading to possible carbon leakage*"

Centre for Low Carbon Futures 2011 states that: "*number of representatives identified the high and rising costs of energy and energy taxes in the UK, as well as rising commodity prices, as a barrier to investment. Parent companies see relatively poor returns on investment in the UK compared with other countries. The representatives consulted referenced the TUC/EIUG report (2010) on the cumulative impacts of climate change policy on the energy intensive industries, with both electricity and gas costs expected to rise by up to 22% by 2020."*

MPA (2009) states that: *"It is very difficult to accurately forecast future demand and production - therefore assumptions used for roadmaps and milestones may not be accurate. Growth in the construction sector will provide a platform for investment in new products. Without construction sector* *growth UK assets will continue to decline and will place the UK vulnerable to imports when demand returns."*

The final barriers, 10 and 11 – a perception that **UK government is not backing CCS R&D as strongly as other countries** and **Technological feasibility and affordability of CCS -** concern CCS/U which could have a significant impact on decarbonisation in the sector. These are also discussed in the enablers section in terms of how investment and uncertainly around CCS/U means that this is difficult to be implemented. In particular, the projected costs of implementing CCS/U would likely make any such UK plants uncompetitive with non-CCS/U plants. As the technology is currently unproven, interviewees all indicated that no company had a desire to be the first mover on CCS/U without some form of support mechanisms to minimise the financial risks. Barrier 11 discusses the technical uncertainties and overall viability that remain around CCS/U as a practical solution as well as the affordability aspects.

IEAGHG 2013 states that: "*CCS will be required if cement manufacturers are to meet overall decarbonisation targets as efficiency savings have limitations. With current legal and economic conditions around CCS would impair the competitiveness of cement production and this inhibits the development of CCS"*

Centre for Low Carbon Futures 2011 states that: "*Transformative technologies, such as carbon capture and storage, remain perhaps 10-15 years away from commercial deployment."*

Senior level decision-makers stated:

"*Our big wish is for proper government funding for CCS!"*

"*The capital cost of doing CCS would basically double the cost of a plant. A new plant in the UK would be £200-250m, but price and plant size would double with CCS in place. And if we captured the carbon, then what do we do with it? Many plants are a long way from storage in seas and the plants can't be moved away from their quarries easily or cheaply. Biggest issues would mainly be transport and storage of the carbon along with capital costs. If you were first to do it then you'd need it to be supported by government as the risk and cost is just so big. Why would you invest in that if you weren't sure it would work?*"

"*Other than a few projects that have been happening elsewhere, there is still a lack of understanding about whether CCS will ever be commercially and technically viable. I cannot see that the cement industry would be the first to prove success of this technology*."

3.5 Technologies to Reduce Carbon Emissions

The options distilled from the literature review, interviews, evidence-gathering workshop, discussions with the Trade Associations and input from academia, which have been modelled are presented in appendix C (the data for these options are also listed). The energy saving and decarbonisation opportunities are classified into twelve categories that represent the principal areas of the cement making process and key cross-cutting areas of potential performance improvement, in order to group similar technology options:

- **Kiln process technology (Best available techniques kiln):** the implementation of the most modern kiln technologies, considering size and related efficiency.
- **Electrical efficiency improvements:** motor management plan, maintenance, voltage and power optimisation, strategic motor selection (including Variable/Adjustable Speed Drives), properly sized motors, high efficiency belts (cog belts more energy-efficient than pneumatic or screw conveyors). Switching off unnecessary lights replacing by daylight, replacing lighting by energy-efficient lighting, optimised utility systems, within others.

- **Electricity from waste heat:** the use of waste heat in order to reduce CO_2 emissions by raw material drying, power generation (steam cycle, Kalina cycle, Organic Rankine Cycle).
- **Cementious substitution:** reducing the amount of clinker per unit of cement by substituting the clinker with other cementitious materials, such as pulverised fuel ash (a waste from coal fired power stations) or ground granulated blast furnace slag (a by-product from iron and steel manufacture), natural pozzolanic materials, fillers such as limestone.
- **Alternative raw materials (calcined):** improves the energy efficiency of the thermal processes in the kiln and so their use leads to a reduction in the thermal requirement per unit of clinker produced.
- **Fuel switching to natural gas:** use of natural gas to reduce CO_2 emissions for cement production.
- **Fuel switching to biomass:** use of biomass to reduce CO_2 emissions for cement production.
- **Hydrogen fuel:** use of hydrogen to reduce CO_2 emissions for cement production.
- **Alternative cements:** there are several diverse, novel or 'new' cements which are generally non-Portland, based on non-traditional processes or raw materials. They tend to embody less energy and emit less CO_2 during manufacture than 'Portland cement CEM I' (formerly called ordinary Portland cement) although there is no precise definition for what constitutes a low energy, low carbon cement. These include Magnesium oxide (MgO) alternatives, belite-aluminate, sulpho-aluminate, other, lower CO_2 cement alternatives.
- **Fluidised bed kiln:** In this technology clinker is produced in a fluidized bed system, under addition of grinded coal, and raw material injection. The raw material is granulated in the kiln system to a specific size. Subsequently the clinker is cooled in two steps (fluidized bed quenching and a packed bed cooler). The result is a finely granulated clinker.
- **Carbon capture:** the capture of CO_2 generated by combustion processes. The CO_2 is then transported, typically by pipeline, and stored underground in suitable geological features.
- **Oxygen enrichment technology:** the use of oxygen enriched combustion air in the clinker burning process. This allows an increase of the fuel efficiency, production capacity or substitution of fossil fuels by low calorific value (or secondary fuels). This option includes oxygen enriched combustion and oxyfuel combustion.

This short list of options was used in the pathway analysis (section 4).

3.5.1 Biomass Carbon Intensity

Pathways including biomass reflect biomass carbon intensity (unless the biomass in the pathway is assumed to be waste biomass). The carbon intensities (below) are applied to two scenarios to help reflect and bound the uncertainties around biomass carbon availability; these are (i) unlimited availability – as deployed in the Max Tech pathway or (ii) no availability.

In all cases, combustion emissions are assumed to be zero (in line with EU Renewable Energy Directive methodology), on the basis that all biomass used is from renewable sources and thus additional carbon dioxide is removed from the atmosphere equivalent to that emitted on combustion. This means that all biomass is assumed to be sourced from material that meets published sustainability criteria.

Given the wide variation in pre-combustion emissions, a carbon intensity (based on pre-combustion emissions) was derived from a low scenario from the DECC-commissioned Bioenergy Emissions and Counterfactual Model report (published 2014) for modelling purposes. An emission value of 20 $kgCO_2e/MWh(th)$ has been used for solid biomass use, and this has been modified to 25 $kgCO_2e/MWh(th)$ if the pathways includes pyrolysis, and 30 $kgCO_2e/MWh(th)$ if the pathways includes production of biogas.

3.5.2 Cost of Options

Limited information related to the capital cost of technologies was identified in this project as summarised in appendix C. In gathering capital cost-related data, literature and/or engagement with stakeholders – together with expert judgement - were used to establish an initial order of magnitude dataset for use in the cost analysis assessment. The degree of stakeholder engagement in relation to the cost dataset was lower than for the carbon reduction pathways. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs will have a major impact on the decarbonisation and energy efficiency pathways. For example, some options (e.g. carbon capture and electrification of firing) will greatly increase energy use and costs of a process plant.

Costs analysis was carried out for the pathways, which is presented in section 4. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. As well as costs of operation and energy use – other significant costs not included in the analysis are research, development, demonstration, civil works, modifications to plant and costs to other stakeholders, which are significant for many options. Great care must be taken in how these costs are interpreted and it is recommended to check with trade associations.

4. PATHWAYS

4.1 Key Points

In this study, four pathways were modelled for each of three scenarios:

- Challenging world scenario
  - BAU
  - 20-40%
  - Max Tech no CCS
  - Max Tech with CCS
- Current trends scenario
  - BAU
  - 20-40%
  - Max Tech no CCS
  - Max Tech with CCS
- Collaborative growth scenario
  - BAU
  - Max Tech no CCS
  - Max Tech with CCS

The two principal external factors appraised for each scenario are the sector production and electricity grid decarbonisation. These factors translate to a moving reference trend before any decarbonisation options are applied, and these baseline emissions are plotted as a black line in Figure 10 below. Figure 10 shows a 9% emissions reduction from 2012 to 2050 solely resulting from electricity grid decarbonisation since there is no change in production of cement under current trends.
It should be noted that the forecast decarbonisation of power generation will require significant policy intervention to maintain the projected trajectory to 2050 and may increase cost to industry through price pass through in power prices to consumers unless further mechanisms are introduced by government to address this.

The pathways analysis shows that the technical decarbonisation potential of the sector, under the current trends scenario (not taking into account cost), is a reduction from 7.5 Mt CO_2 emissions to emissions in 2050 between 2.8 Mt CO_2, for the Max Tech with CCS pathway, and 6.7 Mt CO_2, for the BAU pathway. These absolute emissions in 2050 correspond to reductions in emissions of 62% and 12%, respectively, compared with emissions in 2012. These 2050 CO_2 emissions figures may be compared with the figures determined in the MPA's cement GHG Reduction Strategy; which projects 2050 emissions of 2.85 Mt CO_2 and 5.7 Mt CO_2 under two different pathways considered in the MPA strategy. These correspond to emissions reductions in 2050 of 28.4% and 65.6%, respectively, compared with 2012.

Emissions reductions in 2050, compared with 2012, range from 24% to 53% under the challenging world scenario, and -6% to 55% under collaborative growth. Such reductions could be achieved through a range of options, the most significant being:

- Carbon capture
- Switching from fossil fuels to biomass
- Cementitious substitution
- Decarbonisation of the electricity grid

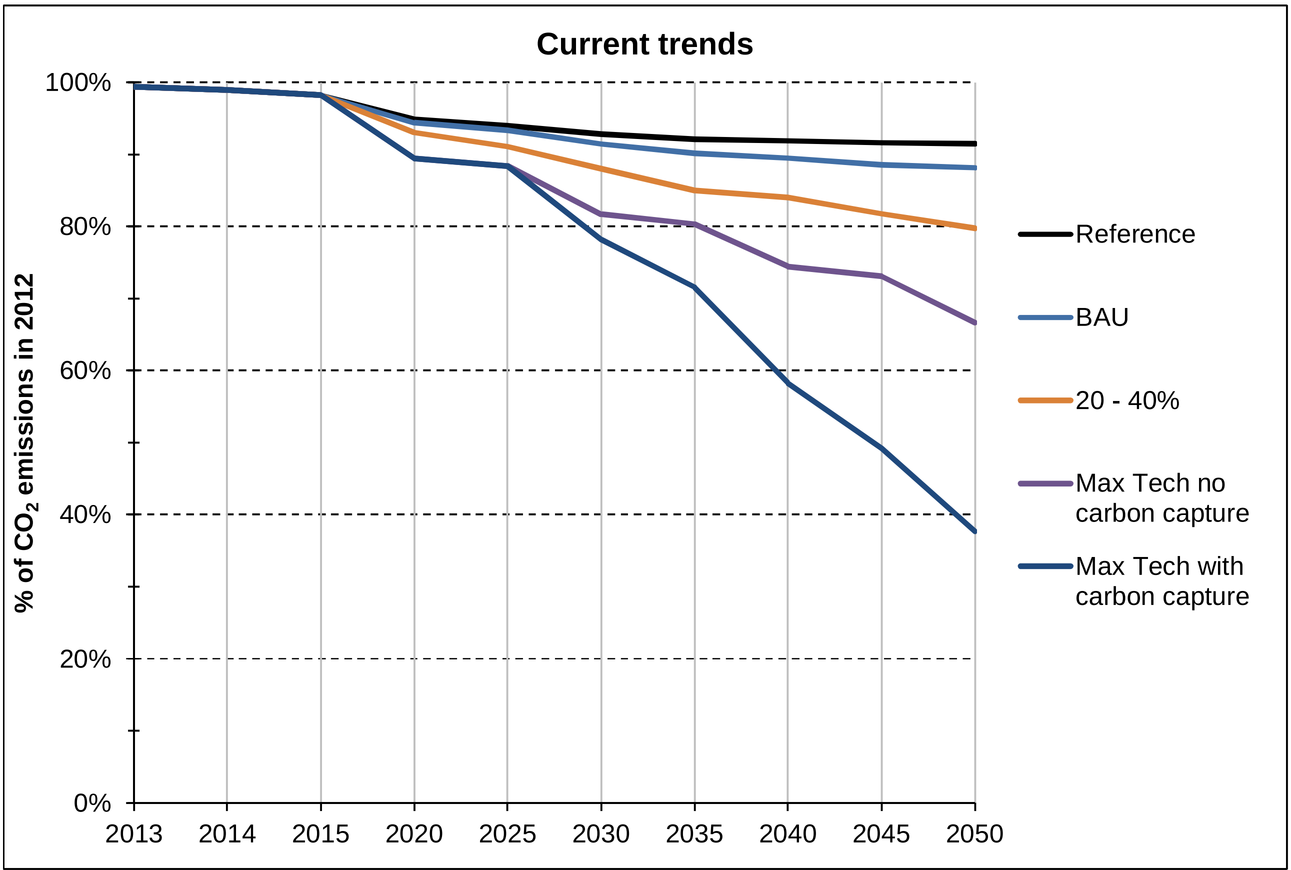

Figure 10: Performance of pathways for the current trends scenario

Figure 10 shows the wide range of decarbonisation and energy efficiency pathways that are possible for the current trends scenario. The following describes the rationale for each of these pathways:

- **BAU** represents a pathway where only those options that are already planned, or would be followed for best practice or economically advantageous reasons are utilised. This would build on the significant decarbonisations already achieved by the cement sector, as discussed earlier in this report, and requires significant additional investment by the sector to meet commitments made, and is subject to government policy decisions.
- In the **20-40%** CO_2 reduction pathway, some options have a greater rate of adoption, and the option of fuel switching to biomass is deployed beyond the current adoption level, in order to achieve a CO_2 emission reduction by 2050 in the range 0%-20%; options selected are those considered to be most readily employed, with most attractive costs.
- For the **Max Tech with CCS** pathway only technical limitations are applied. There are no commercial restrictions on the use of the technology. This pathway gives the maximum possible level of CO_2 emission reduction by 2050.
- The purpose of the **Max Tech, no CCS** pathway was to see what the impact would be if carbon capture was not available to the cement sector, but still only technical limitations apply to all other options.

A small number of options shown in the deployment tables are not deployed in any pathways, based on evidence from interviews and workshops. These have been retained in the tables for completeness but show zero deployment.

Pathway analysis was based on the 'maximum interaction' case, as this gave the minimal, worst-case CO_2 reductions within the context of the pathway. Maximum interaction means that where multiple options could apply to the same emissions, emissions are assumed to be saved only once, i.e. by one of the options only, to avoid potential double-counting.

4.2 Pathways and Scenarios – Introduction and Guide

As set out in section 3, the pathways development uses evidence gathered to create a set of decarbonisation 'pathways'. These provide a quantitative component to the roadmap and help inform the strategic conclusions.

A pathway consists of decarbonisation options deployed over time from 2015 to 2050, as well as a reference emissions trend. The analysis covers three: 'scenarios': with pathways developed under a central trend ('Current Trends' scenario) and alternative future outlooks ('Challenging World' and 'Collaborative Growth' scenarios).

A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs, and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways. A detailed description of these scenarios is provided in appendix A.

The three scenarios were developed, covering a range of parameters. They characterise possible versions of the future by describing assumptions relating to international consensus; international economic context; resource availability and prices; international agreements on climate change; general technical innovation; attitude of end consumers to sustainability and energy efficiency; collaboration between sectors and organisations; and demographics (world outlook). These scenarios were used during the workshop to help decide on deployment rate for the different options.

Quantitative parameters were also part of the scenarios, including production outlook (agreed sector-specific view) and grid CO_2 factors (DECC supplied) which both impact decarbonisation (assuming production and carbon emissions have a linear directly proportional relationship). Other quantitative parameters within the scenarios governed forward price forecasts and technology deployment.

The purpose of the model that underpins this pathways analysis is to bring together the data captured from various sources and to broadly reflect, using a simple 'top down' approach, how emissions might develop to 2050. The model is therefore capable of indicating magnitudes of emissions reduction that can be achieved, when various technology options are applied, and also how different deployment timings and high-level economic outlooks for a sector might change the results. A sector model was used to create pathways based on reference emissions and energy consumption in 2012. The model is not intended to give exact results and is not of sufficient detail to account for all mass/ energy/ carbon flows, losses and interactions in a sector (i.e. it is not 'bottom up' and does not use automatic optimisation techniques).

The methodology is summarised in Figure 11.

