Technology Roadmap

Low-Carbon Transition in the Cement Industry

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The **International Energy Agency** (IEA) examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 7 association countries and beyond.

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- **Environmental Awareness**: Analysing policy options to offset the impact of energy production and use on the environment, especially for tackling climate change and air pollution; and
- **Engagement Worldwide**: Working closely with association and partner countries, especially major emerging economies, to find solutions to shared energy and environmental concerns.

The **Cement Sustainability Initiative** (CSI) is a global effort by 24 major cement producers with operations in more than 100 countries who believe there is a strong business case for the pursuit of sustainable development. Collectively, these companies account for about one-third of the world's cement production, and range in size from large multinational companies to small local producers.

All CSI members have integrated sustainable development into their business strategies and operations, as they seek strong financial performance with an equally strong commitment to social and environmental responsibility. The CSI is an initiative of the World Business Council for Sustainable Development (WBCSD). The CSI is one of the largest global sustainability project ever undertaken by a single industry sector. To find out more, visit www.wbcsdcement.org.

CSI members: CEMEX, CRH, HeidelbergCement, InterCement, LafargeHolcim, SCG Cement, Taiheiyo Cement, Titan, Votorantim Cimentos, Cementos Argos, China Resources Cement, Cimenterie Nationale, Çimsa, China National Building Material, Dalmia Bharat Cement, GCC, Orient Cement, Secil, Shree Cement, Siam City Cement, Tianrui Cement, UltraTech Cement, West China Cement and Cementos Progreso.

Foreword

Awareness is growing of the urgent need to turn political statements and analytical findings into climate mitigation action that leads to a more sustainable future. We can and must change the path that we are on. Innovative low-carbon technologies will play a central role in this transition.

Goal 13 of the United Nations 2030 Agenda for Sustainable Development, adopted by world leaders in September 2015, calls for urgent action to combat climate change and its impact. The Paris Agreement, negotiated in December 2015 at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, attempts to limit the rise in global temperatures this century to less than 2°C above preindustrial levels.

To spark this movement and build on a long-standing collaboration, the International Energy Agency (IEA) and the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD) have partnered to develop this update of the global *Cement Technology Roadmap* that was produced jointly in 2009 (the first industry-specific roadmap).

The cement industry currently represents about 7% of the carbon dioxide (CO_2) emissions globally and is the third-largest industrial energy consumer. Cement companies in the CSI have been long taking action to reduce CO_2 and voluntarily reporting independently verified CO_2 and energy performance information (representing 21% of global cement production). The analysis for this roadmap is based on a compilation of performance data and information related to cement production from the best available data sources worldwide, a key source being the Getting the Numbers Right database managed by CSI, which is externally verified, as well as other sources.

The vision of this roadmap is based on an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. In contribution to this effort, the roadmap uses a bottom-up approach to explore a possible transition pathway based on least-cost technology analysis for the cement industry to reduce its direct CO_2 emissions by 24% below current levels by 2050.

The outlined transition for such CO_2 emissions reductions in cement production is ambitious, and the changes must be practical, realistic and achievable. The transition of the cement industry can only be attained with a supportive regulatory framework and effective and sustained investments. The roadmap outlines these policy priorities and regulatory recommendations, assesses financial needs, discusses investment stimulating mechanisms and describes technical challenges with regard to research, development and demonstration needs and goals.

While this roadmap focuses on cement manufacturing, the IEA and CSI recognise the need to consider CO_2 emissions reduction over the overall life cycle of cement, concrete and the built environment by working collaboratively along the whole construction value chain. For instance, by optimising the use of concrete in construction or by maximising the design life of buildings and infrastructure, further CO_2 emissions savings can be realised.

This roadmap aims to contribute to the required international collaborative effort among stakeholders, and to be a source of inspiration for international and national policy makers to support evidence-based decisions and regulations in support to the sustainable transition of the cement industry.

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Key findings

Cement is used to make concrete, the most consumed manufactured substance on the planet. Concrete builds homes, schools, hospitals, workplaces, transport systems and infrastructure for clean water, sanitation and energy, which are important for quality of life and social and economic wellbeing.

The cement sector is the third-largest industrial energy consumer, comprising 7% of the global industrial energy use (10.7 exajoules [EJ]). Cement production involves the decomposition of limestone (calcium carbonate), which represents about two-thirds of the total CO_2 emissions generated in the process, with the remainder of CO_2 emissions being due to combustion of fuels. Thus despite considerable progress on energy efficiency, the use of alternative fuels and clinker replacements, the sector has the second-largest share of total direct[1] industrial carbon dioxide (CO_2) emissions, at 27% (2.2 gigatonnes of carbon dioxide per year [$GtCO_2$/yr]) in 2014.

Rising global population and urbanisation patterns, coupled with infrastructure development needs, drive up the demand for cement and concrete. Global cement production is set to grow by 12-23% by 2050 from the current level. Some regions, such as People's Republic of China and the Middle East, have excess cement production capacity, with cement production per capita levels well above the global average. Other regions, such as India and Africa, are set to increase their domestic cement production capacity to fulfil their infrastructure development needs.

Direct CO_2 emissions from the cement industry are expected to increase by 4% globally under the International Energy Agency (IEA) Reference Technology Scenario (RTS[2]) by 2050 despite an increase of 12% in global cement production in the same period.

Realising the sustainable transition of the 2 degree Celsius (°C) Scenario (2DS) implies a significant reduction of the global direct CO_2 emissions from cement manufacture by 24% compared to current levels by 2050 still with the expected increase in global cement production. This represents cumulative emissions reductions of 7.7 $GtCO_2$ compared to the RTS by 2050, reaching 1.7 $GtCO_2$, equivalent to around 90% of current total global industrial direct CO_2 emissions. Implementing this vision requires accelerated development and deployment of CO_2 emissions reduction levers, supportive policy, public-private collaboration, financing mechanisms and social acceptance.

1. Direct CO_2 emissions refer to emissions that are generated and released in the cement production process.

2. Please refer to Box 1 below for details on scenarios.

Improving energy efficiency, switching to alternative fuels (fuels that are less carbon intensive), reducing the clinker to cement ratio and integrating carbon capture into cement production are the main carbon mitigation levers supporting the sustainable transition of the cement sector. The integration of emerging and innovative technologies like carbon capture and reducing of the clinker content in cement are identified to provide the largest cumulative CO_2 emissions reductions in the 2DS compared to the RTS by 2050, with 48% and 37% contributions, respectively. The remainder of the reduction arises from switching to lower-carbon fuels and, to a lesser extent, energy efficiency.

Alternative binding materials in principle offer opportunities for carbon emissions reductions but considerable further analysis is required to produce robust, independent and publicly available life-cycle assessment of these materials, including a comparative quantification of the production costs and their long-term performance. Further process optimisation at the demonstration phase and product standardisation could open more avenues for commercial deployment.

Adopting a whole life-cycle approach and working collaboratively along the whole construction value chain offers additional opportunities for carbon emissions reductions beyond the cement manufacturing boundary. Optimising the use of concrete in construction by reducing waste, encouraging reuse and recycling, maximising design life and using concrete's properties to minimise operational energy of the built environment, are key strategies in this area.

Realising the RTS would incur cumulative additional investments of United States dollars (USD)[3] 107 billion to USD 127 billion by 2050 compared to a situation where the current energy and carbon emissions footprint of cement making remain unchanged. This effort is equivalent to 24-28% of the total cumulative investment estimated to sustain global cement production over that period at current performance levels. Between USD 176 billion and USD 244 billion of additional global investments are estimated as necessary to implement the 2DS cumulatively by 2050 compared to the RTS. This represents 32-43% of the total cumulative investment estimated to realise the RTS. Governments, in collaboration with industry, can play a determinant role in developing investment risk-mitigating mechanisms that unlock private finance in areas with low likelihood of independent investment but important in the sustainable transition of society.

3. Investment figures are based on 2015 USD.

Key actions to 2030

Actions by all stakeholders are critical for realisation of the vision laid out in this roadmap for the cement industry. These are consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100 (2DS). Government and industry must take collaborative action to create a favourable investment framework for accelerating the sustainable transition of the cement industry globally, to achieve the levels of carbon emissions reductions envisioned. These actions include the following.

Creating an enabling level playing field

Governments should pursue efforts towards developing stable and effective international carbon pricing mechanisms complemented by interim financial stimulus packages that compensate asymmetric pricing pressures in different regional markets. While a considerable proportion of cement production is not exposed to cross-border competition, it is crucial that carbon pricing mechanisms are coupled with measures that ensure local lower-carbon cement production remains competitive against higher-carbon cement imports.

Putting technological change into action

All stakeholders should intensify collaborative action to increase implementation of state-of-the-art technologies and share best operating practices. Industry stakeholders should assess, at the cement plant level,[4] opportunities to use low-carbon technologies and should develop plant-level action plans to increase the speed and scale of deployment of such technologies.

Governments, in collaboration with industry, should develop legislation to support the use of fuels that are less carbon intensive in cement kilns. Cement manufacture provides an efficient use of waste for heating purposes and incorporates non-combustible components into a valuable product compared to landfilling. This is preferable to using landfill sites or other, less-efficient thermal treatment methods. Emissions monitoring must be regulated, and awareness-raising campaigns and industry training should be enhanced.

Governments and industry should ensure sustained funding and supportive risk-mitigating mechanisms to promote the development and demonstration of new technologies and processes that offer the potential for CO_2 emissions reduction. Immediate action is required to achieve the commercial-scale demonstration of oxy-fuel carbon capture technologies in cement production by 2030, as well as to gain experience of operating large-scale post-combustion technologies in cement plants. Public-private collaborative platforms can be supportive actors in such exercises.

Governments need to promote market mechanisms that value the provision of flexibility in the energy system to stimulate power generation from renewable sources of energy and power generation capacity additions based on excess heat recovery (EHR), in the cement industry.

Facilitating uptake of sustainable products

Governments need to ensure regulations and standards are in place to enable greater use of cementitious constituents to lower the clinker content of cement and to support wider penetration of blended cements while ensuring appropriate product performance. Awareness-raising campaigns, industry training and education can enhance acceptance by markets and also widespread dissemination.

Governments and industry should further collaborate to accelerate the development of standards and durability testing of alternative binding materials for cements, to facilitate market deployment. Joint efforts are also required to review and establish building regulations and specifications aimed at achieving carbon neutrality of the built environment over its entire life cycle, including during the use phase and at end of life.

4. For example, Cement Sustainability Initiative (CSI) member companies in India have assessed the potential for implementing carbon mitigation technologies in a sample of cement plants to gain site-level insights into the opportunities for wider deployment at the national level as Phase II of the *Technology Roadmap: Low-Carbon Technology for the Indian Cement Industry* (IEA and WBCSD, 2013).

Table 1: Key indicators for the global cement industry in the 2DS by 2030

	2DS low-variability case	
	2014	***2030***
Clinker to cement ratio	0.65	0.64
Thermal energy intensity of clinker (gigajoule per tonne of clinker [GJ/t clinker])	3.5	3.3
Electricity intensity of cement (kilowatt hour per tonne of cement [kWh/t cement])	91	87
Alternative fuel use (percentage of thermal energy)	5.6	17.5
CO_2 captured and stored (million tonne of carbon dioxide per year [MtCO_2/yr])	-	14
Direct CO_2 intensity of cement (tonne of carbon dioxide per tonne of cement [tCO_2/t cement])	0.54	0.52

Notes: Thermal energy intensity of clinker does not include any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g. carbon capture). Electricity intensity of cement production does not include reduction in purchased electricity demand from the use of EHR equipment or any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g. carbon capture). Alternative fuel use includes biomass, and biogenic and non-biogenic wastes. Direct CO_2 intensity refers to gross direct CO_2 emissions, after carbon capture.

1. Introduction

The concrete and cement societal needs nexus

Concrete is the most-used manufactured substance on the planet in terms of volume. For example, it is used to build homes, schools, hospitals, workplaces, roads, railways and ports, and to create infrastructure to provide clean water, sanitation and energy. These are important for quality of life and social and economic well-being.

Raw materials for concrete are abundant and available in most parts of the world. Concrete is affordable, strong, durable and resilient to fire, floods and pests. It has the flexibility to produce complex and massive structures. There is no other material currently available that is available in the quantities necessary to meet the demand for buildings and infrastructure.

Cement is used to manufacture concrete. It is described as the glue that binds the aggregates together. The demand for concrete, and therefore for cement, is expected to increase, by 12-23% by 2050 compared to 2014, as economies continue to grow, especially in Asia.[5]

Increasing global population, urbanisation patterns and infrastructure development will increase global cement production. However, the use of concrete and cement is expected to become more efficient, and losses at the application phase are expected to decrease. The cement sector faces the challenge of meeting an increasing demand for its product while cutting direct CO_2 emissions from its production.

5. See the Annex for regional definitions.

Roadmap objectives

This Technology Roadmap builds on the long-standing collaboration of the IEA with the CSI, a project of the WBCSD. It provides an update of the *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050* (IEA and WBCSD, 2009), and aims to capture the current situation of the global cement industry by analysing recent regional production volume and energy performance trends.

Implemented and announced carbon emissions mitigation strategies led by governments and industry are discussed, in the context of renewed international climate ambitions. Technology strategies, regulatory frameworks and investment needs to enable CO_2 emissions reductions in the cement industry consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100 (the 2DS) are analysed, within the framework of the modelling and analysis in the IEA *Energy Technology Perspectives* (ETP) project.

This roadmap sets a strategy for the cement sector to achieve the decoupling of expected cement production growth from related direct CO_2 emissions through the use of four levers: improving energy efficiency, switching to fuels that are less carbon intensive, reducing the clinker to cement ratio, and implementing emerging and innovative technologies such as carbon capture. The report therefore outlines a detailed action plan for specific stakeholders to 2050 as a reference and a source of inspiration for international and national policy makers to support evidence-based decisions and regulations.

Box 1: Scenarios used in this Technology Roadmap

The RTS serves as a baseline scenario for this roadmap. It considers energy consumption trends, as well as commitments by countries to limit carbon emissions and improve energy efficiency, including nationally determined contributions pledged under the Paris Agreement. The RTS represents a considerable shift from a "business as usual" approach with no meaningful climate policy response. Efforts made under the RTS would result in an average temperature increase of 2.7°C by 2100, at which point temperatures are unlikely to have stabilised and would continue to rise.

The 2DS sets out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100 (IPCC, 2014). Annual energy sector CO_2 emissions will be reduced by around 60% from current levels by 2050, with cumulative carbon emissions of around 1 170 $GtCO_2$ between 2015 and 2100 (including industrial process emissions). To stay within this range, CO_2 emissions from fuel combustion and industrial processes must continue their decline after 2050, and carbon neutrality in the energy

Box 1: Scenarios used in this Technology Roadmap (continued)

system must be reached by 2100. The 2DS represents an ambitious and challenging transformation of the global energy system that relies on a substantially strengthened response compared to current efforts.

The scenarios are based on technologies that are commercially available or at demonstration phase. Industrial technological shifts are a result of the minimisation of overall costs of production among available technologies as they reach successful commercialisation over time. The scenarios assume that non-technical barriers to the deployment of new technologies are overcome, including social acceptance, ineffective regulatory frameworks and information deficits. The analysis does not assess the likelihood that these assumptions will be fulfilled, but it highlights that ambitious CO_2 emissions reductions can only be realised with the collective contribution of all stakeholders: governments, industry and society.

These scenarios are not predictions. They are internally consistent analyses of cost-optimal pathways that may be available to meet energy policy objectives, given a certain set of techno-economic assumptions.

Roadmap approach

Partners and collaborators with specialised expertise from around the world have developed this roadmap. The IEA has overseen data analysis and modelling (see Annex below) to understand the impact of various strategies on energy efficiency improvements and CO_2 emissions reductions. The analysis benefits from best available information in terms of state-of-the-art cement manufacturing technologies and technical expertise from industry experts from the CSI companies and beyond, as well as cement technology researchers from the European Cement Research Academy.

The vision outlined in this roadmap is based on the 2DS, which is comparatively discussed with a context of continued trends, and the consideration of implemented and announced energy-related and climate policies and pledges by countries (the RTS) (Box 1).

Projecting cement demand: Sensitivity analysis

The future demand for cement is estimated from data on gross domestic product (GDP) growth, per capita income, current cement consumption levels, regional cement demand saturation levels derived from historical regional cement demand intensity curves and resource endowments. Regional GDP and population projections are based on data from various sources (IEA, 2016b; IMF, 2016; UN DESA, 2015).

Two cement demand variants have been developed to cope with the inherent uncertainty of projecting future material demand levels: a low-variability case and a high-variability case. The low-variability case is considered the future evolution of cement production that is most likely, and thus is considered as the reference case for the analysis. The high-variability case has been developed by scaling up the relative variation of cement demand over time in different regions (either relative increase or decrease), to provide a sensitivity analysis on the cement production levels.

The global analytical results discussed in this Technology Roadmap arise from the aggregation of analysing the net impact of the cost-optimal combination of the above-mentioned carbon mitigation levers within 39 specific regional contexts. Quantitative insights on this roadmap are discussed, focusing on the following aggregated regions: Africa, America, China, Eurasia, Europe, India, Middle East and Other Asia Pacific.[6] The analysis is designed as an exercise that benefits from country/regional specific projects that gather detailed data (Box 2) and information on specific regional contexts. These will enrich the analytical results as well as the evolution of the demonstration and learning experiences from implementing emerging and innovative technologies.

6. See the Annex for regional definitions.

Box 2: Data sources and the importance of getting the numbers right

Monitoring energy performance and CO_2-related indicators of cement production is the first step in understanding the potential for improvement. It is critical for tracking progress and prioritising actions towards future targets. Data collection and reporting systems that set a homogeneous boundary and rely on transparent monitoring and verification procedures facilitate the comparison of performance data across the cement industry and provide accurate information to industry stakeholders, policy makers and analysts.

Getting the Numbers Right (GNR) is a voluntary and independently managed database of CO_2 and energy performance information of the cement industry managed by the CSI. It compiles uniform and accurate data from 934 individual facilities that produce 889 million tonnes per year (Mt/yr) of cement or 21% of the global cement production. The developed protocol ensures consistency across the reported data. The data in the GNR database is externally verified (CSI, 2017).

The analysis for this roadmap is based on a compilation of performance data and information related to cement production from the best available data sources worldwide. These comprise the GNR database (independently verified), the China Cement Association, the Confederation of Indian Industries and the Brazilian Sindicato Nacional da Indústria do Cimento, as well as consultations with local cement experts. Expanding the regional coverage of uniform and verified energy performance data collection would improve the quantitative analysis of the progress of carbon mitigation strategies in cement production. This could circumvent potential methodological inconsistencies across different regional reporting structures.

Some differences in reporting may be related to inconsistent boundaries when accounting for energy consumption (e.g. inclusion of the electricity consumed that is generated from EHR systems at the cement site, or the reporting of energy use from alternative fuels) or defining the clinker to cement ratio. Regional differences related to local aspects, such as the characteristics of raw materials and the specific product quality requirements, influence directly the energy performance of local cement production, thus making comparisons across different regions difficult.

Roadmap scope

Although this Technology Roadmap focuses on energy savings and carbon mitigation strategies within the cement manufacturing process, the authors recognise the need to consider CO_2 emissions reduction in the broader context of the whole life cycle of cement, concrete and the built environment.

The roadmap therefore also discusses synergies of the cement industry with the wider energy system and potential constraints in the upstream sourcing of raw materials and cement constituents for blended cements and cements based on alternative binding materials. It discusses process requirements for the curing of specific alternative binding materials due to the synergies in reducing the overall net carbon footprint for this type of cement.

The cement sector is extending its support of emissions reduction opportunities that can be achieved beyond the manufacturing stage. Adopting a life-cycle approach and working collaboratively along the whole construction value chain provides the potential for additional opportunities for emissions reductions. Such areas offer opportunities for sustainable collaborative stakeholder action by:

- **Optimising the use of concrete in construction.** The efficient specification and use of concrete with a lean design can help to cut wastage by aligning the lowest carbon option with the optimal technical performance required for the specific application.
- **Maximising design life of buildings and infrastructure.** The durability of concrete provides opportunities for a long design life

and minimum maintenance, while a purposeful design can ensure the built application is future proof and remains relevant.

- **Reducing operational energy.** Optimal use of the inherent thermal mass properties of concrete can reduce the operational carbon emissions of a building over its lifetime.
- **Contributing to the albedo effect.** For example, the light colour and reflective properties of concrete surfaces can result in lower air temperatures in cities and can reduce the need for lighting in tunnels.
- **Encouraging reuse and recycling.** Reducing the impact of new builds by reusing concrete buildings and infrastructure components and recycling concrete can reduce the demand for primary concrete, thus avoiding the carbon emissions associated with production.
- **Optimising recarbonation**. Cement based products absorb and chemically fix CO_2 over their life. Recarbonation is a slow process that can be enhanced, especially at end of life by increasing the exposed surface area with the ambient.

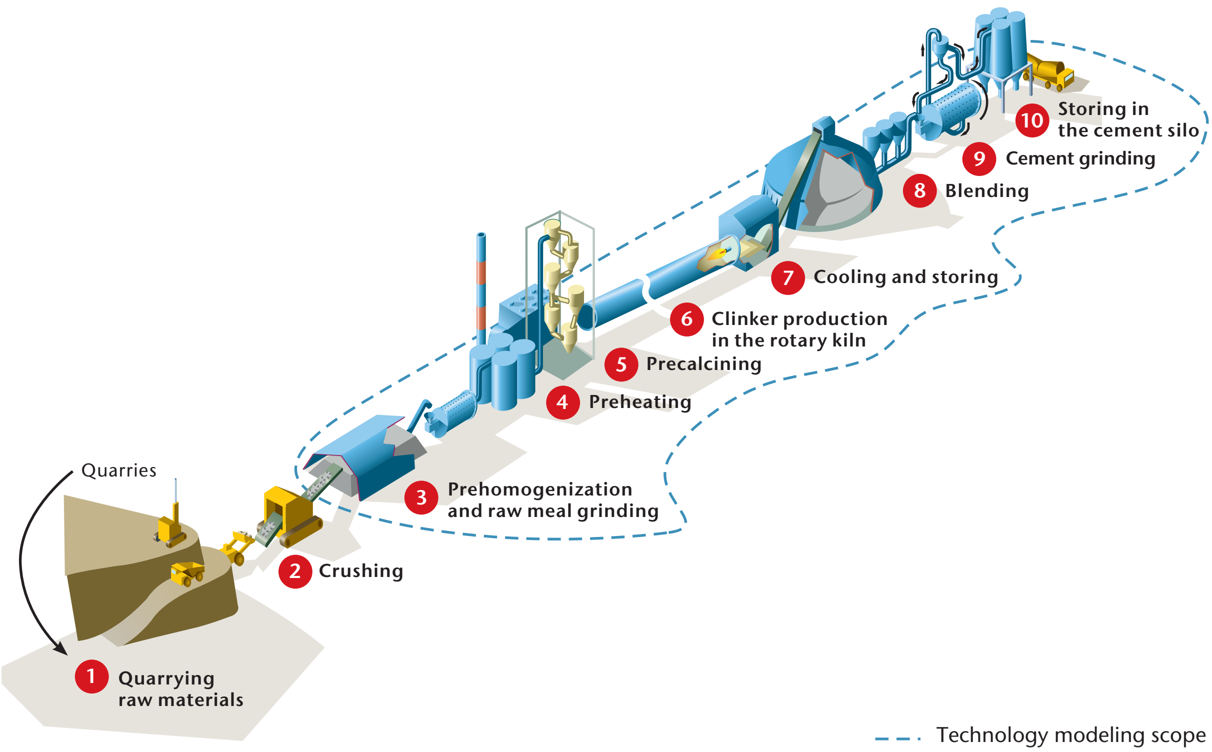
2. Overview of cement manufacturing

Cement manufacture is a three-stage process: raw materials preparation, clinker production and clinker grinding with other components to produce cement (Figure 1). Different raw materials are mixed and milled into a homogeneous powder, from which clinker is produced in high-temperature kilns where direct emissions of CO_2 occur. Typically, 30-40% of direct CO_2 emissions comes from the combustion of fuels; the remaining 60-70% comes from the chemical reactions involved in converting limestone to calcium oxide, a precursor to the formation of calcium silicates, which gives cement its strength. Clinker is then interground with gypsum to produce cement. Other components, including fly ash, ground granulated blast furnace slag (GGBFS) and fine limestone, can be interground or blended, depending on the required technical properties of the finished cement. Cement can be produced at the kiln site, or at separate grinding or blending plants. Blended cements or "combinations" can also be produced at the concrete plant.

