MISSION

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

POSSIBLE

ENERGY TRANSITIONS COMMISSION

SECTORAL FOCUS

CEMENT

The **Energy Transitions Commission (ETC)** brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

In November 2018, the ETC published ***Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century***. This flagship report is available on our website. This report describes in turn:

- Why reaching net-zero CO_2 emissions across heavy industry and heavy-duty transport sectors is technically and economically feasible;
- How to manage the transition to net-zero CO_2 emissions in those harder-to-abate sectors of the economy;
- What the implications of a full decarbonization of the economy are for the energy system as a whole, in particular in terms of demand for electricity, hydrogen, bioenergy/bio-feedstock, and fossil fuels, as well as carbon storage requirements;
- What policymakers, investors, businesses and consumers must do to accelerate change.

This Sectoral Focus presents in more details the underlying analysis on cement decarbonization that fed into the ETC's integrated report *Mission Possible*. It constitutes an updated version of the consultation paper with the same title published by the ETC in July 2018.

We warmly thank all experts from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have provided feedback on this consultation paper. Their insights were instrumental in shaping the *Mission Possible* report and this updated Sectoral Focus.

The *Mission Possible* report and the related Sectoral Focuses constitute **a collective view of the Energy Transitions Commission**. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report. The list of our Commissioners at the time of publication can be found in the *Mission Possible* report.

In 2019, the Energy Transitions Commission will continue to engage actively and work with key policymakers, investors and business leaders around the world, using our analysis and the unique voice of the ETC to inform decision-making and encourage rapid progress on the decarbonization of the harder-to-abate sectors. We are keen to exchange and partner with those organizations who would like to progress this agenda. Please contact us at info@energy-transitions.org.

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REACHING NET-ZERO CARBON EMISSIONS FROM CEMENT

Cement accounts for 2.2Gt of CO_2 emissions in 2014, including 1.2Gt of process emissions and 0.75Gt of emissions from heat[1]. **Decarbonizing the cement sector poses one of the most difficult challenges in the shift to a low-carbon economy** due to process emissions, which are particularly difficult to avoid.

New cement chemistries could be less carbon-intensive, but there is a risk that these new chemistries can only make a moderate contribution to emissions reductions due to scarcities of local resource supply and differences in the resulting cement properties. **Eliminating process emissions will require the use of carbon capture**, which will inevitably add some cost, even if the CO_2 is then used as input to concrete rather than simply stored.

Meanwhile, **carbon emissions from heat** used in cement production could be reduced via a switch from coal to gas (particularly in China) and could eventually be eliminated via heat electrification, the use of biomass or the use of hydrogen. But, each of these three routes would likely entail significant additional costs.

Reducing carbon emissions from cement will therefore also entail better demand management. Cement is an essential construction material, key to the development of regions like India and Africa which are still in the process of urbanizing and building up key infrastructure. Unless there is a major shift to use **timber as a substitute for buildings material**, which is not without its own challenges, total global cement production will continue to grow rapidly. However, **demand growth could be slowed down via greater materials efficiency in building design, waste reduction and some materials circularity**.

Given these challenges, **cement decarbonization is likely to imply a significant increase in cement prices and could account for circa 60% of the global costs of decarbonizing all the harder-to-abate industrial sectors**[2]. But these costs can probably be absorbed by the economy without adverse consequences, given the inherently local nature of cement production and distribution, and the limited impact on end consumer prices.

SUPPORTING ANALYSIS AND REPORTS

The Energy Transitions Commission work on cement has drawn extensively on the existing literature (cited throughout this document), and more particularly on inputs from **two knowledge partners**:

- A report by **Material Economics** on the potential for greater materials circularity, which particularly focused on Europe – *The circular economy: a powerful force for climate mitigation* (2018) and a follow-up analysis replicating this work at a global scale (commissioned by the ETC);
- A report by **McKinsey & Company** on supply-side decarbonization options across several industrial sectors – *Decarbonisation of the industrial sectors: the next frontier* (2018).