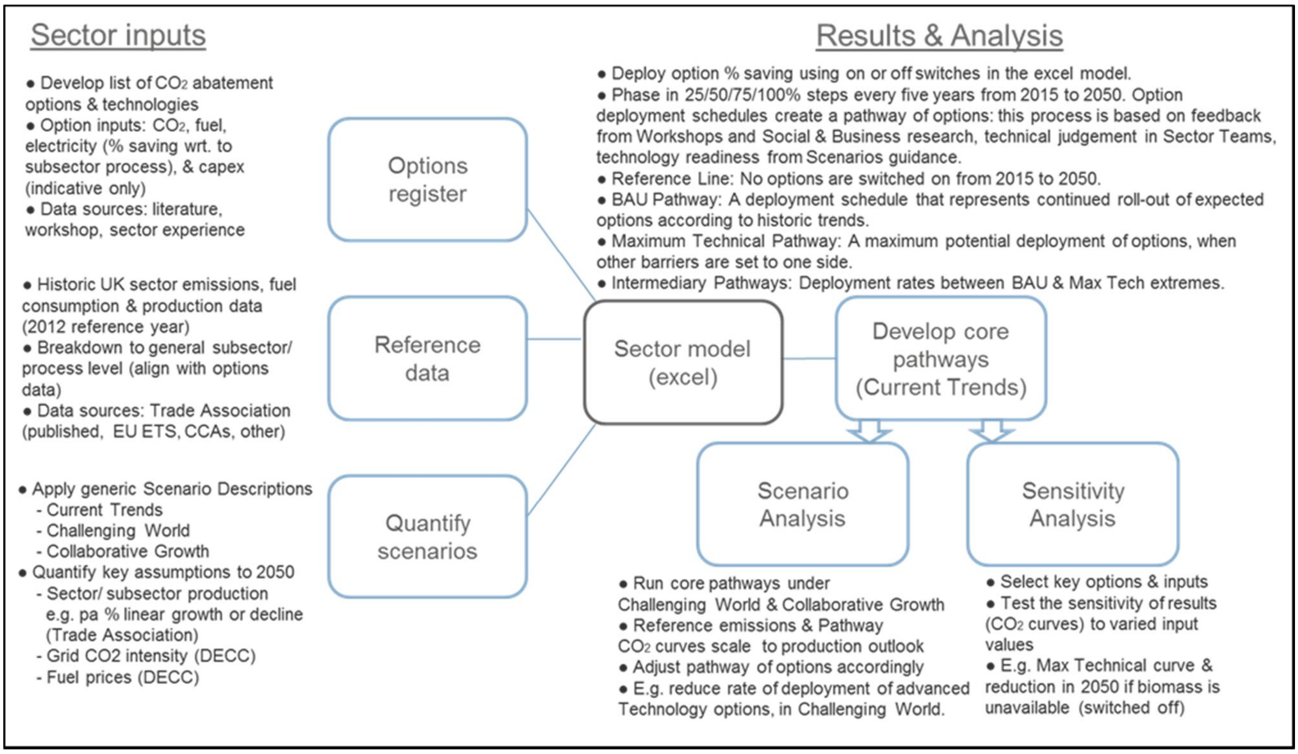

Figure 11: Summary of analysis and methodology

This section of the report is structured to present the pathways in the current trends scenario (section 4.5.1), whilst also briefly describing how the pathways change when modelled under other scenarios. Table 7 illustrates this structure and acts as a guide to the section.

Sections 4.5.2 and 4.5.3 summarises the pathway analysis in the other two scenarios (challenging world and collaborative growth).

Pathway	Current Trends Scenario	Challenging World Scenario	Collaborative Growth Scenario
Reference Emissions Trend	Scenario assumptions only linked to production outlook and grid decarbonisation. No options are deployed in the model.		
BAU	Builds on the reference line by deploying options from 2015 to 2050 in the model, to construct a BAU pathway. Run model under current trends.	Builds on BAU pathway current trends by adjusting option selections and deployment schedule, to reflect the scenario assumptions and technology constraints. Run model under challenging world.	Adjust BAU pathway current trends, i.e. option selections and deployment schedule, to reflect scenario assumptions and technology constraints. Run model under collaborative growth.
20-40% [13]	Builds on BAU for example by: deploying more advanced options, extending further across sector, deploying options earlier. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
40-60%	Builds on 20-40% in the same way. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
60-80%	Builds on 40-60% in the same way. Run model under current trends.	Builds on 40-60% CO_2 reduction pathway current trends in the same way. Run under challenging world	Adjust 40-60% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
Max Technical	Configure a schedule of options from 2015 to 2050 that broadly represents a maximum rate and spread across the sector. Run model under current trends.	Adjust Max Tech pathway current trends in the same way. Run under challenging world.	Adjust Max Tech pathway current trends in the same way. Run under collaborative growth.

Table 7: Pathway and scenarios matrix

Section 4.6 presents results from the sensitivity analysis, which aims to demonstrate the impact of key options and sensitivity of the pathways to critical inputs.

Section 4.8 summarises the enablers and barriers to the options and pathways developed in the modelling, taking account of information gathered from literature and stakeholders.

[13] intermediary pathways may or may not be developed for a sector, depending on the carbon reductions of the BAU and Max Tech Pathways

4.3 Baseline evolution - Principal Question 3

This section provides assessment of the range of questions under principal question 3: 'How might the baseline level of energy and emissions in the sectors change over the period to 2050?'

The market for cement in the UK is highly dependent on overall economic conditions. The recent recession has had a major impact on the cement market, with a significant decline in demand that has only partly bounced back during the economic recovery. Under stable economic conditions – growing in line with long term UK economic forecasts and trends - the market for UK produced cement is anticipated to be broadly flat, with domestic producers able to maintain their position against competition from abroad, but any increased demand being supplied by increasing imports (cement imported by non-GB manufacturers currently accounts for around 14% of the GB cement market). However, any future economic contraction, or above-trend growth could be anticipated to impact market demand, while a changing dynamic in international competition could enhance or degrade UK production and market share. Based on the above assumptions and together with MPA, we have developed the following growth estimates for the different future scenarios:

- Current trends – 0.0% annual growth
- Challenging world – 0.5% annual decline
- Collaborative growth – 0.5% annual growth

4.4 Emission-Reduction Potential and Pathway Analysis – Principal Question 4 and 5

This section provides an assessment of the range of questions under principal questions 4 and 5:

- What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050?
- What emissions pathways might each sector follow over the period to 2050, under different scenarios?

For a detailed description of the pathways development and analysis, see appendix A.

4.4.1 Baseline - Business as Usual Pathway

Pathway Summary

The guiding principle for the BAU pathway was to outline a set of decarbonisation and energy savings options that would be expected if current rates of efficiency improvement in the UK cement industry continued, and no significant intervention or outside support was provided to decarbonise the sector by 2050. options requiring no policy intervention (compared to today) were chosen, however the adoption of some of the options would require significant investment commitments.

Deployment for the Current Trends Scenario

Figure 12 shows the option deployment for the BAU pathway under the current trends scenario. This figure shows the different technical options on the left, followed by the estimated adoption rate in 2012 and the applicability rate. The applicability rate indicates to what level this option is applicable to the sector, as a percentage of cement production capacity. To the right of the applicability rate is the actual deployment of the option over time to 2050, as well as the direct emissions and electricity savings from each option, and the contribution of each option in 2050. The CO_2 reductions are estimated based on the adoption rate, applicability rate and deployment.

In the BAU pathway under current trends, the option for cementitious substitution is deployed to 50% of potential in 2050. Additionally, the option for alternative cements is deployed to 75% of potential from 2045. Efficiency improvements are considered to be evolving incrementally through to 2050 and applied across the sector to maximum extent.

BAU - current trends

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Kiln process technology (BAT kiln)	0%	100%	0%	0%	0%	0%	0%	0%	0%	10%	10%
02 Electrical efficiency improvements	0%	100%	0%	0%	75%	75%	75%	75%	75%	100%	100%
03 Electricity from waste heat	0%	25%	0%	0%	25%	25%	50%	50%	75%	75%	100%
04 Cementitious substitution	8%	11%	0%	0%	10%	10%	25%	25%	40%	40%	50%
05 Alternative raw materials (calcined)	1%	2%	0%	0%	10%	10%	25%	25%	40%	40%	50%
06 Fuel switching to natural gas	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Fuel switching to biomass	18%	80%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 Hydrogen fuel	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Alternative cements	0%	5%	0%	0%	0%	10%	25%	50%	50%	75%	75%
10 Fluidised bed kiln	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 Carbon capture	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12 Oxygen enrichment technology	0%	75%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 12: Option deployment for the BAU pathway under current trends

For BAU, three principal options were identified to contribute to the emissions reduction by 2050. These have been discussed below, and are shown in absolute terms in Figure 13 and in relative terms in Figure 15:

- Alternative cements, deployed to 10% of the potential maximum 5% applicability (i.e. 0.5% adoption) by 2025, 25% by 2030, 50% by 2035 and to a maximum of 75% by 2045, represents emissions reduction of 1.7%, compared to 2012, which is 51% of the total options CO_2 reduction for BAU pathway.
- Cementitious substitution is initially deployed to 10% of potential in 2020, increasing to 25% in 2030, 40% in 2040 and reaching a maximum of 50% deployment by 2050. This option represents a 1.2% CO_2 reduction in 2050, compared to 2012, which is 37% of the total options reduction for BAU pathway.
- The option to use alternative raw materials (calcined) is deployed with the same profile as cementitious substitution. This option represents emissions reduction of 0.3% in 2050, compared to 2012, which is 9% of the total options reduction for the BAU pathway.

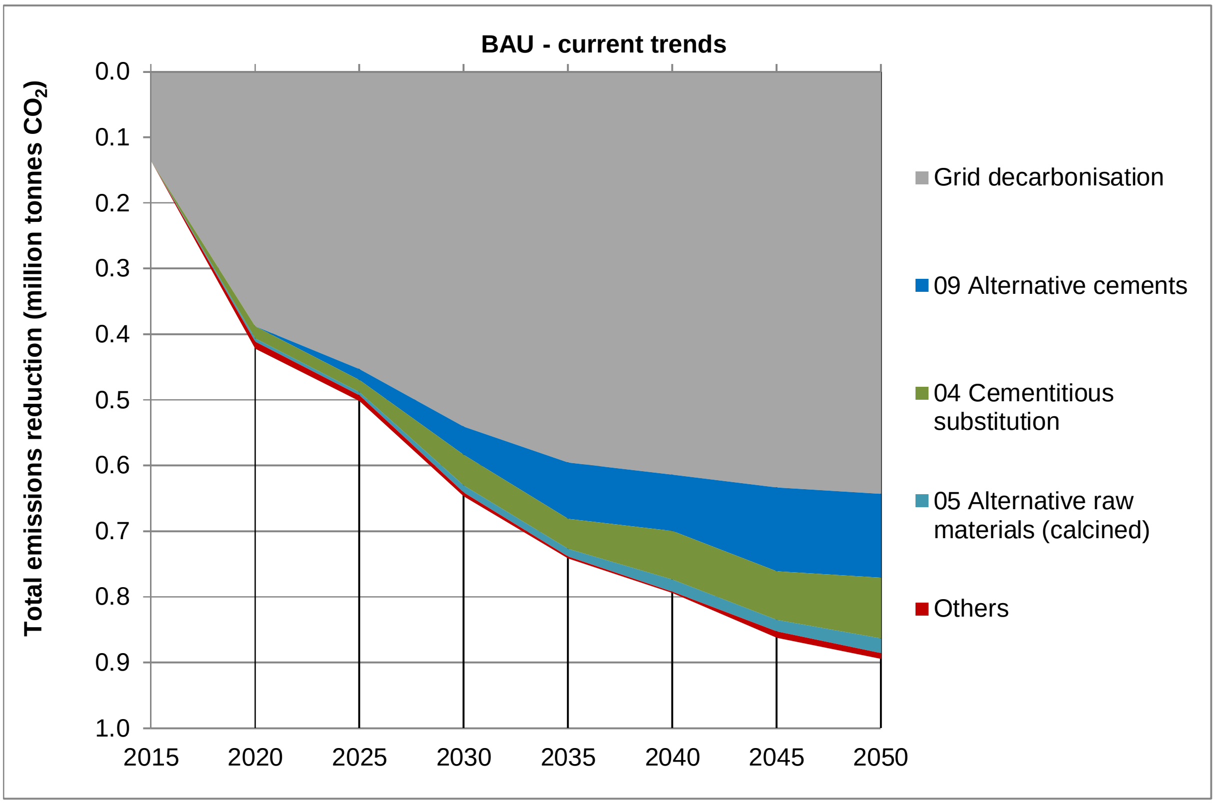

Figure 13: Contribution of principal options to the absolute emissions reduction throughout study period, for the BAU pathway, current trends scenario

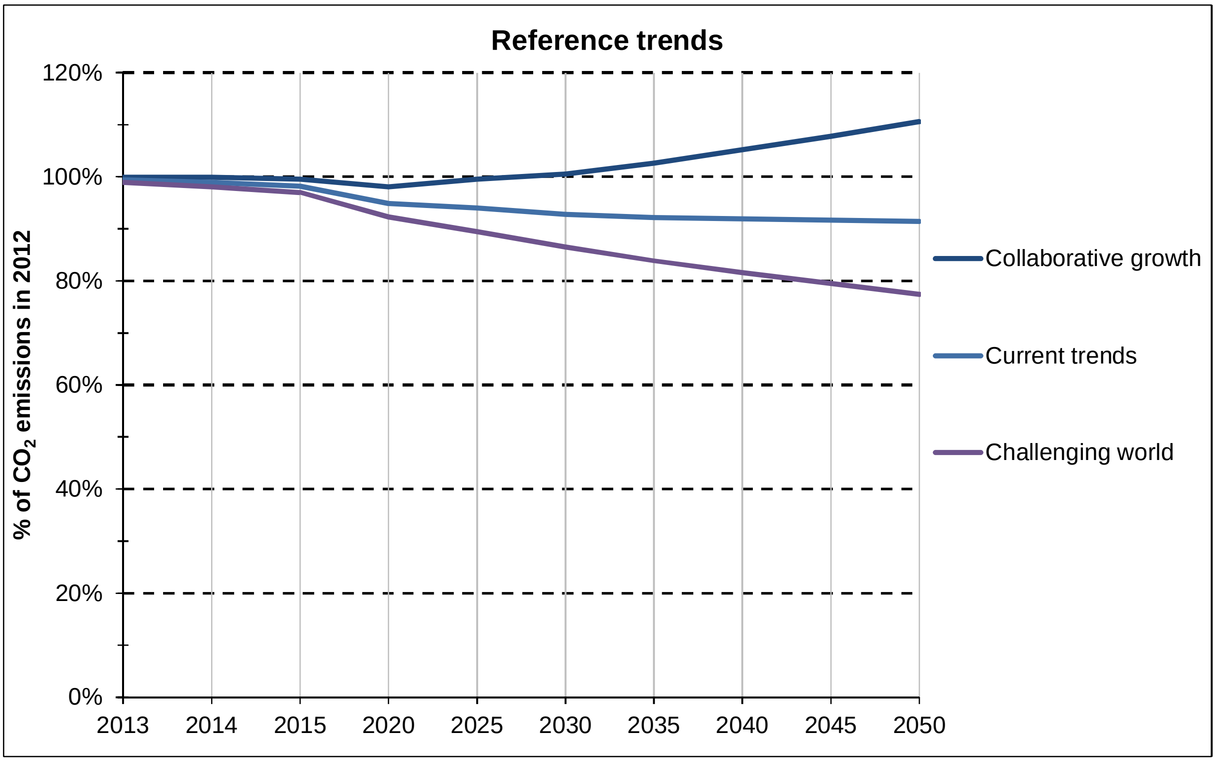

Figure 14: Reference trends for the three scenarios

The total CO_2 reduction for a pathway is the sum of the reference trends (shown in Figure 14 for each scenario) and the emissions reduction resulting from the deployment of options. The reference trends account for changes in production (which determines direct emissions) and electricity grid decarbonisation (indirect emissions).

For the current trends scenario, the options deployed in the BAU pathway give a reduction of 3.3% CO_2 in 2050, compared to 2012. Adding the reductions from the option deployment (3.3%) to the reference reduction for current trends (8.5%) gives an overall reduction for the BAU pathway of 11.9% CO_2 reduction, after rounding. Since there is no change in production from the sector, the reference reductions solely represent the contribution of the decarbonisation of the grid (8.5%), corresponding to 0.64 Mt CO_2 emission reductions.

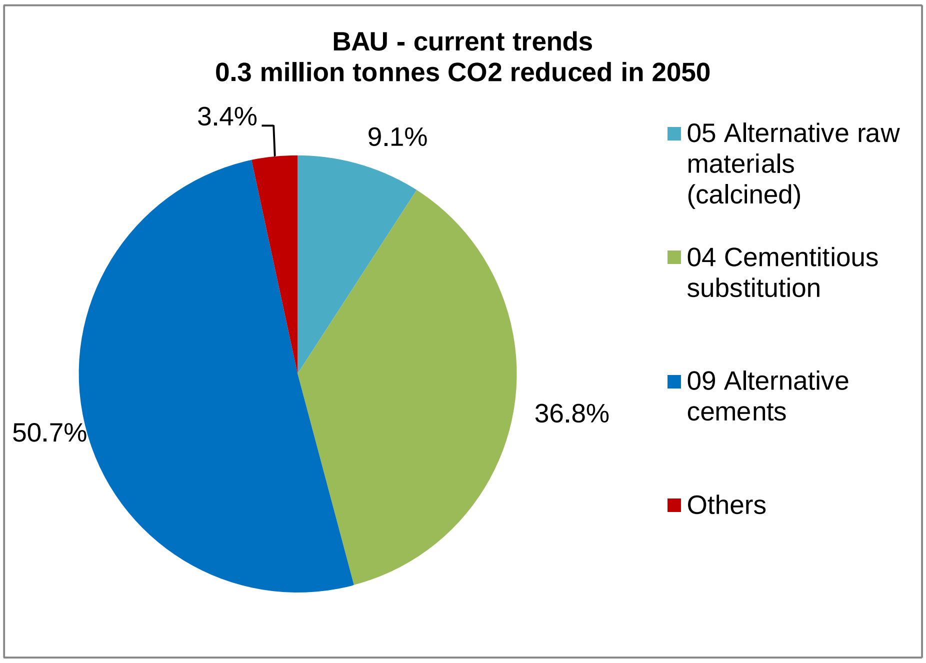

Figure 15: Breakdown of 2050 emissions reduction, for the BAU pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that the biggest carbon reduction in BAU came from three key options (Figure 15): alternative cements, cementitious substitution and alternative raw materials (calcined).