There are two basic types of clinker production – "wet" or "dry" – depending on the moisture content of raw materials, and there are also different kiln designs. The wet process consumes more energy than the dry process, as the moisture needs to evaporate.

The cement making process is complex – it requires control of the chemical formulation and involves multiple steps that require specialised equipment.

Figure 1: Cement manufacturing



Note: A dry-process kiln is shown with a precalciner and multistage cyclone preheater, which is considered state-of-the-art technology. The modelling results used for the analysis in this roadmap include steps 3-10 of the above figure.

Source: IEA and WBCSD (2009), *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050*, www.iea.org/publications/freepublications/publication/Cement.pdf.

KEY MESSAGE: Cement manufacturing involves multiple steps.

1. Quarrying raw materials

Naturally occurring calcareous deposits, such as limestone, marl or chalk, provide calcium carbonate, which is a key ingredient for cement. They are extracted by heavy duty machines from quarries, which are often located close to the cement plant. Small amounts of other materials, such as iron ore, bauxite, shale, clay or sand, may also be excavated from deposits to provide the extra iron oxide, alumina and silica needed in the chemical composition of the raw mix to meet the process and product performance requirements.

2. Crushing

The quarried materials are crushed, typically to less than 10 centimetres in size, and are transported to the cement plant.

3. Preparing raw meal

Raw materials are mixed to achieve the required chemical composition in a process called "prehomogenisation". The crushed material is then milled to produce a fine powder called "raw meal". The chemistry of the raw materials and raw meal is monitored and controlled, to ensure consistent and high quality of cement.

4. Preheating and co-processing

A preheater is a series of vertical cyclones through which the raw meal is passed. During this process, the raw meal comes into contact with swirling hot kiln exhaust gases moving in the opposite direction. Thermal energy is recovered from the hot flue gases in these cyclones, and the raw meal is preheated before it enters the kiln. The chemical reactions therefore occur quickly and efficiently. Depending on the raw material moisture content, a kiln may have up to six stages of cyclones with increasing heat recovery at each stage. The raw meal temperature is raised to over 900°C.

Cement production can co-process wastes and by-products generated from other industries and municipalities, as materials for the raw mix or as fuels for pyro-processing. Wastes and by-products vary widely in nature and moisture composition. They may need sorting, shredding and drying before feeding into the cement kiln.

5. Precalcining

Calcination is the decomposition of limestone into lime. It takes place in a "precalciner" in most processes. This is a combustion chamber at the bottom of the preheater above the kiln, and is partly in the kiln. Here, the chemical decomposition of limestone into lime and CO_2 typically emits 60-70% of the total CO_2 emissions. Fuel combustion generates the rest of the carbon emissions. Approximately 65% of all fuel is burnt in this step of the process, in plants with precalciner technology.

6. Producing clinker in the rotary kiln

The precalcined meal then enters the kiln. Fuel is fired directly into the kiln to reach temperatures of up to 1 450°C. As the kiln rotates (about three to five times per minute), the material slides and falls through progressively hotter zones towards the flame. The intense heat causes chemical and physical reactions that partially melt the meal into clinker. The reactions in the kiln include completion of the calcination of limestone that has not taken place in the precalciner and emission of CO_2 from other CO_2 combined minerals. The CO_2 released from the raw materials during production is referred to as "process CO_2 emissions".

7. Cooling and storing

Hot clinker from the kiln is cooled from over 1 000°C to 100°C rapidly on a grate cooler, which blows incoming combustion air onto the clinker. The air blowers use electricity and heated blown air circulation to improve thermal efficiency. A typical cement plant will have clinker storage between clinker production and the cement grinding process. Clinker may be loaded onto transportation, and can then be traded or further processed into cement.

8. Blending

Clinker is mixed with other mineral components to make cement. All cement types contain around 4-5% gypsum to control the setting time of the cement. Slag, fly ash, limestone or other materials can be interground or blended to replace part of the clinker. This produces blended cement.[7]

9. Grinding

The cooled clinker and gypsum mixture is ground into a grey powder, known as Portland cement (PC), or ground with other mineral components to make blended cement. Ball mills have traditionally been used for grinding, although roller presses and vertical mills are often used in modern plants due to their greater energy efficiency.

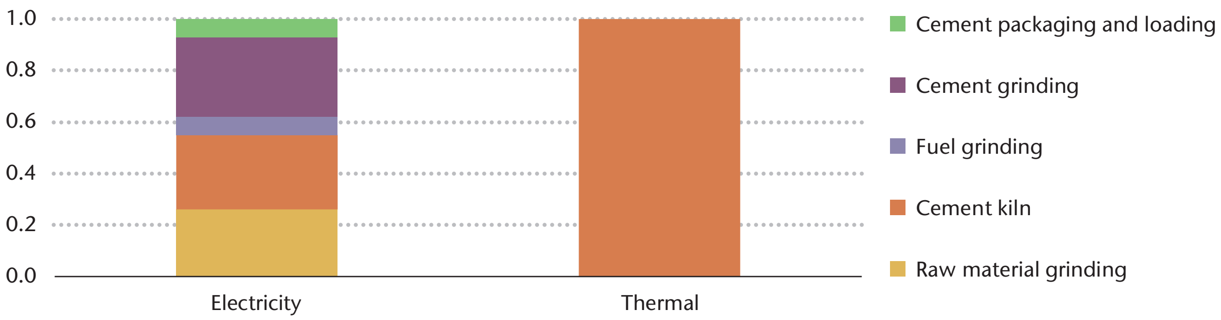
7. The described process steps reflect the cement production process that is most commonly adopted. The order of blending and grinding process steps could be reversed.

10. Storing in silos for loading and packaging

The final product is homogenised and stored in cement silos for dispatch later. Cement is packed in bags or loaded in bulk for transportation to customers.

Every stage of the cement manufacturing process requires energy. Electricity is used to run grinding and loading equipment, and fuels are used to provide the thermal energy needed in the kiln and precalciner for the chemical reactions required to produce clinker (Figure 2). Thus, the clinker production step generates direct CO_2 emissions due to fuel combustion and the carbon released from raw materials.

Figure 2: Energy demand distribution by process step



Sources: Madlool et al. (2011), *A Critical Review on Energy Use and Savings in the Cement Industries*; ECRA and CSI (2017), *Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead,* www.wbcsdcement.org/technology.

KEY MESSAGE: Electricity is used throughout the cement manufacturing process, whereas the cement kiln is the thermal energy-intensive process step.

Efforts made towards achieving low-carbon cement production

The cement sector has progressed in energy efficiency and carbon emissions reductions since the IEA and WBCSD published the *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050* (IEA and WBCSD, 2009). All regions have contributed by improving the energy and carbon emissions performance indicators of their cement industries.

Local factors, such as the average capacity of cement plants, the moisture content and burnability of raw materials, the availability and nature of alternative fuels and the cement standards, influence the energy demand and CO_2 footprint of cement production. Thus, regional progress should be assessed on a case-by-case basis within the same local context considerations.

The regulatory framework on climate and energy issues has also evolved. The United Nations 2030 Agenda for Sustainable Development, adopted by world leaders in September 2015, comprises 17 Sustainable Development Goals, which will guide policy and funding for the next 15 years. Goal 13 calls for urgent action to combat climate change and its impact (UN, 2015). Parties at the 21st session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) negotiated the Paris Agreement in December 2015. This agreement attempts to limit the rise in global temperatures this century to less than 2°C above preindustrial levels.

Governments are increasingly taking action to mitigate carbon emissions and build climate resilience. For instance, in China (the largest cement producer in the world, with almost 60% of global cement production), Provincial Emission Trading Schemes have been in operation since 2013, and the use of a nationwide scheme is being studied. The Chinese government has also established requirements for new dry-process modern kilns to install power generation systems based on EHR (11th and 12th Five-Year Development Planning of Cement Industry). Measures facilitating interconnection to the electricity grid (Energy Conservation Law of the People's Republic of China) have sustained this rapid deployment in China (IIP and IFC, 2014). Additionally, as part of the excess capacity mitigation strategy, the Chinese government has set an ambitious target to reduce the thermal energy intensity of clinker production to 3.07 GJ/t clinker on average by 2020, as part of the 13th Five-Year Plan (2016-20). This represents a 1%[8] annual reduction in the specific thermal energy demand of clinker from 2014.

India is in the process of implementing policies:

- new solid waste management rules, released in 2016.
- new composite cement standards, issued by the government of India.
- nationally appropriate mitigation actions focusing on co-processing of refuse-derived fuel from municipal solid waste in cement kilns, proposed by the Ministry of Environment, Forest and Climate Change of India.

The Performance Achieve Trade (PAT) system is a market-based mechanism implemented by the government of India in 2008, aimed at improving energy efficiency in industries by trading energy efficiency certificates in energy-intensive sectors, including cement. Designated consumers are assigned targets under this system for reducing their specific energy consumption based on their current levels of energy efficiency. The first PAT system cycle ran from 2011/12 to 2014/15. This included 85 cement plants, with an overall energy demand reduction equivalent to 0.062 EJ in that period, or 9% of the energy consumption in the Indian cement manufacturing in 2014 (surpassing by around 80% the original reduction targets).

In the European Union, the Emissions Trading System started in 2005 and is now well established as a route to ensure specific CO_2 targets are achieved. It is currently being revised and will include an Innovation Fund. This fund is worth billions of euros for the period 2021-30, and is to support the demonstration of carbon emissions reductions technologies in several areas including energy-intensive industries. A minimum of 400 million allowances would be reserved from 2021 onwards. The consultation process with experts from energy-intensive industries organised by the European Commission identified 40 cement-related technologies that could benefit from the Innovation Fund (Climate & Strategy Partners, 2017).

In Europe, the Mandate to the Technical Committee 51, in charge of developing standards covering terminology, specification and test methods for cement and limes within the European Committee for Standardisation, was recently reviewed and opened to possible alternative low-carbon cements that rely on different raw material mixes or different raw materials compared to PC.

Private-led initiatives have also recently gained momentum in the cement sector. In 2015, 18 cement companies – all members of the CSI – established a shared statement of ambition, by which their CO_2 emissions should be reduced in the range 20-25% by 2030 compared to "business as usual". This is equivalent to nearly 1 $GtCO_2$ of savings. To move towards this aspirational goal, seven levers of action have been identified (LCTPi, 2015).

There has also been some progress made since 2009 from a technology demonstration perspective. For example, a pilot plant capturing 1 tonne of carbon dioxide (tCO_2) per hour in Dania, Denmark, tested the use of oxy-fuel in a kiln precalciner. The results led to a costs and feasibility study of retrofitting this technology to an existing commercial-scale facility in Le Havre, France (IEAGHG TCP, 2014). Between 2013 and 2016, a cement plant in Brevik, Norway, undertook successful trials of CO_2 capture based on chemical absorption with a mobile capture unit (Bjerge and Brevik, 2014). Also, a plant started operation in Texas to chemically capture and transform 75 thousand tonnes of carbon dioxide per year ($ktCO_2$/yr) from a cement plant into sodium bicarbonate, bleach and hydrochloric acid that can be sold (Perilli, 2015). The government of Australia has put in place a world-leading framework for the licensing, management and reporting of carbon capture and storage (CCS) projects, including sophisticated mechanisms for handling long-term liabilities and environmental damage from failed projects.

8. Calculated as compound annual growth rate (CAGR).

Box 3: Regional collaborative efforts arising from the IEA and WBCSD *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050*

Since the publication of the *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050* (IEA and WBCSD, 2009), the CSI and the IEA have continued to work with global private and public stakeholders to adapt the findings to specific national and regional contexts, to scale up the impact in the cement sector globally.

India (6% of global cement production in 2014). The IEA and WBCSD-CSI engaged with Indian partners such as the Confederation of Indian Industry and the National Council of Cement and Building Materials, and obtained financial support from the International Finance Corporation to develop the *Technology Roadmap: Low-Carbon Technology for the Indian Cement Industry* (IEA and WBCSD, 2013). The 2013 roadmap outlined four key levers and policy and financial support necessary to reduce CO_2 emissions within the Indian cement manufacturing process in line with the 2DS. To facilitate implementation of this roadmap, various plants conducted feasibility studies to gain site-level insights of the opportunities for deployment at the national level. This assessment led to the identification of over 300 projects suitable for energy savings, with a total carbon emissions reduction potential of 508 762 tonnes of carbon dioxide per year (tCO_2/yr). Nearly 30% of this potential was already achieved by early 2017. Members of CSI India have been able to save USD 8.5 million in energy costs through projects identified in these studies. The programme has incentivised carbon mitigation actions outside India, with the last beneficiary of the programme being located in Nepal. CSI India is collaborating with the IEA to develop a first-of-a-kind exercise to track the progress of the Indian cement industry upon completion of the five years since the publication of the 2013 roadmap (CII, WBCSD and IEA, forthcoming). This exercise will help in reorienting action plans in terms of technical, financial and policy actions needed to achieve further milestones towards low-carbon growth of the Indian cement industry.

Brazil (2% of global cement production in 2014). The CSI and IEA are partnering with local private stakeholders (Sindicato Nacional da Indústria do Cimento and Associação Brasileira de Cimento Portland) to develop a low-carbon technology roadmap specific to the Brazilian cement industry. This will outline technology strategies and supportive regulatory frameworks needs to enable CO_2 emissions reductions in the Brazilian cement industry consistent with at least a 50% chance of limiting the average global temperature increase to 2°C.

Latin America (4% of global cement production in 2014). The Federación Interamericana del Cemento is engaging with the WBCSD-CSI and the IEA to develop a set of tools to support cement industries in Latin America. This will identify energy savings and CO_2 mitigation potentials, as well as supportive regulatory mechanisms, based on the areas for action identified by the *Cement Technology Roadmap 2009* and encompassing technology papers. This project aims to contribute to addressing the regional needs for adaptation to the effects of climate change.

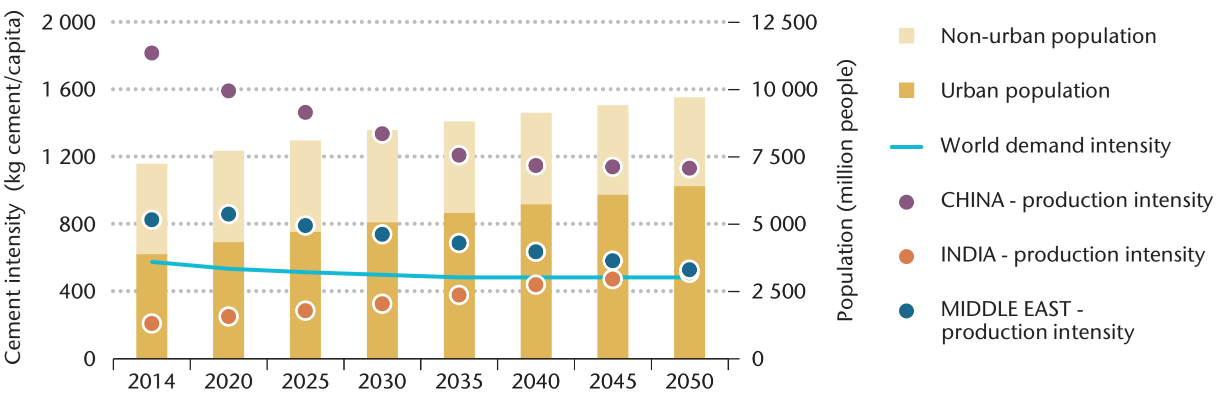
3. The vision

Rising population, urbanisation patterns and infrastructure development needs are expected to increase global cement production, which is set to grow by 12-23% above the 2014 level by 2050. The total population is expected to grow by 34% by 2050 compared to 2014. This increase will be fuelled by increasing urban population, which will reach 6.5 billion people in 2050 or about two-thirds of the global population (UN DESA, 2015).

Cement production intensity levels vary widely across different regions. Some, such as China[9] and the Middle East, have excess cement production capacity with cement production intensities well above global levels (1 818 kilogrammes (kg) of cement produced per capita in China and 827 kg of cement produced per capita in the Middle East in 2014 compared to 575 kg of cement produced per capita globally). Other countries, such as India, are set to increase their domestic cement production to fulfil their infrastructure development needs, aligning with global levels by 2050. The aggregated global average of cement demand per capita is expected to level out at around 485 kg cement per capita over the same period (Figure 3).

9. Chinese domestic production peaked in 2014, according to estimated cement production in 2016.

Figure 3: Global cement demand intensity and population, and cement production intensity for selected regions



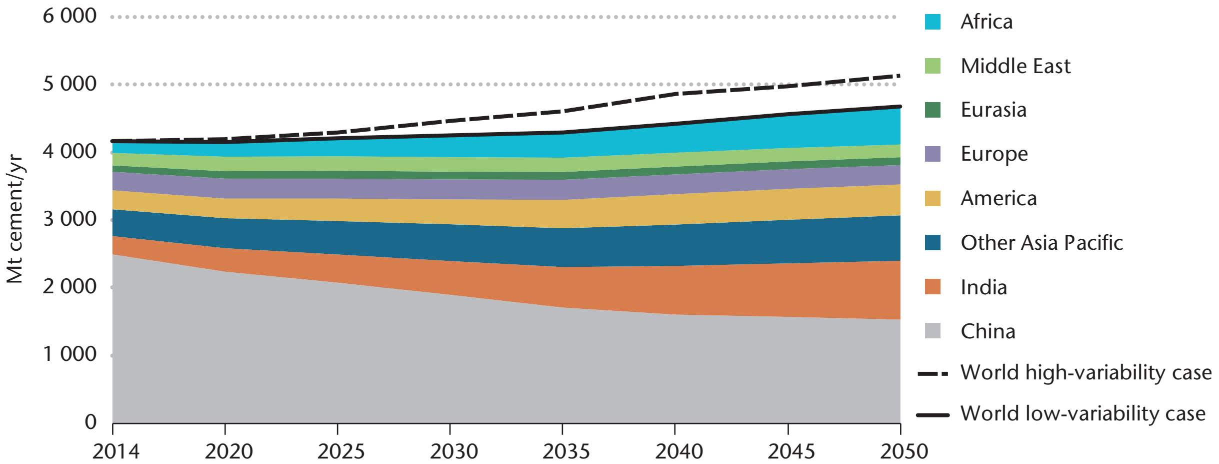
Note: Cement demand and production intensities displayed refer to the low-variability case.

Sources: Population data from UN DESA (2015), *World Population Prospects: The 2015 Revision*, https://esa.un.org/unpd/wpp/. Base year cement production data from van Oss, H. G. (2016), *2014 Minerals Yearbook: Cement*, United States Geological Survey data release, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2014-cemen.pdf

KEY MESSAGE: Global aggregated cement demand per capita is expected to remain stable towards 2050, while population is set to increase by about one-third over the same period.

Overall cement production in Asia Pacific remains stable over the analysed horizon. Expected cement production growth in India (triple its current production level by 2050) and Other Asia Pacific countries (double current production levels by 2050) represents more than 90% of the envisioned decrease in cement production in China over the same period. Chinese cement production is set to lose 27% of the global cement production share in the process of adjusting national production capacity to domestic cement needs by 2050. The rest of the additional foreseen global cement production increase is in Africa (more than triple its current cement production level by 2050) and America (almost double its current cement production level by 2050), to support domestic growing demand (Figure 4).

Figure 4: Cement production by region



Note: See Annex for regional definitions.

Sources: Base year cement production data from van Oss, H. G. (2016), *2014 Minerals Yearbook: Cement*, United States Geological Survey data release, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2014-cemen.pdf.

KEY MESSAGE: Strong growth in cement production growth in Asian countries compensates for the decline in Chinese cement sector activity, but the region still loses 10% of its global production share by 2050.

The vision laid out in this Technology Roadmap for the global cement industry is consistent with the carbon emissions trajectory of the 2DS (Box 1). This vision sets a cost-effective technology pathway for the cement industry to decrease its global direct CO_2 emissions by 24% from current levels (2.2 $GtCO_2$/yr) by 2050, or a reduction of 32% of the global direct CO_2 intensity of cement.[10] This effort is realised while meeting increasing cement demand to support the development and transition of society to a 2DS world. The roadmap vision requires 7.7 $GtCO_2$ cumulative direct carbon emissions savings compared to the RTS by 2050 from cement making. This is a decrease equivalent to almost 90% of current total industrial direct CO_2 emissions globally. This would be implemented through improving energy efficiency, switching to fuels that are less carbon intensive (alternative fuels), reducing clinker content in cement and implementing innovative technologies such as carbon capture.

10. Direct CO_2 intensity refers to gross direct CO_2 emissions, after carbon capture.

Table 2: Key indicators for the global cement industry in the RTS and the roadmap vision (2DS)

		RTS Low-variability case			Roadmap vision (2DS) Low-variability case		
	2014	2030	2040	2050	2030	2040	2050
Cement production (Mt/yr)	4 171	4 250	4 429	4 682	4 250	4 429	4 682
Clinker to cement ratio	0.65	0.66	0.67	0.66	0.64	0.63	0.60
Thermal energy intensity of clinker (GJ/t clinker)	3.5	3.4	3.3	3.2	3.3	3.2	3.1
Electricity intensity of cement (kWh/t cement)	91	89	86	82	87	83	79

Table 2: Key indicators for the global cement industry in the RTS and the roadmap vision (2DS) (continued)

		RTS Low-variability case			Roadmap vision (2DS) Low-variability case		
	2014	2030	2040	2050	2030	2040	2050
Alternative fuel use (percentage of thermal energy consumption)	5.6	10.9	14.4	17.5	17.5	25.1	30.0
CO_2 captured and stored ($MtCO_2$/yr)	-	7	65	83	14	173	552
Direct process CO_2 intensity of cement (tCO_2/t cement)	0.34	0.34	0.34	0.33	0.33	0.30	0.24
Direct energy-related CO_2 intensity of cement (tCO_2/t cement)	0.20	0.19	0.18	0.17	0.19	0.16	0.13

Notes: Thermal energy intensity of clinker does not include any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g. carbon capture). Electricity intensity of cement production does not include reduction in purchased electricity demand from the use of waste heat recovery equipment or any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g. carbon capture). Alternative fuel use includes biomass, and biogenic and non-biogenic waste. Direct CO_2 intensity refers to net CO_2 emissions, after carbon capture.