[1] IEA (2017), *Energy Technology Perspectives*
[2] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM CEMENT

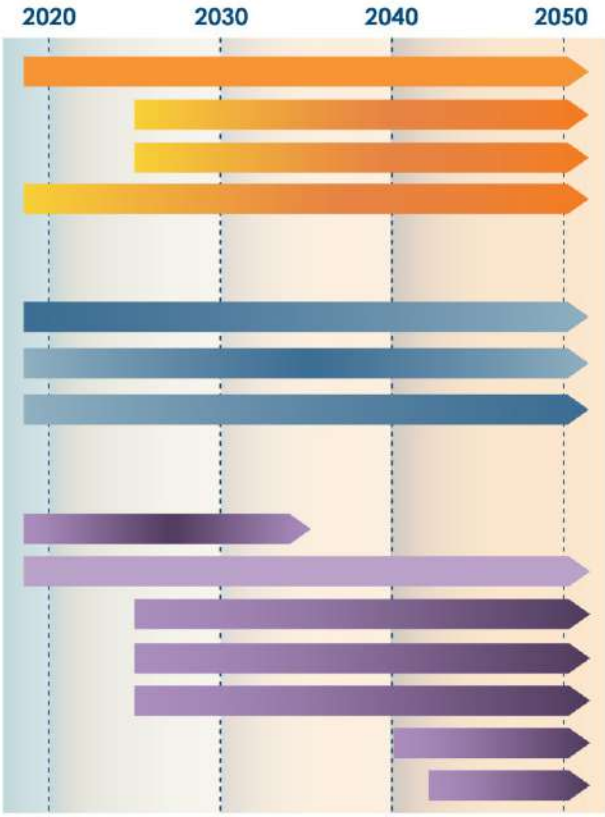
7% OF TOTAL GLOBAL EMISSIONS

TODAY	2050 BAU
2.2 $GtCO_2$	2.3 $GtCO_2$

REACHING NET-ZERO CO_2 EMISSIONS FROM CEMENT IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Designing buildings more efficiently	-34%
	Recycling un-hydrated cement	
	Reusing concrete	
	Substituting concrete with timber	UNCERTAIN
2 ENERGY EFFICIENCY	Switch to dry kilns	-10%
	Multistage cyclone heaters	
	Decrease of clinker-to-cement ratio	
3 DECARBONIZATION TECHNOLOGIES	Gas (transition fuel)	-25%
	Biomass/waste for heat generation (localized)	-50%
	Carbon capture on production and process emissions	-90%
	Belite clinker	-10%
	Pozzolan-based concrete	-70%
	Cement-less concrete	-100%
	Kiln electrification	-50%

TECHNOLOGY APPLICABILITY / AVAILIBILITY OVER TIME



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2	B2B COST	COST TO END CONSUMER
CO_2: +$110/130	+$100 PER TONNE OF CEMENT; +100%	+$15,000 ON A $500K HOUSE; +3%

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Pilot new industrial processes producing a purer CO_2 stream and reducing the cost of carbon capture
- Develop low-carbon heat technologies (e.g. hydrogen or electric kiln furnaces) to commercially feasible scale
- Develop new construction materials, including new cement and concrete chemistries

POLICY

- Set a domestic/regional carbon price of $100 per tonne of CO_2
- Use public procurement of buildings and infrastructure to create initial demand for low-carbon construction materials
- Strengthen existing building standards to include embedded carbon intensity targets and shift from materials specification to performance specification

INDUSTRY/BUSINESSES

- Cement producers: invest in R&D and pilot carbon capture at commercial scale
- Construction industry: increase materials efficiency in buildings and address the barriers to higher recycling rates
- Construction industry, building buyers and occupiers: commit to "green buildings" defined as low operational and embedded carbon emissions

1. OVERVIEW OF THE CHALLENGE

A. DEMAND TRENDS TO 2050

Cement is a vital input to concrete, which in turn plays a fundamental role in the construction of most modern buildings and infrastructure, for instance for roads, dams, airports and wind turbine bases. Current global demand of circa 4.2 billion tonnes per year is forecasted by the IEA's Reference Technology Scenario to **grow to 4.7 billion tonnes by 2050**[3]. The biggest increase in demand for cement is not expected in developed economies such as the US and Europe, but rather in the rapidly growing and urbanizing economies, which are still going through a major construction phase. While the US and Europe account for only 13% of global cement production, **China's 2.5 billion tonnes currently account for 60%**[4]. This figure is likely to fall as the huge Chinese construction boom is coming to an end. By contrast, **cement production in India and Africa is likely to more than triple over the next 35 years** as urbanization drives huge demand for concrete [Exhibit 1].