Option Deployment for other Scenarios

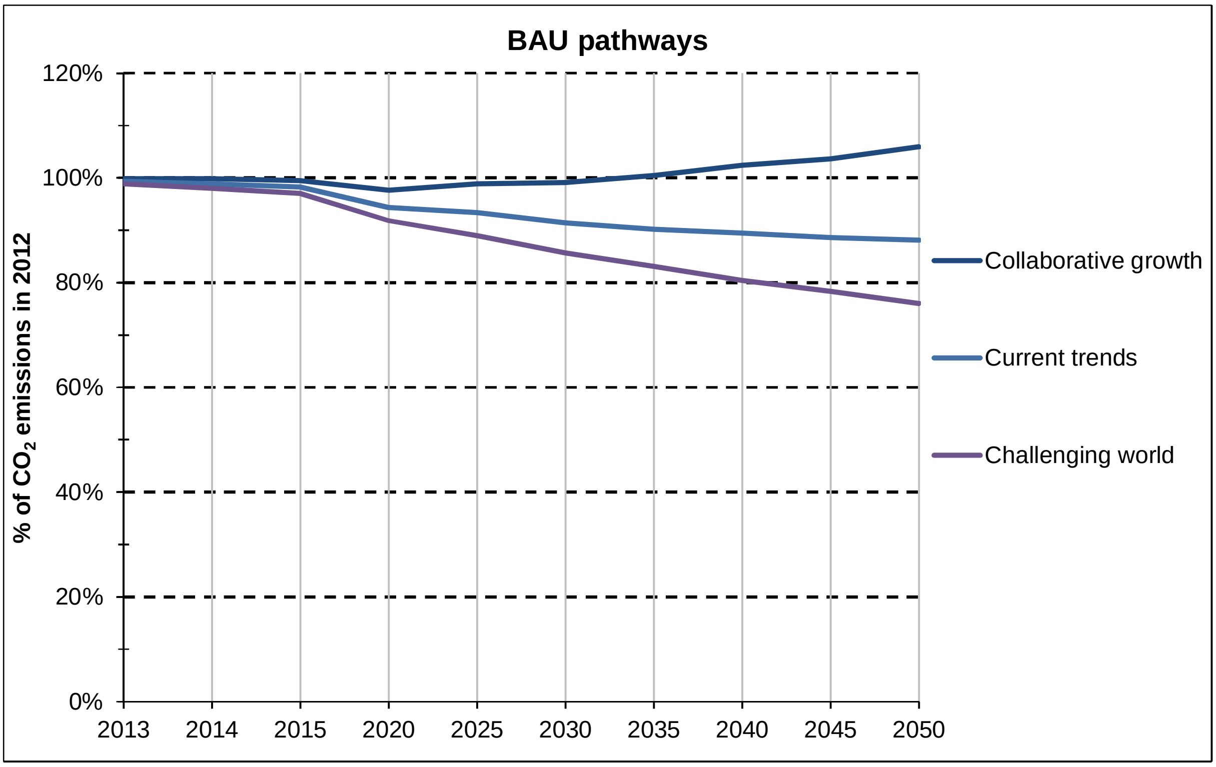

Figure 16: BAU pathway for the different scenarios

In the challenging world scenario, some options included under the current trends scenario were deployed at a slower rate and reached a lower level of deployment in 2050, such as the option for electrical efficiency improvements. In some cases, options deployed in the current trends scenario were not deployed at all in the challenging world scenario, as was the case for alternative cements. The deployment of the option for cementitious substitution remained unchanged, however. Overall, the BAU pathway gives an emissions reduction of 24% in 2050, compared with 2012 emissions. However, this is mainly due to the downturn in the demand and hence production of cement which lowers the direct CO_2 emissions. The reference trends in Figure 16 show that, for the challenging world scenario, in 2050 an emissions reduction of 23%, compared with 2012, is realised from reduced production and electricity grid decarbonisation.

In the collaborative growth scenario, all options included under the current trends scenario were deployed at the same rate as in the current trends scenario, with the addition of oxygen enrichment technology deployed to 25% of potential by 2045. The BAU pathway results in an increase in CO_2 emissions of 6% in 2050 compared to 2012. The reference trends for the collaborative growth scenario show an 11% increase in emissions in 2050, compared with 2012. Thus, the options deployments result in a reduction of 5% to counteract the increased emissions from increased production illustrated in the reference trends.

The deployment of options in the challenging world and collaborative growth scenario is shown in appendix D.

4.4.2 20-40% CO_2 Reduction Pathway

Pathway Summary

The 20 to 40% CO_2 Reduction pathway refers to BAU plus the further deployment of options necessary to achieve an additional CO_2 reduction by 2050. This includes both additional deployment of several of the options included in BAU plus the addition of an extra option.

Deployment for the Current Trends Scenario

Figure 17 shows the option deployment for the 20 to 40% CO_2 Reduction pathway for the current trends scenario.

The same options have been deployed in this scenario as in the BAU pathway, with cementitious substitution and the use of alternative raw materials deployed more quickly, and the deployment of the fuel switching to biomass option to increase from the current adoption level.

20 - 40% - current trends

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Kiln process technology (BAT kiln)	0%	100%	0%	0%	0%	0%	0%	0%	0%	10%	10%
02 Electrical efficiency improvements	0%	100%	0%	0%	75%	75%	75%	75%	75%	100%	100%
03 Electricity from waste heat	0%	25%	0%	0%	25%	25%	50%	50%	75%	75%	100%
04 Cementitious substitution	8%	11%	0%	0%	25%	25%	50%	50%	75%	75%	100%
05 Alternative raw materials (calcined)	1%	2%	0%	0%	25%	25%	50%	50%	75%	75%	100%
06 Fuel switching to natural gas	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Fuel switching to biomass	18%	80%	0%	0%	5%	10%	15%	25%	25%	33%	40%
08 Hydrogen fuel	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Alternative cements	0%	5%	0%	0%	0%	10%	25%	50%	50%	75%	75%
10 Fluidised bed kiln	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 Carbon capture	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12 Oxygen enrichment technology	0%	75%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 17: Option deployment for the 20-40% CO_2 reduction pathway under current trends

In 20-40% CO_2 reduction, the principal options that contribute to the emissions reduction in 2050 are (Figure 17):

- The option of fuel switching to biomass, to increase from the 18% current adoption level towards the maximum potential 80% applicability level, is deployed in 2020 with a 5% deployment, gradually rising to a maximum of 40% by 2050. It is assumed that all additional biomass above the current level will be virgin biomass, rather than additional waste biomass. This option represents emissions reduction of 7.0% in 2050, compared to 2012, which is 60% of the total options reduction for 20-40% CO_2 reduction pathway.
- Cementitious substitution is initially deployed to 25% of maximum potential in 2020, increasing to 50% by 2030, 75% by 2040 and 100% by 2050. This option represents a 2.4% CO_2 reduction in 2050, compared to 2012, which is 20% of the total reduction for the 20-40% CO_2 reduction pathway.
- Alternative cements, deployed to 10% by 2025, 25% by 2030, 50% by 2035 and 75% by 2045 (the latter figure being equivalent to 3.75 % of the total cement market size), represents an emissions

reduction of 1.6% in 2050, compared to 2012, which is 14% of the total reduction for the 20-40% CO_2 reduction pathway.

- The alternative raw materials (calcined) option is deployed with the same profile as cementitious substitution, and results in a 0.6% emissions reduction in 2050, compared with 2012. That is 5% of the total reduction for the 20-40% CO_2 reduction pathway.

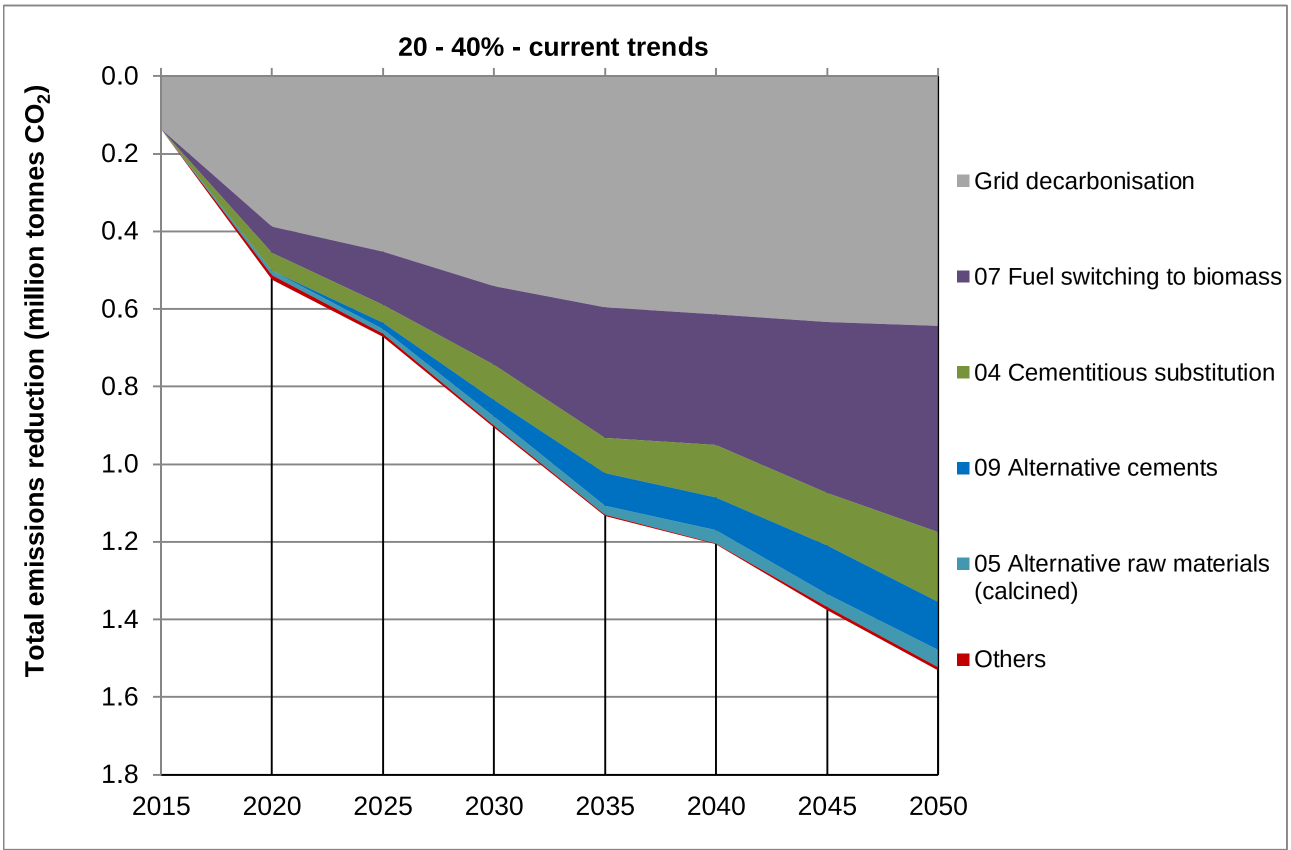

Figure 18: Contribution of principal options to the absolute emissions reduction throughout study period, for the 20-40% CO_2 reduction pathway, current trends scenario

For the current trends scenario, the options deployed in 20-40% CO_2 reduction pathway give an overall reduction of 12% in 2050, compared to 2012. Adding the reduction from the option deployment to the reference trends gives an overall CO_2 reduction of 20%. The contribution of the decarbonisation of the grid is 8.5%, corresponding to 0.64 Mt CO_2 emissions reduction.

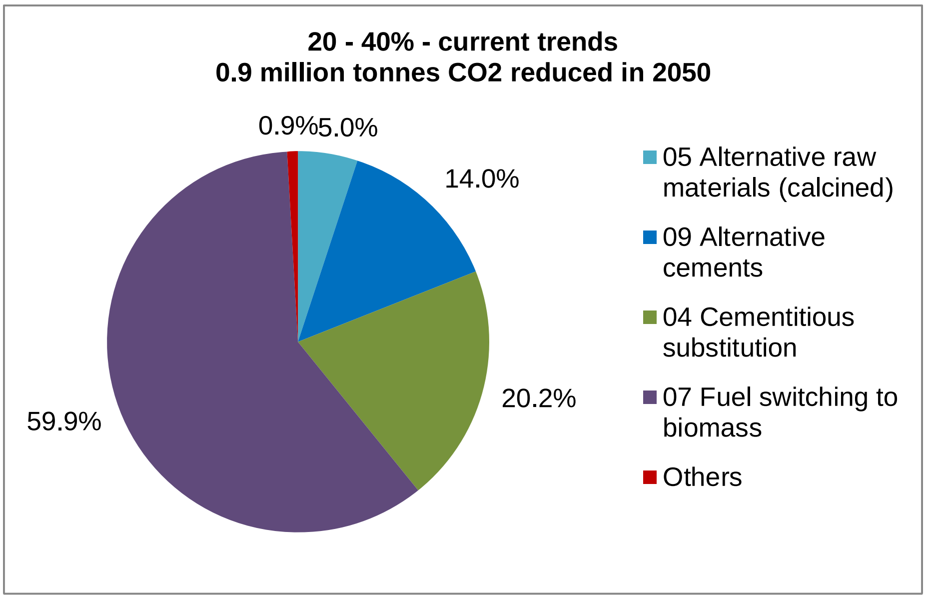

Figure 19: Breakdown of 2050 emissions reduction, for the 20-40% CO_2 reduction pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that the biggest carbon reduction in 20-40% CO_2 reduction pathway come from a small number of key options (Figure 19): fuel switching to biomass, cementitious substitution, alternative cements and alternative raw materials (calcined).

Option Deployment for other Scenarios

In the challenging world scenario, some options included under the current trends scenario were deployed at a slower rate, reaching a lower level of deployment by 2050 (cementitious substitution reaching 50% deployment by 2050). In some cases, options deployed in the current trends scenario were not deployed at all in the challenging world scenario, as was the case for alternative cements. The 20-40% CO_2 reduction pathway achieves an emissions reduction of 29% in 2050, compared with 2012, under the challenging world scenario. Similarly to the BAU pathway, a large proportion of this reduction is a result of the reduction in demand and supply of cement which lowers the direct CO_2 emissions. The options deployments result in a reduction of 6%, added to 23% for the reference trends resulting from reduced production and electricity grid decarbonisation.

In the collaborative growth scenario, all options included under the current trends scenario were deployed at the same rate as in the current trends scenario, except for oxygen enrichment technology. Oxygen enrichment technology is assumed to reach 25% deployment by 2045. The 0-20% CO_2 reduction pathway results in 3% emissions reductions in 2050 compared to 2012. The reference trends for the collaborative growth scenario gives an increase in emissions of 11% in 2050, compared with 2012. The options deployment results in an emissions reduction of 13%.

The deployment of options for the collaborative growth scenarios for 0-20% CO_2 reduction is shown in appendix D.

4.4.3 Maximum Technical with no CCS Pathway

Pathway Summary

The Max Tech pathway with no CCS under the current trends scenario includes most of the technical options, including oxygen enrichment technology. It excludes CCS. It also excludes fluidised bed kiln, hydrogen fuel and fuel switching to natural gas, as these options were determined to be either not viable or less attractive than other available technology options. All of the other viable technical options are deployed to 100% by 2050, with most beginning deployment from 2020. Max Tech no CCS will decarbonise the sector mostly by fuel switching to biomass and cementitious substitution.

Deployment for the Current Trends Scenario

Figure 20 shows the option deployment for the Max Tech with no CCS pathway for the current trends scenario.

Technology options are deployed in a similar way as for the BAU and 0 to 20% CO_2 reduction pathways, with the addition of the option for oxygen enrichment technology. The other options are deployed earlier, at a faster rate and reach a higher level of deployment. Kiln process technology, cementitious substitution, alternative raw materials and fuel switching to biomass options are all deployed to 100% in 2050 in both of the Max Tech pathways.

Max Tech no carbon capture - current trends

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Kiln process technology (BAT kiln)	0%	100%	0%	0%	0%	0%	10%	25%	50%	75%	100%
02 Electrical efficiency improvements	0%	100%	0%	0%	75%	75%	75%	75%	75%	100%	100%
03 Electricity from waste heat	0%	25%	0%	0%	25%	25%	50%	50%	75%	75%	100%
04 Cementitious substitution	8%	11%	0%	0%	25%	25%	50%	50%	75%	75%	100%
05 Alternative raw materials (calcined)	1%	2%	0%	0%	25%	25%	50%	50%	75%	75%	100%
06 Fuel switching to natural gas	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Fuel switching to biomass	18%	80%	0%	0%	25%	25%	50%	50%	75%	75%	100%
08 Hydrogen fuel	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Alternative cements	0%	5%	0%	0%	0%	10%	25%	50%	50%	75%	100%
10 Fluidised bed kiln	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 Carbon capture	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12 Oxygen enrichment technology	0%	75%	0%	0%	0%	0%	0%	0%	25%	50%	100%

Figure 20: Option deployment for the Max Tech with no CCS pathway under current trends

For Max Tech no CCS, the principal options that contribute to the emissions reduction in 2050 are (Figure 21):

- Fuel switching to biomass is deployed to 25% by 2020, and increased in 25% increments to 50% by 2030, 75% by 2040 and 100% by 2050. It is assumed that all additional biomass above the current level will be virgin biomass, rather than additional waste biomass. This option results in an emissions reduction of 17% in 2050, compared with 2012, which is 70% of the total emissions reduction from deployment of options in 2050.
- Cementitious substitution follows the same deployment pattern as that of fuel switching to biomass. This option achieves a total emissions reduction of 2.3% in 2050, compared to 2012, which is 9% of the total Max Tech no CCS pathway reduction.
- Alternative cements are deployed 10% of potential by 2025, gradually increasing to 100% deployment by 2050. This option results in a 2.1% emissions reduction in 2050, compared with 2012, which accounts for 8% of the total emissions reduction from deployment of options in 2050.
- Oxygen enrichment technology is deployed to 25% of potential by 2040, increasing to 50% by 2045 and reaching 100% deployment by 2050. This option results in an emissions reduction of 2.0% in

2050, compared with 2012, which accounts for 8% of the total emissions reduction from deployment of options in 2050.