Box 4: Exploring scenarios that are more ambitious: Beyond 2DS

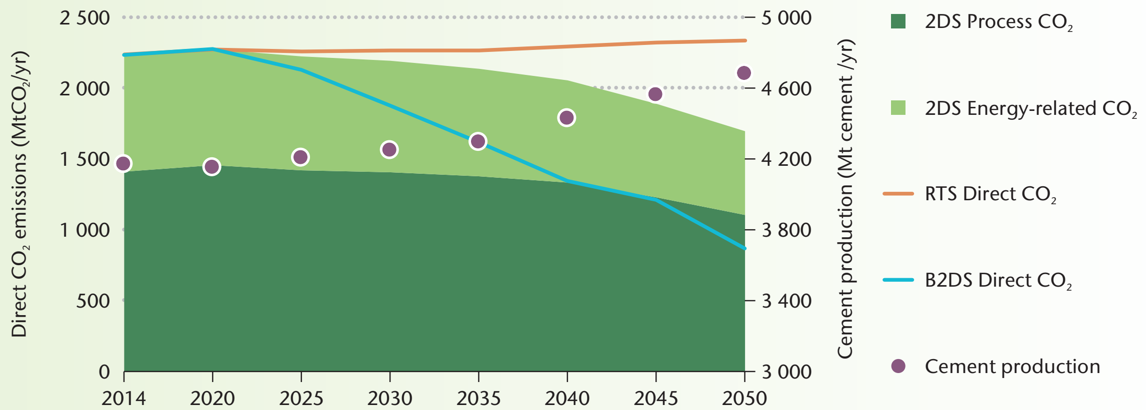
Climate ambition was heightened at the 21st session of the COP (UNFCCC) by aiming for a global temperature rise "well below 2°C" and pursuing efforts towards a 1.5°C increase. The scale of the challenge is highlighted by the considerable gap between a 2°C target and the trajectory resulting from current trends, announced policies and the non-conditional commitments contained in nationally determined contributions. In response to the conclusions from the 21st session of the COP, the IEA explored the impact of moving beyond 2°C by analysing cost-effective pathways of meeting a 1.75°C trajectory in the Beyond 2°C Scenario (B2DS) with technologies that are commercially available or at demonstration stage. The B2DS provides an illustration of this challenge, although it is not definitive of a "well below 2°C" pathway.

If climate goals even more ambitious than those in the 2DS were pursued, the policy and technology challenges of bridging the gap with the decarbonisation pathway of choice would be amplified. Emissions reductions greater than those in the 2DS will be challenging to achieve. The cement sector would need to further reduce emissions by 3.2 $GtCO_2$ cumulatively by 2050 compared to the 2DS, which is about a 45% increase in the cumulatively carbon emissions reduction effort to get to the 2DS from the RTS (Figure 5).

This enormous transformation would require exploiting the full carbon mitigation potential of strategies implemented in the 2DS within the constraints set by the sustainable availability of resources (e.g. biomass), while expanding the deployment of technologies such as carbon capture. Captured CO_2 emissions from cement manufacturing that are permanently stored as a share of total direct generated CO_2 emissions in the sector more than double (from 25% to 63%) in the B2DS compared to the 2DS by 2050.

Box 4: Exploring scenarios that are more ambitious: Beyond 2DS (continued)

Figure 5: Global direct CO_2 emissions in cement production by scenario



KEY MESSAGE: The B2DS would require the cement industry to increase by about 45% the cumulative carbon emissions reductions effort compared to the 2DS, which is the reference carbon emissions reduction scenario for this roadmap's vision.

The thermal energy intensity of clinker is reduced by 10% by 2050 in the roadmap vision, reaching a global average of 3.1 GJ/t clinker.[11] This is close to the reported best available technology performance levels (2.9-3.0 GJ/t clinker for dry-process kilns with a precalciner and a six-stage cyclone preheater) (ECRA and CSI, 2017; IEA, 2007).

The specific electricity consumption per tonne of cement[12] is reduced by 14% globally by implementing efficient grinding and milling technologies for raw materials, fuel preparation and cement finishing.

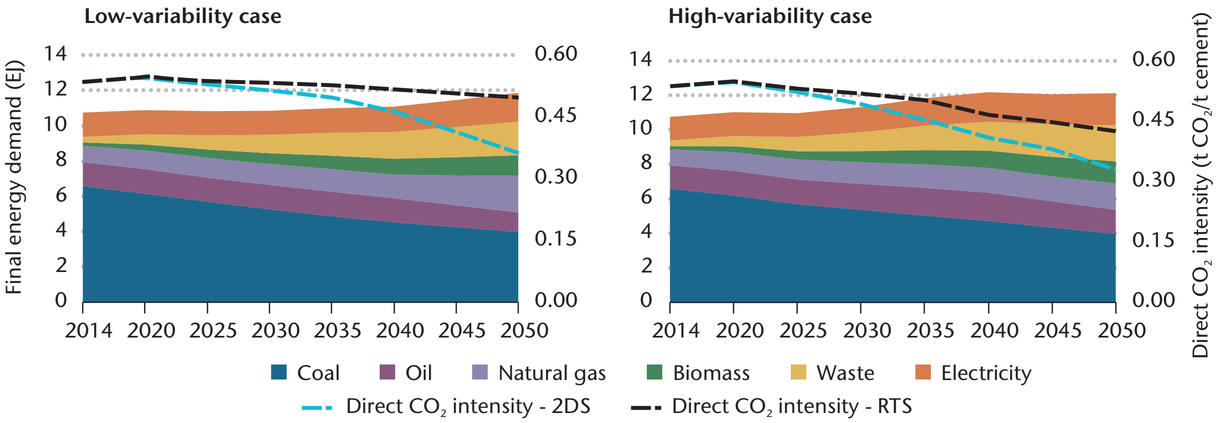
11. The thermal intensity of clinker does not include increases related to carbon mitigation levers beyond improving energy efficiency.

12. The electricity intensity of cement does not include increases related to carbon mitigation levers beyond improving energy efficiency.

The shift towards alternative fuels that are less carbon intensive, with biomass and waste[13] increasing to 30% globally as a share of thermal energy by 2050 and displacing mainly coal and petroleum coke, contributes to the reduction of global direct energy-related CO_2 emissions of cement by 36% in the same period. Biomass and waste use in cement kilns increases sixfold by 2050 in the roadmap vision, reaching about 3.1 EJ or almost half of current global coal use in the cement sector (Figure 6).

13. Waste includes biogenic and non-biogenic waste materials.

Figure 6: Global final energy demand and direct CO_2 intensity of cement production in the roadmap vision (2DS)



Notes: Waste includes biogenic and non-biogenic waste sources. Petroleum coke is reported within oil.

KEY MESSAGE: A reduction in the direct CO_2 intensity of cement of 32-38% is supported by a global reduction of the share of fossil fuels in cement kilns of 24-27% by 2050 in the roadmap vision.

Total CO_2 emissions from cement making can be decreased by reducing the clinker to cement ratio.[14] Process CO_2 emissions released from raw materials during the production of clinker can therefore be decreased by integrating alternative cement constituents that reduce the clinker to cement ratio, which drops by 5% globally by 2050 in the roadmap vision. This enables a reduction of the process CO_2 intensity of cement of 30% by 2050 from current levels, with 364 million tonnes of carbon dioxide ($MtCO_2$) of carbon emissions savings. This is equivalent to 16% of current global direct CO_2 emissions from cement making.

The reduction of the clinker to cement ratio also enables CO_2 emissions savings related to the avoided thermal energy consumption that results from a lower clinker demand for the same amount of cement produced. Cement constituents that can be used instead of clinker include gypsum, natural volcanic materials, limestone and industrial by-products such as GGBFS (generated in the iron and steel industry) and fly ash (produced in coal-fired thermal plants), as well as others derived from widely available resources such as calcined clay.

14. Clinker is the main constituent of most types of cement. The share of clinker in cement on a mass basis is defined as the clinker to cement ratio.

The calcination process of raw clay would incur additional thermal energy needs. These are estimated to increase the thermal energy intensity of clinker by 11% globally in the roadmap vision by 2050 compared to the average thermal energy intensity of clinker in that same year. The reduction of the clinker content in cement is highly dependent on the local availability of cement constituents instead of clinker, as well as on the required properties for the final cement product, which are dictated by local standards and technical requirements of the end-use applications.

The roadmap vision assumes that the integration of carbon capture technologies in cement production reaches commercial scale by 2030. Captured CO_2 emissions represent 25% of the total emitted CO_2 in the sector globally in 2050, or 552 $MtCO_2$/yr as part of the carbon emissions reductions strategies that enable the roadmap vision. The use of carbon capture has a penalty on energy consumption, which increases the cement electricity intensity by 19% by 2050 globally compared to the electricity intensity achieved without considering carbon capture and other carbon mitigation levers.

The roadmap vision realises 7.7 $GtCO_2$ cumulative carbon emissions reductions by 2050 compared to the RTS by combining energy efficiency, switching to alternative fuels, reducing the clinker to cement ratio and integrating innovative technologies including carbon capture. Current trends and announced commitments integrated in the RTS have already put the thermal energy intensity of clinker at a 0.2%[15] annual reduction trend, leading to a global average of 3.16 GJ/t clinker[16] by 2050. This is just 2% above the level achieved in the roadmap vision in the same year.

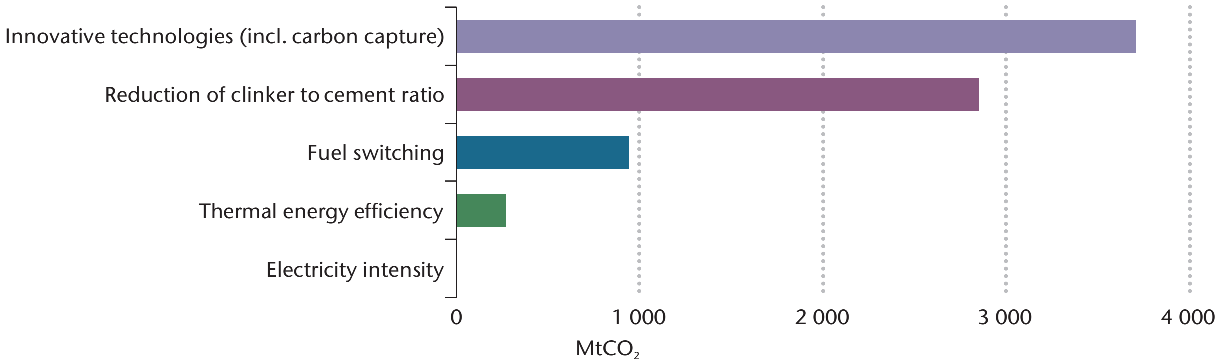
The impact of improving the electrical energy efficiency of cement production is offset by the increased electricity demand arising from the use of carbon capture and other carbon emissions mitigation levers. However, as the vision of this roadmap sees global electricity CO_2 intensity dropping 93% by 2050 (reaching 41 grammes of CO_2 per kilowatt hour (kWh) final electricity), these two counter-effects lead to negligible cumulative CO_2 savings in the sector.

The integration of carbon capture in cement production (CO_2 emissions reduction of 48%) and the reduction of the clinker to cement ratio in cement (CO_2 emissions reduction 37%) lead the way in cumulative CO_2 emissions reductions in the roadmap vision compared to the RTS by 2050. Their contributions are jointly equivalent to almost 80% of current global direct CO_2 emissions from the total industrial sector (Figure 7).

15. Reduction rate reported as CAGR.

16. The thermal intensity of clinker does not include increases related to carbon mitigation levers beyond improving energy efficiency.

Figure 7: Global cumulative CO_2 emissions reductions by applying the roadmap vision (2DS) compared to the RTS



Note: Cumulative CO_2 emissions reductions refer to the period from 2020 to 2050 and are based on the low-variability case of the scenarios.

KEY MESSAGE: Innovative technologies including carbon capture (CO_2 emissions reduction of 48%) and reduction of the clinker to cement ratio (CO_2 emissions reduction of 37%) lead the way in cumulative CO_2 emissions reductions in cement making in the roadmap vision compared to the RTS by 2050.

4. Carbon emissions reduction levers

This chapter analyses strategies or levers for reducing the CO_2 emissions footprint of cement production and for supporting the global cement industry in achieving the roadmap vision pathway by:

- **Improving energy efficiency:** deploying existing state-of-the-art technologies in new cement plants and retrofitting existing facilities to improve energy performance levels when economically viable.
- **Switching to alternative fuels (fuels that are less carbon intensive than conventional fuels):** promoting the use of biomass and waste materials as fuels in cement kilns to offset the consumption of carbon-intensive fossil fuels. Wastes include biogenic and non-biogenic waste sources, which would otherwise be sent to a landfill site, burnt in incinerators or improperly destroyed.
- **Reducing the clinker to cement ratio:** increasing the use of blended materials and the market deployment of blended cements, to decrease the amount of clinker required per tonne of cement or per cubic metre of concrete produced.
- **Using emerging and innovative technologies that:**
    - contribute to the decarbonisation of electricity generation by adopting EHR technologies to generate electricity from recovered thermal energy, which would otherwise be wasted, and support the adoption of renewable-based power generation technologies, such as solar thermal power.
    - integrate carbon capture into the cement manufacturing process for long-lasting storage or sequestration.

Alternative binding materials offer potential opportunities for process CO_2 emissions reductions by using different mixes of raw materials or alternatives compared to PC, although their commercial availability and applicability differ widely. However, there is currently no independent, publicly available and robust life-cycle assessment for alternative binders or a comparative quantification of production costs. This makes it premature to include them in a techno-economic-based evaluation of least-cost technology pathways for cement production.

The CO_2 emissions reduction impact of these levers is not always additive since they can individually affect the potential for emissions reductions of other options. For instance, the use of alternative fuels generally requires greater specific thermal energy and electricity due to their higher moisture content than fossil fuels, the operation of the kiln at greater excess air levels compared to conventional fossil fuels and the pre-treatment of alternative fuels.

The integration of carbon capture equipment typically increases the specific energy intensity of cement manufacture, as additional energy is needed to operate the CO_2 separation and handling processes. The global analytical results discussed in this roadmap result from the aggregation of analysing the net impact of the cost-optimal combination of these strategies within 39 specific regional contexts.

Improving energy efficiency

Energy efficiency improvements provide 0.26 $GtCO_2$ or 3% of the cumulative CO_2 emissions savings by 2050 globally in the 2DS compared to the RTS. This is equivalent to 12% of current direct CO_2 emissions of global cement production.

Rotary dry-process kilns are currently the process technology that is most widely deployed for cement production. Dry kilns have lower energy intensities than wet-process kilns, as they operate with a lower level of raw material moisture content, thereby reducing the energy requirement for evaporation of water. The global average thermal energy intensity of clinker decreases by 10% from current levels by 2050 through the use of energy efficiency improvements and adoption of state-of-the-art technology in replacement and new capacity additions, to support the direct carbon emissions constraint in the 2DS.

Dry-process kilns with a precalciner, a multistage cyclone preheater, and multichannel burners[17] are considered state-of-the-art technology for clinker production. They lead to best available energy performance levels of 3.0-3.4 GJ/t clinker[18] based on empirical data and theoretical modelling in the European context (ECRA and CSI, 2017).

17. Modern multichannel burners can operate with alternative fuels by enabling optimal combustion conditions with varying fuel mixes (ECRA and CSI, 2017).

18. Thermal energy intensity range based on a six-cyclone stage preheater.

A theoretical minimum energy requirement of 1.85-2.80 GJ/t clinker is defined by chemical and mineralogical reactions and drying needs, which vary depending on the moisture content of the raw materials (ECRA and CSI, 2017).

Long-dry-process kilns can be retrofitted to incorporate a precalciner and multistage preheater[19] to dry and precalcine raw materials with recovered process excess heat before they enter the kiln. Different strategies can be implemented to improve the thermal energy intensity of clinker, beyond operating state-of-the-art kiln technology. These include increasing the burnability of raw materials by adding substances called mineralisers, which lower the viscosity and the temperature at which clinker melt begins to form. Operating the kiln with oxygen-enriched air can lead to up to 5% thermal energy savings (ECRA and CSI, 2017). In comparison with planetary and rotary coolers, grate clinker coolers enable greater EHR from hot clinker, which can be used for drying of raw materials when integrated with a precalciner (equivalent to 0.1-0.3 GJ/t clinker energy savings) or for enabling electricity generation (ECRA and CSI, 2017).

Some of these strategies have an impact on the electricity intensity of cement due to side effects. For instance, the addition of mineralisers may worsen the grindability of clinker. Other strategies, such as installing a precalciner, increasing the stages of the preheater or upgrading the clinker cooler, involve additional electricity needs to operate the new or upgraded equipment. These could be offset in specific terms, as many of these measures increase the clinker production capacity.

Electricity in cement production is used for cement grinding (31-44%), raw material grinding (26%), fuel grinding (3-7%) and clinker production (28-29%), with solid fuel grinding, cement loading and packaging accounting for the remainder (ECRA and CSI, 2017; Madlool et al., 2011). The use of efficient grinding and milling technologies decreases the global electricity intensity of cement by 14% by 2050 compared to 2014 in the 2DS.

The state-of-the-art grinding technologies considered in the analysis are high-pressure grinding rolls and vertical roller mills. These can theoretically provide up to 50% (high-pressure grinding rolls) and 70% (vertical roller mills) electricity savings compared to the current widely used ball mills (ECRA and CSI, 2017). Electricity demand for cement grinding is highly dependent on product quality requirements. The higher the strength class needed, the finer the cement needs to be ground. Therefore, in-field achievable electricity savings from installing an efficient grinding technology rely on product fineness requirements. Other electricity saving strategies include cross-cutting measures such as upgraded cement process controls and the use of variable speed drives to run mechanical equipment across the site (e.g. grinding machines, fans, solid matter transport or kiln rotation).

Energy efficiency improvements are offset by additional energy requirements related to the use of other carbon mitigation levers. For instance, a greater use of alternative fuels (from 6% to 30% globally by 2050 in the 2DS), typically with lower calorific content, results in an increased specific thermal energy demand of clinker (an additional 0.11 GJ/t clinker globally by 2050 in the 2DS). The reduction of the clinker to cement ratio can also incur an additional energy demand, such as the need to calcine raw clays used as cement constituents. This is estimated to result in almost an additional 0.35 GJ/t clinker produced by 2050 in the 2DS globally, or around 11% of the global average thermal energy intensity of clinker in that year (Figure 8).

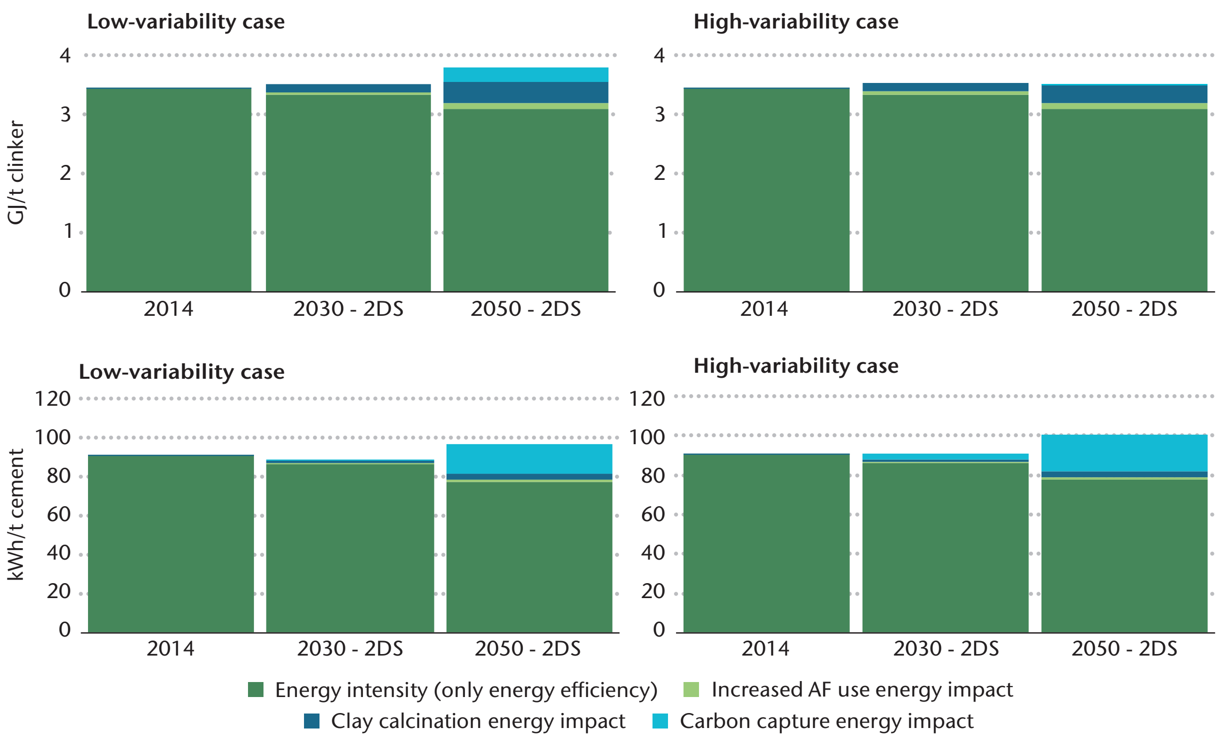
The integration of carbon capture[20] equipment in cement plants[21] in the 2DS similarly leads to additional electricity demand and thermal energy use, with thermal energy use being specific to post-combustion capture technologies to regenerate the saturated sorbent. For instance, capturing CO_2 from cement plants in the 2DS globally results in an additional 15-19 kWh/t cement or 19-24% of the electricity intensity of cement production considering only efficiency gains by 2050. Environmental regulations to lower dust and emissions of nitrogen oxides and sulphur dioxide also lead to higher cement-specific electricity demand levels, as additional electricity is required to operate emissions avoidance or abatement equipment.

19. An additional cyclone stage in a multistage preheater can result in a thermal energy intensity reduction of 0.08-0.10 GJ/t clinker. However, this is only possible if the raw material moisture content is below that which the preheater design considered, and if there are no dimensional constraints on the site (ECRA and CSI, 2017).

20. See the section below discussing carbon capture technologies for details of the technologies.

21. The 2DS vision considers CO_2 emissions capture starting commercial-scale deployment in 2030.

Figure 8: Global aggregated thermal energy intensity of clinker and electricity intensity of cement production in the 2DS



Notes: Electricity intensity of cement production does not include reduction in purchased electricity demand from the use of EHR equipment. The thermal energy impact related to the calcination of clay for use as clinker substitute is displayed in the above graph on a gigajoule per tonne of clinker basis so that its order of magnitude can be compared to the thermal energy intensity of clinker production. Post-combustion carbon capture technologies are deployed in the cement stock only in the low-variability case, with oxy-fuel capture technologies dominating carbon capture equipment roll-out in the high-variability case. For more information on the differences among carbon capture technologies, please refer to the section below on carbon capture, storage and utilisation.
AF = alternative fuel.

Sources: Base year data from CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*; CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).

KEY MESSAGE: Global cement production approaches best energy performing levels on average by 2050 in the 2DS. Energy efficiency improvements are offset by additional energy demands resulting from the use of other carbon mitigation levers beyond improving energy efficiency in that period.