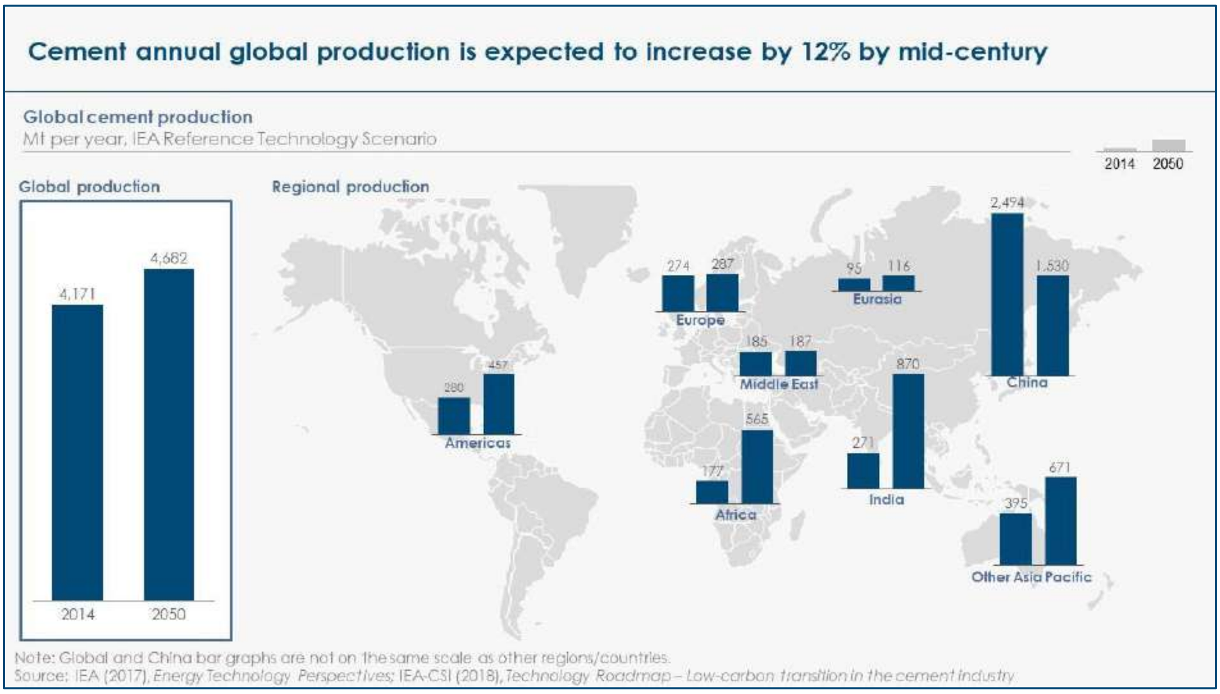


Exhibit 1

B. CARBON EMISSIONS

Global carbon emissions from cement production are **currently around 2.2Gt CO_2 per annum**, about 7% of global energy system emissions. Business as usual scenarios suggest that this **could rise to 2.3Gt per annum by 2050**[5] [Exhibit 2], with the growth in global cement demand driven by regions that are more unlikely to make significant progress on the decarbonization front.

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[3] IEA & CSI (2018), *Technology Roadmap – low carbon transition in the cement industry*
[4] IEA (2017), *Energy Technology Perspectives*
[5] IEA (2016), *Energy Technology Perspectives*

The production of Portland cement (which is currently the predominant cement type) entails the heating of ground limestone ($CaCO_3$) to an extreme temperature (>1400°C) in kilns to produce calcium oxide (CO) where CO_2 is emitted as a result. While process emissions from the production of cement releases 1.2Gt of CO_2 per annum, the heat input to cement production currently generates roughly 0.75Gt of CO_2 per annum, while other manufacturing steps also cause indirect emissions from electricity used to operate machinery.

Accordingly, CO_2 emissions per tonne of cement can be broken down as follows[6]:

- **Direct process emissions**, which are inherent to the chemical reaction, are about 0.5 tonnes of CO_2 per tonne of cement produced and are the same regardless of the energy source of the heat production but can vary depending on the feedstock.
- **Emissions resulting from the combustion of fuel to produce heat**, which are on average about 0.3 tonnes of CO_2 per tonne of cement today, will vary considerably depending on the fuel input and could potentially be brought down to zero in future.
- **Smaller indirect emissions** resulting from the generation of electricity used in the various crushing and grinding processes, which amount to less than 0.1 tonnes of CO_2 per tonne of cement, given the typical carbon intensity of electricity generation today[7].