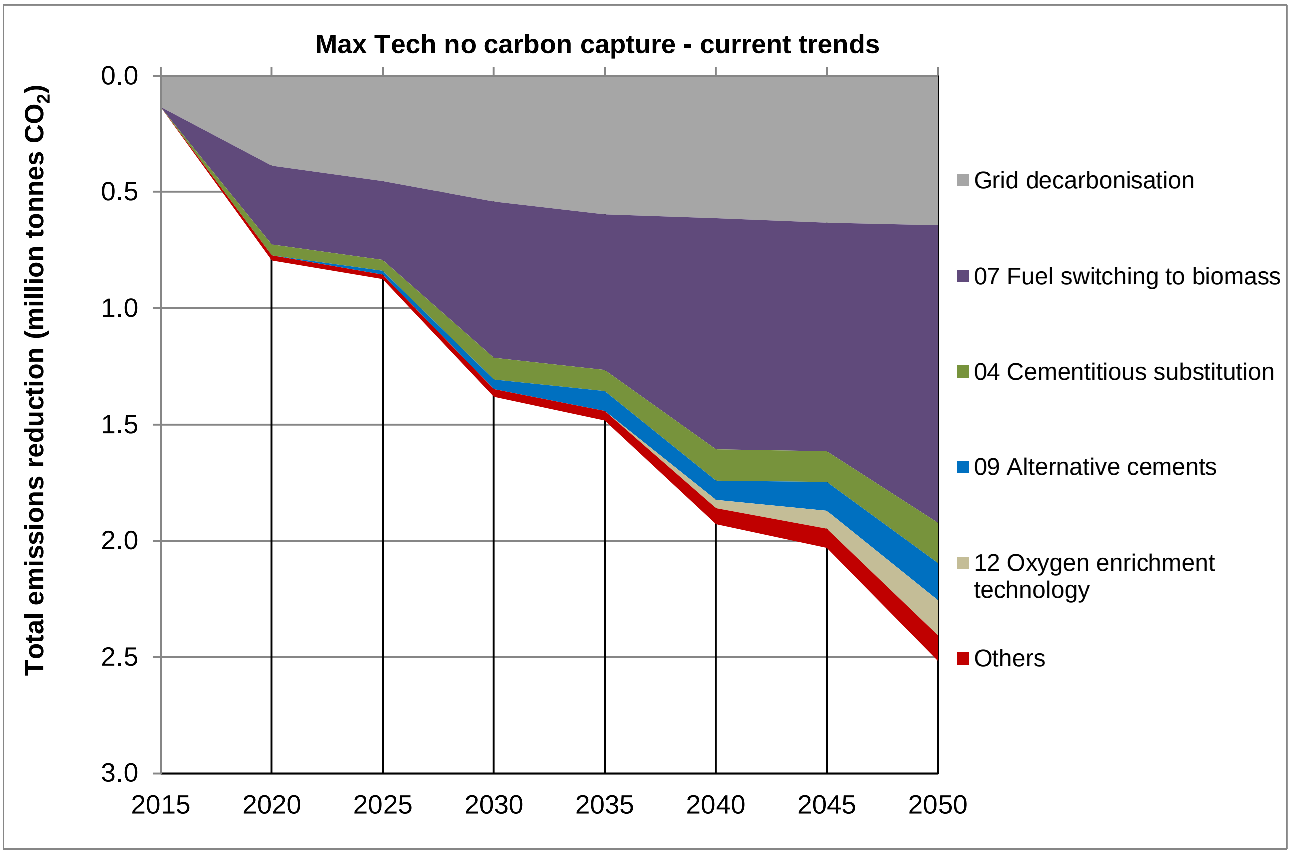

Figure 21: Contribution of principal options to the absolute savings throughout the study period, for the Max Tech 1 pathway, current trends scenario

For the current trends scenario, the options deployed in the Max Tech no CCS pathway give an overall reduction of approximately 25% in 2050, compared to 2012. Adding the reduction from the option deployment to the reference trends gives an overall reduction of 33%. Electricity consumption increases considerably for the Max Tech no CCS pathway, and the increase of indirect emissions is included with the direct emissions reduction to give net emissions reduction for each option. The contribution of the decarbonisation of the grid remains at 8.5% of 2012 emissions, corresponding to 0.64 Mt CO_2 emissions reduction.

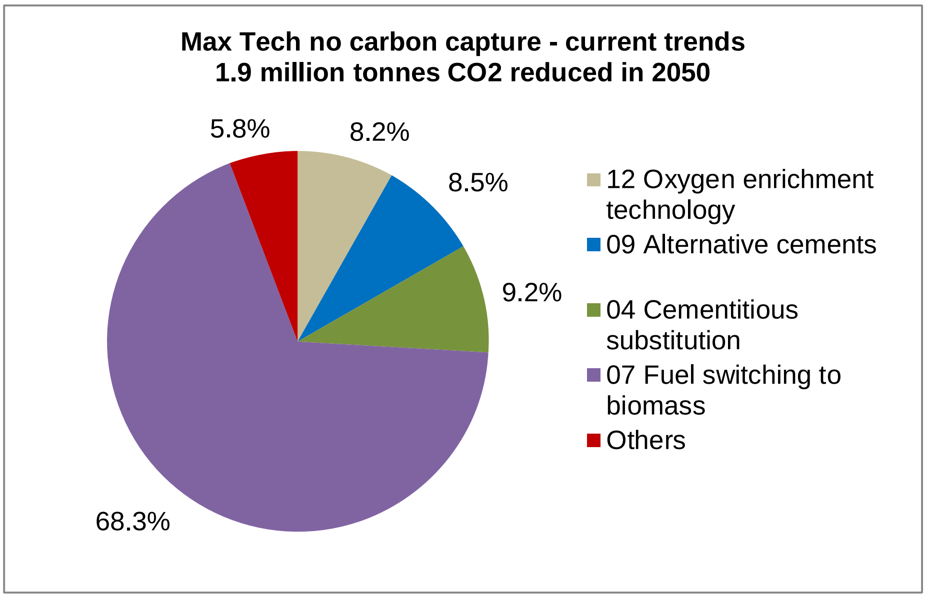

Figure 22: Breakdown of 2050 emissions reduction, for the Max Tech no CCS pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that the biggest carbon reduction in the Max Tech no CCS pathway come from a small number of key options (Figure 22): fuel switching to biomass, cementitious substitution, alternative cements and oxygen enrichment technology.

Option Deployment for other Scenarios

For the challenging world scenario, the technical options were deployed at the same rate, with the exception of alternative cements which were not deployed under this scenario. The Max Tech no CCS pathway results in a total reduction of CO_2 emissions of 41% in 2050, compared to 2012. The reference trends for the challenging world scenario gives an emissions reduction of 23% resulting from decreased production and electricity grid decarbonisation. Thus, the deployment of options in the Max Tech no CCS pathway results in 18% emissions reductions.

In the collaborative growth scenario, all options included under the current trends scenario were deployed at the same rate as in the current trends scenario. The total reduction of CO_2 emissions is 19% in 2050 compared to 2012. The reference trends for the collaborative growth scenario gives an increase in emissions of 11% in 2050, compared with 2012. The deployment of options in the Max Tech no CCS pathway results in 30% emissions reductions to counteract the reference trends.

The deployment of options for the challenging world and collaborative growth scenarios for Max Tech no CCS are shown in appendix D.

4.4.4 Maximum Technical with CCS Pathway

Pathway Summary

The Max Tech with CCS pathway for the current trends scenario includes all technical options thought feasible by the experts, now including the carbon capture option and with the deployment of oxygen enrichment technology reduced from the Max Tech, no CCS pathway. CCS accounts for the highest emissions reduction contribution in 2050, 60%, followed by fuel switching to biomass and cementitious substitution.

Deployment under Current Trends

Figure 23 shows the option deployment for the Max Tech with CCS pathway for the current trends scenario.

Option Technologies are deployed in the same way as in the Max Tech, no CCS pathway, except that CCS is now deployed from 2030 and the deployment of oxygen enrichment technology is reduced. All options are fully deployed by 2050; with the exception of oxygen enrichment technology which reaches a deployment of 33% by 2050 (i.e. it is deployed on all remaining applicable sites that do not have CCS).

The deployment of CCS begins in 2030 with 10% (nominally one site equipped with CCS) and increases to 100% by 2050.

Max Tech with carbon capture - current trends

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Kiln process technology (BAT kiln)	0%	100%	0%	0%	0%	0%	10%	25%	50%	75%	100%
02 Electrical efficiency improvements	0%	100%	0%	0%	75%	75%	75%	75%	75%	100%	100%
03 Electricity from waste heat	0%	25%	0%	0%	25%	25%	50%	50%	75%	75%	100%
04 Cementitious substitution	8%	11%	0%	0%	25%	25%	50%	50%	75%	75%	100%
05 Alternative raw materials (calcined)	1%	2%	0%	0%	25%	25%	50%	50%	75%	75%	100%
06 Fuel switching to natural gas	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Fuel switching to biomass	18%	80%	0%	0%	25%	25%	50%	50%	75%	75%	100%
08 Hydrogen fuel	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Alternative cements	0%	5%	0%	0%	0%	10%	25%	50%	50%	75%	100%
10 Fluidised bed kiln	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 Carbon capture	0%	50%	0%	0%	0%	0%	10%	25%	50%	75%	100%
12 Oxygen enrichment technology	0%	75%	0%	0%	0%	0%	0%	0%	10%	20%	33%

Figure 23: option deployment for the Max Tech with CCS pathway under current trends

For Max Tech CCS, the principal options that contribute to the emissions reduction in 2050 are (Figure 24):

- CCS is deployed to 10% in 2030, increasing to 25% by 2035, 50% by 2030, 75% by 2045 and 100% by 2050. CCS results in an emissions reduction of 33.2% in 2050, compared with 2012, which accounts for 62% of the total emissions reduction from deployment of options in 2050.
- Fuel switching to biomass, deployed to 25% in 2020 and increasing to 100% in 2050, results in emissions reduction of 14.9% in 2050, compared with 2012, which accounts for 28% of the total emissions reduction from deployment of options in 2050. It is assumed that all additional biomass above the current level will be virgin biomass, rather than additional waste biomass.
- Cementitious substitution, deployed in 25% increments each decade from 2020, increasing to 100% of potential by 2050, results in emissions reduction of 2.0% in 2050, compared with 2012, which accounts for 4% of the total emissions reduction from deployment of options in 2050.

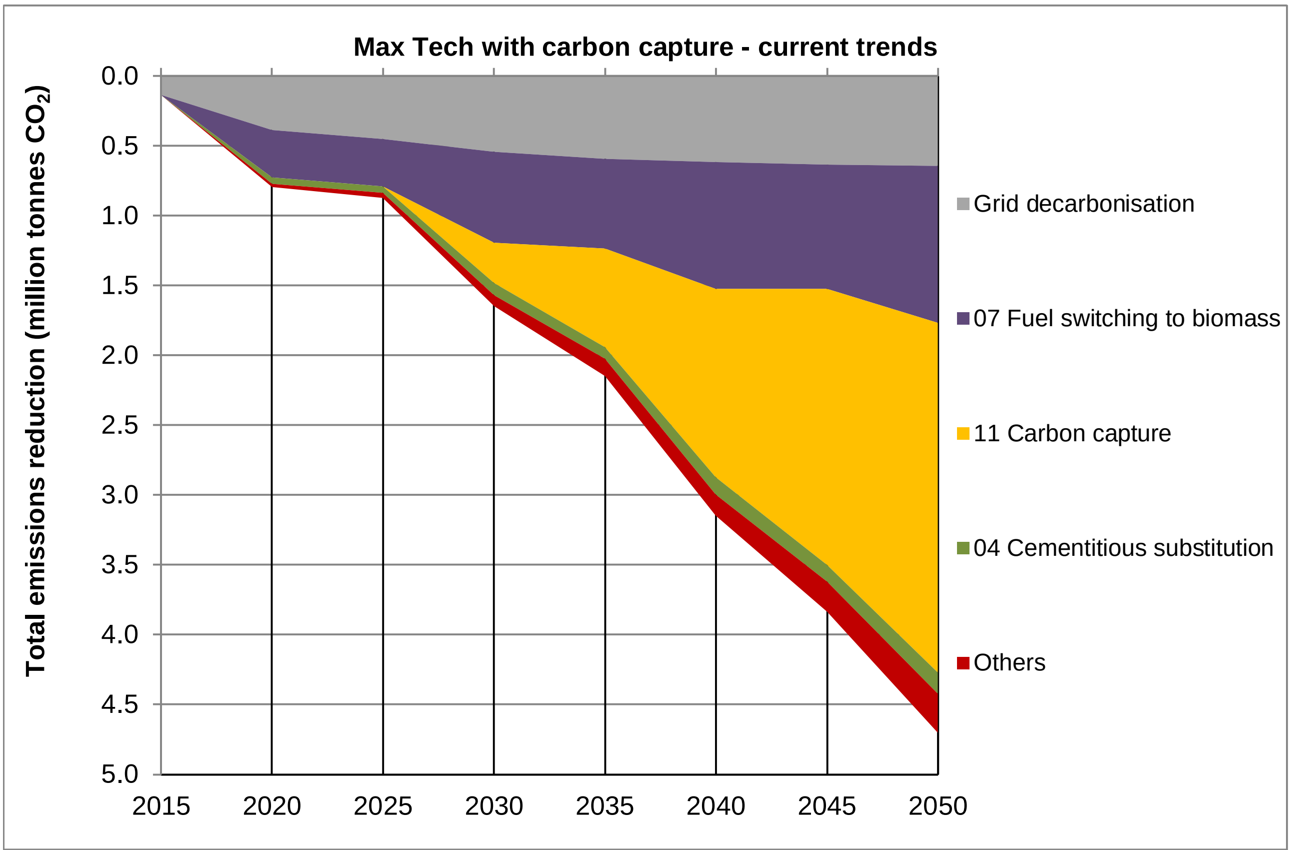

Figure 24: Contribution of principal options to the absolute emissions reduction throughout the study period, for the Max Tech with CCS pathway, current trends scenario

For the current trends scenario, the options deployed in the Max Tech with CCS pathway give an overall emissions reduction of 54% in 2050, compared to 2012. Adding the reduction from the option deployment to the reference trends gives an overall reduction of 62%. From the reference trends, decarbonisation of the electricity grid contributes emissions reductions in 2050 of 8.5%, compared with 2012, corresponding to absolute emissions reductions of 0.64 Mt CO_2. The reference trends account for decarbonisation of electricity assuming that the proportion of electricity consumed remains constant at the level in the reference year. Emissions reduction resulting from switching to greater electricity consumption are accounted for as part of the options savings and are netted off from the direct emissions reduction achieved to give the overall emissions reduction of these options.

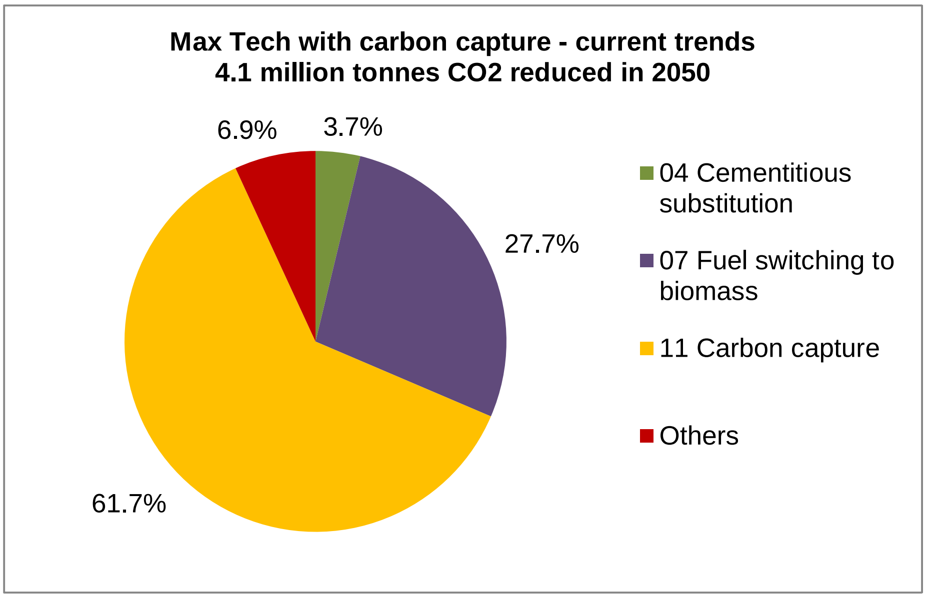

Figure 25: Breakdown of 2050 emissions reduction, for the Max Tech 2 pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that the biggest carbon reduction in the Max Tech with CCS come from a small number of key options (Figure 25): CCS, fuel switching to biomass and cementitious substitution.