Regional implementation to 2030

Growing cement production presents two energy efficiency benefits. These are the acceleration of the adoption of state-of-the-art technology in new plants and the decrease in the energy intensity of the average size of cement plants, because new facilities tend to be designed at higher capacities.

The RTS captures regional policy developments that already have a considerable impact on energy intensity, such as the Chinese government's target to reach a 3.07 GJ/t clinker national average by 2020, included in the 13th Five-Year Plan (2016-20). This represents a 1%[22] annual reduction in the specific thermal energy demand of clinker from 2014, which is equivalent to about two-thirds of the effort to reach best thermal energy performance levels. Achieving this target relies on an excess capacity management strategy that prioritises best energy performing facilities, in the present Chinese context of expected decreasing cement production.

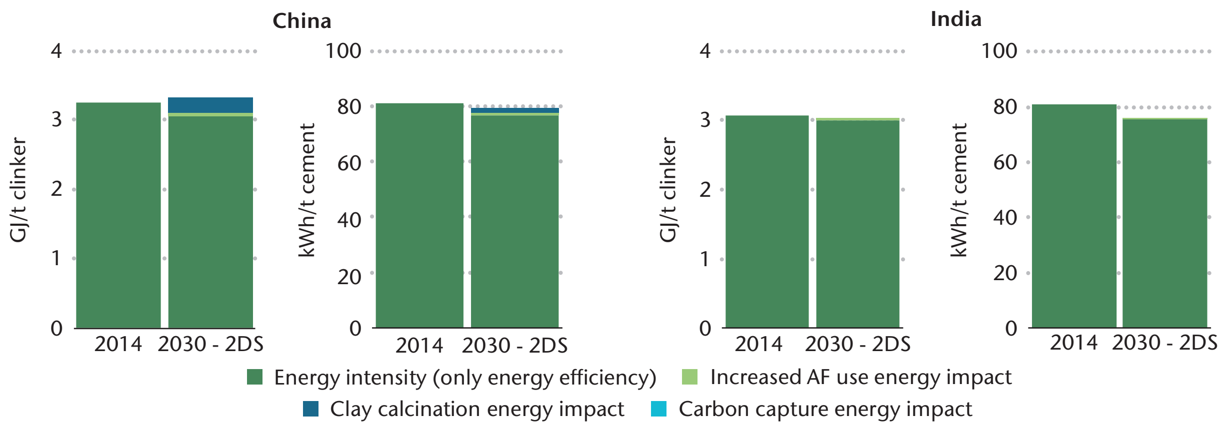
22. Calculated as CAGR.

Regional factors such as moisture content and burnability of raw materials, typical clinker composition and average capacity of cement plants affect the thermal intensity of clinker. The electricity intensity of cement is also influenced by region-specific product fineness requirements. In the 2DS, the regional spreads[23] of clinker thermal energy intensity and cement electricity intensity in the base year (3.07-5.71 GJ/t clinker and 81-116 kWh/t cement) are reduced by 2030 (3.00-4.56 GJ/t clinker and 76-103 kWh/t cement[24]) (Figure 9). This is a result of cost competition across energy efficiency measures, stock turnover dynamics and different best achievable energy performance levels from inherent regional characteristics. Further regional energy efficiency improvements are required in the long term for the global average to reach best available energy performance levels by 2050 in the 2DS.

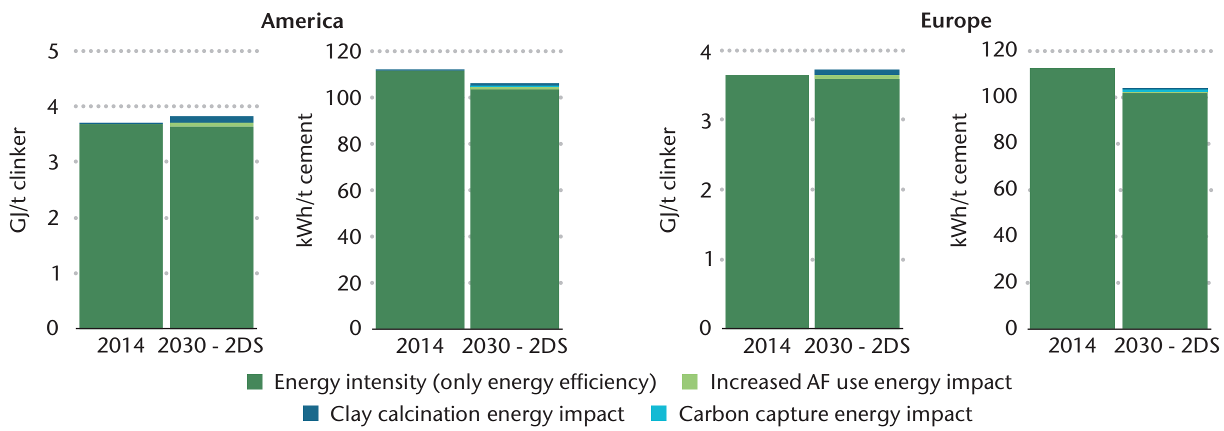
23. The regional spread of a given indicator is defined in this context as the range between the minimum and maximum values within the regions analysed.

24. These energy intensity values exclude the impact of other carbon mitigation levers beyond improving energy efficiency.

Figure 9: Aggregated thermal energy intensity of clinker production and electricity intensity of cement production in the 2DS by region

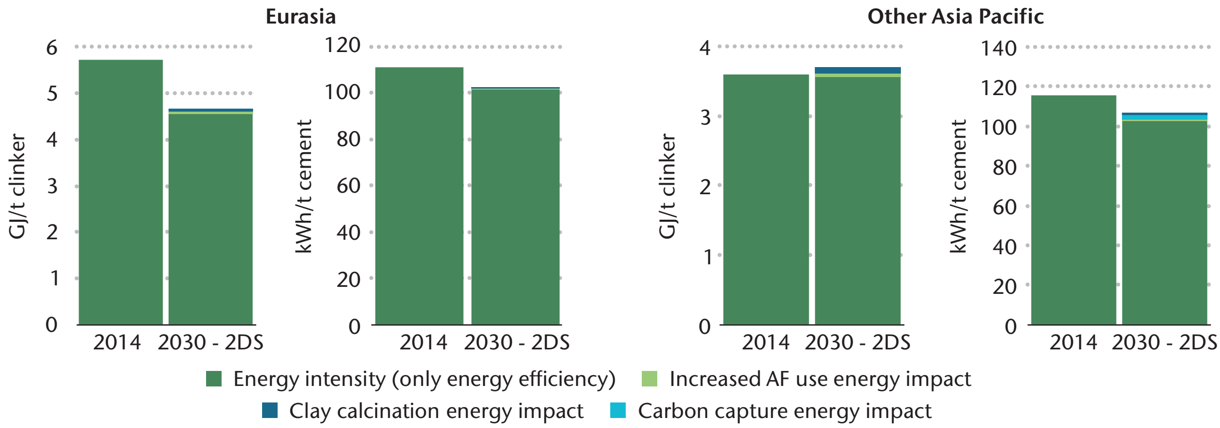


Sources: Base year data from CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).

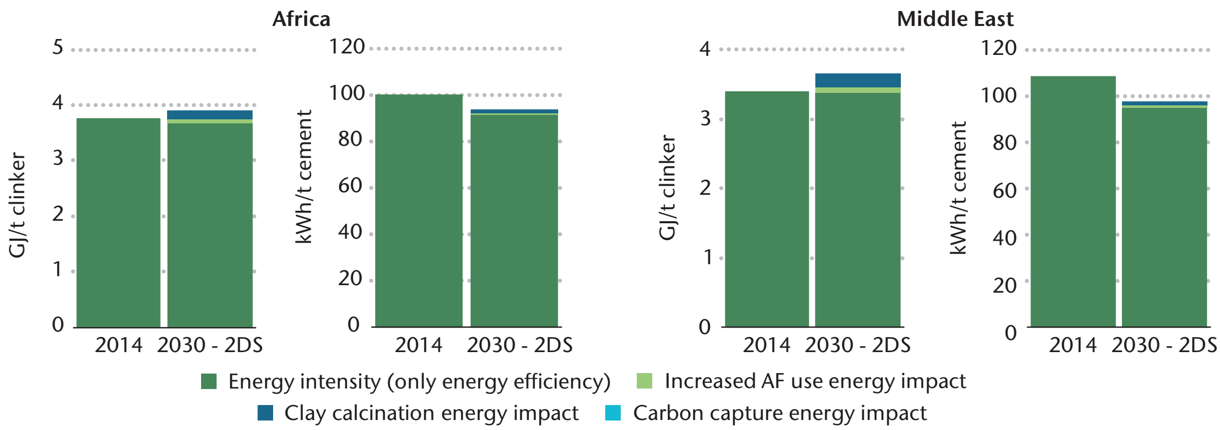


Sources: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*.

Figure 9: Aggregated thermal energy intensity of clinker production and electricity intensity of cement production in the 2DS by region (continued)



Source: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR.



Source: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR.

Notes: Modelling results refer to the low-variability case. Electricity intensity of cement production does not include reduction in purchased electricity demand from the use of EHR equipment. The thermal energy impact related to the calcination of clay for use as clinker substitute is displayed in the above graph on a gigajoule per tonne clinker basis so that its order of magnitude can be compared to the thermal energy intensity of clinker production. AF = alternative fuel.

KEY MESSAGE: Energy intensity of cement manufacturing is influenced by regional characteristics such as raw material moisture content and burnability, plant size distribution and cement standards.

Challenges to implementation

- **Capital costs** can be significant. A considerable decrease in specific energy consumption will only be achieved through major retrofits, which often have high investment costs that are financially unviable.
- **Operation system and operator upskilling** is needed to operate upgraded facilities. Energy efficiency is achieved by suitable operation, as well as the use of adequate process equipment. Advanced energy-efficient technology requires new operation and maintenance practices.

- **A suitably sized market** is needed to run facilities at full capacity. Process equipment operating at maximum design continuous loads delivers maximum energy performance.

- **Local conditions**, such as raw material characteristics, clinker composition and typical plant size, as well as cement fineness requirements, affect the energy required per tonne of cement.

- **Other carbon emissions reductions levers** can be correlated with energy efficiency. For example, increased use of alternative fuels generally increases specific energy consumption because of a higher air requirement and moisture content. Current technologies are mature enough to recover excess heat to serve different uses in enhancing energy efficiency. Therefore, the overall lower CO_2 emissions through increased use of alternative fuels outweigh the disadvantage of increased specific energy consumption.

- **Strengthened environmental requirements** can increase power consumption in some cases (e.g. limits on dust emissions require more power for dust separation, regardless of the technology applied).

Research and development needs and goals

There is a range of grinding technologies at the research and development (R&D) phase. Their applicability and impact on the cement industry should be investigated. One example is contact-free grinding systems (e.g. vortex technology),[25] which could present clear advantages given the limited durability of wear elements of current grinding systems. The European Cement Research Academy has established a research project dedicated to efficient grinding in the cement industry. The project is precompetitive and involves cross-sectoral stakeholders including equipment suppliers (ECRA and CSI, 2017).

25. Other grinding technologies at the R&D phase include ultrasonic comminution, high-voltage power-pulse fragmentation and low-temperature comminution.

Further optimisation, taking a holistic approach in areas such as particle size distribution and grinding aids, could yield energy efficiency benefits.

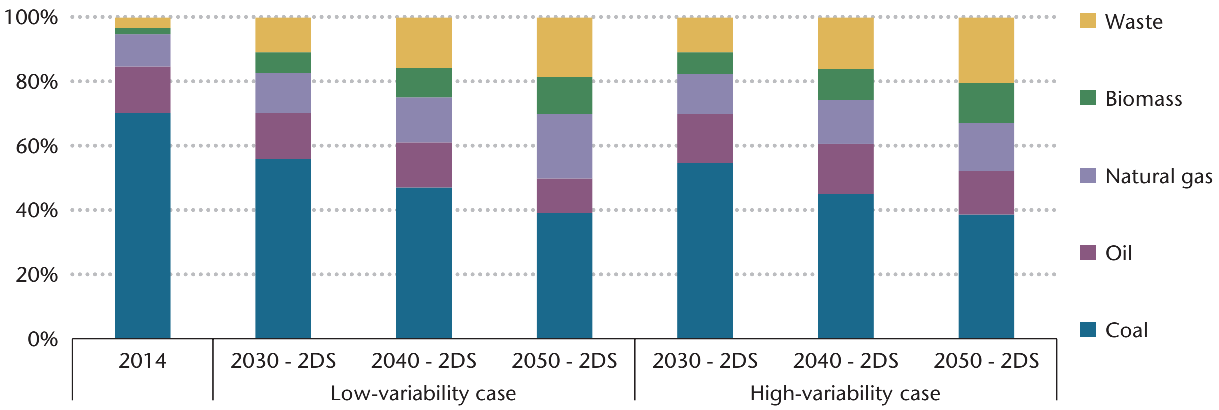
Switching to alternative fuels

Switching to alternative fuels that are less carbon intensive than conventional fuels delivers 0.9 $GtCO_2$ or 12% of the cumulative CO_2 emissions savings by 2050 globally in the 2DS compared to the RTS. This is equivalent to 42% of current direct CO_2 emissions of global cement production.

Coal is the fuel that is most widely used in cement production, representing 70% of the global cement thermal energy consumption. Oil and natural gas jointly contribute 24% to the thermal energy demand in global cement production, and biomass and waste[26] (alternative fuels) contribute just above 5% of the global thermal energy use in the sector. Switching to fuels that are less carbon intensive enables a reduction of 24% globally by 2050 in the share of fossil fuels in the 2DS (Figure 10). This results in the reduction of the CO_2 intensity of the global cement thermal energy demand from 0.088 tonne of carbon dioxide per gigajoule (tCO_2/GJ) to 0.058 tCO_2/GJ over that period, equivalent to 0.9 gigatonne (Gt) of cumulative CO_2 savings in the 2DS compared to the RTS.

26. Waste includes biogenic and non-biogenic waste sources. Biomass and biogenic fractions of waste are considered neutral in terms of CO_2 emissions generation from combustion.

Figure 10: Global thermal energy mix in cement in the 2DS



Note: Waste includes biogenic and non-biogenic waste sources.

Sources: Base year data from CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*; CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).

KEY MESSAGE: The share of fossil fuels in the cement thermal energy demand decreases from 94% to 67-70% in the 2DS by 2050 due to a greater use of waste and biomass.

Material efficiency strategies, such as reuse of consumer goods and products that are less material intensive in a low-carbon society, affect the type and amount of waste materials available in the future. Typical wastes that can be used as alternative fuels in cement kilns include the following, some of which are totally or partially biogenic in nature:

- discarded or shredded tyres.
- waste oils and solvents.
- pre-processed or raw industrial waste, including lime sludge from paper and similar industries.
- non-recyclable plastics, textiles and paper residues.
- fuels derived from municipal solid waste.
- effluent treatment sludge from water and wastewater treatment plants.

Fuels that are based entirely on biomass in the cement industry include waste wood, sawdust and sewage sludge. The use of other biomass-based matter from fast-growing cultivated species (e.g. certain wood, grass and algae) is possible from a technology perspective, but it is not currently globally economical for the cement industry. There are technical requirements that should be satisfied, for example, a high minimum average calorific value of 20-22 GJ/t fuel in the firing of the kiln compared to levels provided by typical organic materials (10-18 GJ/t).[27] Precalciner kilns can integrate up to 60% of fuels with a low calorific content, as the precalciner operates at a lower process temperature (ECRA and CSI, 2017).

In low-carbon contexts such as the 2DS, where end-users increasingly compete for biomass energy sources to support carbon emissions reductions strategies, the price of biomass is likely to increase. The 2DS considers that a maximum of 140 EJ of biomass feedstock can be sustainably supplied globally by 2050 (IEA, 2017). The flexibility of cement kilns to operate with a wide range of fuels without requiring major equipment refurbishment makes them cost-effective biomass users in a carbon-constrained world compared to industrial manufacturing processes based on a single fuel. Cement production absorbs about 7% of the biomass-related final energy demand of the overall industrial sector globally by 2050 in the 2DS.[28]

27. Calorific values are provided in net terms, considering losses for evaporation of contained water.

28. Biomass use reported here does not include biomass demand for onsite power generation units in the industrial sector.

Regional implementation to 2030

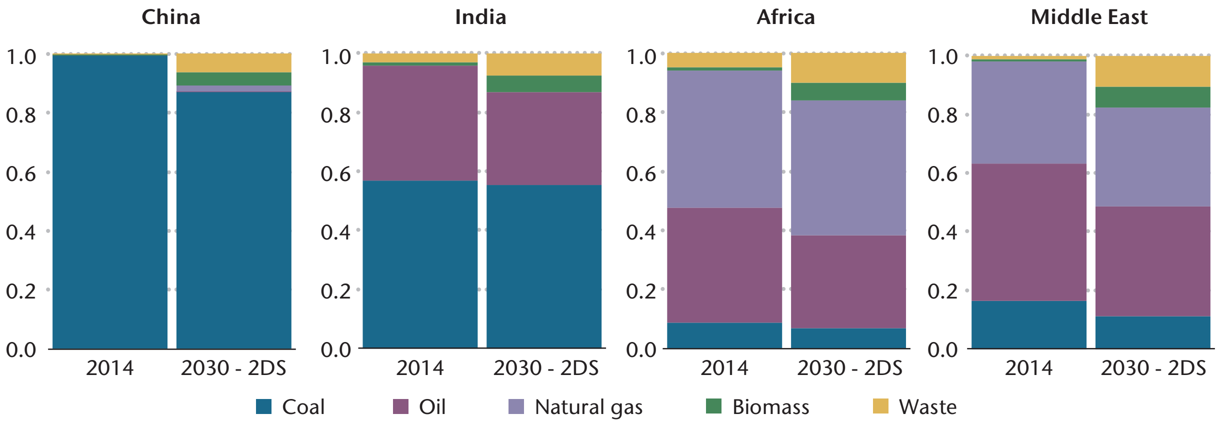
Making waste available as alternative fuel for industrial users has strong policy implications. It requires a policy-driven redirection of disposing waste at landfill sites towards processes that convert waste into heat and electricity. Introducing controlled waste collection, treatment and processing is critical for ensuring quality control of alternative fuels, to avoid emissions of basic and hazardous pollutants and an impact on productivity of cement plants through operation control and monitoring systems.

The use of biomass and waste as fuels in cement production varies greatly across different regions. Countries in which cement plants operate with high shares of alternative fuels have typically implemented policies that focus on setting emissions limits and preventing landfilling instead of restricting the characteristics of alternative fuels for industrial use. This approach allows cement plants or industrial operators the flexibility to treat the alternative fuel combination that they find most cost-competitive and suitable to meet the legislation. For instance, the alternative fuel share in the cement thermal energy demand in countries such as Germany or the Czech Republic is reported at more than 60% (Ecofys, 2017).

Reaching higher shares of alternative fuels in cement kilns, typically with greater moisture content and lower calorific content compared to conventional fossil fuels, could entail an increase of thermal energy demand (0.2-0.3 GJ/t clinker for up to a 65% alternative fuel share) and electricity (2-4 kWh/t clinker) consumption for drying (thermal energy) and handling (electricity) purposes (ECRA and CSI, 2017). No region reaches such high levels by 2030 in the 2DS. The region with the highest share of alternative fuels in thermal energy for cement production on average is Europe, which reaches 40% by that year, followed by America (26%) and Other Asia Pacific (24%). A redirection of waste to the cement sector and a strong growth of biomass use in kilns as a result of adequate supportive policy and cost-competitive access to sustainable biomass are needed to realise the levels of alternative fuels explored in the 2DS.

The 2DS considers efforts to integrate greater shares of biomass and waste in cement production. Strong urbanisation trends in developing countries put pressure on setting waste management policies that support sustainable development of either new urban areas or the expansion of existing ones. Some regions multiply many times over their current shares of alternative fuels of cement thermal energy by 2030 in the 2DS (e.g. China by 62, Eurasia by 33 and the Middle East by 10). This enormous shift in relative terms also highlights the low starting levels in terms of substitution of conventional fossil fuels in cement production (below 2% in 2014 on average in these regions) compared to global practice (6% in 2014). However, despite these radical shifts in the fuel composition of cement production, biomass and waste demand for cement production jointly in these regions represent 0.5 EJ by 2030 in the 2DS or 6% of the global cement thermal energy demand in the same year (Figure 11).

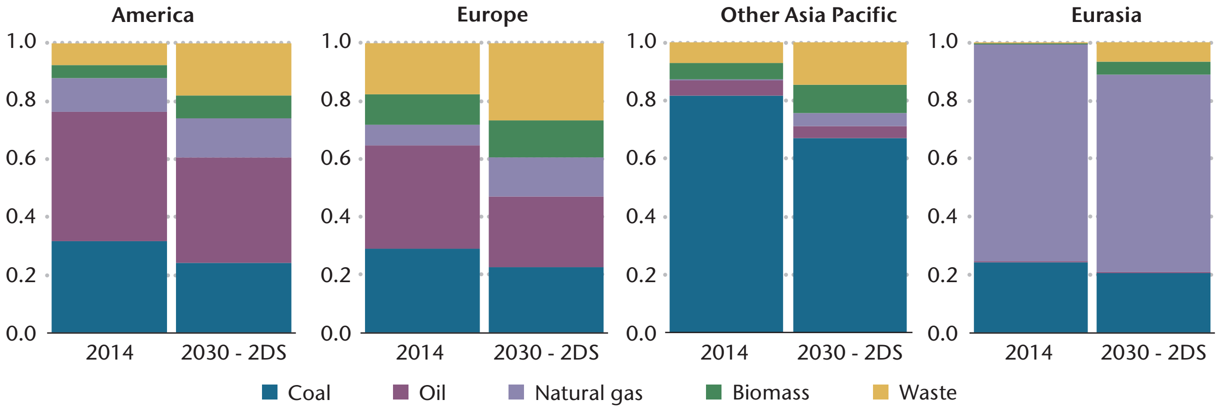
Figure 11: Regional thermal energy mix in cement in the 2DS



Notes: Results shown for the thermal energy fuel mix of cement are based on the low-variability case of the 2DS. Waste includes biogenic and non-biogenic waste sources.

Sources: Base year data from CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*; CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).

Figure 11: Regional thermal energy mix in cement in the 2DS (continued)



Notes: Results shown for the thermal energy fuel mix of cement are based on the low-variability case of the 2DS. Waste includes biogenic and non-biogenic waste sources.

Sources: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*.

KEY MESSAGE: Alternative fuels become further deployed across all regions, replacing conventional fossil fuels in the 2DS.

Challenges to implementation

Although cement kilns could use up to 100% of alternative fuels, there are some practical limitations preventing that from happening. The physical and chemical properties of most alternative fuels differ significantly from those of conventional fuels. While some (such as meat and bone meal) can easily be used by the cement industry, many others can cause technical challenges. These are related, but not limited, to their low calorific value, high moisture content and high concentration of chlorine or other trace substances. For instance, metals (e.g. mercury, cadmium and thallium) must be managed carefully, and proper removal of cement kiln dust from the system is necessary. This means pre-treatment is often needed to ensure uniform composition and optimum combustion, as well as to minimise the content of potentially problematic substances.