Important variations in the carbon intensity of fuels used for heat generation explain the differences in carbon emissions from cement production across different geographies and sites today. Current fuel sources indeed include coal (which in itself varies in quality and therefore in carbon intensity from region to region), pet coke (derived from oil), gas and various forms of biomass or waste. Across the world, coal is used for 66% of current production, with variations from over 86% in China to less than 25% in the EU[8].

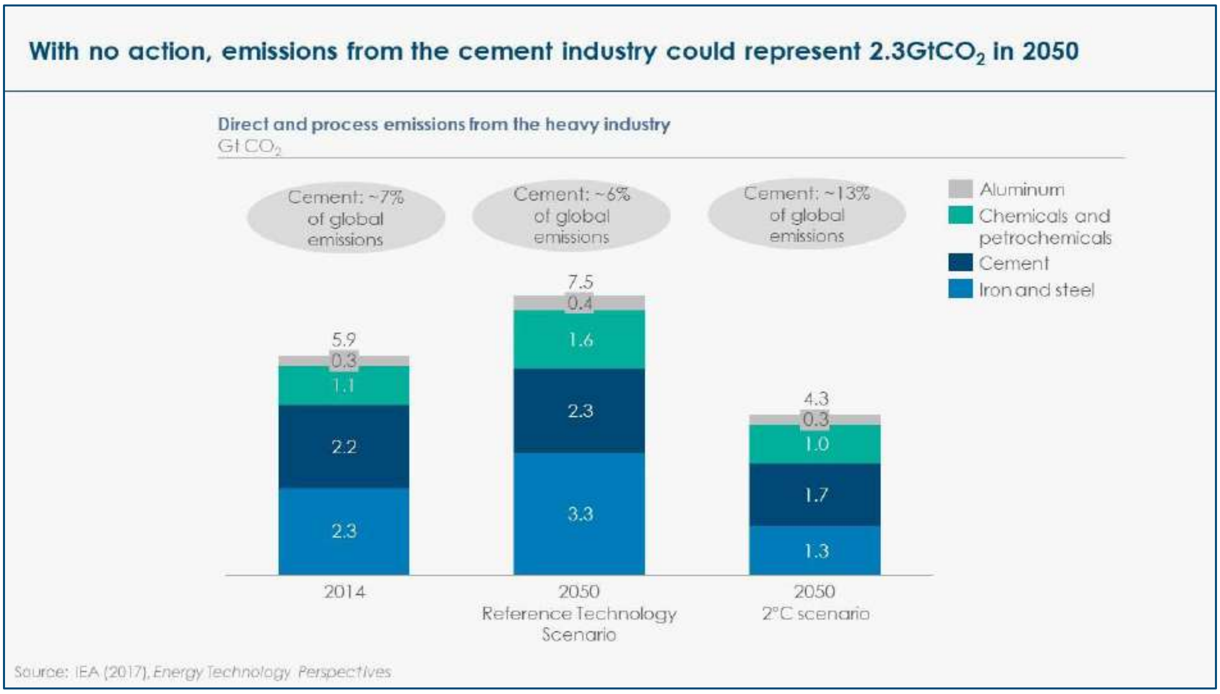


Exhibit 2

[6] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[7] ETC calculations based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[8] IEA & CSI (2018), *Technology Roadmap – low carbon transition in the cement industry*

2. REDUCING CARBON EMISSIONS THROUGH CEMENT DEMAND MANAGEMENT

Decarbonizing cement production – while possible through a variety of different routes – is almost certain to result in significant additional costs. Moreover, the potential role of carbon capture and storage as a route to eliminate process emissions may be limited in specific geographies by a lack of storage capacity. **It is therefore vital to explore all possible routes to reduce the demand for cement while continuing to provide the end products or services which deliver customer benefits.**

In the report *The Circular Economy: a powerful force for climate mitigation* (2018), our knowledge partner Material Economics assesses the potential to reduce the demand for each of the major construction materials in Europe. Commissioned by the ETC, they then replicated this work at a global level. Their analysis suggests **a potential to reduce primary cement demand by up to 35%**[9] [Exhibit 3]. In addition, ETC analysis highlights **the large long-term potential to substitute timber for cement in building construction** as well as other material substitutions options.