Option Deployment under Other Scenarios

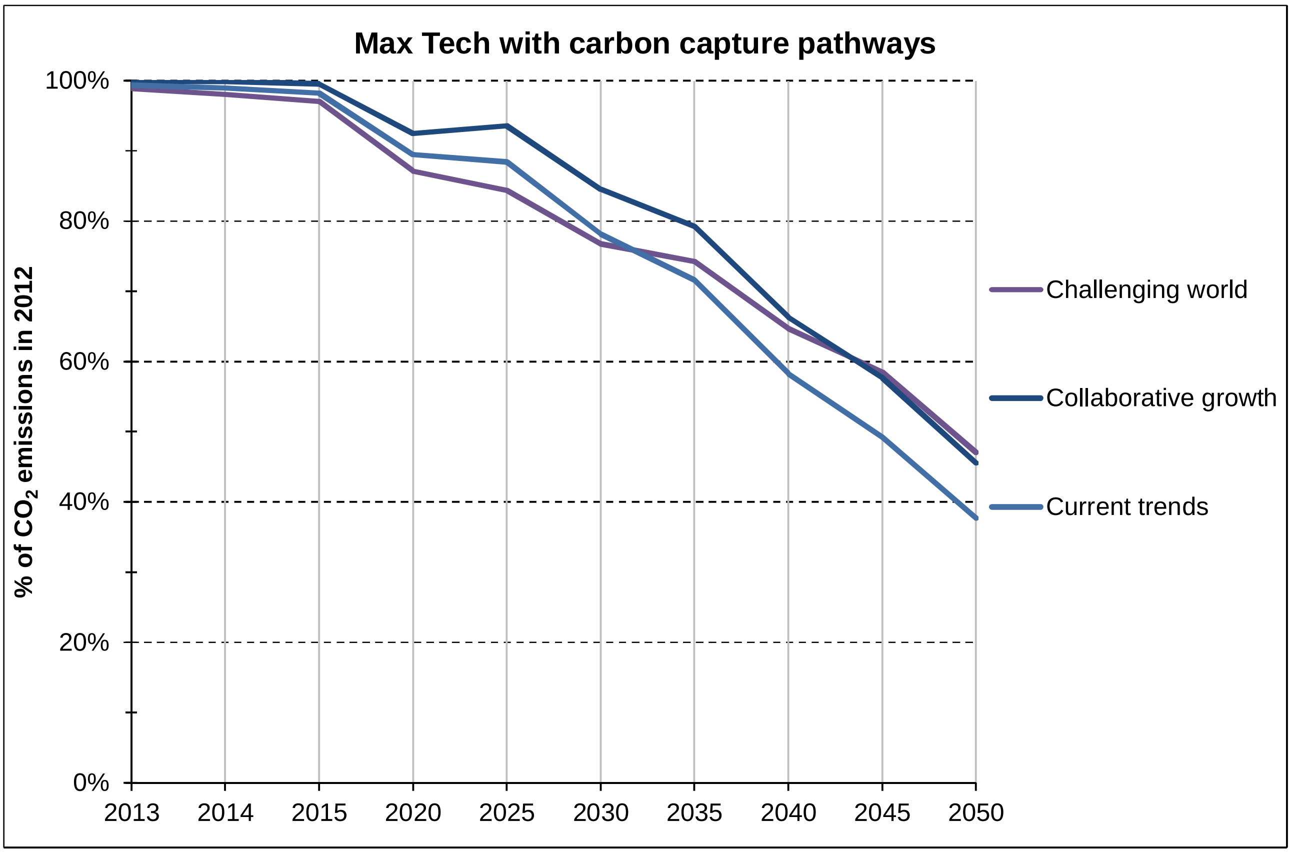

Figure 26: Max Tech with carbon capture pathway for the different scenarios

For the challenging world scenario, all technologies are deployed in the same way as in the current trends scenario, with the exception of CCS being delayed (deployed to 10% by 2040 and increasing to 50% by 2050). Oxygen enrichment technology, on the other hand, is deployed to 66% of potential by 2050, rather than 33% in the current trends scenario. These differences result in a total reduction of CO_2 emissions for this scenario of 53% in 2050 compared to 2012. The option deployments result in a reduction of 30%, added to 23% for the reference trends resulting from reduced production and electricity grid decarbonisation.

In the collaborative growth scenario, all options included under the current trends scenario were deployed at the same rate as in the current trends scenario. The total reduction of CO_2 emissions for this scenario is 54% in 2050 compared to 2012. The reference trends for the collaborative growth scenario gives an increase in emissions of 11% in 2050, compared with 2012. The options deployment results in an emissions reduction of 65%.

The deployment of options for the challenging world and collaborative growth scenarios for Max Tech CCS are shown in appendix D.

4.4.5 MPA Cement GHG Strategy 2050 Scenarios

To provide context and comparison, the assumptions made in the MPA cement GHG Strategy 2050 are mapped onto the technology options considered in the current pathways below.

- **04 – Cementitious substitution:** Reaches technical limit of 10.5% by 2050, equivalent to a deployment of 100%, therefore consistent with the 20-40% and two Max Tech pathways which have 100% deployment.
- **07 – Fuel switching to biomass:** Increases from 2012 adoption of 18% to a total of 40% by 2050 as a result of doubling proportion of waste fuels used. This is equivalent to a deployment of 35% in 2050 in the pathways model, therefore very consistent with the 20-40% CO_2 reduction pathway which has 33% deployment.
- **09 – Alternative cements:** Referred to as 'lower carbon cements' in MPA Strategy, assumes production of 0.5 mtpa by 2050. This is equivalent to a deployment of 100% in 2050 in the pathways model at the assumed applicability of 5%, and is therefore consistent with the Max Tech pathways.
- **11 – Carbon capture:** Under scenario including CCS, 3 mtpa of CO_2 captured by 2050. This is equivalent to a deployment of 97% in 2050 in the pathways model at the assumed applicability of 50%, therefore very consistent with the Max Tech with CCS pathway under the current trends scenario which has 100% deployment.

There is one other relevant option considered in the MPA cement GHG Strategy 2050 that does not map directly onto technology options in the current pathways, since the level of thermal improvement considered by the implementation of a 'BAT Kiln' is significantly different::

- Plant efficiency - 22% improvement in thermal efficiency by 2050.

4.5 Scenario Analysis

The figures within this section of the pathways development and analysis show the CO_2 reduction trends of the pathways for each scenario. Scenario analysis was based on the 'maximum interaction' case, as this gave the minimal, worst-case CO_2 reductions.

4.5.1 Current Trends

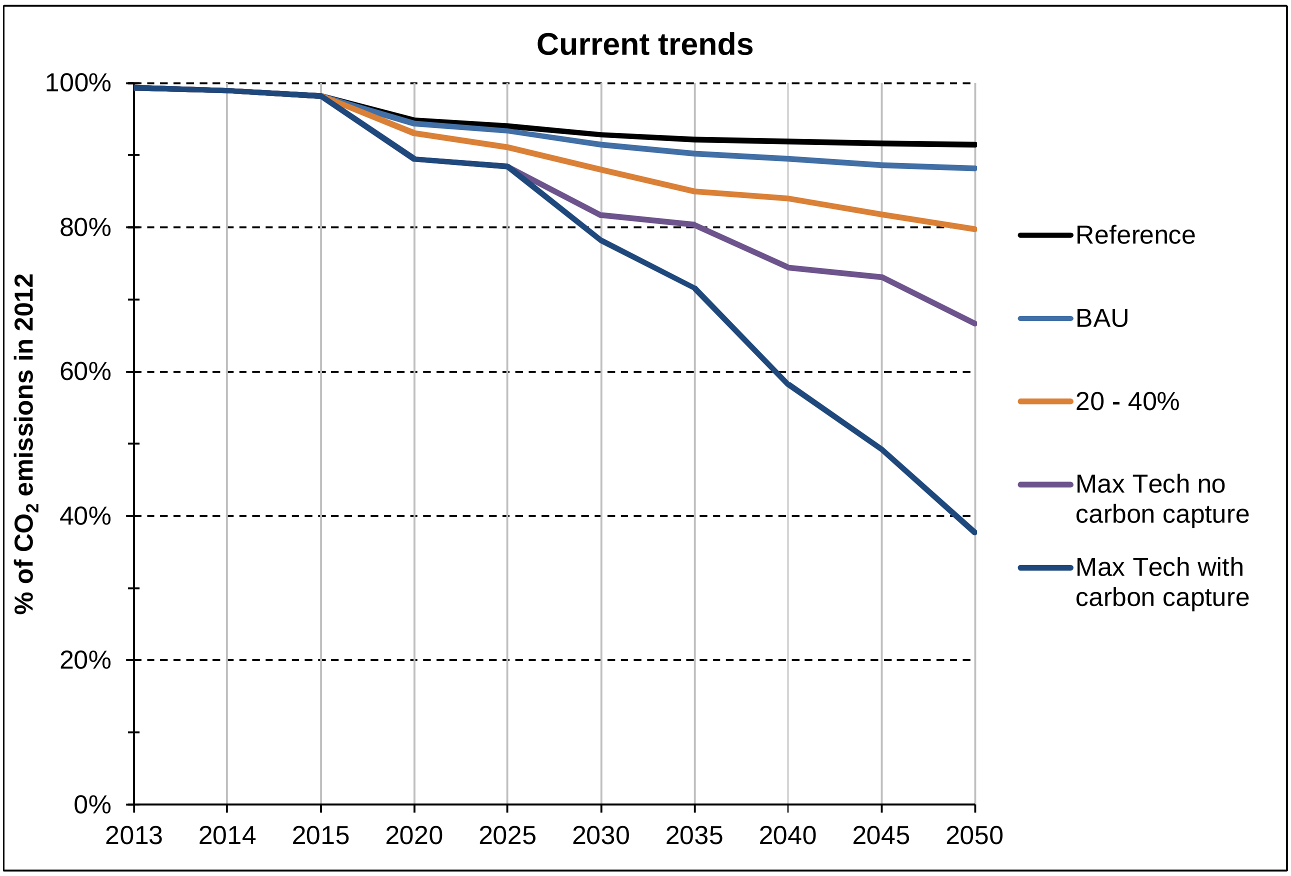

Figure 27: Performance of pathways for the current trends scenario

Under current trends, production is assumed to remain the same (0.0% increase) each year and the CO_2 emissions from the electricity grid are assumed to be reduced to 100g CO_2 per kWh by 2030 and 26g CO_2 per kWh in 2050. This decarbonisation of the grid is represented by the reference trends, where no technical options have been deployed. Decarbonisation of the grid accounts for approximately 8.5% CO_2 reduction in 2050 compared to 2012.

4.5.2 Challenging World

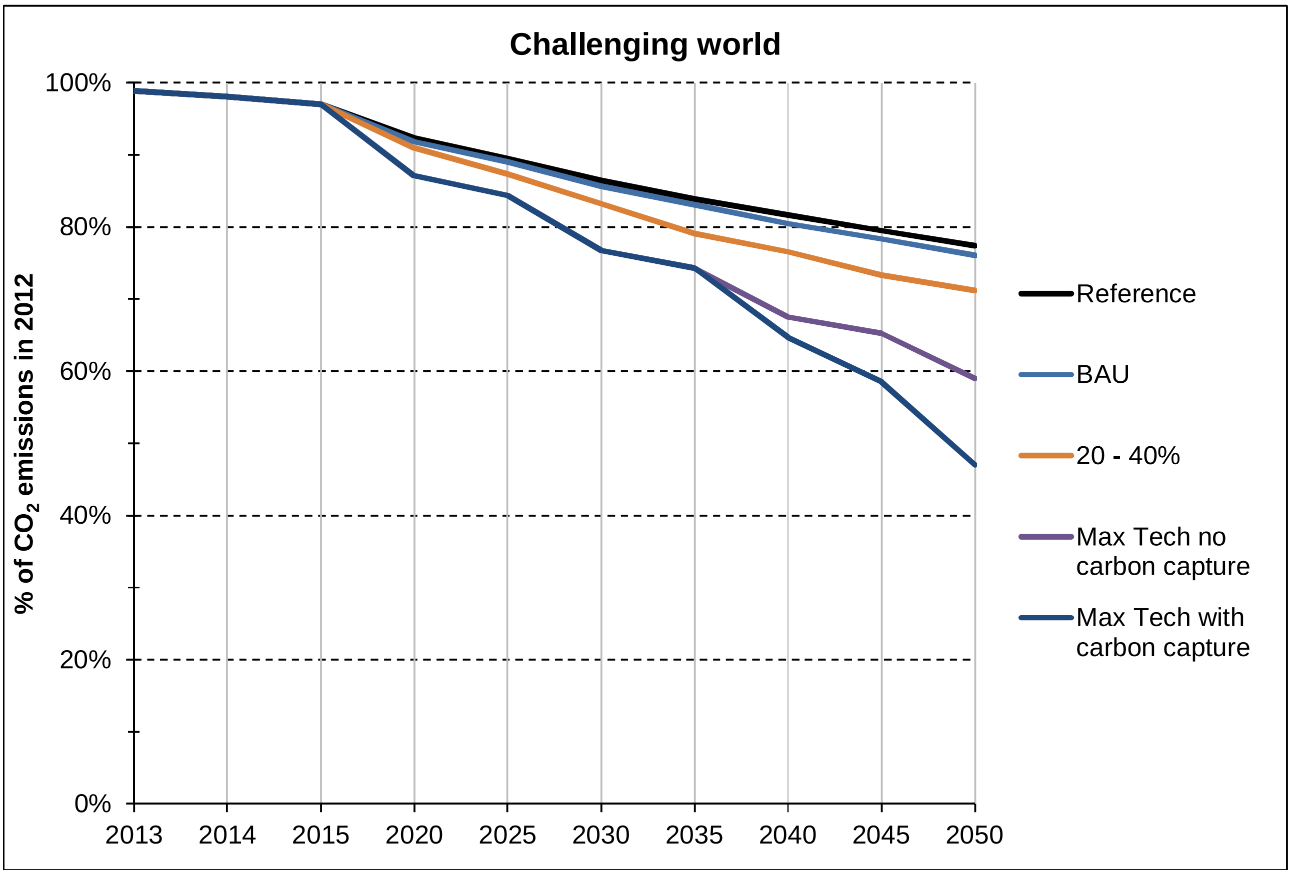

Figure 28: Performance of pathways for the challenging world scenario

For the challenging world scenario, production is assumed to fall by 0.5% annually and the CO_2 emissions from the electricity grid are assumed to be reduced to 200g CO_2 per kWh by 2030 and 150g CO_2 per kWh by 2050. The reference trends show a 23% reduction in CO_2 emissions by 2050 compared to 2012. If we exclude the effect of decreasing production, decarbonisation of the grid accounts for approximately 6.8% CO_2 reduction in 2050 compared to 2012.

The CO_2 reduction potential of the sector under this scenario, based on the deployments of options is between 24% and 53% in 2050 compared to 2012. This corresponds to absolute emissions in 2050 of 5.7 Mt CO_2 and 3.5 Mt CO_2.

The BAU and 20-40% CO_2 reduction pathways consist of the options deployed at a slower rate than under the current trends scenario, except for kiln process technology and alternative cements which are no longer deployed. The Max Tech pathways are broadly similar to the equivalent pathways under the current trends scenario, except that the alternative cements option is no longer deployed and there is some variation in the deployment of the carbon capture and oxygen enrichment technology options.

The decline in production is the main driver behind the CO_2 reduction under this scenario.

Under challenging world, the sector generally deploys the decarbonisation options more slowly than under current trends and to a lesser extent. This is as a result of fewer decarbonisation drivers (e.g. a slow-down in climate policies) and reduced investment in new plant, equipment or innovation for this scenario.

As a result, the decarbonisation options provide a smaller contribution towards decarbonisation than for the current trends scenario and the pathways move closer together. The decline in production and grid emissions decarbonisation were the more significant drivers behind the CO_2 reduction for this scenario.