There are several barriers to increasing the use of alternative fuels in the cement industry:

- **Waste management legislation** significantly affects availability. Higher substitution of fuels only takes place if local or regional waste legislation promotes energy recovery in cement kilns over landfilling or other less-efficient thermal treatment methods, and allows controlled waste collection and treatment of alternative fuels.
- **Local waste collection networks** must be adequate.
- Level of **social acceptance** of co-processing waste fuels in cement plants can notably affect local uptake. People are often concerned about harmful emissions from co-processing, even though emissions levels from well-managed cement plants using alternative fuels do not represent a specific problem.
- **Complex bureaucracy:** in many cases, obtaining a permit for the use of alternative fuels involves lengthy procedures and several different administration requirements.

R&D needs and goals

To use alternative fuels safely and cleanly, suitable materials must be identified and classified, and collection and treatment processes should comply with standards. Knowledge gained during R&D of the processing and use of such fuels should be shared. This would enable widespread expertise in using high and stable volumes of alternative fuels. Identifying adequate conditions to ensure complete combustion is important, as well as developing strategies for easier use of alternative fuels in cement kilns (e.g. automatic alternative fuel assessment and adjustment of kiln operating conditions).

Reducing the clinker to cement ratio

Reducing the clinker to cement ratio delivers 2.9 $GtCO_2$ or 37% of the cumulative CO_2 emissions savings by 2050 globally in the 2DS compared to the RTS. This is equivalent to 128% of current direct CO_2 emissions of global cement production.

Clinker is the main constituent of most types of cement; it causes cement to harden when it reacts with water. The share of clinker in cement on a mass basis is defined as the clinker to cement ratio. Other possible cement constituents include gypsum, natural volcanic materials, limestone and industrial by-products such as GGBFS and fly ash.

The clinker to cement ratio relies on regional standards to set the amount of cement that must be integrated in concrete products to meet the required mechanical and durability properties for different end-use applications. Ordinary PC typically contains more than 90% clinker, with the remainder being gypsum and fine limestone. Blended cements with lower clinker to cement ratios require less clinker and therefore generate less CO_2 emissions when manufactured, as the CO_2 footprint of some clinker substitutes is low or even zero.

A global clinker to cement ratio of 0.60 is realised by 2050 in the 2DS, through the increased use of cement constituents instead of clinker and greater penetration of blended cements (Figure 12). This is down from 0.65 in 2014, which translates into a reduction of the process CO_2 intensity of cement by 30% over that period, reaching 0.24 t process CO_2/t cement globally on average. Energy-related CO_2 emissions are also decreased because of the reducing need for clinker production (5 Gt clinker cumulatively avoided by 2050 compared to the RTS). The reduction of the clinker to cement ratio as a carbon mitigation strategy in the global cement sector represents 2.9 $GtCO_2$ cumulative savings in the 2DS compared to the RTS, or almost 35% of current annual industrial direct CO_2 global emissions.

Generated in the production of pig iron, GGBFS can be integrated at high proportions in cement. For example, a European standard (CEN, 2000) covers several cements with up to 95% GGBFS on a mass basis. The IEA estimates that 480-560 Mt/yr blast furnace and steel slag was produced globally in 2014. Fly ash results from the separation of dust particles from flue gases produced in pulverised coal-fired furnaces, such as coal-based thermal power plants. It is estimated that more than 675 Mt/yr of fly ash is available globally, but highly variable quality drives down the amount of fly ash used in cement, which is estimated at around 5% of the global cement production.[29] The use of fly ash is limited to 25-35% on a mass basis in cements for technical performance reasons (ECRA and CSI, 2017).

The thermal and electrical energy penalty from the use of GGBFS and fly ash in cement related to drying, grinding and blending is offset by the energy savings derived from the reduced clinker production needs (ECRA and CSI, 2017). While cements containing GGBFS and siliceous fly ash may have a lower short-term strength, high shares of these constituents lead to increased long-term strength, and better resistance to the penetration of corrosive agents in the case of GGBFS (ECRA and CSI, 2017).

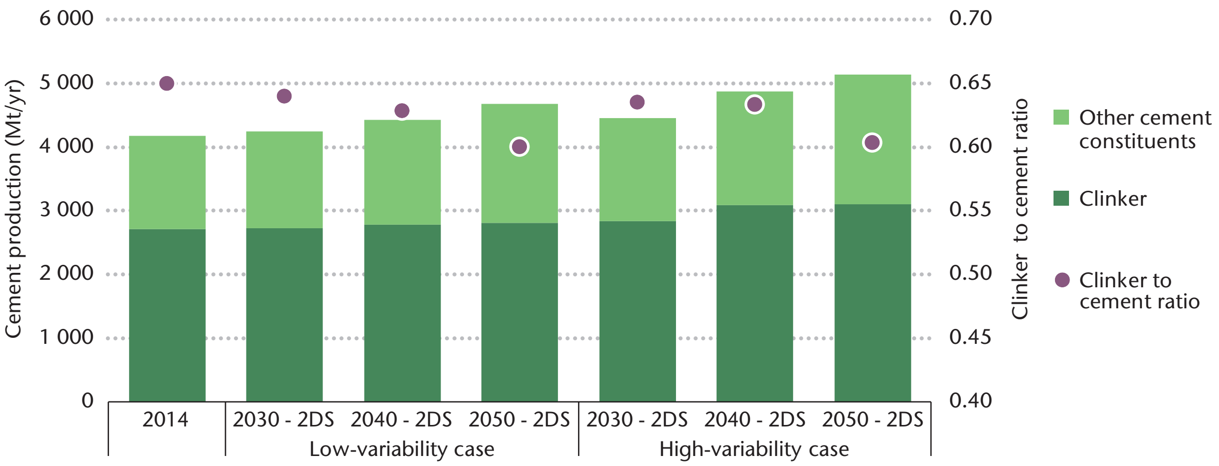
The availability of GGBFS and fly ash is set to decrease in the 2DS, increasing the competition among industrial players for these by-products. In such a scenario, the iron and steel sector shifts away from the current widely used blast furnace route towards scrap-based electric arc furnaces, which are less energy intensive, and optimised directly reduced iron and smelt reduction routes, which are less carbon intensive, in response to restringent carbon emissions.

Material efficiency strategies also support the steel industry in reducing its carbon footprint in the 2DS. This can be done by making more scrap available for remelting, back from consumers, and by reducing the overall demand for crude steel due to improved manufacturing and semi-manufacturing yields while delivering the same service to steel product users.

Coal-fired power plants and industrial heaters are set to drastically decrease their market shares in the 2DS, as power generation and industrial heating significantly reduce their CO_2 emissions, thus affecting the availability of fly ash. The joint mass share of GGBFS and fly ash in the global cement production by 2050 in the 2DS is envisioned to more than halve. This increases the need to explore alternative cement constituents to avoid an increase in the clinker to cement ratio and to even support its reduction.

29. Fly ash is used in considerable amounts in concrete in countries such as the United States, China and Germany (ECRA and CSI, 2017).

Figure 12: Global cement production and clinker to cement ratio in the 2DS



Sources: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17); CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*.

KEY MESSAGE: The clinker to cement ratio is decreased by 7-8% in the 2DS by 2050 globally, despite expected cement production growth and limited availability of industrial by products used as cement constituents.

Natural pozzolanic materials, obtained from volcanic compounds or sedimentary rocks with adequate composition, can be used instead of clinker. Their availability and reactivity vary widely from region to region. Pozzolanic materials with interesting properties for cement making are ash from agricultural residues (e.g. rice husk ash) and silica fume (a by-product of silica and ferro-silica alloy production processes). However, their use in cement production is highly dependent on factors such as variable local availability, seasonality and competition with other industrial uses.

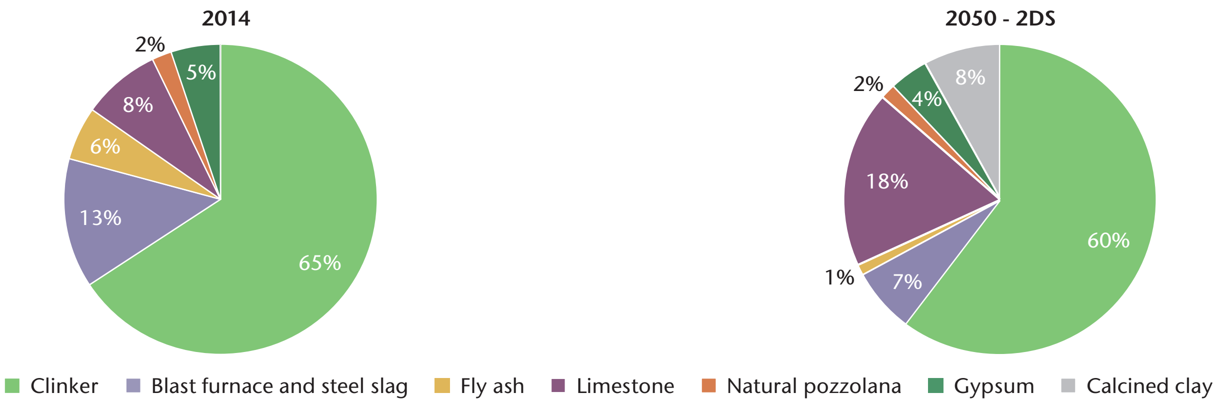
Limestone can also be used instead of clinker in cement. Limestone-containing cements typically have a reduced water demand, which results in better workability for concrete. They need to be ground finer to achieve the same strength as PC, but the grindability of limestone is much higher than that of clinker. Typically, the mass content of limestone in such cements is 25-35%; up to 50% is possible, but needs to be coupled with sophisticated measures both in the cement production process and in the use phase for concrete (ECRA and CSI, 2017). It is estimated that cements using limestone as a filler currently represent 25-30% of the global cement production, and that the share will increase by up to 48% by 2050 in the 2DS.

Thermal treatment can enhance the reactive properties of natural pozzolanic materials. This entails a thermal energy penalty reported as up to 0.15 GJ/t cement compared to a reference plant thermal energy performance of 2.64 GJ/t cement (ECRA and CSI, 2017). Such is the case of calcined clay, a result of drying, crushing and calcining clay.

Calcined clay has been used in cement production for a long time (bridge construction applications were reported as early as 1932 in San Francisco), with Brazil systematically producing about 2 million tonnes (Mt) calcined clay per year since the 1970s (UNEP, 2016). Early compressive strength of cement decreases with greater portions of calcined clay used due to the slower reaction kinetics of this cement constituent compared to clinker (ECRA and CSI, 2017). However, recent developments benefit from optimised combinations of calcined clay and ground limestone as cement constituents, potentially enabling up to 50% clinker displacement without affecting cement properties (UNEP, 2016).

These are promising developments that support the reduction of the clinker to cement ratio in the 2DS. The global reserves of raw clay are considered effectively unlimited compared to global cement production volumes; however, other clinker substituents, such as GGBFS and fly ash, are envisioned to be significantly less available in the 2DS. Cements based on calcined clay and ground limestone are considered to penetrate the market in the 2DS, reaching 27% of the global cement production by 2050.

Figure 13: Global average estimates of cement composition



Notes: Cement composition estimates are provided as shares of cement production on a mass basis. The 2050 global average cement composition estimates shown are based on the low-variability case of the 2DS.

Sources: Base year data from CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*; CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry;* UNEP (2016), *Eco-efficient Cements: Potential, Economically Viable Solutions for a Low-CO_2, Cement-based Materials Industry;* data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).

KEY MESSAGE: The increased use of emerging cement constituents instead of clinker and greater market penetration of blended cements reduce the global clinker to cement ratio to 0.60 by 2050 in the 2DS.

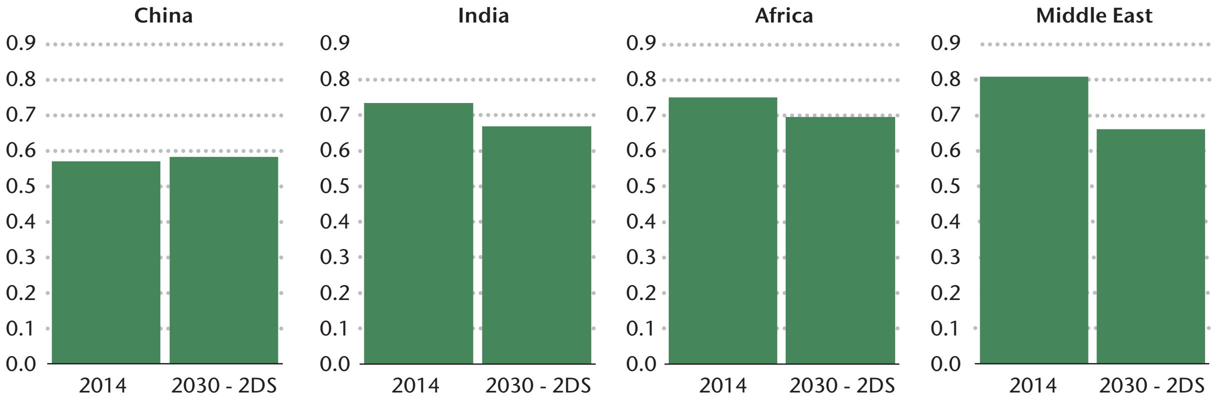
Regional implementation to 2030

Differences in the availability of cement constituents, in the competition for these materials with other final uses such as concrete production and in cement standards set a wide range of clinker to cement ratios across different regions. Regional reported data and IEA estimates for the clinker to cement ratio in 2014 range from 0.57 (China) to 0.87 (Eurasia), and result in 0.65 globally.

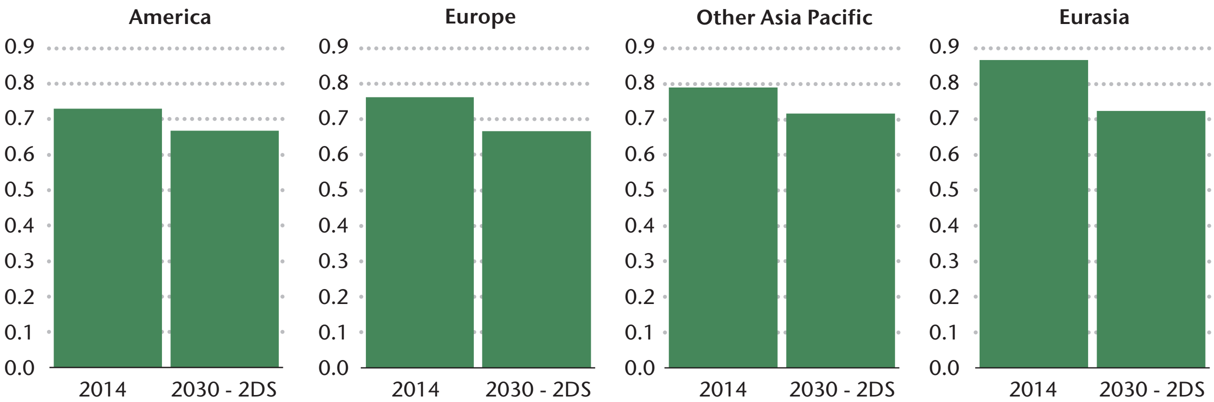
The regional spread of the clinker to cement ratio observed currently is almost halved in the 2DS by 2030. China remains the region with the lowest clinker to cement ratio (0.58) compared to a highest 0.72 average level shared by Eurasia and Other Asia Pacific. Considerable clinker to cement ratio reductions in relative terms are considered across different regions in the 2DS by 2030 compared to current levels, ranging from 8% to 19% (Figure 14). These are in response to limited direct CO_2 emissions and different regional contexts in terms of current shares of clinker in cement, cement constituent availability and cement standards.

However, this regional shift in cement composition is not seen to the same extent in global terms. Chinese cement production, with the lowest international clinker to cement ratio, still accounts for 45% of the global cement production by 2030, despite the expected decrease in domestic activity over the time frame.

Figure 14: Regional clinker to cement ratio in the 2DS low-variability case



Sources: Base year data from CII, WBCSD and IEA (forthcoming), *Status Update Project from 2013 Low-Carbon Technology for the Indian Cement Industry*; CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; data submitted via personal communication by Sinoma Research Institute and China Cement Association (2016-17).



Sources: CSI (2017), *Global Cement Database on CO_2 and Energy Information*, www.wbcsdcement.org/GNR; SNIC (forthcoming), *Low-Carbon Technology for the Brazilian Cement Industry*.

KEY MESSAGE: The clinker to cement ratio becomes considerably reduced across different regions by 2030 in the 2DS.

Challenges to implementation

- **Regional availability** of cement blending materials remains critical, in terms of quantity/quality and its impact on prices. Availabilities of GGBFS and fly ash are expected to decline.

- **Common practice, market awareness and acceptance** should be enhanced because, in some regions, consumers and contractors are reluctant to select blended cements over PC. This can be attributed to a lack of awareness by consumers and to lack of training/education of contractors.

- **Building standards** vary regionally in terms of the type of blended cements that are allowed for construction.

- **Distances between sources of blending materials and cement and concrete plants, and logistics,** can be barriers to the use of blending materials because they affect economic viability.

R&D needs and goals

The availability of cement blending materials should be quantified globally, building from bottom-up local assessments. The need to continuously assess their properties on a global scale is imperative, taking into account the varying nature of most cement blending materials. Priority should be given to determining their environmental footprint (including CO_2), in addition to their effect on cement strength and durability. These studies should take a holistic view by considering specific construction-related needs.

The availability of current materials and shifts in industrial process routes make it imperative that research efforts also focus on identifying and developing new cement blending materials. Calcined clays are a possible candidate, and ongoing research is expected to provide critical information on their performance and durability.

In the same context, similar benefits may be realised from valorising other materials, including electric arc furnace slag, vegetable ashes, bauxite residue and tailings from mining operations. Targeted R&D actions are crucial in addressing the challenges that will allow the use of alternative blending materials, such as improving hydraulic or pozzolanic properties and handling the possible presence of heavy metals.

Using emerging and innovative technologies

Emerging and innovative technologies provide 3.7 $GtCO_2$ or 48% of the cumulative CO_2 emissions savings by 2050 globally in the 2DS compared to the RTS. This is equivalent to 166% of current direct CO_2 emissions of global cement production.

Contributing to the decarbonisation of electricity

Electricity consumption currently represents 13% of the global final energy consumption of cement making, similar to the contribution of oil to the energy mix of the sector. The additional electricity requirements from implementing other carbon emissions mitigation levers are expected to increase the global electricity intensity of cement by 6% by 2050 in the 2DS compared to the current level. This is despite the energy efficiency improvements in electricity-intensive equipment analysed in this roadmap. There are different options that the cement sector can use to support the reduction of the carbon footprint of electricity generation based on the use of energy sources that are less energy intensive.

Excess Heat Recovery (EHR) for power generation

EHR technologies for power generation are not widely deployed in the cement sector of many countries. EHR for power generation can be considered as emerging in global terms, despite EHR technologies being known in the sector for a long time. However, there are certain countries, such as China, India, Japan and Korea, in which domestic clinker production capacities are equipped with considerable shares of EHR to power, ranging from 30% to almost 90%. China is the leading country in implementing EHR to power technologies in the cement sector, with almost 90% of its domestic clinker production capacity equipped with such technologies. This increased the global share to just above 50% in 2014, as a result of the significant contribution of China to global cement production (60% in 2014).

State-of-the-art dry-process kiln systems already include EHR techniques to use part of the thermal energy of kiln flue gases. These are used to preheat raw materials through a series of cyclones[30] before entering the kiln. Additionally, the air used to cool the clinker can be employed as secondary combustion air. Thermal energy can be recovered in the dry-clinker-making process, depending on the moisture content[31] of the raw materials. This medium-temperature[32] additional recovered energy can be used for drying cement constituents (e.g. slag) or alternative fuels. The use that is most widespread is power generation for onsite use or export. Between 8 kWh and 25 kWh[33] of electricity import savings per tonne of clinker are reported, depending on the dry-process kiln configuration and the moisture content of the raw materials (ECRA and CSI, 2017; Hongyou, 2015; IEA, 2016a).

30. The number of cyclones of a dry rotary kiln is determined by the moisture content of the raw materials, so that each preheating stage increases the level of thermal recovery (the greater the number or stages, the lower the kiln exhaust output temperature). Dry kilns are typically equipped with three to six stages of cyclones.

31. Moisture content in raw materials can reach levels even greater than 10% mass, in which case, the thermal recovery potential is significantly reduced due to the need to use most of the recoverable excess heat for drying. Typical commercially viable EHR arrangements operate with raw materials of a low moisture content of 2-6% mass.

32. Medium temperature in this context refers to 200-400°C.

33. Greater electricity generation levels are reported for plants with supportive co-firing in the boiler or by modifying the kiln preheater arrangement (ECRA and CSI, 2017).

The cost-competitiveness of EHR technologies is highly dependent on local conditions such as cement plant arrangement and raw material and fuel characteristics, electricity and fuel prices, and availability of suitable thermal energy users in the locality of the cement plant. Other factors such as the policy context can also influence the economics of EHR technologies depending on whether electricity exports to the grid are possible.

Global clinker capacity equipped with EHR for power generation increases to 65-80% by 2050 in the 2DS. This is because electricity prices are increasingly driven by growing electricity demand in the 2DS due to greater shares of carbon-free power generation finding cost-effective means to electrify end-uses. Such EHR to power technologies can also provide low-carbon electricity generation solutions in areas with unreliable electricity supplies. The applicability of EHR to power technologies in cement plants operating with greater levels of moisture content can improve by using organic Rankine cycles (ORCs) and Kalina cycles. These operate at lower-temperature levels (benefiting from the use of thermal fluids with lower boiling temperatures than water) and can recover heat from lower-temperature sources than standard steam cycles.[34]

Renewable power generation

The cement sector can support the reduction of carbon emissions from electricity production by improving the uptake of renewable power generation, given the appropriate economic conditions. This can be achieved through different strategies including implementing renewable-based captive power generation, power purchase agreements that ensure electricity imports are provided from renewable sources or demand-side response strategies that enable a flexible electricity demand (e.g. a flexible operating strategy of grinding plants throughout the day).

Various renewable-based options are available for cement manufacturers including wind power, solar photovoltaic power, solar thermal power and small hydropower generation. Potential deployment of these technologies in cement plants is highly dependent on local conditions such as the availability of local renewable sources, electricity prices, cement plant size and policy contexts. The current level of installed renewable-based captive power generation in the global cement sector is minor.

However, recent developments are promising in countries such as India with 216 megawatts (MW) offsite installed wind capacity operated by cement companies, and 13 MW solar photovoltaic capacity installed within cement plants in 2014 (CII, WBCSD and IEA, forthcoming). A project that demonstrates the integration of solar thermal power with already existing EHR to power technology in a cement plant started in 2014 in Morocco. This was a sustainable solution for remote locations with good availability of renewable energy sources (Italcementi, 2015). Kalina cycles and ORCs represent a good technical solution for geothermal and solar energy recovery, as they operate with lower boiling point thermal fluids.

Integrating carbon capture, storage and utilisation

After being generated in the cement kiln (post-combustion capture techniques), CO_2 can be captured, or purified from kiln flue gases when the combustion happens under oxy-fired conditions (oxy-fuel capture technologies). Precombustion capture technologies have limited mitigation potential in cement production, as only energy-related CO_2 emissions, which represent around 35% of the total cement carbon emissions, would be affected.