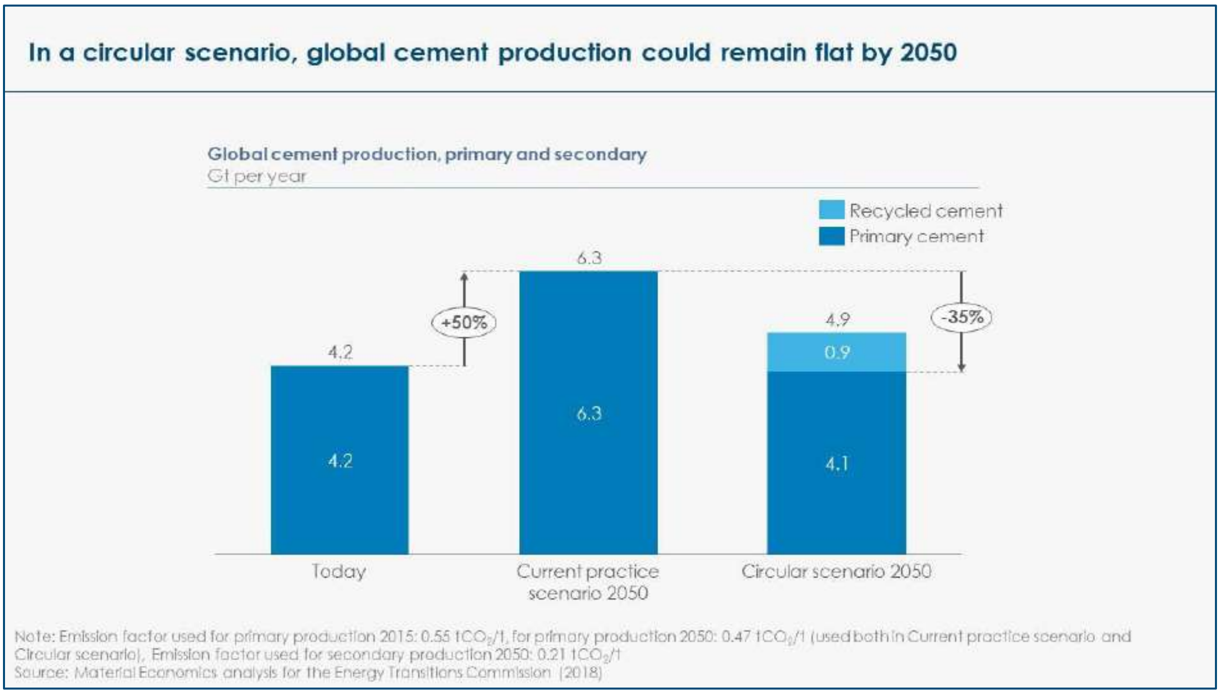


Exhibit 3

[9] Material Economics analysis for the Energy Transitions Commission (2018)

A. REDUCING PRIMARY CEMENT PRODUCTION THROUGH INCREASED RECYCLING, REUSE, AND MATERIALS EFFICIENCY

The Material Economics analysis considers **3 ways in which materials use in buildings could be reduced** – through greater materials recirculation, more efficient use of materials in buildings, and by getting greater value out of each square meter of building during its life [Exhibit 4]. Along each of these dimensions, they identify significant opportunities to reduce cement demand.

Exhibit 4

RECYCLING CONCRETE AND RECOVERING CEMENT

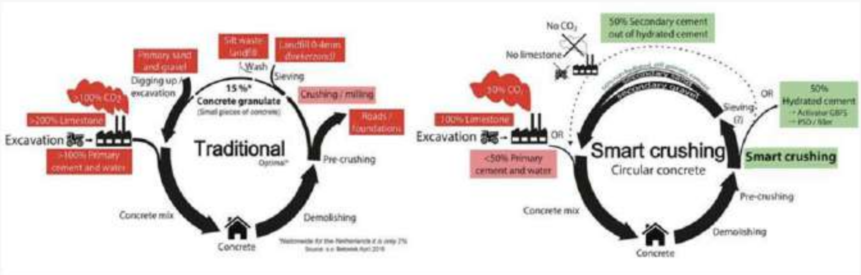
It is often said that it is virtually impossible to recycle hydrated cement (i.e. cement which has reacted with water) in the same simple way that one can in principle recycle plastics or scrap steel by melting them down for reuse, but there is still considerable scope for reducing cement demand via a more circular approach to cement and concrete use since:

- **A large proportion of cement remains un-hydrated within concrete** and can be recovered and reused if carefully designed processes are used to crush the concrete and separate the different constituent materials [Exhibit 5].
- The hydrated cement recovered through this process could also potentially be reused, but it would need to be **reprocessed in a cement kiln** – as a substitute to limestone – to be turned back into useful cement. Since the hydrated cement does not contain CO_2, reusing it in this way reduces emissions compared with the alternative of making new cement from limestone.
- **Concrete can be recycled** and used again as aggregate, for instance in road-based construction. Many countries have extensive concrete recycling systems designed to prevent the landfill of concrete waste. However, the impact of concrete recycling on

carbon emissions is small, since it is used primarily to substitute uncemented aggregates rather than newly mixed concrete. Nevertheless, the existence of a large concrete recycling industry, if combined with the cement recovery techniques of smart crushing, could help achieve reduced cement demand.

Cement-to-clinker process is irreversible, but Smart crusher enables recycling of un-hydrated cement in concrete

Smart crusher technology enables recycling of sand, gravel and unused cement



- Traditional crushing methods release original concrete rubble mass as 0-4 mm crusher sand, which currently has limited valuable use
- Small amounts of cement stone are released and polluted with fine silicate particles, and can therefore not be used for making traditional cement

- The Smart Crusher does not break through the sand and gravel but only crushes the cement stone, resulting in:
  - Separation of fines into unhydrated cement, hydrated cement, sand and gravel
  - Sand and gravel retrieved with improved quality, resulting in 25% increase in strength
  - Extra strength can reduce cement input by ~15%
  - Unused cement is retrieved and unpolluted by sand etc., and can be used again

Source: Smartcrusher website

Exhibit 5

IMPROVED MATERIALS EFFICIENCY IN CONSTRUCTION

There are also many opportunities **to construct high-quality buildings and infrastructure with significantly reduced construction material input** per square meter of usable space.

- Industry experts suggest that, in Europe, 10 to 20% of building materials may be wasted in the construction process[10].
- There is also a widespread tendency to over-specify the design including material quantities well in excess of structural requirements.
- The potential to reuse entire structural elements of older buildings in new ones is also significant. Examples such as a German residential area near Berlin that has reused precast concrete elements, reducing the cost of construction by 30%[11], should inspire the construction industry.

MAKING MORE USE OF EACH BUILDING

Significant reductions in total carbon emissions from construction – and in particular, cement inputs – could also be achieved **if building lifetimes were longer**. New modular approaches to building design could enable periodic fundamental renovation to adapt to new building functions (e.g. shift to residential use rather than commercial use) and new architectural preferences, while keeping much of the basic structural frame unchanged.

[10] Material Economics (2018), *The circular economy – a powerful force for climate action*
[11] Material Economics (2018), *The circular economy – a powerful force for climate action*

In addition, the value derived from each square meter could be enhanced if **commercial space were utilized more intensively via office sharing approaches**. A similar principle can be applied in the residential sector, for instance through building designs that include shared collective spaces alongside private flats (like shared laundry rooms or guest rooms), but behavioral change constitutes a greater barrier to adoption than in the commercial sector.

TOTAL POTENTIAL FROM CIRCULAR APPROACHES TO THE BUILDINGS SECTOR

An indicative scenario developed by Material Economics suggests that European construction emissions in 2050 could be reduced by 34% if more circular approaches were applied to the four major material inputs to the construction sector – steel, plastics, aluminum and cement [Exhibit 7]. **Cement emissions in particular could be reduced by up to 45%[12].**

The scenario presented by Material Economics is for Europe, and one of the potential recirculating levers – cement recovery and reuse – may be less applicable in developing countries, which lack a large existing stock of buildings and concrete from which cement can be recovered. But other levers – in particular, improved materials efficiency – are equally applicable across the world, and vitally important to use in countries going through rapid urbanization.

The cost implications of these routes to demand and emissions reductions is also inherently uncertain. **Some of the measures which improve material efficiency are likely to entail negative abatement cost per tonne of CO_2 saved** and should logically be pursued even without a carbon price. However, in average, these measures come with a net cost (see Section 5). But the fragmented structure of the construction industry, with multiple small companies and complex contracting chains spanning diverse parties, reduces the incentives for cost minimization, which means that market competition does not deliver the theoretically possible lowest-cost result. The costs of recapturing and reusing concrete relative to primary production are currently unclear but would almost certainly fall significantly if developed on a large scale, thanks to strong policy incentives. Policy measures which might drive materials efficiency and circularity are considered in Section 7 below.