4.5.3 Collaborative Growth

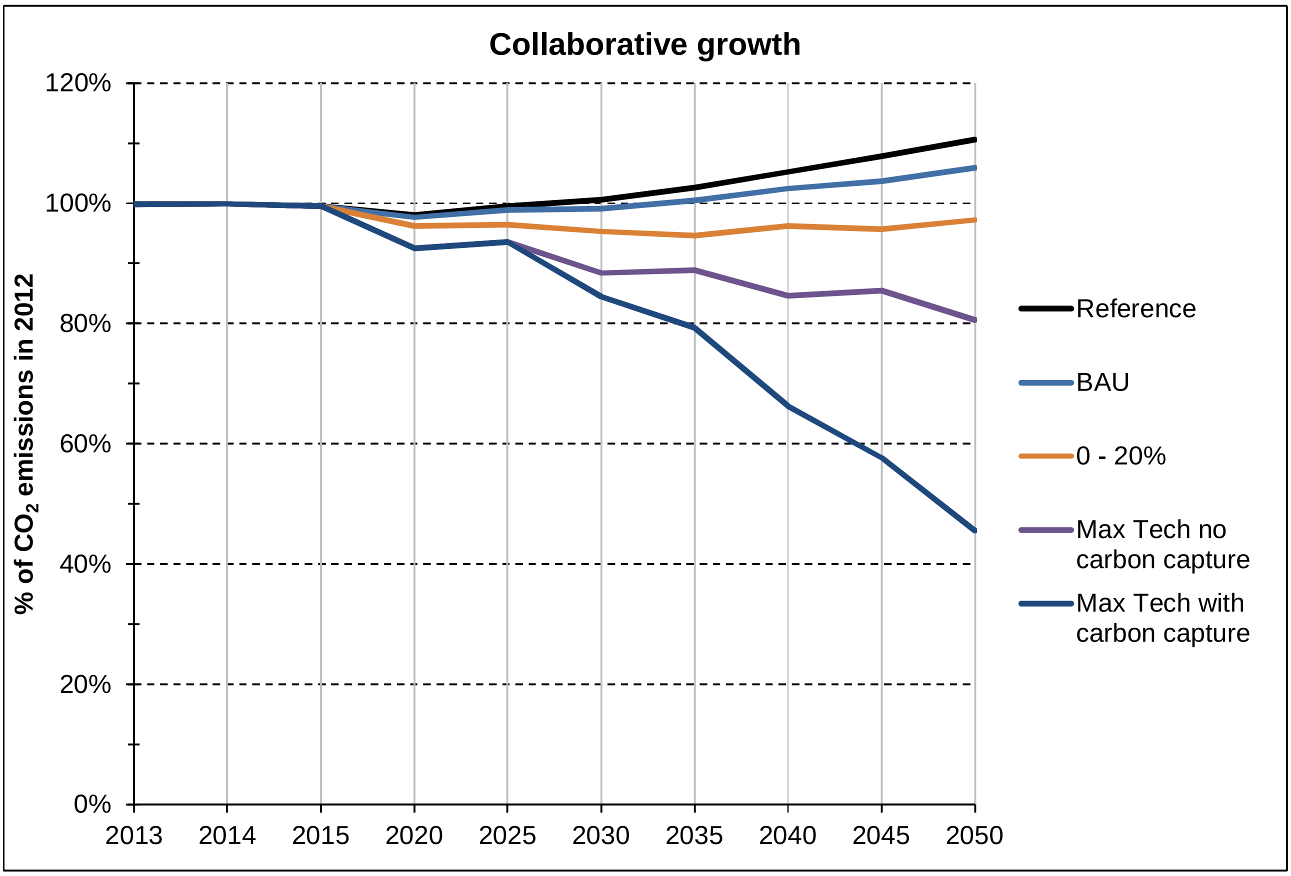

Figure 29: Performance of pathways for the collaborative growth scenario

For the collaborative growth scenario, production is assumed to grow by 0.5% annually and the CO_2 emissions from the electricity grid are assumed to reduce to 50g CO_2 per kWh by 2030 and 25g CO_2 per kWh by 2050. The reference trends show a 10% increase in CO_2 emissions in 2050 compared to 2012. If we exclude the effect of increasing production, decarbonisation of the grid accounts for approximately 8.4% CO_2 reduction in 2050 compared to 2012.

The CO_2 reduction potential of the sector for this scenario, based on the deployment of options, is between 6% increase and 55% in 2050 compared to 2012. This corresponds to absolute emissions in 2050 of 8.0 Mt CO_2 and 3.4 Mt CO_2.

For the collaborative growth scenario, the deployment of options for each pathway is the same as for the current trends, except that the deployment of oxygen enrichment technology is accelerated in the Max Tech pathways, and introduced in the BAU and 0-20% CO_2 reduction pathways. This is driven by stronger internationally agreed climate policies, greater levels of collaboration and higher levels of investment and innovation.

As for previous scenarios, the decarbonisation of the grid accounts for a significant amount of the total CO_2 reduction, along with cementitious substitution, fuel switching to biomass, carbon capture and oxygen enrichment technology.

4.6 Sensitivity Analysis

One sensitivity case was run in the model to test the significance of the biomass fuel option on pathway outcomes and to highlight its importance in defining potential actions. It was run on the Max Tech (no CCS) pathway in the current trends scenario to explore the impact on the base case.

The pathway was re-run without the '07 fuel switching to biomass' option being deployed. No alternative options were available to be deployed to replace the biomass option. The sensitivity resulted in the Max Tech (no CCS) pathway delivering lower CO_2 emissions reductions from 2020 onwards, as shown in Figure 30 below. There was a reduction of the emissions in 2050 from around 33% of 2012 emissions under the Maximum Technical (no CCS) pathway to a 17% reduction under the sensitivity pathway.

The main conclusion of the sensitivity analysis is that increasing the use of biomass fuel is critical to delivering reductions in carbon emissions by the cement sector. This finding lends significance to the potential actions necessary to overcome the barriers to implementing increased use of biomass and to maintain the availability of existing sources of biomass/waste fuels to the sector.

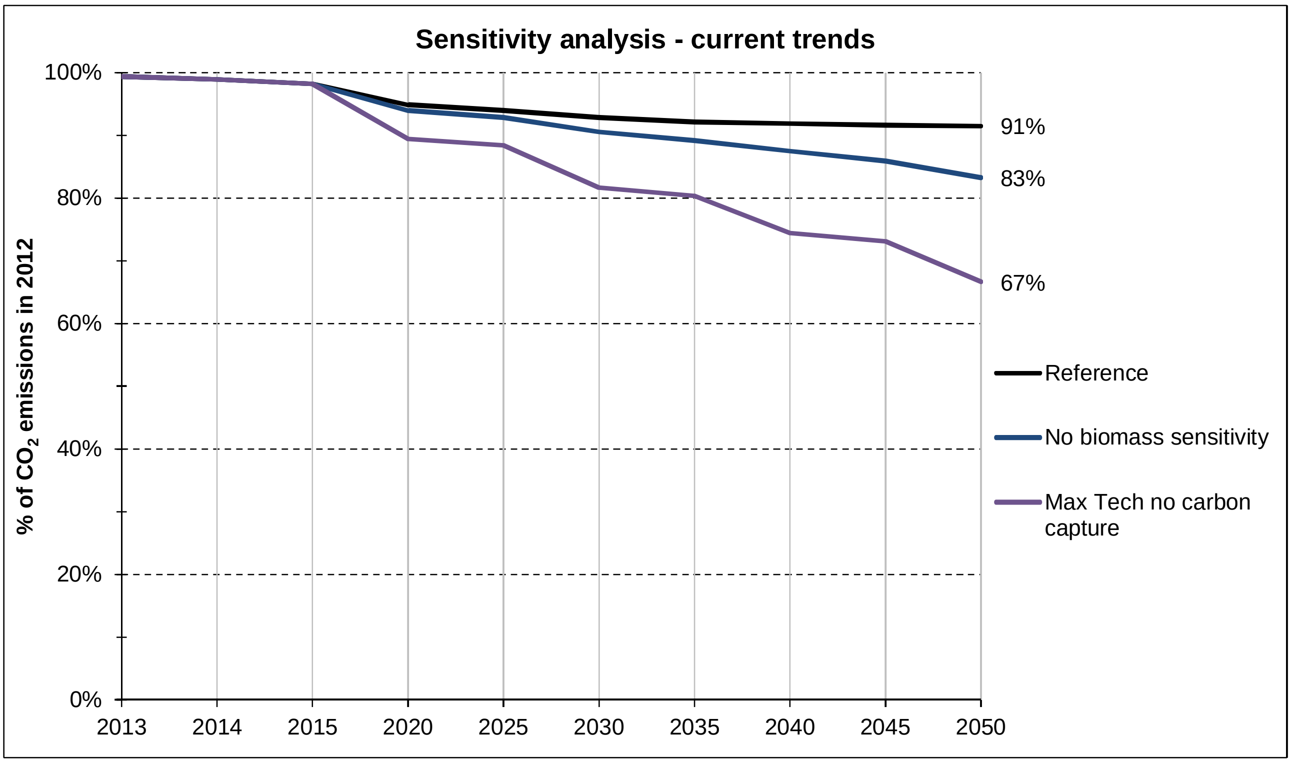

Figure 30: Pathways for current trends sensitivity analysis

In the option interaction calculation, the 'no interaction' case adds approximately 10% to the carbon reduction in 2050 in the Max Tech pathway.

4.7 Pathway Costs

4.7.1 Introduction

Estimates of the costs of new technologies and/or capital improvements with a time horizon to 2050 is fraught with difficulties; any long term forecasts should be treated with caution. The cost analysis presented in this report is intended to provide a high level estimate of the total capital cost of each pathway to the UK as a whole, in a form which is consistent with the government's approach to assessing the relative capital costs of alternative decarbonisation options from a social perspective[14]. It is based on an analysis of 'order of magnitude' option capital costs. The purpose of developing and presenting this cost analysis is to provide an indication of the capital costs for the pathways, which could form a basis for further work.

In gathering capital cost-related data, literature and/or engagement with stakeholders were used to establish an initial dataset for use in the cost analysis assessment. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs resulting from the decarbonisation pathways will have a major impact on any economic assessment. For example some options (e.g. carbon capture and electrification of firing) greatly increase energy use and/or operating costs of a process plant.

4.7.2 Calculation of Pathway Costs

The pathway costs and carbon dioxide savings are measured with respect to the reference trend, i.e. they are calculated as the difference between costs and emissions under the decarbonisation pathway and those under the reference trend. This means the costs represent the additional capital costs for the pathway compared to a future in which there was no deployment of options. The pathway costs have been assembled from the estimated costs of the combination of decarbonisation and energy efficiency options, in accordance with each carbon reduction pathway including the selected deployment rates of each option. The methodology for calculating the total discounted capital costs which produce the CO_2 reductions for each pathway can be summarised as follows:

1. Capital costs of deployment for each decarbonisation and energy efficiency option are calculated based on the order of magnitude capital costs to deploy that option at one site (or installation or unit of equipment). This is then deployed to the applicable number of sites (or installations or units of equipment) for the (sub) sector in the pathway as defined by the model.
2. Capital costs reflect the additional cost of delivering the carbon dioxide and/or energy reduction options compared to continuing production without deploying the options. For a number of major investment options, including replacement of life-expired assets with BAT (for a list of options in this category see Appendix C), only a proportion of the cost is assumed to be attributed to carbon dioxide emission or energy reduction, as a significant factor for the investment in this case would be to replace retiring production capacity and to recognise that options may be implemented for reasons other than decarbonisation / energy efficiency. In the absence of detailed information this proportion (attributed to the capital cost calculation in this analysis) is assumed to be 50%. For all other technology options the entire capital cost (i.e. 100%) is attributed to energy / carbon reduction.

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[14] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/360316/20141001_2014_DECC_HMT_Supplementary_Appraisal_Guidance.pdf

Capital costs are applied at the year of each deployment step (as modelled in the carbon reduction pathways), and adjusted in cases where the asset life defined in the option register would extend beyond 2050 to reflect their residual value on a linear depreciation basis.

3. The annual capital expenditure of each pathway is calculated from the capital cost and deployment of each of the options selected. Capital costs are presented in present day value (i.e. 2015) and assumed to remain constant throughout the period. The discount rate for costs has been chosen to be 3.5% to value the costs from a social perspective and in accordance with standard HM Treasury methodology for this type of assessment. In other words, all proposed capital expenditure on the various pathways are adjusted for the time value of money, so costs (which occur at different points in time) are expressed on a common basis in terms of their 'net present value' using the discount rate of 3.5%. The effect of this standard methodology is to reduce the apparent cost of large investments that are deployed in the pathways later in the study period.

The following specific assumptions apply:

i. Asset replacement is assumed to take place at the end of life of an existing asset. No allowance has been made for loss of production during the shutdown period associated with the implementation of major and/or disruptive technology options. Similarly no allowance has been made for loss of EU ETS allowances or civil works associated with a major shutdowns and plant rebuilds. Although costs may be incurred in a case where a plant is written off before the end of its life, this has not been taken into account in this analysis.
ii. It has been assumed that minor incremental improvements would be implemented in the shadow of other rebuild or maintenance work so that no additional costs for shutdown would be incurred.
iii. No allowance has been made for the costs of innovation and it is assumed that the costs of development of breakthrough technologies would be funded separately and not be charged to subsequent capital investments. Technology licensing costs are assumed to be included in the capital costs.
iv. No carbon price or other policy costs are included in the calculations.
v. Changes in other operating costs including labour, maintenance or consumables associated with the deployment of options have not been included (although it is noted these will be significant for many options).
vi. This analysis covers capital costs for carbon reduction; changes to energy use and energy costs (as a result of deployment of the options) has not been quantitatively included although it will be significant for many options.

4.7.3 Limitations

The project methodology for cost data collection and validation did not deliver a complete dataset for the capital cost of options, and where data was available, it was qualified at low confidence levels. Further, estimates based on expert judgement have been made where data gaps remained. Also, the degree of stakeholder engagement in relation to this cost analysis was lower than for the carbon reduction pathways.

All costs in the data input tables are subject to wide variation, for example between sites and sub-sectors and for technology options that have not been demonstrated at commercial scale. Hence, the cost data represent 'order of magnitude' estimates that require extensive further development and validation prior to any further use including with sector stakeholders.

Moreover, the assumptions and constraints on confidence levels limit the valid uses for the results of this cost analysis, therefore the following applies to use of this analysis:

- The values are a starting point to help assess relative benefits of different technologies over the long term.

- The cost analysis results should not be used in isolation to compare decarbonisation technologies or decide on priorities for their development – additional techno-economic analysis should be carried out on individual options or groups of options.
- The cost analysis is part of a process of research and exploration and is being shared in a transparent way to support the development of broader strategy. The results are effectively provisional order of magnitude estimates which need to be developed further on the basis of thorough research before they can be used to inform decisions.

4.7.4 Cost Analysis Results

The results of the cost analysis of decarbonisation for the various pathways within the current trends scenario are summarised in Table 8below.

Results can be used for relative comparison between pathways in a sector. No cost moderation process between the eight sectors has been carried out and therefore in the absence of further data validation and analysis comparison between sectors is not recommended.

The carbon dioxide emission abatement offered by each pathway has been totalled for each year to present a **cumulative** carbon abatement figure for the period from 2013-2050 compared to the reference pathway.

Although this analysis of discounted capital cost does not include energy costs, it should be noted that energy cost changes will be subject to the uncertainties of future energy cost projections and the significant divergence between energy costs applicable to the different levels of energy consumption. A high level qualitative assessment of the impact of energy use and cost is presented in the table below.

Pathway	Total Discounted Capital Cost 2014-2050 (million £)[15]	Cumulative CO_2 Abated 2014-2050 (million tonnes CO_2)[16]	Projected Impact on Fuel or Energy use and Fuel or Energy cost
BAU	300	4.0	This pathway includes deployment of options such as using alternative cements and cementitious substitution. In the study period from 2013 – 2050, this pathway is projected to result in a saving in energy and fuel used. The value of this saving will depend on the fuel cost forecast adopted.
20-40%	300	14	This pathway includes deployment of fuel switching to biomass, using alternative cements and cementitious substitution. In the study period from 2013 – 2050, this pathway is projected to result in a potential saving in energy and fuel used. The predicted value of this saving will depend on the fuel cost forecast adopted.
Max Tech with CCS	600	50	The carbon reduction in this pathway is dominated by carbon capture. This will increase energy use, and therefore a large overall increase in energy use and costs is projected. The scale of the increased cost will depend on the fuel cost forecast adopted.

Table 8: Summary costs and impacts of decarbonisation for the pathways

4.8 Implications of Enablers and Barriers

From the pathways described above, there are a number of options that will need to make significant contributions to decarbonisation under some or all of the pathways and scenarios. These are:

- CCS
- Fuel Switching to Biomass
- Cementitious substitution
- Oxygen enrichment technology
- Alternative cements

[15] Model output rounded to 1 significant figure to reflect 'order of magnitude' input data
[16] Model output rounded to nearest million tonnes of CO_2

From the evidence gathered during the project (from literature, interviews and workshops) there are a number of enablers and barriers associated with these options. These are discussed below.

4.8.1 Alternative cements

There are several diverse novel or 'new' cements which are generally non-Portland, based on non-traditional processes or raw materials. They tend to embody less energy and emit less CO_2 during manufacture than 'Portland cement CEM I' (formerly called ordinary Portland cement) although there is no precise definition for what constitutes a low energy, low carbon cement.

Typically they would have some or all of the following characteristics. They would:

- Embody less energy than traditional Portland cements, including those that contain additional inorganic or mineral constituents.
- Be manufactured using a novel process that ideally utilises waste-derived fuels and raw materials.
- Be expected to reduce both waste and emissions, in particular the greenhouse gas CO_2.
- Be expected to be utilised in the same construction applications as currently marketed cements

Five of the more interesting novel cement types are listed below. They are either already in production in some parts of the world but at small scale and nowhere near the scale of production of Portland cements or under development and can fulfil the above characteristics to varying degrees. They are:

- Alkali-activated cements including geopolymeric cements (e.g. Zeobond/e-crete, Blue World Crete/Geo-Blue Crete, banah/banahCEM).
- Low energy CSA-belite cements (e.g. Aether).
- Cements based on magnesium oxide derived from carbonates or from silicates (e.g. Eco-cement, Calix/Novacem).
- 'Ecocement' based on municipal solid waste incinerator ash (MSWIA).
- Thermoplastic carbon-based cements (e.g. C-Fix cement).

Magnesium oxide (MgO) based cements are attracting particular interest because they require a much lower temperature of about 700°C to form the required phases, thus reducing fuel-related emissions by about 50%, as well as avoiding the process emissions associated with CEM I production.

Other lower CO_2 cement options, which emit calcination-process CO_2 emissions and fuel-related CO_2 emissions but to a lower extent than in Portland cement production, include the belite-aluminate cements, which uses 12% less fuel and 8% less limestone than CEM I, and the sulpho-aluminate cements which uses 40% less fuel and generates ~50-60% less calcination related CO_2 per tonne of clinker produced than CEM I clinker.

Long testing periods are required to ensure confidence in durability, possibly decades rather than years before some alternative cements are considered safe for structural use. As such not all alternative cements would be able to replace Portland cement in all applications. In addition, specifiers and architects are very risk averse so gaining their confidence in new cements will be challenging (MPA have further information on alternative cements via fact sheets available on the MPA website).

For some alternative cement formulations, the required raw materials may not be widely accessible or available in the UK, particularly at the scale needed to replace Portland cement.