Post-combustion capture technologies do not require fundamental modifications of cement kilns and could be applied to existing facilities provided there is enough physical space available on the site:

- **Chemical absorption**[35] is the post-combustion capture technology that is most advanced, and enables up to 95% optimum capture yields[36] (ECRA and CSI, 2017). Thermal energy is required for regeneration of the sorbent[37] used, and electricity is needed to operate the capture unit.[38] This would increase the plant

34. A cement plant in Germany first integrated ORCs in 1999, with several similar projects following on different continents. A few Kalina cycles are known to operate within cement plants, namely in Pakistan and United Arab Emirates (ECRA and CSI, 2017).

35. Chemical absorption processes have been commercially used as part of core operations in other industrial sectors for a long time.

36. Capture yield is referenced to the gas stream entering the capture unit.

37. Amine-based sorbents are most commonly used in CO_2 separating processes, but sorbents that are more efficient, based on ammonia or activate potassium carbonate, are being investigated.

38. Energy penalties related to chemical absorption for CO_2 capture in cement kilns are reported as 1.0-3.5 GJ/t clinker and 50-90 kWh/t clinker compared to average operational levels (ECRA and CSI, 2017).

energy imports, as simulations show that under normal circumstances, no more than 15% of the additional thermal energy required can be recovered from the cement kiln (IEAGHG TCP, 2013). A cement plant with a mobile capture unit in Brevik, Norway, undertook successful chemical absorption trials using amine-based sorbents between 2013 and 2016 (Bjerge and Brevik, 2014). A plant started operations in 2015 in Texas to chemically capture and transform 75 ktCO_2/yr from a cement plant into sodium bicarbonate, bleach and hydrochloric acid, which could be sold, so that the sorbents, once saturated, do not need to be regenerated (Perilli, 2015).

- Using **membranes** as a CO_2 separation technique could theoretically produce a yield of more than 80%. However, membranes have only been proven on small or laboratory scales where up to 60-70% recovery yields were achieved (ECRA and CSI, 2017). Membranes do not have energy requirements for regeneration but can be sensitive to sulphur compounds and other potential contaminants, and in some cases, to high temperatures. Another option being investigated is the combination of a single-membrane separation unit for bulk separation with a CO_2 liquefaction train from which the waste stream is recycled and mixed with the feed to the membrane system. This combination would enable both systems to operate in their optimal ranges in terms of CO_2 concentration (Bouma et al., 2017).

- **Calcium looping** separates the CO_2 contained in flue gases from sorbents based on calcium oxide through sequential carbonation-calcination[39] cycles (Romano et al., 2013). A pilot plant using calcium looping to capture 1 tCO_2 per hour was commissioned in 2013 in Chinese Taipei (Chang et al., 2014). The Zero Emission of Carbon with MIXed Technologies research infrastructure in Italy is investigating the calcium looping process to capture CO_2 from coal gasification and steam methane reforming processes (Stendardo et al., 2016).

Oxy-fuel capture technologies are differentiated by the extent to which oxy-firing is applied in the cement kiln. Partial oxy-fuel consists of the application of oxy-combustion only at the precalciner stage. Full oxy-fuel also includes oxy-fuel in the firing of the cement kiln. While CO_2 separation yields for the partial option are reported in the range 55-75%, full oxy-fuel can theoretically reach 90-99% (ECRA and CSI, 2017). Even if these technologies do not necessarily incur additional fuel consumption, their use requires re-engineering the plant to optimise the heat recovery system and minimise air ingress. The oxygen provision also needs to be satisfied through onsite generation or imports of electricity. There is experience in operating with oxy-enrichment conditions in Europe and the United States, and several simulations and trials have been undertaken over the past years. The industry has specific plans for a first demonstration project of oxy-fuel capture technologies in Europe but uncertainty around funding makes realisation unlikely before 2020.

There are **other carbon capture technologies** or configurations being explored that do not strictly fit within the post-combustion or oxy-fuel categories discussed above:

- The advantages of **replacing part of the raw meal with the purge from a calcium looping** system in a cement kiln are being investigated in Italy. Reported theoretical optimisation results indicate a reduction of up to 75% in fuel consumption and 85% in CO_2 emissions compared to conventional cement plant performance levels (Romano et al., 2013).

- A new concept called **direct separation** that captures process CO_2 emissions by applying indirect heating in the calciner is being piloted at a cement plant in Belgium (LEILAC, 2017).[40]

As CO_2 emissions limitations become increasingly stringent over time in the 2DS, more-expensive carbon mitigation strategies that provide greater CO_2 reductions, such as carbon capture, need to be deployed. Carbon captured emissions for permanent storage in the 2DS represent 6-10 GtCO_2 by 2050 globally or 7-12% of the cumulative total generated CO_2 in the cement sector over the same period. Absolute carbon capture deployment levels need to reach 552-707 MtCO_2/yr globally in 2050 in the 2DS (Figure 15).

39. Carbonation is the reaction of calcium oxide and CO_2 to give calcium carbonate, or the inverse to calcination.

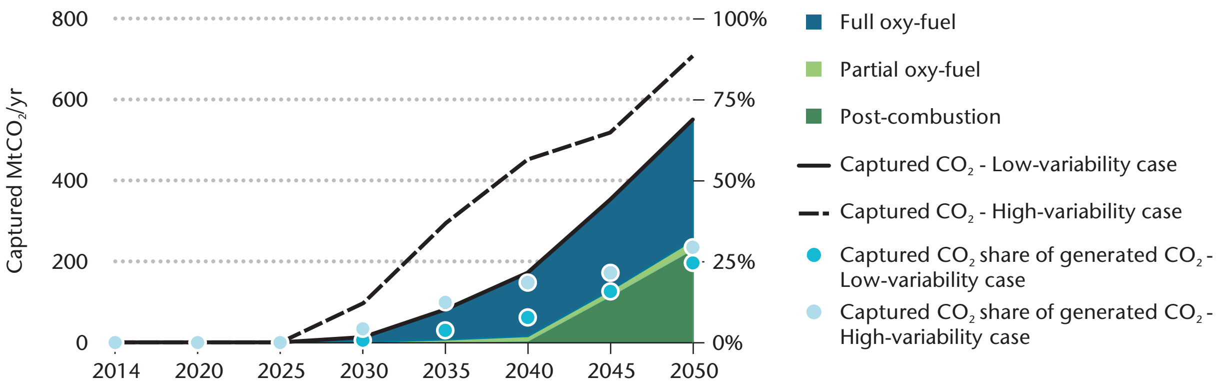
40. This arrangement involves re-engineering the calciner with a special steel vessel to enable indirect heating of raw materials, so that pure CO_2 can be captured as it is released from the limestone. This system can be complemented with other carbon capture technologies such as oxy-fuel to handle energy-related CO_2 emissions.

Reported CO_2 abatement costs in techno-economic studies performed for theoretical cement plants range from about 55-70 United States dollars per tonne of carbon dioxide (USD/tCO_2) avoided[41] for oxy-fuel technologies and about 90-150 USD/tCO_2 avoided for post-combustion, subject to reference plant size and excluding CO_2 transport and storage (ECRA and CSI, 2017; IEAGHG TCP, 2013).

Oxy-fuel techniques could account for greater shares of cumulative carbon captured CO_2 emissions by 2050 in the 2DS globally in contrast with post-combustion, based on current knowledge of the techno-economic performance of carbon capture technologies in cement plants. Even though oxy-fuel technologies are currently considered a carbon capture option that is more economic in cement kilns, costs associated with integrating CO_2 capture in cement plants are still uncertain, as there are no real plant data available, especially when assessing different options for steam supply to support sorbent regeneration in post-combustion capture technologies. Nevertheless, further experience in integrating CO_2 capture in the cement process as market deployment develops could lead to better optimised systems, which could reduce investment costs and the related energy penalty.

41. Avoided CO_2 emissions refer to direct CO_2 emissions generated in the cement plant. Costs are reported in 2015 USD. Costs reported in original sources are 40-50 euros per tonne (EUR/t) avoided CO_2 for oxy-fuel and 65-110 EUR/t avoided CO_2 for post-combustion (IEAGHG TCP, 2013); >50 to >70 EUR/t avoided CO_2 (ECRA and CSI, 2017).

Figure 15: Global deployment of CO_2 capture for permanent storage in the cement sector in the 2DS



KEY MESSAGE: Between 25% and 29% of total generated direct CO_2 emissions in cement are captured annually in 2050 globally in the 2DS.

Captured CO_2 can be geologically stored (CCS), either permanently or over geological time scales, and either directly or after a commercial application. For instance, CO_2 can be injected into oil reservoirs to enhance the oil recovery yield, and it can be geologically stored in the reservoir once the field exploitation is completed. Currently, 3.7 MtCO_2/yr is stored in dedicated geological sites globally, and almost 28 Mt of anthropogenic CO_2 per year is captured and stored through injection for CO_2 enhanced oil recovery worldwide. This is mainly based in North America (91%) and related to natural gas processing and synthetic gas production processes (79%) (Global CCS Institute, 2017).

Captured CO_2 can also be stored for long periods in inert materials by reacting it with widely available natural alkaline minerals[42] or reactive industrial by-products such as fly ash to form carbonates, which can then be used for construction or stored underground. No large-scale demonstration plant is

42. Examples of alkaline minerals are silicates rich in magnesium and calcium.

known but several patents exist. The R&D literature on this technique reports that high amounts of mineral feedstock and energy are required (1.8-3.0 t of relatively pure mineral per tonne of CO_2 captured and 3 GJ/tCO_2 plus additional electricity for mechanical operations) (ECRA and CSI, 2017).

Captured CO_2 can also be used (carbon capture and utilisation; CCU) as a feedstock for the production of chemicals and fuels by reacting it with hydrogen. This is called the "power-to-x route", in reference to electricity-based hydrogen production instead of the routes based on fossil fuels currently widely used. For instance, products such as methanol, methane and other hydrocarbons can be produced from CO_2 and hydrogen. Upon combustion of these fuels, the potential incineration or degradation of derived-product wastes or during the use of derived products, the locked CO_2 would be released to the atmosphere, so that these routes do not provide long-lasting carbon storage.[43]

Most of the routes using CO_2 as a feedstock are at early stages of development, with the main research driver being exploration of the energy storage possibilities these can offer. Fuels produced from renewable electricity-based hydrogen and CO_2 can be used to store energy. This supports the integration of greater shares of variable renewable sources and thus the decarbonisation of power generation. Current economics are not widely favourable due to high technology costs related to the need to explore technical feasibility at large scale, high specific energy requirements and current costs of electricity compared to fossil fuels.

While systemic approaches encompassing sector-driven strategies should be pursued, from a direct carbon mitigation perspective within the cement sector, achieving the 2DS vision would entail long-lasting storage of captured CO_2 (under expected activity growth), unless there is a radical shift in the nature of cement production that circumvents the generation of process CO_2.

Demonstration needs to 2030 for carbon capture

The cement industry has performed a few pilot studies of carbon capture technologies, including a commercial-scale demonstration project on amine-based post-combustion.

Oxy-fuel capture technologies are still not proven at commercial scale in the cement industry. There is potential to improve the process integration across the additional units (e.g. air separation units for oxygen production) and the cement plant, to reduce the air in-leakage and to obtain operational insights from scaling up the system. Operational knowledge could also be gained by operating full-scale demonstrations of amine-based post-combustion capture technologies in the cement industry. Pilot testing of other carbon capture options should also be pursued.

The roadmap vision considers that the integration of carbon capture technologies in the cement sector reaches commercial-scale deployment by 2030. It sets key milestones within that time frame, including accomplishing commercial-scale demonstration of oxy-fuel carbon capture technologies in cement production and gaining experience in operating large-scale post-combustion technologies in cement plants.

Challenges to implementation

EHR for power generation

- **Economic viability** would be the deciding factor for wider deployment in the cement industry, given the adaptability of EHR technologies to different plant conditions and location (e.g. availability of water), and considering the absence of legal mandatory installation requirements. It is generally not economically feasible without additional financial support or other indirect economic benefits (e.g. avoided costs of unexpected kiln stoppages due to unreliable electricity supply or valorising the provision of flexibility to the electricity grid).

Renewable power generation

- **The availability of local renewable sources** (e.g. solar radiation or wind speed and conditions) is the primary factor influencing the deployment of renewable power generation technologies at cement or grinding plants. In general, grinding units are more suitable for using renewable energy, due to the flexibility in operating hours during the day.

- **Electricity prices** (e.g. electricity exchange conditions) and **policy contexts** (e.g. availability of incentives or easy permit policies), may also influence the uptake of renewable-based electricity in cement making. This could either be through self-generation or through renewable-certified power purchase agreements.

43. For example, urea (the main precursor of fertilisers) is commercially produced from CO_2 and ammonia, but the CO_2 is released back into the atmosphere as the fertilisers get hydrated when applied to agricultural sites.

Carbon capture, storage and utilisation

- **Effective policies** providing the economic incentive to reduce the carbon footprint of cement production and supporting cross-sectoral public-private co-operation are the main challenge to market deployment of CCS and the identification of optimal locations and designs for CO_2 transport and storage infrastructures, as well as to the technical integration of carbon capture technologies being demonstrated at commercial scale in the cement process.

- **High estimated costs for CO_2 capture** compared to the specific cost of cement production. However, it is expected that the cost of carbon capture will decrease in the future due to technical and scientific progress. Public awareness of CCS is still low, and the public has formed little firm opinions on CCS and its role in mitigating climate change, except in a few European countries.

- **Commercial hurdles** hinder emerging and new CO_2 utilisation routes from advancing rapidly and achieving maturity from laboratory to market, beyond technical limitations. This is partly due to the low prices of alternative fuels and often to reliance on an abundance of renewable electricity. Achieving hydrogen generation with zero carbon emissions would ensure CO_2 emissions reductions in those cases.

- **Land and water availability, and size of downstream markets** are other limiting factors for CCU applications. A life-cycle assessment approach should be applied to measure the specific contribution of each CCU route, to enable environmental acceptance.

R&D needs and goals

Continued research into carbon capture technologies could lead to better optimised systems with reduced investment costs and energy intensities.

The technical and innovation challenges for CO_2 utilisation focus on increasing the efficiency of chemical processes and innovation for new CO_2 utilisation pathways. Intensified research, better catalysts and better process designs will bring higher efficiency levels, lower costs and lower material consumption or waste production.

New and innovative ways of using CO_2 and the use of non-purified CO_2 may make more applications possible. Challenges for mineralisation are the reduction of processing costs and the widening of the range of (waste) materials that can be used as input (Sandalow et al., 2017). Research should be carried out through collaborative projects across different industrial sectors, engaging emitters, transformers (e.g. chemical industry) and final users.

Transportation is the crucial link between CO_2 emissions sources and storage sites. In most countries, there is insufficient attention paid to technology and infrastructure needs. Pipeline transportation presents different regulatory, access and developmental challenges in different regions. The magnitude, complexity and geographic spread for integrated CCS transport pipelines require region-specific assessments.

Further research is also needed to better understand storage availability on a global level. Cement kilns are usually located near large limestone quarries, which may not be close to suitable CO_2 storage sites. It is also likely that CCS clusters will be influenced by their proximity to much larger CO_2 sources such as coal-fired power plants.

Spotlight: Alternative binding materials for cements

During calcination in the kiln for the production of clinker, CO_2 is released from raw materials (see Table 3). This is referred to as process CO_2 emissions, and accounts for about two-thirds of the total direct CO_2 emissions from cement production. Clinker contains 40-80% alite on a mass basis (ECRA and CSI, 2017), resulting in typically around 0.52 t of process CO_2 released per tonne of clinker produced.

Reducing the clinker to cement ratio is a carbon mitigation strategy, which together with carbon capture, storage and utilisation, reduces the impact of process CO_2 emissions in the cement sector. A global clinker to cement ratio of 0.60 is realised by 2050 in the 2DS, through the increased use of cement constituents instead of clinker and greater penetration of blended cements. This translates into a reduction of the process CO_2 intensity of cement by 30% over that period.

Table 3: Process CO_2 emissions released upon calcination of raw materials by clinker compounds

	Process CO_2 emissions (kilogramme of CO_2 per tonne of material)
Alite (Ca_3SiO_5)	579
Belite (Ca_2SiO_4)	512
Tricalcium aluminate ($Ca_3Al_2O_6$)	489
Tetracalcium alumino-ferrite ($C_4Al_2Fe_2O_{10}$)	362
Lime from limestone (CaO)	786
Wollastonite ($CaSiO_3$)	379
Ye'elimite ($Ca_4Al_6SO_{16}$) from calcium sulphate	216
Periclase from magnesium carbonate (MgO)	1 100
Periclase from magnesium silicate rocks (MgO)	0

Note: Limestone is considered to provide the main source of calcium in clinker.

Source: UNEP (2016), *Eco-efficient Cements: Potential, Economically Viable Solutions for a Low-CO_2, Cement-based Materials Industry.*

Recent blended cement developments have shown that up to 50% clinker displacement is possible through optimised combinations of calcined clay and ground limestone as cement constituents without affecting cement properties (UNEP, 2016). This demonstrates interesting prospects for reducing the clinker to cement ratio as a carbon mitigation strategy, as it would rely on widely available resources such as raw clay, rather than on other clinker substitutes (e.g. GGBFS and fly ash), which are foreseen to have significantly reduced availability in the 2DS.

Alternative cement binding materials that rely on different raw material mixes or different raw materials compared to PC clinker are commercial or are being tested and developed by the cement industry to mitigate the environmental impact of process CO_2 emissions.

Commercially available alternative binding cement materials

- **Belite clinker** contains no or little alite, and between 40% and 90% belite,[44] leading to about a 6% reduction of the process CO_2 intensity of clinker (Gartner and Sui, 2017). This type of clinker also benefits from a reduced burning temperature (1 350°C) compared to PC clinker, thereby reducing the fuel needed for calcination. Less than 10% thermal energy savings have been reported. The greater hardness of belite increases electricity use for grinding by about 5% compared to PC (Gartner and Sui, 2017). Belite cements are produced at even lower temperatures (600-900°C), and have been produced at the laboratory scale (ECRA and CSI, 2017). Current market deployment of belite cements is limited (and confined to a small number of countries) due to their much lower early-strength characteristics. Their low heat of hydration[45] means that belite cements have mainly been used in massive concrete dams and foundations (UNEP, 2016). China has been producing belite cements over the past 15 years, with the first successful application for dam construction in the third phase (2003-09) of the Three Gorges Hydropower Project (Gartner and Sui, 2017). In 2014, China produced about 1 Mt of belite cement; Japan is also using high-belite cements for mass concrete and high-strength concrete (Gartner and Sui, 2017).
- **Calcium sulphoaluminate (CSA) clinker** contains ye'elimite as the main constituent, which directly reduces released process CO_2 emissions. For instance, a commercial CSA clinker yields a 44% reduction in process CO_2 intensity of clinker

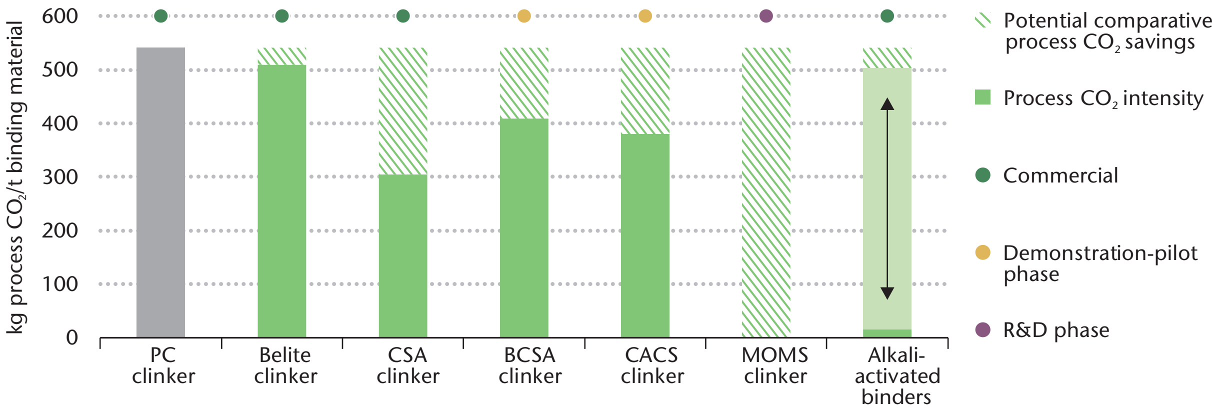
44. A specific commercial example of belite clinker would be more than 40% belite and less than 35% alite according to the Chinese standard GB200-2003 for low-heat PC (Gartner and Sui, 2017).

45. Heat of hydration refers to the heat released as a result of the exothermic reaction between cement and water. It needs to be limited in mass concrete applications to reduce the risk of thermal cracking.

compared to PC (Figure 16). These CSA clinkers have rapid strength development and reduced drying-shrinkage cracking of cement (Gartner and Sui, 2017). They have been commercially produced for more than 30 years, primarily in China where current annual production is around 2 Mt/yr (ECRA and CSI, 2017).

- **Alkali-activated binders** (sometimes called geo-polymers) are produced by the reaction of an alumino-silicate (the precursor) with an alkali activator. They can reduce CO_2 emissions depending on the carbon emissions associated with the production of alkali activators. They rely on materials similar to those used in blended PCs to reduce the clinker to cement ratio, either from natural (e.g. natural pozzolana) or industrial (e.g. GGBFS) origin. Therefore, their availability has a high regional dependence, and is expected to decline in the future for GGBFS or fly ash. Given the wide range of mix designs, sources and doses of the activator and the energy mix to produce the precursors, it is impossible to provide a single value or even a well-defined range to describe the CO_2 footprint of producing alkali-activated binders compared to PC clinker. Two extreme cases could be 97% CO_2 and energy savings compared to PC related to mortar based on blast furnace slag with sodium carbonate as the activator and containing high amounts of granular limestone, and less than 10% savings for an inefficient mix design and an energy mix highly reliant on coal (Provis, 2017). Global commercial use of alkali-activated binders remains limited, and they have been primarily used in non-structural applications (ECRA and CSI, 2017; UNEP, 2016). Australia, Brazil, Canada, China, Czech Republic, India, Netherlands, Russian Federation (hereafter "Russia"), South Africa, Ukraine, United Kingdom and United States have reported commercial-scale production and use (Provis, 2017).

Figure 16: Process CO_2 emissions generation intensity for selected cement binding materials



Notes: BCSA = belite calcium sulphoaluminate, CACS = carbonation of calcium silicates, CSA = calcium sulphoaluminate, MOMS = magnesium oxide derived from magnesium silicates, PC = Portland cement. PC clinker mainly contains 63% alite, 15% belite, 8% tricalcium aluminate and 9% tetracalcium alumino-ferrite. Belite clinker mainly contains 62% belite, 16% alite, 8% tricalcium aluminate and 9% tetracalcium alumino-ferrite. CSA clinker mainly contains 47.5% ye'elimite, 23.9% belite, 12.9% wollastonite and 8.6% tetracalcium alumino-ferrite. BCSA clinker mainly contains 46% belite, 35% ye'elimite and 17% tetracalcium alumino-ferrite. Commercial compositions of CACS clinker are not currently available. The CACS clinker in this assessment is considered to primarily consist of wollastonite, but commercial composition is likely different, and possibly higher in process CO_2 emissions. Process CO_2 emissions generated in CACS clinker making are, in principle, re-absorbed during the curing process. MOMS are considered to be sourced from magnesium silicate rocks. Given the wide range of mix designs, sources and doses, it is not possible to provide a single value or even a well-defined range to describe the CO_2 footprint of alkali-activated binders. The figure above shows two possible extreme examples ranging from 97% to 10% CO_2 savings compared to PC.