B. REDUCING DEMAND FOR CEMENT THROUGH MATERIAL SUBSTITUTION

An alternative way to reduce cement demand would be to use other building materials instead of concrete. **Timber could in principle play a major material substitution role in the buildings sector, with a dramatic potential effect on total carbon emissions**. Cross-laminated timber can be used as an alternative to concrete and steel in an increasingly wide range of building sizes – a 53-meter building currently stands in Vancouver, another 52-meter one is in construction in Brisbane, and a planned skyscraper project in Japan would significantly surpass these heights at 350 meters, comprised of 90% timber[13]. It may also prove to be a cheaper and easier-to-handle material than concrete and can in some circumstances be equally fire resistant[14].

Since the energy input in manufacturing timber is less than 30% that of cement, and the process emissions are nil, **total emissions from timber production represent less than 15% of**

[12] Material Economics (2018), *The circular economy – a powerful force for climate action*
[13] Guardian (2017), *Tall Timber;* Ravenscroft, 2018, *World's tallest timber tower proposed for Tokyo*
[14] Vladan Henek et al (IOP Conference Series: Earth and Environmental Science) (2017), *Fire Resistance of Large-Scale Cross-Laminated Timber Panels*

those generated by cement production[15]. In addition, **timber acts as an effective carbon sink,** storing the CO_2 absorbed during forest growth for as long as the building exists (and longer if the timber is then reused in new buildings). In principle, a major shift to timber in construction could therefore have a massively beneficial impact on carbon emissions.

The major constraint is the supply of timber currently available. If 25% of the 6.4 billion cubic meters of concrete used each year were replaced by timber, the market would need to increase total global forest cover by about 14%[16] – a land area 1.5 times the size of India. And, even if starting a massive reforestation program today, there would be a lag of 30 years before the timber supply was available for construction. Alternative species, like bamboo, could potentially offer a quicker alternative, especially in tropical countries.

In the short term, timber substitution can probably only make a small difference to total cement demand. But, since cement is likely to prove the costliest and most difficult sector in which to achieve zero carbon emissions from production and given the fact that timber substitution could actually deliver net negative emissions, **a long-term global strategy for construction decarbonization should include a major reforestation program designed to make possible large-scale timber substitution later in the century**. Such a reforestation program should, however, be carefully developed to also take into account land use requirements for food production and implications for biodiversity. This issue is explored further in the ETC's report *Mission Possible* (Chapters 6 and 7)[17].

In addition to timber, **several other alternative building materials** are currently under development and might potentially play a useful role, for instance:

- Products which convert slag from the EAF and BOF steel production furnaces into a construction material by adding CO_2, thus providing a new material while achieving a carbon sink;
- "Plasma rock", which is created by using extreme heat to turn landfill waste into a vitrified material which can be used as a strong and leach resistant building material[18];
- Materials which use thermal cleaning to convert asphalt into a recyclable construction material with around 30 to 50% less CO_2 emissions than cement/concrete[19].

C. ASSESSING THE OVERALL POTENTIAL FOR CEMENT DEMAND REDUCTION

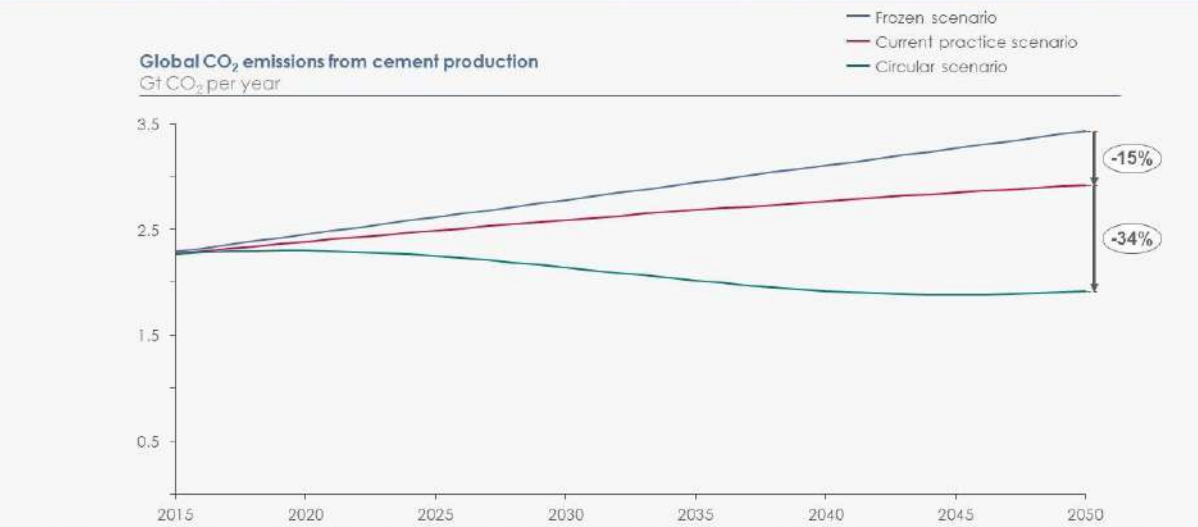
The multiple different routes described above suggest that demand reduction could play a major role in reducing cement-related emissions. Material Economics estimates that the emissions from cement production in a circular economy could be 34% lower than in a current practice scenario, bringing them down to a stable 1.9Gt CO_2 per year [Exhibit 6]. In particular, cement-related emissions in the European construction sector could be reduced by half (46%) [Exhibit 7].