For the current trends scenario, the alternative cements option gives the largest percentage reduction on the BAU pathway of 18%.

Enablers	Some alternative cements already in use on a very small scale Growing industry
Barriers	Durability unknowns or concerns about performance standards Availability of raw materials for their production Further R&D needed Industry is considered small

4.8.2 Cementitious Substitution

This option involves reducing the amount of clinker per unit of cement by substituting the clinker with other cementitious materials, such as pulverised fuel ash (a waste from coal fired power stations) or ground granulated blast furnace slag (a by-product from iron and steel manufacture). Several main constituents beside clinker are available for the production of blended cements. The production of cements containing constituents such as pozzolanic materials, GGBS and materials such as limestone reduce the amount of clinker needed for cement production. Thus CO_2 emissions from clinker production can be saved.

For the current trends scenario, the cementitious substitution option has the biggest impact on BAU (78.28%), and 20-40% (62.91%), pathways.

Cementitious substitution already takes place at concrete mixer sites and to some extent at the cement manufacturing plant. Packed cement products all contain cementitious substitutes in the UK. In the EU most cementitious substitution takes place at the cement manufacturing plant but in the UK most takes place at the concrete mixer. This results from different market structures in the UK and mainland Europe; the overall rate of substitution in the UK is comparable with the rest of the EU. The advantage of mixing at the concrete plant is that transportation volumes and distances are reduced (i.e. substitute material is moved directly from source to concrete plant, not via cement plant), therefore from a full life-cycle perspective there is a disadvantage in moving substitution to the cement plant. In addition, and perhaps more importantly, by blending at the concrete plant the construction company can blend a concrete to have the best composition for the application rather than having to accept pre-determined clinker levels which might result in the consumption of more clinker than necessary. This option presents the highest emissions reduction contribution by 2050 in the 20-40% scenario under current trends (62.91%) and the BAU scenario, also under current trends (78.28%).

Enablers	Technically feasible, currently being implemented in the sector
Barriers	There is concern associated with uncertainty regarding availability of suitable cementitious substitute materials (e.g. fly ash) in the UK cements with high levels of substitute materials are not applicable for all uses Cost of substitutes may increase with increased demand Production largely relies on local coal fired power generation and local steel production providing long-term supply of substitution materials

4.8.3 Carbon Capture and Storage (CCS)

This option relates to the capture of CO_2 generated by combustion processes. The CO_2 is then transported, typically by pipeline, and stored underground in suitable geological features. Carbon capture and use (CCU) is an area of huge potential for many industrial sectors including cement although a detailed assessment of its potential is beyond the scope this project.

CCS can be combined with oxy-fuel combustion. Indeed, oxy-combustion CO_2 capture technology has been identified by MPA and the cement companies as the preferred technology option for the cement sector, offering cost and performance advantages over the alternative post-combustion capture technology. Making a CO_2 transportation network available to tie in to would enable the uptake of CCS, although the option still faces many barriers (additional energy requirements for carbon capture, plants that are not located within the CCS clusters will have difficulties to get access to transport pipelines and hence storage facilities, contaminants in flue gas stream, high capex, need for collaboration, etc.).

Geological storage of CO_2 emitted from cement plants requires the CO_2 to be transported to and permanently stored deep underground in suitable storage facilities. The existing level of adoption within the UK cement sector is 0% as there is currently no carbon capture being employed, no transport network or suitable viable storage facilities available.

This option presents the highest emissions reduction contribution by 2050 in the Max Tech with CCS pathway under current trends scenario (49.96%), and therefore represents the primary potential option to reduce CO_2 emissions in the cement sector.

Enablers	Technically feasible and demonstrated in power generation sector Government policies are being developed to support growth of technology Make CO_2 transportation network available to tie in to R&D and technology already available: leverage developments in power sector Grant funding, and alternative financing with low interest rates
Barriers	Plants within UK are currently not located within likely CCS clusters, only potentially applicable to a few plants Large capital investment required Unstable cement market conditions disincentivise major investments Significant increases in energy consumption required and availability of electricity infrastructure External support need to develop suitable technologies for cement Availability of transport and storage infrastructure Location of cement plants: distance from storage site Issues of storage, including long-term liability Availability of funding for capital investment in CCS Demonstration of commercial scale within cement sector Contaminants in flue gas stream Internal capability and knowledge Business value of implementing CCS when currently this merely adds cost and reduces efficiency On an EU level there has been opposition to implementation in certain countries Risk of carbon leakage due to increased capital and operating cost

4.8.4 Fuel switching to biomass

This option refers to the use of biomass or biomass mixed streams with a biomass content as a fuel for cement production, reducing the emissions produced by fossil fuels burned during this process.

As the fuel-related CO_2 emissions are currently 40% of the total emissions, the CO_2 reduction potential is significant if fuels consisting of 100% biomass are used. Such 100% biomass fuels used in the cement industry today are mainly biomass wastes like animal meal, waste wood, sawdust; and sewage sludge. Biomass is also present in mixed waste streams which are utilised to a much greater degree than 100% biomass fuels, these mixed waste streams include RDF and tyres. Economic barriers for the use of this fuel are considered to be strong. Existing total level of adoption of biomass fuel within the UK cement sector: 18%.

While existing biomass fuels consist principally of waste biomass, following consultation with DECC it has been assumed for the purposes of this roadmap study that any additional biomass fuel would comprise virgin biomass material.

This option presents the highest emissions reduction contribution by 2050 in the Max Tech with no CCS pathway under current trends scenario (43.42%). This option also impacts all other pathways.

Enablers	Technically feasible, currently being used by the sector Increase already happening at EU level There is the potential for the product (unit price) to be cheaper than coal There is an advantage to using waste biomass sources in cement in that the ash content following combustion of the fuel is safely captured in the product so from a waste reduction point of view it has advantages over incineration which generates an ash for disposal
Barriers	Competition with sectors that are being funded and supported to use biomass Biomass availability Regulatory uncertainty Uncertainty about return on capital

4.8.5 Oxygen Enrichment Technology

This option involves the use of oxygen enriched combustion air in the clinker burning process. This allows an increase of the fuel efficiency, production capacity or substitution of fossil fuels by low calorific value (or secondary fuels).

Since this option results in an increase in electrical power consumption (for air separation), grid decarbonisation is essential for it to contribute to CO_2 reduction. A reliable source of affordable, low carbon electricity is required to be able to support investment in oxygen enrichment.

Existing level of adoption within the UK cement sector: 0%. This is because of the high capital cost and limited economic benefits currently associated with the use of oxygen enrichment.

This option presents the highest emissions reduction contribution by 2050 in the Max Tech with no CCS pathway under current trends scenario (14.97%). This option presents a lower deployment in Max Tech with CCS under current trends scenario (2.75%).

Enablers	Increase in fuel efficiency Greater production capacity Enables additional substitution of fossil fuels Established in some cement plants worldwide Development of new, low cost, high efficiency oxygen air separation technologies
Barriers	Substantial operating costs Decrease in electrical energy efficiency Further R&D is required Technical feasibility Durability and wear concerns Large investment required

4.8.6 Others

Sections 4.4.1 to 4.4.5 above focus on the options that provide the most significant decarbonisation potential. From the evidence gathered as part of this Roadmap, other options share many of the same enablers and barriers such as:

- Major innovative technology changes require significant further development before they could be considered for deployment.
- Long-term stability in carbon pricing is needed in order to make major investments.

Finally, even though decarbonised grid electricity is included in all pathways and is not under the direct control of the sector, it is a major contributor to decarbonisation, providing 8.5% decarbonisation in the current trends pathway, and so would rank as the 3rd most significant option, if included within the pathways.

5. CONCLUSIONS - PRINCIPAL QUESTION 6

This section provides assessment of the questions under principal question 6: 'What future actions might be required to be taken by industry, government and others to overcome the barriers in order to achieve the pathways in each sector?'

The section is structured as follows:

- Eight 'strategic conclusions' or themes have been developed by analysing the main enablers and barriers. Example next steps/potential actions are also included for each strategic conclusion.
- Key technology groups are discussed, many of which link to the themes above. As described in section 4, a small group of technologies make a significant contribution to decarbonisation in 2050, especially for Max Tech reductions[17]. Example next steps are included to assist with developing, funding and implementing the technologies.

It is intended that government and industry use the roadmap to develop and implement an action programme in support of the overall aim of decarbonisation while maintaining competitiveness in the sector.

5.1 Key Points

The following conclusions have been drawn from the evidence and analysis:

Leadership, Organisation and Strategy

Leadership is important at company, sector, regional and UK government level. It links to all of the themes below. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis. The cement sector continues to illustrate good practice in relation to strategy, for example with publication of the 2050 greenhouse gas reduction strategy published by the MPA.

Business Case Barriers

The R&D, demonstration and commercial deployment of energy efficiency projects and major technologies requires significant upfront capital. Decisions to invest are impacted by a number of technical and economic factors such as policy costs and certainty, availability and access to internal finance and an evaluation of technical and commercial risks and returns. A range of options could be developed to overcome business case barriers including incentive-based policy and external project finance.

Future Energy Costs, Energy Supply Security, Market Structure and Competition

Some of the key technological options considered by the pathways, such as carbon capture (plus storage or use), will require significant capital costs and higher energy consumption and thus increase operating costs. This will reduce the overall cost-competitiveness of the sector compared to businesses overseas without measures to level the international playing field. For example, future action needs to address concerns on all components of the future electricity price relative to other regions.

[17] These technology groups broadly apply to the cement sector and also the other seven sector roadmaps.

Industrial Energy Policy Context

The long-term direction of energy and climate change policies and regulations in the UK may put at risk international competitiveness of the cement industry. Uncertainty (perceived or real) reduces investors' confidence and reduces the ability of the sector to justify the business case for major investments in energy efficiency and decarbonisation technologies. It is reported by the sector that the business case for investment needs to be very strong and to include risk identification and effective risk mitigation and control measures. Industry would encourage that policy should consider the right balance of bankable incentives to encourage such investments.

Life-Cycle Accounting

The sector uses raw materials from, and provides its products to, other parts of the economy. There needs to be further development of the understanding the overall carbon impact of the entire product life-cycle. For example, by constructing buildings from concrete, which increases their thermal inertia, there can be significant long-term carbon benefit through reduced energy use and long-term durability. Recarbonisation of concrete (reabsorbing CO_2) could form part of this assessment. The sector is trying to communicate these messages but the recognition of whole life benefits in construction is very limited. Government and industry could do more to achieve this market acceptance.

Value Chain Collaboration

The value chain for the cement sector extends from feedstock supply (quarries and alternative feedstock sources), through cement manufacture, concrete production, procurement and specification of cement/concrete products by customers and their architects / engineers. Transportation of materials through the supply chain is an integral element. The carbon emissions of the cement sector are affected by the expectations of consumers, the business needs of builders and other industrial users of concrete products together with product standards and the requirements of building regulations. Collaboration across the value chain could enable products with lower lifecycle carbon emissions to be developed and adopted. The cement sector utilises waste materials from the power generation and iron and steel sectors as alternative feedstocks. Maintaining strong dialogue to understand the future strategies in these sectors, the future availability of these materials and maximising synergies benefits all sectors.

Research, Development and Demonstration (RD&D)

The development and demonstration of new technologies required to deliver decarbonisation is challenging for companies and government alone for example, due to lack of confidence from industry on a stable policy framework and technical challenges. This includes early R&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Technologies should be selected through a collaborative process. It should be noted that RD&D largely happens at a group global level rather than in the UK businesses, so groups will tend to put the effort into where the benefits are maximised on a group-wide level – hence government support for RD&D in the UK could potentially bring such projects to the UK rather than elsewhere.

People and Skills

New manpower resources with specialised skills and knowledge in energy and heat engineering are increasingly needed by the UK cement sector. Currently, key responsibilities of energy teams include ensuring compliance with existing regulation which diverts attention and effort from identification and implementation of energy efficiency activities.

The key technology groups that, in this investigation, make the largest contributions to sector decarbonisation or energy efficiency are as follows:

Electricity Grid Decarbonisation

Decarbonisation of this electricity imported to cement sites supply could provide a significant contribution to the overall decarbonisation of the sector. Actions (mainly by government and utilities) will be required to ensure that this takes place while maintaining cost-competitiveness. The Government's reforms of the electricity market are already driving electricity grid decarbonisation and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Fuel and Feedstock Availability (Including Biomass)

The availability of low carbon fuels and feedstocks is a potential issue for cement sector decarbonisation, given the important role biomass could play. This availability is affected by demand in the cement sector and other sectors and/or with other demand (for example, the use of biomass for electricity generation or in the non-manufacturing sector such as domestic heating). The challenges are to understand where the greatest decarbonisation potential can be achieved with a limited resource, as well as to maximise the availability of the resource (links to Life-cycle carbon accounting).

Energy Efficiency and Heat Recovery Technology

There are opportunities to increase heat recovery in the cement sector, both to improve energy efficiency and to produce electric power. However, the payback periods of such projects are typically above the 2-3 year threshold that must be achieved to justify company investment. Alternative financing mechanisms to facilitate investment in energy efficiency projects could increase their implementation across the sector.

The development and demonstration of new technologies required to deliver decarbonisation is difficult to achieve. It is clear that the sector shows good leadership and is committed to decarbonisation however the issues for the sector are largely lack of certainty and predictability in the regulatory regime and market along with the big step of overcoming technical difficulties. This includes early R&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment.

Carbon Capture

Individual cement plants are not considered to be of a sufficient scale to justify their own CO_2 pipeline and storage infrastructure. Collaboration both within the sector and externally is necessary to establish the networks, along with the availability of sources of funding appropriate to this type of shared infrastructure. The scale of CO_2 emissions from each site in the cement sector means that carbon capture and utilisation applications would need extensive technical breakthrough to be developed into large scale options for use of CO_2 in products with associated value (this is a key area of current and future research where significant development is needed). A future strategy for the development of a CO_2 transportation network should be considered with government taking a lead. This would enable industry to understand if and when there is likely to be access to a CO_2 pipeline from their site for storage or use and can then plan accordingly.

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The report has been compiled with the aim that is has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy.

5.2 Strategic Conclusions

5.2.1 Strategy, Leadership and Organisation

Strategy is important in any industrial sector or company in that it provides long-term aims and a plan of action of how to achieve the aims. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis.

In order to achieve the identified pathways going forward, it is considered critical that the cement sector, government and other stakeholders continue to recognise the importance of strategy and leadership in the context of decarbonisation, energy efficiency and competitiveness for the sector. The evidence for this conclusion comes from interviews, where several senior industry managers explained that both companies and government need to work collaboratively on those issues that need multi-disciplinary action. If through collaboration decarbonisation is given greater impetus within the sector and in government, then the specific example actions described in this document will have a higher chance of success.

This links to all other conclusions below, including policy context, research and development, the benefits of cement in the value chain, technology deployment, and optimising fuel and feedstock usage.

A possible action to address this issue is to set up a government-industry working group with responsibility for the cement sector strategic priorities. This group could bring:

- Government support for potential cross sector benefits within an energy intensive industries industrial strategy.
- Leadership and vision to the UK sector, emphasising how cement production adds strategic value for the UK and why it is important to face the challenges and develop the opportunities for the sector.
- A high level link between industry, government and the EU and a clear framework within which production, technology, energy efficiency and decarbonisation agendas can be taken forward. Members of the working group could engage with executives in corporate headquarters to better inform the UK cement sector strategy.
- Government may wish to consider expanding the current sectoral scope of to put an industrial strategies in place to give confidence that the industry will be still have a significant level of production in the UK in 20+ years. This confidence would in turn facilitate future investment in both current and new plants.
- A means to take forward the Roadmap agenda with shorter term action plans, for example, in five year intervals.

This conclusion is also applicable to individual company strategy, where companies have a key role in overcoming barriers and strengthening enablers. This links to a number of enablers and barriers, for example, management commitment to decarbonisation and energy efficiency, value chain opportunities and the need for skilled people.

5.2.2 Business Case Barriers

Given the progress already made by the cement sector companies on energy efficiency (energy being a substantial part of operating costs), remaining options carry technical and economic challenges and risks – making cases for energy efficiency projects challenging against other priority investments. Energy efficiency projects are judged on their return on capital and payback in relation to other projects requiring capital for continued operation of the business both in the UK and for company international assets. This competition is generally for resources of all kinds e.g. capital, technical staff and management time. For these reasons, projects that appear to be economically worthwhile may not be implemented, even if a solid and well-justified business case is made.

Examples of actions to overcome these issues include:

- Government could consider how to assist in developing external project financing mechanisms. These need to take account of the likely long-term nature of energy-saving projects.
- As part of the standard policy evaluation process, Government to assess the balance between positive and negative incentives.
- Industry to consider using third parties to implement projects in order to avoid capital and other resource limitations. For example, an external company could be employed to install a specific energy efficiency measure (which they would fund) in return for a share of the benefits.
- Industry and suppliers to continue to use a full range of outputs from other actions in this section to make the strongest possible internal business cases for decarbonisation investments. This will need to be an on-going activity.
- Investigate and identify financing for the cement projects described below, including demonstration projects.

Significant improvement in the investment environment is required to permit the necessary increase of investment likely to be required in the sector to deliver changes contributing to decarbonisation from 2025, as evidenced by the pathways analysis.

5.2.3 Future Energy Costs, Energy Supply Security, Market Structure and Competition

Many decarbonisation measures are expensive and potentially time consuming to implement. Where measures do not have the shared benefit of reducing energy consumption, companies are not able to recover the cost of investment because consumers are currently not willing to pay higher prices for low-carbon cement products. Additionally, if operating costs for UK companies rise too high, they will be unable to compete against foreign made products that may be manufactured to lower environmental standards (hence increasing global CO_2 emissions and reducing jobs in the UK). Imports from inside and outside the EU already have 14% market share in the UK even at low CO_2 prices.