Sources: Quillin (2010), *Calcium Sulfoaluminate Cements: CO_2 Reduction, Concrete Properties and Applications*; UNEP (2016), *Eco-efficient Cements: Potential, Economically Viable Solutions for a Low-CO_2, Cement-based Materials Industry*; Gartner and Sui (2017), *Alternative Cement Clinkers*.

KEY MESSAGE: Alternative binding materials offer possibilities for reductions in the generation of process CO_2 emissions in cement manufacturing.

Alternative binding cement materials at demonstration and pilot phases

- **Belite calcium sulphoaluminate (BCSA)** clinker is being investigated to circumvent the high raw material costs of CSA clinkers while delivering a CO_2 footprint advantage for ordinary concrete applications. This is achieved by increasing the proportion of belite and adding alumino-ferrite to CSA clinkers, thus delivering a clinker process CO_2 intensity 20-30% lower than that of PC (Gartner and Sui, 2017). Such BCSA clinkers can be produced with lower sintering temperatures and with 30-50% lower electricity demand for grinding as they are more friable (ECRA and CSI, 2017). They are not commercially produced yet, and specific norms for this type of clinkers do not currently exist, with the exception of those BCSA clinker compositions that are within Chinese norms for CSA clinkers. This type of cement can be commercially applied in Europe for well-defined applications, although specific local technical approval would be required (ECRA and CSI, 2017).

- Cements based on **carbonation of calcium silicates (CACS)** can sequester CO_2 as they cure. Therefore, even if they are based on similar raw materials to PC clinker, these types of cement can yield zero process CO_2 emissions in net terms, as the emissions would essentially be re-absorbed during the curing process. Thus, the main CO_2 emissions related to the manufacturing of CACS clinkers are related to the energy consumed in the kiln. The curing process occurs with relatively pure CO_2 at atmospheric pressure and controlled ventilation, temperature and relative humidity. This limits the application of CACS cements to precast products; in addition, they should not be too large in cross-section to ensure adequate curing. The fuel mix may be more restrictive than in normal PC practice, with the fuel sulphur content needing to be kept low and the use of wastes needing to be potentially limited. They are not expected to protect conventional steel reinforcement against corrosion, which therefore provides limited applicability to non-reinforced products or non-steel-reinforced products such as glass-fibre-reinforced panels. Such a CACS clinker is being developed by a single private venture, and its use is limited to local technical approval (Gartner and Sui, 2017).

- The manufacture of cement based on **pre-hydrated calcium silicates (PHCS)** is beneficial because these materials can be easily produced at low temperatures and under pressure-controlled conditions. Then, they are activated by intergrinding hard filler (silica-rich) materials and heating at low temperatures (UNEP, 2016). This type of cement can lead to CO_2 emissions savings compared to PC, through the use of high proportions of inert fillers such as quartz. However, the overall manufacturing process is complex, and there is still large potential for optimisation, especially on the activation through to grinding step. A first industrial-scale demonstration is planned for 2018 (ECRA and CSI, 2017).

Alternative binding cement materials at the R&D phase

- Cements based on **magnesium oxides derived from magnesium silicates (MOMSs)** are, in principle, able to counterbalance or even absorb more CO_2 than the amount released in the manufacturing process while curing (i.e. yielding net negative CO_2 emissions). This characteristic would only be a true environmental advantage if the magnesium oxides are provided from natural magnesium sources free of carbon, such as magnesium silicate rocks, in contrast to magnesium carbonate. Currently, there is no industrial-scale optimised process developed, and the unresolved issue that is most critical is the production at industrial scale of magnesium oxides from basic magnesium silicates with acceptable energy efficiency levels (Gartner and Sui, 2017; UNEP, 2016).

There are barriers to wider market deployment of alternative binding materials compared to PC clinker. These are related to technology and raw material costs, technical performance, range of possible market applications and level of standardisation for such materials.

Belite, CSA, BCSA and CACS clinkers can be produced in conventional PC manufacturing plants by modifying the raw material mix, so that technology investment costs associated with clinker production capacity are likely similar to those for PC (Gartner and Sui, 2017). Some operational optimisation is possible. For example, increased clinker production could be possible by switching to belite cement production due to its lower thermal energy requirements. Existing cement grinding capacity may be limiting as belite is harder than the main constituent of PC clinker (Gartner and Sui, 2017).

Producing different cement types presents additional logistical costs, related to managing and storing different products, for cement plants. This may prevent wider production of alternative clinkers and limit them to large mass projects where the investment can be justified. Cement products based on CACS clinker would incur additional technology investments compared to PC clinker. These are due to the special CO_2 curing chambers required, as well as the provision of CO_2, which could be supplied from onsite flue gases generated in the kiln or from other industrial sources.

On the other hand, the capital costs of a plant producing alkali-activated binders would be significantly lower than that of a PC plant, as a rotary kiln would not be necessary. However, greater capital-intensive capacity would be needed for the production of the activator, which represents a small mass portion (5-10%) of the cement production (Provis, 2017). The manufacture of PHCS clinker is more complex than that of PC clinker, as it includes more steps; the industrial manufacture process of MOMS clinkers has not yet been developed.

Belite and CACS clinkers are mainly based on limestone like PC, from a raw material perspective, with the advantage that even lower quality limestones can be used compared to PC. However, alternative clinkers such as CSA, and BCSA to a lesser extent, include concentrated aluminium and sulphur sources as secondary raw materials. There is therefore strong competition with other industries such as the manufacture of aluminium and other specialty products, thus leading to high raw material costs. Alkali-activated binders compete in the market with blended PC for alumino-silicate materials, whose reserves and availability are limited.

However, it appears economically and environmentally effective to use such materials in blended cements rather than in the manufacture of alkali-activated binders (ECRA and CSI, 2017; UNEP, 2016). The main alkali metal used as an activator is sodium, which is sourced from synthesized sodium carbonate and sodium hydroxide from sodium chloride obtained from seawater, or from naturally[46] available sodium carbonate. The industries in competition for these activators include the commodity chemical industries, such as detergents, zeolites and adhesives, as well as paper- and glass-making industries (Provis, 2017). Reserves of magnesium silicates exceed the potential growth of cement demand, but they are much less homogeneously distributed than limestone, which could limit production of MOMS clinker to specific regions with larger deposits (Gartner and Sui, 2017).

Belite cements are well suited for mass concrete and high-strength concrete commercial applications, but are not adequate for precast concrete manufacturing and other applications where early strength development is important. In China, the annual production of belite cement is expected to increase over the next two to three years, to support two large hydropower projects. This type of cement has become the main one used for hydraulic mass concrete structures in China[47] (Gartner and Sui, 2017).

One of the challenges to the application of alkali-activated materials in construction is the development and provision of mixtures for rheology[48] control, which currently relies on optimisation of mix designs (Provis, 2017).

Cements based on BCSA clinker can be used in a wide range of applications from precast products to ready-mixed and for-site-mixed concrete applications. However, only limited long-term durability test[49] data have been published for newer BCSA clinkers. Considerable further research and testing are needed to develop better clinker formulations, especially with regard to cost-competitiveness.

The CACS-based cements harden by reaction with CO_2 when curing, so deployment is limited to factory-made concrete production such as

46. Proven natural mineral reserves of sodium carbonate are 23 billion tonnes of trona ore in north-western United States, and multiple hundreds of tonnes in Botswana, Turkey, Mexico and other locations. Just under half of current global sodium carbonate production (more than 50 Mt) is related to mineral sourcing (Provis, 2017).

47. A change in clinker composition should be carefully planned to minimise the duration and frequency of transition periods, which tend to be less energy efficient and more CO_2 intensive.

48. Rheology in this context refers to the behaviour of the solution-solid interface of alkali-activated binding materials during their application.

49. Durability tests examine cement aspects such as sulphate resistance, dimensional stability or ability to protect reinforcing steel against corrosion.

precast applications. As no pressurised conditions are needed in curing chambers, mobile curing equipment is possible to enable onsite cured applications. However, the size of the CACS-based concrete pieces should be limited to enable adequate diffusion of the CO_2 inwards and the water outwards from the concrete mass (Gartner and Sui, 2017).

The concrete applications of MOMS-based cements have not been explored yet at the industrial scale.

Demonstrating technical performance, especially durability under different ambient conditions, and long-term safety of cements based on alternative binding materials is of paramount importance, especially when used for structural applications. Product standards are therefore an important precursor to their widespread use.

Belite cements are already covered by existing standards in many regions of the world (Gartner and Sui, 2017). There are numerous prescriptive standards for alkali-activated cements and concretes in Ukraine, Russia and other countries in the region, where these materials have been used for decades. The standardisation of alkali-activated binding materials is developing quickly compared to the dynamics observed in the construction materials industry. National guidelines integrate specific references to this type of materials in Switzerland. In the United Kingdom, a publicly available specification has recently been published for alkali-activated binders. In China, the use of these materials for chemical resistance applications is described by a specific standard, and alkali-activated binders can be used under performance-based ASTM standards; further testing standards are under development. In some cases, the standardisation process was developed bottom-up from application specifiers rather than top-down from regulators, as in Australia (Provis, 2017).

Standardisation of BCSA clinkers is still progressing, but slowly. Their use in specific well-defined cases is possible through technical approval, similar to CACS clinkers (Gartner and Sui, 2017). However, standardisation of this type of clinker at national/regional levels in the long term would be desirable to facilitate market deployment in applications where they can yield economic and environmental advantages.

Conclusions

Alternative binding materials to PC clinker can offer opportunities for carbon emissions reductions. However, there is currently no independent, publicly available and robust life-cycle analysis for any of the discussed alternative binders or associated comparative quantification of production costs, and their versatility in terms of commercial applicability differs widely. Alternative binders theoretically yielding greater CO_2 savings are often related to greater production costs, restricted available raw materials and limitations of market application, or are at early stages of development. These circumstances make it premature to perform a techno-economic-based evaluation that analyses least-cost technologies and pathways for cement production.

There is a lack of incentives to reduce carbon emissions in cement manufacturing in many regions. Therefore, the deployment of commercially available alternative binding materials is highly driven by production costs, with raw materials being the determining cost factor at present. Research into process optimisation of alternative binders at demonstration phase and the encompassing progress of standardisation could create possibilities for commercial deployment, yielding environmental improvements from current industry performance.

Public-private partnerships can be a mechanism for leveraging funding resources to support demonstration testing and early research. Patent legislation should be flexible enough to disclose information on cement formulations using new or widely deployed binding materials while still providing a commercial advantage to patent owners for the standardisation process to progress effectively and to encompass market deployment.

5. Policy, finance and international collaboration: Actions and milestones

National and international policy frameworks, as well as close co-operation between private and public stakeholders, are needed to achieve the carbon emissions reductions outlined in the vision for this roadmap. These efforts involve multiple levels of action including those of municipal bodies, regional authorities, national governments, supranational bodies and global institutions.

Some regions of the world have been, or are currently, implementing some of the recommendations listed below. However, regulator progress made over past years in the development and deployment of enabling policies needs to be amplified and accelerated.

Policy priorities and regulatory frameworks

Support transition to low-carbon cement production

1. Promote the adoption of state-of-the-art energy efficiency technologies for new and retrofit plants

- Governments to eliminate energy price subsidies, which can act as a barrier to the use of energy-efficient technologies.
- Industry to phase out inefficient long-dry kilns and wet production processes.
- Governments to develop plant- or sector-level energy efficiency improvement target-setting programmes.

2. Encourage and facilitate increased use of alternative fuels and alternative raw materials (waste co-processing in cement kilns)

- Governments and industry to promote deployment of an economy based on resource efficiency.
- Governments to develop and reinforce waste management regulations, encompassing waste avoidance, collection, sorting and treatment. These regulations should give priority to waste co-processing versus incineration and landfilling.
- Governments and industry to develop and promote sets of guidelines on use of alternative fuels inspired by international best practice, and to ensure operators have adequate processes in place for acceptance, traceability, impact monitoring, etc.
- Governments to ensure training of authorities and adequate technical backgrounds of civil servants responsible for permits, control and supervision.
- Governments and industry to engage with non-governmental organisations and civil society to raise awareness of the benefits of optimal waste management.

3. Encourage and facilitate reduction of the clinker to cement ratio

- Independent organisations to develop cement and concrete standards and codes that allow widespread use of blended cements while ensuring product reliability and durability at final application.
- Governments to promote the use of blended cements in sourcing and public procurement policies.
- Governments and industry to ensure traceability/labelling/ethical and responsible sourcing of construction materials.
- Industry and universities to conduct R&D into processing techniques for potential cement blending materials that cannot currently be used due to quality constraints.
- Industry to promote international training events with national standardisation bodies and accreditation institutes, to exchange experiences on reducing the clinker to cement ratio, cement and concrete standards, and environmental and economic impact.

4. Support development and deployment of emerging and innovative low-carbon technologies for cement production including carbon capture, storage and utilisation

- Governments and international development institutions to mitigate risks through investment mechanisms that use private funding for low-carbon innovative technologies and through the promotion of private-public partnerships. For example, programmes such as Horizon 2020 or the Innovation Fund in the European Union help to attract private investment and reduce the risks associated with innovative technologies.

- Governments to co-ordinate identification and demonstration of CO_2 transport networks at regional, national and international levels, to optimise infrastructure development and to lower costs by collaborating with industry, to investigate linkages into existing or integrated networks and opportunities for cluster activities in industrial zones.
- Governments and industry to promote international co-operation, for example through the UNFCCC, to harmonise approaches for safe site selection, operation, maintenance, monitoring and verification of CO_2 permanent storage.
- Governments to develop internationally co-ordinated regulatory frameworks for CCS and CCU and to collaborate with industry to significantly expand efforts to educate and inform the public and key stakeholders about carbon storage, to build social acceptance.
- Governments to reward clean energy investments and provision of flexibility to local energy grids – for example fiscal incentives for EHR.
- Governments and industry to support demonstration, testing and early-stage research for cements based on alternative binders, and to develop standards to facilitate market deployment.
- Governments and industry to encourage joint scientific and engineering research projects among countries, and to establish collaborative research programmes or networks among companies and equipment suppliers.

Support transition to a low-carbon built environment

- Governments to pursue establishing stable international carbon pricing mechanisms encompassed with interim financial stimulus packages and complementary measures to compensate asymmetric pricing pressures in different markets. While cement production is not exposed to cross-border competition, it is crucial that carbon pricing mechanisms are coupled with measures that ensure local lower-carbon cement production to remain competitive against higher-carbon cement imports.
- Governments to revisit, strengthen and establish, in collaboration with industry, building regulations and specifications aimed at achieving carbon neutrality of the built environment over its entire life cycle, including use phase and end of life of buildings and infrastructure applications. Supportive strategies include reusing and recycling concrete in construction, and optimising recarbonation among others.
- Governments to enhance development and deployment of low-carbon solutions in the construction sector that consider a life-cycle approach, by including them in their public procurement policies.
- Universities and industry to adequately train architects/engineers on the applicability of lower-carbon concrete mixes and eco-design opportunities in buildings and infrastructure.
- Universities and industry to adequately train engineers and contractors to use different types of cement.

Investment requirements and financial support

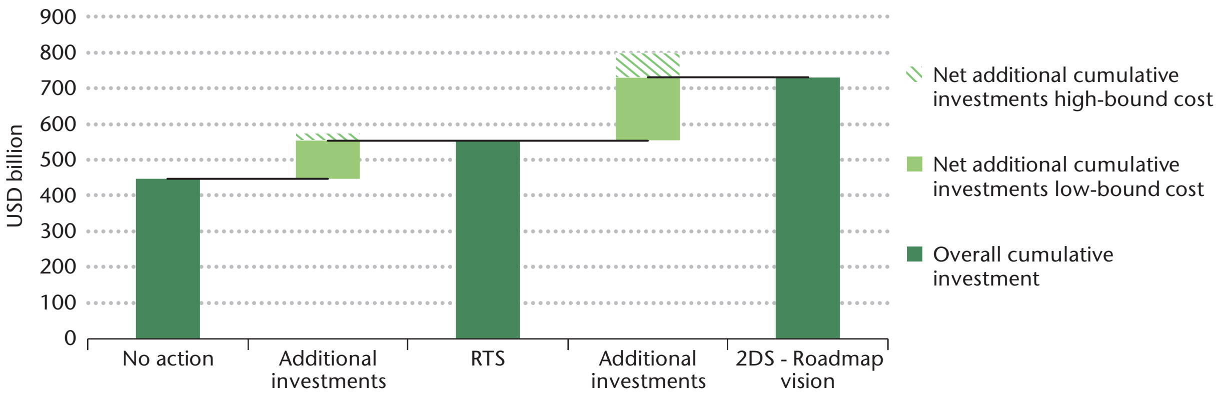
Between USD[50] 176 billion and USD 244 billion net cumulative additional investment costs are estimated as necessary to implement this roadmap vision compared to the RTS (Figure 17). These estimates are based on examining low- and high-cost sensitivity boundaries of technology specific investment costs to cope with the inherent uncertainty of assessing technologies that have not yet reached commercial readiness. The investment discussion is centred on the low-variability case analysed as the reference case of this roadmap.

The RTS already integrates considerable shifts in terms of energy and CO_2 emissions savings in the cement industry, in response to implemented and announced policies and pledges. For instance, the thermal energy intensity of clinker is reduced by 8% and the electricity intensity of cement is reduced by 9% by 2050 below current levels in the RTS globally. The contribution of fossil fuels to the global cement thermal energy mix drops by 12% in the same period. The clinker to cement ratio remains stable over time, despite the increase that the drop in Chinese cement production has at the global level. The RTS considers that pilot testing

50. Investments are estimated based on 2015 USD.

and feasibility studies on integrating carbon capture technologies in the cement industry would translate into a modest deployment in the long term, with carbon captured emissions representing 3% of the total generated CO_2 emissions in the cement sector globally by 2050. Thus, estimated cumulative additional investments of the vision would increase to between USD 283 billion and USD 371 billion if the current energy and carbon emissions footprint of cement making was kept unchanged globally.

Figure 17: Overall cumulative investment needs by scenario by 2050



Note: Net cumulative additional investment numbers are assessed considering low- and high-bound sensitivity ranges for specific investment costs. Overall cumulative investments displayed in the above graph refer to the low-bound cost range.

KEY MESSAGE: USD 107 billion to USD 127 billion are estimated as cumulative additional investments to realise the RTS globally, which would need to increase to between USD 176 billion and USD 244 billion to reach to implement the roadmap vision (2DS).

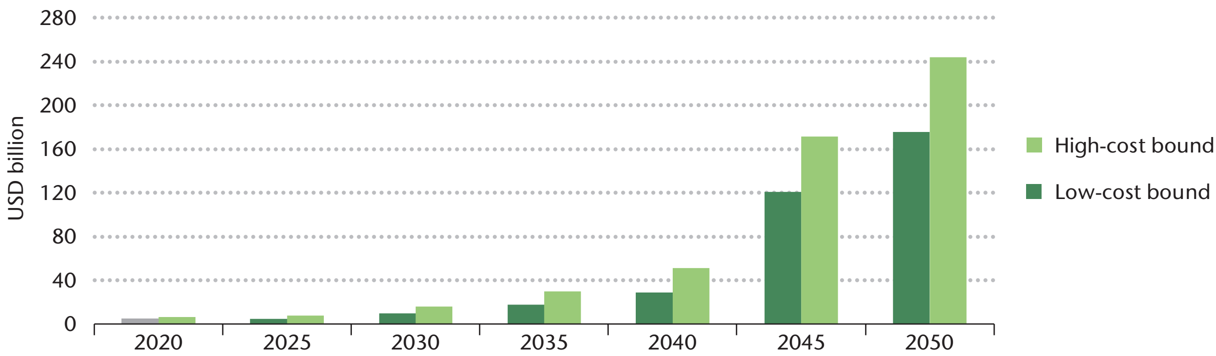
The integration of carbon capture technologies in cement production in the roadmap vision accounts for between USD 204 billion and USD 254 billion cumulative additional investments needs by 2050 in global terms. This represents the largest investment requirement compared to the RTS. Investment costs associated with carbon capture exclude CO_2 transport and storage costs. These investment estimates are sensitive to the future evolution of costs of carbon capture technologies as they become demonstrated at greater scales.

Shifting towards using fuels that are less carbon intensive and reducing the clinker to cement ratio in this roadmap's vision are estimated to incur more modest additional cumulative investments – between USD 41 billion and USD 62 billion jointly by 2050 globally.

In the vision of this roadmap, additional investment related to a wide uptake of state-of-the-art kilns and grinding technologies compared to less-advanced equipment, as well as the addition of onsite power generation capacity based on EHR, is offset by the lower clinker production and raw material and fuel grinding demand resulting from ambitious energy efficiency improvements and clinker to cement ratio reductions. Between USD 68 billion and USD 72 billion net cumulative savings globally are related to the shifts on kilns, grinding and EHR equipment used in this vision compared to the RTS.

The bulk of the estimated global cumulative additional investments in the 2DS compared to the RTS would occur in the period post-2030 (Figure 18). This highlights the strong market deployment needs of new processes in the second half of the modelling horizon to realise the vision. It also demonstrates the urgency of the need to focus on related demonstration projects prior to 2030, to ensure technologies can reach commercial readiness early enough. While increasing cement demand poses greater pressure in reducing carbon emissions to achieve the vision, the installation of new cement capacity creates opportunities for integrating state-of-the-art technology in an advantageous situation compared to revamping projects.

Figure 18: Global cumulative additional investments in the roadmap vision (2DS) compared to the RTS, based on the low-variability case by 2050



Note: Additional investment numbers are assessed considering low- and high-bound sensitivity ranges for specific investment costs.

KEY MESSAGE: The bulk of the 2DS global cumulative additional investments occurs after 2030.

Mobilising financial support

There is an urgent need to mobilise public-private investment to support the sustainable transition of the cement industry. Robust carbon pricing can be one of the key elements in low-carbon transition of society, but governments worldwide struggle with implementation or with ensuring a stable price level. Traditional financing criteria used by industry are not appropriate for carbon mitigation technologies unless a global carbon price (or incentive) is sufficiently high and regionally symmetric to adequately value the cost of reducing CO_2 emissions.

Governments should pursue investment risk-mitigating mechanisms that are results oriented and unlock private finance in areas with low likelihood of independent private investment. In the past, funding of CCS demonstration projects has had a primary focus on power generation projects, but those should be expanded to target industrial applications including the cement sector. These mechanisms could reduce the risk associated with initial capital investment. They could also help investors to maintain a better cash flow by unlocking shares of total allocated financial support upon completion of predefined milestones through the development or demonstration processes.

International foundations can also play an important role in supporting technology implementation and demonstration projects that contribute to the sustainable transition of cement manufacturing, especially in developing countries. The Green Climate Fund, which is accountable to the United Nations, mobilised pledges for USD 10.3 billion in 2014 from governments to finance the pressing mitigation and adaptation needs in developing economies and to unlock private investment (GCF, 2017). The Mission Innovation initiative was announced in 2015, with 22 participating countries and the European Union seeking to double investments in clean energy R&D over five years to 2021. The initiative has focused on seven innovation challenges, which include carbon capture and clean energy materials (Mission Innovation, 2015).