Some of the key technological options considered and discussed by the pathways in section 4, such as carbon capture, require higher energy consumption and thus increased overall operational as well as capital cost. This could reduce the overall cost-competitiveness of the sector compared to competing businesses operating overseas, e.g. North Africa or Middle East. This could in turn reduce the attractiveness of the sector in the UK for future investment. Example actions that would partially mitigate this include:

- Industry and government to collaborate on technology demonstration to drive down cost and ensure performance is demonstrated before mass adoption. This would be an on-going activity as technologies become ready but with the overall approach put in place before 2020 (links to the Collaboration themes below).
- Establish a global carbon price as part of global agreements – ideally applying to other sectors beyond the cement sector (see Policy and Incentives above).
- Explore how other decarbonisation options included in this report could happen in a commercially viable manner.

5.2.4 Industrial energy policy context

The need for long-term energy and climate change policy is key to investor confidence, according to literature and other evidence-gathering sources (see section 3.4.5 'enablers and barriers'). Many in the sector have emphasised a desire for long term certainty around policy support for decarbonisation and energy efficiency, as changes in policy (around incentive schemes) can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy prices. Possible actions as next steps to address this conclusion are as follows:

- Government to explore creating incentives which will encourage companies to invest in decarbonisation measures and energy efficiency technologies
- Government to review unilateral UK carbon price and establish an effective price for CO_2 that incentives the reduction of carbon while also evaluating measures to minimise the risk of carbon leakage. Work on this should start now on the assumption that it will take a number of years to implement and many of the decarbonisation options in the pathways depend on investment that needs this to underpin them.
- Government to explore funding arrangements to recognise mid- to long-term decarbonisation benefits. This would allow the value of these benefits to be taken into account in investment decisions. The effective CO_2 price noted above would be one means of doing this. This action links to the *Finance* theme below.
- Governments to establish a 'level playing field' through a global carbon agreement (with regional breakdowns) before 2020. This could provide an alternative means to avoid possible carbon leakage.
- In addition to a global agreement, reform of the EU ETS is considered a priority for the cement sector. The system is perceived to be unfair towards this sector in terms of allocation of carbon allowances and the industry asserts that the uncertainty over future rounds of allowances discourages investment and the technical rules of the current system perversely encourages the use of older, less efficient plants rather than building newer plants.
- Government to establish a 'level playing field' through modification to the Renewable Heat Incentive scheme to make it (or an equivalent scheme) available to the cement sector, and applicable to the sector's use of biomass fuels. In *The Future of Heating* (2013), DECC committed to exploring options to support direct applications of renewable heat in industrial processes.
- Review planning requirements for industrial renewable energy and low-carbon projects where clear benefits to decarbonisation and energy efficiency, competitiveness and local economy are proposed.

5.2.5 Life-cycle Accounting

The interaction between sectors is significant, with the carbon emissions of the cement sector being necessary for the manufacture of products utilised in a low carbon economy. A thorough lifecycle analysis (LCA) of such activities is necessary to ensure that policies and investments are focussed on the most effective decarbonisation measures overall. LCAs must be comparable to LCAs for other European cement products, as well as other materials. Building on existing standards, the analysis methodology needs to be developed in the short term and its application across the industrial sectors needs to be completed during the next parliament to inform investment and policy decisions in a timely manner.

A wider dissemination of knowledge on the whole life carbon benefits of products would help remove the barriers with respect to understanding the potential of these products and how to deploy them most effectively. This research has identified that industry is trying to communicate these messages but the recognition of whole life benefits in construction is very limited. Government and industry could do more to achieve this market acceptance.

Develop standard tools for evaluating life-cycle 'cradle-to-grave' carbon impacts, from original raw material and feedstock through to final product disposal. These should include defined, consistent boundary conditions to ensure results can be compared across sectors.

Implement policies and incentives that allow the value of carbon benefits to be realised at the appropriate point in the supply chain. For example, when concrete structures are demolished there will have been an uptake of CO_2 into the concrete, and the carbon benefit could have a financial value that can be used to support the supply chain. This will allow these benefits to be used to help justify investment and policy decisions. Global equalization of carbon prices would be one way to allow the market to price in these carbon benefits.

Government to preferentially purchase cement sector products taking into account whole life cycle emissions and performance as a possible way to encourage development of the market taking into account decarbonisation.

5.2.6 Value Chain Collaboration

Increased use of alternative raw materials is vital for the decarbonisation of the cement sector. Identifying future availability of materials such as power station fly ash and blast furnace slag is essential to allow the sector to plan, and identify alternative feedstocks, if necessary. Close cross-sectoral collaboration would build on current good practice, maximise mutual benefits and facilitate further synergies between the cement and iron and steel and power generation sectors.

The cement sector utilises waste materials from the power generation and iron and steel sectors as alternative feedstocks. Maintaining strong dialogue to understand the future strategies in these sectors, the future availability of these materials and maximizing synergies could benefit all sectors.

The role of customers (and their advisors) in understanding life cycle emissions, for example, specifying whole life low carbon building solutions links to 5.2.5 (life-cycle accounting).

5.2.7 Research, Development and Demonstration (RD&D)

Within the cement sector, collaboration between industry and academia in identifying key RD&D requirements and providing support and guidance to the academic community is essential to develop the future technologies demanded by the sector. Research priorities include:

- Development of CO_2 capture technologies specific to the cement sector (oxy-combustion CO_2 capture technology) and the development of processes to use captured CO_2 as a feedstock (CCU), creating value rather than cost from carbon capture.
- Successful carbon capture technology demonstration would reduce risks and encourage wider deployment, however, an opex support mechanism (e.g. equivalent to the CfD FiT in the power sector) may need to be implemented to encourage carbon capture deployment due to its high operating costs.
- Studies into the potential for increased industrial symbiosis between cement and other sectors.
- Development of new substitutes to portland cement.
- Life-cycle carbon footprinting of the cement sector, including feedstocks, fuels, savings in the built environment and post-demolition CO_2 reabsorption.
- Increased collaboration in order to join up industry needs and academic research areas. This could start with an inventory of current activities which are already in the public domain.
- Industry and government to further develop and support centres of excellence and technology 'catapults'.

5.2.8 People and Skills

As identified in the workshops, there is a limited number of staff with specialised skills in energy and kiln engineering in the sector. The priorities of those staff tend to be on ensuring compliance with regulations which diverts attention and effort away from identification and implementation of energy efficiency opportunities. The need for training is reflective of the fact the workforce is ageing and with the development of new technologies, new skills will be required.

Some examples of actions include:

- Manufacturing has to be an attractive career, so more should be done to publicise the benefits of working in industry.
- Industry to invest in training and recruitment to make the necessary skills available
- A review of training and skills to help businesses decarbonise, e.g. writing effective business plans in support of progressive strategies such as utilising advanced financial instruments such as green bonds to decarbonise faster.

The other themes discussed above aimed at making decarbonisation investment more attractive would also tend to encourage the recruitment of staff with the necessary skills and their use on relevant projects.

5.3 Key Technology Groups

5.3.1 Electricity Grid Decarbonisation

Decarbonisation of this key source of energy supply could provide a significant contribution to the overall decarbonisation of the sector (see pathways analysis in section 4). Actions (mainly by government and utilities) will be required to ensure that this takes place while maintaining cost-competitiveness.

5.3.2 Fuel and Feedstock Availability (including biomass)

The supply of biomass is critical to its current and possible future use as a low-carbon energy supply in the cement sector. Actions to assess the likely future availability of biomass, in particular waste biomass streams, would enable the sector to understand how this could add to the future competitive position for the UK. Example actions are provided below:

- Establish a basis for biomass that is cost-competitive with fossil fuel as a heat source, e.g. by extension of the Renewable Heat Incentive, or introduction of an equivalent scheme applicable to direct firing with biomass, urgently for the existing operations of the sector and to support large-scale replacement of fossil fuels with biomass (both waste and virgin) no later than 2035.
- Acknowledge, and provide support for, the unique advantage that the cement sector has in the use of waste or contaminated biomass streams in being able to incorporate the inorganic components of the fuel stream into the cement product. Create a recognition of material efficiency in the waste hierarchy; modify the Waste Framework Directive to include co-processing so that biomass is used efficiently.
- Establish a ‘level playing field’ between the cement sector and other industries that currently receive incentives for the use of biomass and can therefore currently offer higher prices for constrained supplies of biomass, potentially diverting biomass away from the cement sector. This will remove perverse incentives that currently favour the use of biomass in applications that are less energy efficient and where, in particular, waste biomass streams are a less suitable fuel source than in the cement sector.
- Building on the above to create a mechanism to ensure biomass is being utilised where it adds the most value to the economy.
- The EU ETS could regulate the CO_2 emissions from incinerators that burn biomass over time that could otherwise have been used in cement kilns so that the two sectors can compete on a level playing field for biomass resource in mixed wastes. Research potential new sources of biomass fuel to increase potential supply to the sector; both waste materials and virgin biomass. Such assessment must include consideration of quantities, costs and carbon footprints of each potential source.

With regard to cementitious substitution, significant progress and emissions have been made by use of this approach, but long term availability of materials is a concern and an area for ongoing strategic review for the sector to continue to identify secure and competitive supplies of these materials.

5.3.3 Energy Efficiency and Heat Recovery

There are opportunities to increase heat recovery in the cement sector, both to improve energy efficiency and to produce electric power. However, the payback periods of such projects are typically above the 2-3 year threshold that generally must be achieved to justify investment. Alternative financing mechanisms to facilitate investment in energy efficiency projects would increase their implementation across the sector.

The development and demonstration of new technologies required to deliver decarbonisation is challenging. It is clear that the sector shows good leadership and is committed to decarbonisation however the issues for the sector are largely lack of certainty and predictability in the regulatory regime and market along with the big step of overcoming technical difficulties. This includes early R&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Technologies should be selected through a collaborative process. Companies may not have the time and expertise to identify if and how different options may be of benefit to them and so may not progress the R&D activity needed (links to *Employees and skills* below).

5.3.4 Clustering

While not an option assessed in the pathway analysis, studies into the potential for increased industrial symbiosis between cement and other sectors could further develop potential opportunities for carbon and energy savings/benefits, possibly as part of a wider assessment of opportunities in multiple sectors.

5.3.5 Carbon Capture

Individual cement plants are not considered to be of a sufficient scale to justify their own CO_2 pipeline and storage infrastructure. Collaboration both within the sector and externally is necessary to establish the networks, along with the availability of sources of funding appropriate to this type of shared infrastructure. The scale of CO_2 emissions from each site in the cement sector means that carbon capture and utilisation applications would need to be further developed into large scale options for use of CO_2 in products with associated value (this is a key area of current and future research where significant development is needed). A future strategy for the development of a CO_2 transportation network should be considered with government taking a lead. This would enable industry to understand if and when there is likely to be access to a CO_2 pipeline from their site for storage or use and can then plan accordingly.

Issues and potential actions include:

- The most mature CO_2 capture technologies being developed for application within the power generation sector are not directly applicable for efficient capture within the cement sector. Enforcing short-term targets for the application of CCS within the sector would result in technology lock-in with low-efficiency, high-cost technologies that are not optimised and would create a negative reaction to CCS within the sector. Government must recognise that the development of sector specific CO_2 capture technologies will take time, and allow for this when developing future policy
- The cement sector has identified oxy-combustion CO_2 capture technology as the most likely optimum technology for application in the sector. The Air Separation Unit providing the oxygen to the process is a major user of electrical power, therefore ensuring a supply of low carbon, affordable electricity is essential for the application of this technology – and for the application of oxy-combustion more widely, including at plants that do not have CO_2 capture. Additionally, the

development of new, advanced air separation technologies that reduce the electrical power consumption would provide a further cost and environmental benefit.

- Specific Research, Development and Demonstration funding for industrial carbon capture for high temperature industries, including specific focus on capture in the cement sector, will accelerate implementation. Industry stakeholders would value an equivalent emphasis and support on industrial CCS as currently is being put on CCS in the power sector.
- Investigate flue gas composition, in particular the presence of contaminants and trace components, so that potential application of CO_2 capture and CO_2 utilisation in the cement sector can be better understood. It may be possible to learn from experience in the power generation sector regarding technology selection and performance for flue gas clean-up and CO_2 purification, but the differences with cement kiln flue gas need to be characterised.
- Future funding sources for CCS demonstration in the cement sector might include the EU's NER400 mechanism. However the UK cement sector would require UK Government commitment to support projects bidding for funds from this source.
- CCS within the cement sector can only be applied at those plants that will have ready access to CO_2 transportation infrastructure; a CO_2 pipeline, provided by a third party, needs to be available at the site boundary. At present, the future extent of CO_2 pipeline networks is unknown. Clarity could be provided through the development of a UK national strategy for CCS infrastructure – a 'CO_2 Pipeline Roadmap'.
- The application of CCS increases both capital costs and operating costs for a cement plant. Mechanisms to incentivise and or compensate industry for decarbonisation through the application of CCS are essential to facilitate implementation and avoid the UK cement sector being at commercial disadvantage to overseas competitors. Otherwise, the effect could be carbon leakage, rather than the implementation of CCS.

These actions need to be initiated in the near term and sustained throughout the following decades to permit and maintain momentum for development and decarbonisation.

5.3.6 Technologies Specific to the Cement Sector

Based on the pathways analysis, there are a number of options specific to the sector that can contribute further to decarbonisation and energy efficiency in the sector. These use alternative cements and oxygen enrichment technology.

5.4 Closing Statement

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The way in which the report has been compiled is designed to ensure it has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy. It will be successful if, as a result, the government and the cement sector are able to build on the report's evidence and analysis to deliver significant reductions in carbon emissions, increased energy efficiency and a strong competitive position for the UK cement industry in the decades to come.

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7. GLOSSARY

Glossary

Adoption

The percentage of sector production capacity to which a decarbonisation option has already been applied. Therefore, of the list of options being assessed, this is a measure of the degree to which they have already been deployed in the sector.

Applicability

The percentage of the sector production capacity to which a particular option can be applied. This is a measure of the degree to which a decarbonisation option can be applied to a particular part of the sector production process.

Barrier to Decarbonisation or Energy Efficiency

Barriers are factors that hinder companies from investing in and implementing technologies and initiatives that contribute to decarbonisation

Business as Usual

A combination of carbon abatement options and energy savings that would be expected with the continuation of current rates of deployment of incremental improvement options in the sector up to 2050 without significant intervention or outside support.

Decarbonisation

Reduction of CO_2 emissions (in $MtCO_2$) – relative to the reference trend for that scenario. When we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO_2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO_2, are very low.

Carbon reduction band or bins

The percentage ranges of CO_2 reduction achieved for a given pathway in 2050 relative to the base year e.g. 20-40% of the base year emission.

Carbon reduction curve or profile

A quantitative graph which charts the evolution of sector carbon emissions from 2014 to 2050

Competition Law

The UK has three main tasks:

- Prohibiting agreements or practices that restrict free trading and competition between business entities. This includes in particular the repression of cartels.

- Banning abusive behaviour by a firm dominating a market, or anti-competitive practices that tend to lead to such a dominant position. Practices controlled in this way may include predatory pricing, tying, price gouging, refusal to deal and many others.
- Supervising the mergers and acquisitions of large corporations, including some joint ventures. Transactions that are considered to threaten the competitive process can be prohibited altogether, or approved subject to 'remedies' such as an obligation to divest part of the merged business or to offer licences or access to facilities to enable other businesses to continue competing.

Deployment

Once the adoption and applicability of an option has been taken into account, each option can be deployed to reduce part of the sector's CO_2 emissions. Hence, the deployment of the option from 2015 through to 2050 is illustrated in our analysis by the coloured matrix on the pathway presentations.

Enabler for decarbonisation or energy efficiency

Enablers are factors that that make an investment feasible or would either help overcome a barrier.

Grid CO_2 emission factor

A specific scenario assumption relating to the average carbon intensity of grid electricity and projection(s) of how this may evolve to 2050

Maximum Technical Pathway ('Max Tech')

A combination of carbon abatement options and energy savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier/cheaper option is chosen or two alternative max tech pathways are developed.

Option

A carbon reduction measure, often a technical measure, such as a more efficient process or technology

Option Register

The options register was developed jointly by the technical and social and business research teams. This was achieved by obtaining the list of potential options from interviews, literature, asking participants at the evidence gathering workshop which options they would consider viable, and through engagement with members of the relevant trade associations.

Pathway

A particular selection and deployment of options from 2014 to 2050 chosen to achieve reductions falling into a specific carbon reduction band

Projection of Production Changes

A sector specific scenario assumption which defines the changes in production as an annual percentage change to 2050

Reference trend

the carbon dioxide emission trend that would be followed if the 2012 base year emissions were affected by production change and grid decarbonisation in accordance with the sector specific scenarios

Scenario

A specific set of conditions external to the sector which will affect the growth and costs of production in the sector and affect the timing and impact of options on carbon emissions and energy consumption

Scenario assumptions

A set of specific cost and technical assumptions which characterise each scenario. These include forward fuel and carbon price projections, grid CO_2 factor projection and background economic growth rate. The assumptions may include sector forward production projections.

Sensitivity case

The evaluation of the impact of changes in a single assumption on a pathway e.g. the availability of biomass

8. ACKNOWLEDGEMENTS

The authors would like to thank all those who contributed to this project. This included trade associations and their members, academic institutions and government officials within the sector team and also all those who contributed to the project through attending workshops, engaging in interviews and provided data, review and comment to early drafts of the outputs.

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