Assessing investments

The investment estimates discussed in this section are based on bottom-up technology modelling of the cement sector, including full plant capital costs for industrial process equipment installed during the time horizon of the vision to 2050. They do not consider any costs related to capacity already existing in the base year or incurred installation costs over the time horizon. Thus, no additional costs are allocated to energy savings from improved operation and maintenance practices. Also, site-specific potentials to reduce energy consumption or CO_2 emissions without a process change or major integration revamp are not captured in the discussed investment costs due to their dependency on local conditions.

The cost impact of activities outside the plant fence is not included. There may be costs related to alternative fuel collection or handling, or transport and storage of CO_2. Costs related to auxiliary equipment such as air separation units or ORCs, which may be required when implementing new units/processes, are not included in capital investment of carbon capture equipment. Additional commodities needed to operate some of the innovative technologies, such as oxygen, are considered in the least-cost optimisation as increased variable operating costs from importing such commodities.

Costs associated with switching to fuels that are less carbon intensive and reducing the clinker to cement ratio are related to the additional storage capacity on site required to handle additional solid fuels and cement constituents.

Lastly, investment costs related to R&D and pilot testing of novel technologies that are commercially deployed after 2030 are not included in these estimates.

International collaboration

International collaboration is essential to supporting the vision of this Technology Roadmap. The IEA works closely with the principal existing international initiatives that accelerate development and deployment of low-carbon technologies for the global cement industry. The CSI provides a framework for international co-operation among global cement companies to identify actions and accelerate progress towards sustainable development. The UNFCCC plays a specific role in putting in place the right processes for international co-operation and in setting the global reference frame. This ensures progressive deployment of the required level playing field to avoid asymmetric environmental policy strategies across different regions, which could lead to cement production shifting towards countries with less-restrictive carbon mitigation industrial policies.

Stakeholders should strengthen international co-operation, for example through the UNFCCC process, to gather reliable industry-level energy and emissions data, to support policy development, to track performance and to identify regional and national best practice benchmarks, for example through the CSI Getting the Numbers Right database.

The IEA Technology Collaboration Programmes provide a framework for stakeholders from both the public and private sectors to share knowledge and to pool resources to provide integrated, cost-effective solutions to common challenges. The IEA programme on Industrial Energy-Related Technologies and Systems provides an international research platform to accelerate research and technology development on industrial technologies and systems. The IEA programme on Greenhouse Gas R&D is an international collaborative research platform, including governmental and private actors, that evaluates technologies that can reduce greenhouse gas emissions from fossil fuels, including carbon capture.

The seven innovation challenges identified by Mission Innovation offer opportunities for enhanced collaborative efforts. The challenge on Carbon Capture aims to enable near-zero CO_2 emissions from power plants and carbon-intensive industries including cement production. The challenge on Clean Energy Materials aims to accelerate the exploration of new high-performance and low-cost structural materials within a broader range of material applications.

Roadmap action plan

Stakeholders	Action Items
Finance / economy ministries	• Mitigate risks through investment mechanisms that use private funding for low-carbon innovative technologies and through promotion of private-public partnerships. • Eliminate energy price subsidies that can act as a barrier to use of energy-efficient technologies. • Reward clean energy investments and the provision of flexibility to local energy grids, e.g. fiscal incentives for EHR.
Environmental, energy and resource ministries	• Pursue efforts towards developing stable international carbon pricing mechanisms encompassed with stimulus interim packages to compensate asymmetric pricing pressures in different markets. • Promote deployment of an economy based on resource efficiency and ensure national waste disposal policies enable the full potential of co-processing in the cement industry and facilitate stakeholder and public understanding of the role of alternative fuel use in climate change mitigation. • Develop plant- or sector-level energy efficiency improvement target-setting programmes. • Develop new, or revise existing, cement standards and codes, to allow widespread use of blended cement and to facilitate the use of cements based on alternative binding materials. • Co-ordinate identification and demonstration of CO_2 transport networks at regional, national and international levels to optimise infrastructure development, and lower costs by collaborating with industry to investigate linkages into existing or integrated networks and opportunities for cluster activities in industrial zones. • Harmonise approaches for safe site selection, operation, maintenance, monitoring and verification of CO_2 permanent storage. • Fund research, development and demonstration programmes to target knowledge gaps in different aspects of CCS technology development/co development. • Develop internationally co-ordinated regulatory frameworks for CCS and collaborate with industry to expand efforts to educate and inform the public and key stakeholders about carbon storage, to build social acceptance. • Revisit, strengthen and establish, in collaboration with industry, building regulations and specifications aimed at achieving carbon neutrality of the built environment over its entire life cycle, including during the use phase and at end of life of residential, non-residential and infrastructure applications.
Training / science ministries and universities	• Promote international training events with national standardisation bodies and accreditation institutes, to exchange knowledge on reducing the clinker to cement ratio, concrete standards and concrete performance. • Oversee independent environmental impact studies on the use of alternative cement blending and binding materials. • Train architects/engineers on the applicability of lower-carbon concrete mixes. • Train engineers and contractors to use different types of cement and to get a better understanding of sustainability issues related to building materials. • Create institutional frameworks for industry-scale technology initiatives (managing and implementing projects, financing mechanisms, partnership rules and governance models). Collaborate with other stakeholders, to promote co operation among countries and their public and private sectors to pool funding and knowledge.
Multilateral development agencies	• Promote alternative sources of funding for innovative low-carbon technologies in the cement industry, including export credit agencies and multilateral development banks.

Stakeholders	Action Items
Industry	• Phase out long-dry kilns and wet production processes still in operation. • Gather reliable industry-level energy and carbon emissions data to track performance and identify benchmarks. • Collaborate with governments in the development of plant- or sector-level energy efficiency improvement target-setting programmes. • Conduct R&D into processing techniques for potential alternative cement blending and binding materials. • Establish collaborative research programmes or networks among companies, equipment suppliers, research institutes and governments to pool R&D and demonstration resources, and public-private partnerships on emissions reductions (including carbon, capture, storage and utilisation).
State, provincial and local governments	• Review and update local legislation to ensure alternative fuel and biomass use is not restricted but incentivised by policy. • Ensure operators follow common sets of guidelines on alternative fuel use to guarantee adequate processes, e.g. by training, documenting and monitoring for transparency. • Provide adequate training for those responsible for permits, control and supervision, to build trust among communities. • Adapt technology transfer processes to individual regions, recognising that differences exist in availability of supply, legislative support and enforcement, and public understanding. • Promote the use of blended cements in sourcing and public procurement policies. • Enhance the development and deployment of low-carbon solutions in the construction sector that consider a life-cycle approach, by including them in public procurement policies.
Non-governmental organisations and think tanks	• Engage with industry to understand the role of co processing alternative fuels in climate protection and industry's best practice in managing these safely. • Communicate the role of carbon capture, storage and utilisation in climate change mitigation.

Annex

Roadmap modelling framework and methodology

The energy and direct CO_2 results of this roadmap are derived from the cement model of the IEA ETP project, which covers the global energy system. The ETP cement model follows a bottom-up approach, to account for the cement manufacturing processes, from obtaining raw materials and preparing the fuel through to cement grinding and milling.

Each process or technology is characterised by energy performance, material yield and cost, within a set of realistic constraints. The model is based on TIMES[51] and generates a cost-optimal technology portfolio to meet an exogenously set cement production level within defined constraints. Final energy demand by energy carrier, material and direct CO_2 flow, as well as related technology investments, are generated as results from the ETP cement model. The tool provides global coverage by aggregating 39 individually defined countries and regions.

The ETP cement model boundary is aligned with the cement manufacturing process (Figure 19). Additional resource use and emissions are associated with the processes of using cement in concrete, and the eventual disposal of concrete, but these aspects are beyond the scope of this model. The cement sector energy use and technology portfolio is characterised in the base year (2014) using energy use and material production statistics and estimates, including data from the WBCSD-CSI, the China Cement Association, the Confederation of Indian Industry, the Brazilian Sindicato Nacional da Indústria do Cimento and the IEA.

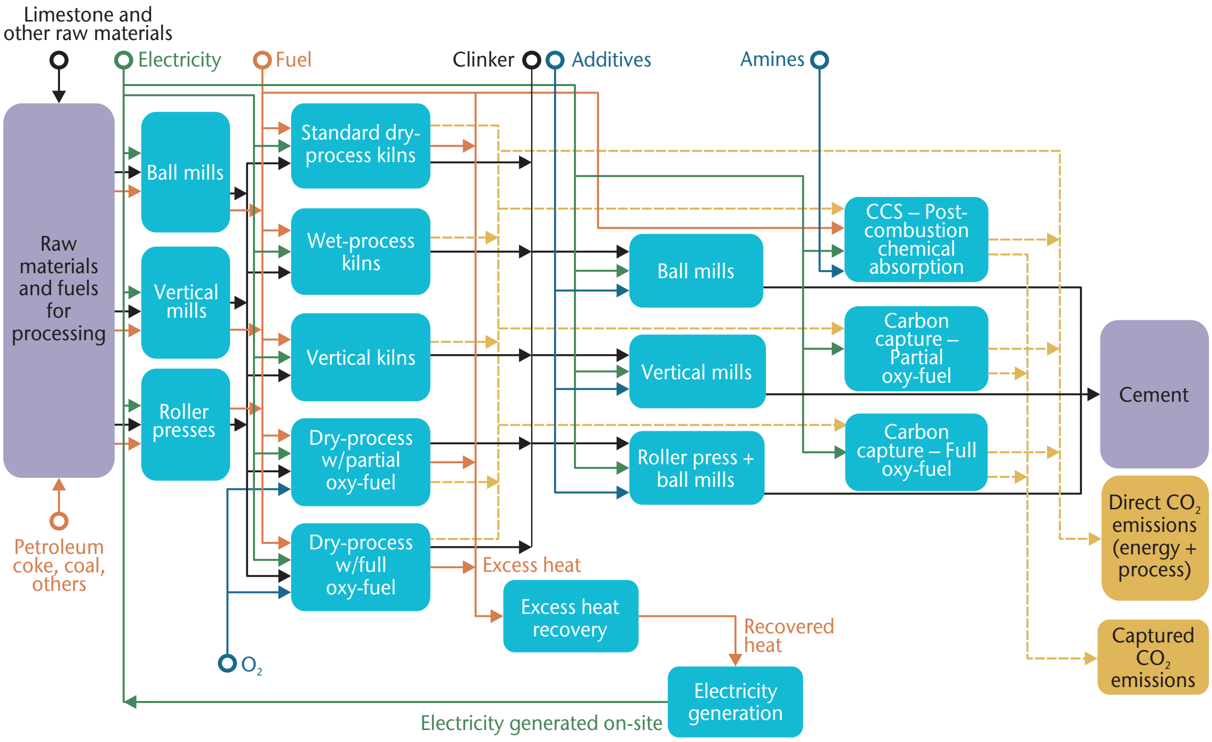
Changes in technology deployment and fuel mix over time in each scenario are influenced by exogenous assumptions of the potential for market penetration and energy performance of state-of-the-art technologies, constraints on the availability of raw materials, techno-economic characteristics of the available technologies and process routes, assumed progress on demonstrating innovative technologies at commercial scale, and the direct CO_2 emissions budget defined in the scenario. The results are therefore sensitive to assumptions of the pace of physical capital turnover, relative costs of various technology options and fuels and incentives for the use of state-of-the-art technology for new capacity. Fuel costs are based on outputs from the ETP supply sector model, and are specific for each scenario analysed.

Demand for materials is an exogenous input to the model, estimated from data on GDP growth, per capita income, short-term industrial capacity, current material consumption levels, regional material demand saturation levels derived from historical regional material demand intensity curves and resource endowments. Regional GDP and population projections are based on various sources (IEA, 2016b; IMF, 2016; UN DESA, 2015).

The low-variability case is considered the future evolution of cement production that is most likely, and thus is considered as the reference case for the analysis. A high-variability case has been developed by scaling up the relative variation of cement demand over time in the different regions to cope with the inherent uncertainty of projecting future material demand levels. The high-variability case is intended as a sensitivity analysis of the cement production levels.

51. TIMES (The Integrated MARKAL-EFOM System) is a model generator developed by the IEA Energy Technology Systems Analysis Programme, and allows an economic representation of local, national and multiregional energy systems on a technologically detailed basis.

Figure 19: High-level structure of the IEA ETP cement sector model



KEY MESSAGE: The ETP cement model covers the cement manufacturing process.

Regional definitions

Africa	South Africa, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of the Congo, Cote d'Ivoire, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mozambique, Namibia, Nigeria, Senegal, Sudan, Tanzania, Togo, Zambia, Zimbabwe, Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland and Uganda
America	United States, Canada, Mexico, Chile, Brazil, Argentina, Bolivia, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, and Turks and Caicos Islands
China	China (Peoples' Republic of)
Eurasia	Russian Federation, Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan

Europe	France, Germany, Italy, United Kingdom, Denmark, Finland, Sweden, Austria, Belgium, Czech Republic, Estonia, Greece, Hungary, Ireland, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, Bulgaria, Croatia, Cyprus*, Latvia, Lithuania, Malta, Romania, Ukraine, Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Kosovo**, Former Yugoslav Republic of Macedonia, Moldova, Montenegro, Serbia, Iceland, Israel, Norway, Turkey*** and Switzerland
India	India
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen
Other Asia Pacific	Japan, Korea, Australia, New Zealand, Indonesia, Malaysia, Philippines, Thailand, Viet Nam, Brunei Darussalam, Cambodia, Lao People's Democratic Republic, Myanmar, Singapore, Bangladesh, Democratic People's Republic of Korea, Mongolia, Nepal, Pakistan, Sri Lanka, Afghanistan, Bhutan, Cook Islands, Timor Leste, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu

* Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue". Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

** This designation is without prejudice to positions on status, and is in line with United Nations Security Council Resolution 1244/99 and the Advisory Opinion of the International Court of Justice on Kosovo's declaration of independence.

*** The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

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Glossary

Aggregate: material used in construction, including sand, gravel and crushed stone.

Alternative fuels: products from full or partial biogenic origin or from fossil fuel origin and not classified as traditional fossil fuels, which are used as a source of thermal energy.

Biomass: any organic (i.e. decomposing) matter derived from plants or animals available on a renewable basis, including wood and agricultural crops, herbaceous and wood energy crops, municipal organic wastes and manure.

Blended cement: Portland cement (PC) mixed with other constituents as well as clinker.

Cement: a building material made by grinding clinker together with various mineral components such as gypsum, limestone, blast furnace slag, coal fly ash and natural volcanic material. Cement acts as a binding agent when mixed with sand, gravel or crushed stone and water to make concrete. Although cement qualities are defined by national standards, there is no worldwide, harmonised definition or standard for cement. In the World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative (CSI) protocol and the Getting the Numbers Right database, "cement" includes all hydraulic binders that are delivered to the final customer. That is, it includes all types of PC, composite and blended cements, and ground granulated slag and fly ash delivered to the concrete mixers, but excludes clinker.

Cementitious product: total of all cements and clinker produced by a cement company, excluding the clinker purchased from another company and used to make cement. The precise definition of cementitious product in this context is according to the WBCSD-CSI cement protocol (CSI, 2011). Cement is the cementitious product when the net balance of clinker sold and purchased is zero.

Clinker: an intermediate product in cement manufacturing and the main substance in cement. It is the result of calcination of limestone in the kiln and subsequent reactions caused through burning.

Clinker to cement ratio: total clinker consumed divided by the total amount of cement produced.

Comminution: a process in which solid materials are reduced in size, by natural or industrial processes including crushing and grinding, or a process in which useful materials are freed from embedded matrix materials. It is used to increase the surface area of solids in industrial processes.

Concrete: material comprising cement, sand and gravel or other fine and coarse aggregate.

Co-processing: the use of waste materials in industrial processes (e.g. cement) as substitutes for fossil fuels or raw materials.

Direct carbon dioxide (CO_2) emissions: CO_2 emissions that are generated and released in the cement production process.

Dry kiln: equipment that produces clinker without using a water/limestone slurry mix as the feedstock.

Electricity intensity of cement: consumption of electricity in cement production, including electricity use in the production of the consumed clinker in the kiln, divided by the cement and substitute production.

Fly ash: exhaust-borne particulates generated and captured at coal-fired power plants.

Gross direct CO_2 emissions: total direct CO_2 emissions from the cement production process including CO_2 related to the combustion of wastes based on fossil fuels but excluding those from biogenic wastes (CSI, 2011).

Oxy-fuel: the combustion of fuels with oxygen instead of air.

Petroleum coke: a carbon-based solid derived from oil refineries.

Portland cement (PC): the most-common type of cement, consisting of over 90% clinker and about 5% gypsum.

Pozzolana: a material that exhibits cementitious properties when combined with calcium hydroxide.

Precalciner: a system that comes before the rotary kiln in the cement manufacturing process where most of the limestone calcination is accomplished, thus making the process more energy efficient.

Process CO_2 emissions: CO_2 generated as a result of chemical reactions from carbon contained in raw materials.

Recarbonation: the chemical reaction in a natural process by which carbon dioxide in the ambient air penetrates and reacts with hydration products.

Thermal energy intensity of clinker: total heat consumption of kilns divided by the clinker production.

Traditional fuels: fossil fuels defined by the guidelines of the Intergovernmental Panel on Climate Change, including mainly coal, petroleum coke, lignite, shale petroleum products and natural gas.

Wet kiln: equipment that produces clinker using water/limestone slurry as the feedstock.

Abbreviations and acronyms

2DS	2 degree Celsius Scenario
B2DS	Beyond 2 degree Celsius Scenario
BCSA	belite calcium sulphoaluminate
CACS	carbonation of calcium silicates
CAGR	compound annual growth rate
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CO_2	carbon dioxide
COP	Conference of the Parties
CSA	calcium sulphoaluminate
CSI	Cement Sustainability Initiative
EHR	excess heat recovery
ETP	Energy Technology Perspectives
GDP	gross domestic product
GGBFS	ground granulated blast furnace slag
GNR	Getting the Numbers Right
IEA	International Energy Agency
MOMS	magnesium oxide derived from magnesium silicates
OECD	Organisation for Economic Co-operation and Development
PAT	Performance Achieve Trade
PC	Portland cement
PHCS	pre-hydrated calcium silicates
R&D	research and development
RTS	Reference Technology Scenario
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
WBCSD	World Business Council for Sustainable Development

Units of measure

°C	degree Celsius
EJ	exajoule (10^{18} joules)
EUR/t	euro per tonne

GJ	gigajoule (10^9 joules)
GJ/t	gigajoule per tonne
GJ/tCO_2	gigajoule per tonne of carbon dioxide
Gt	gigatonne (10^9 tonnes)
GtCO_2	gigatonne of carbon dioxide
GtCO_2/yr	gigatonne of carbon dioxide per year
kg	kilogramme (10^3 grammes)
ktCO_2/yr	thousand tonne (10^3 tonnes) of carbon dioxide per year
kWh	kilowatt hour (10^3 watt hours)
kWh/t	kilowatt hour per tonne
Mt	million tonne (10^6 tonnes)
MtCO_2	million tonne of carbon dioxide
MtCO_2/yr	million tonne of carbon dioxide per year
Mt/yr	million tonne per year
MW	megawatt (10^6 watts)
t	tonne
tCO_2	tonne of carbon dioxide
tCO_2/GJ	tonne of carbon dioxide per gigajoule
tCO_2/yr	tonne of carbon dioxide per year
USD/tCO_2	United States dollar per tonne of carbon dioxide

Disclaimer

This report is the result of a collaborative effort between the IEA and the World Business Council for Sustainable Development's (WBCSD) Cement Sustainability Initiative (CSI). The individual member companies that make up the CSI have participated in the development of this report, but have made no specific commitments on implementation of any technologies described in the report. Users of this report shall take their own independent business decisions at their own risk and, in particular, without undue reliance on this report. Nothing in this report shall constitute professional advice, and no representation or warranty, express or implied, is made in respect to the completeness or accuracy of the contents of this report. Neither the WBCSD, nor the IEA accepts any liability whatsoever for any direct or indirect damages resulting from any use of this report or its contents. A wide range of experts reviewed drafts. However, the views expressed do not necessarily represent the views or policy of either the CSI, or their member companies, or of the IEA, or its individual member countries. For further information, please contact: technologyroadmaps@iea.org or cement@wbcsd.org.

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Technology Roadmap Low-Carbon Transition in the Cement Industry

2017

2020

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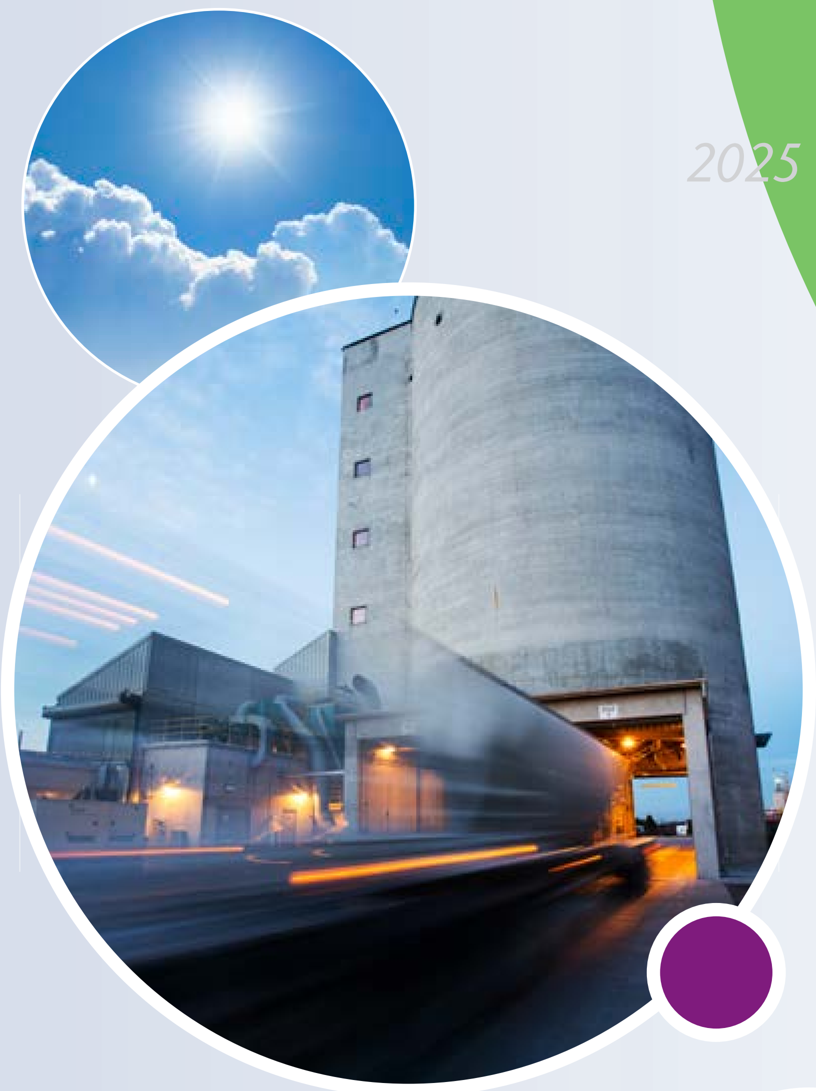

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