Achieving this demand reduction potential would also significantly reduce the cost to the economy, which would arise from a decarbonization strategy relying exclusively on reducing

[15] Chadwick et al. (2014), *Carbon, Fossil Fuel, and Biodiversity Mitigation with Wood and Forests*
[16] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[17] Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*
[18] Inge Sjuiljs website. *Plasma Rock* (http://ingesluijs.wixsite.com/ingesluijs/plasma-rock)
[19] EAPA (2014), *Asphalt the 100% recyclable construction product*

emissions from the cement production process. It is therefore important to **design policies which encourage demand-side innovation,** and which maximize the potential for low-cost demand reduction e.g. through greater material efficiency. Section 7 discusses possible policy levers which might help achieve this. Among them, carbon pricing is probably the most significant policy tool, improving the economics of cement recapture and new material substitution, making material efficiency improvements even more cost-effective, while continuing to encourage supply-side technology developments.

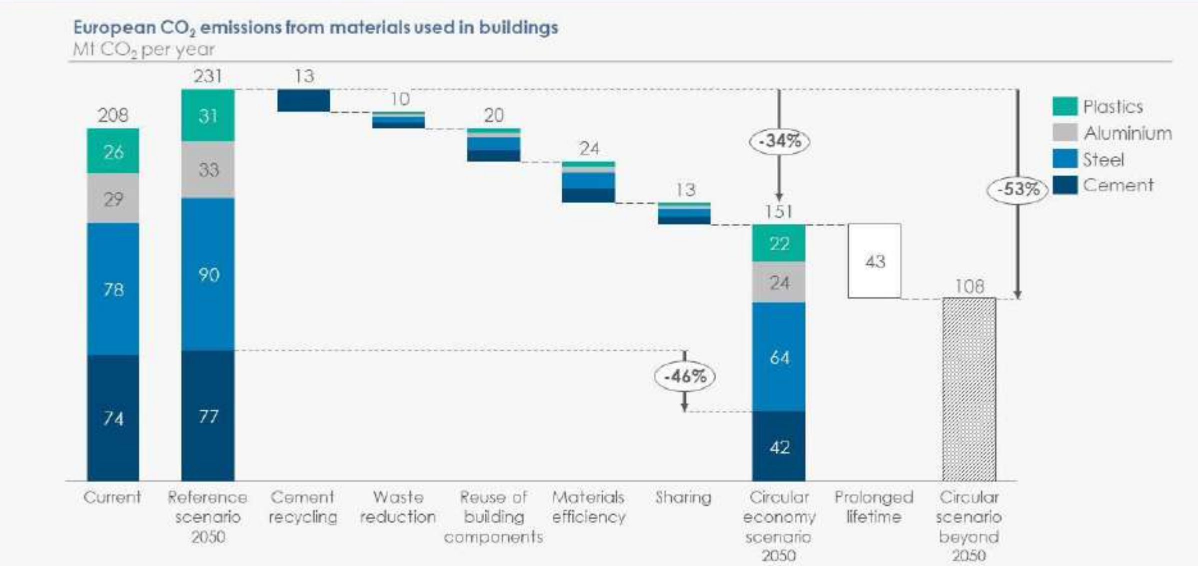
Global emissions from cement production could be reduced by circa 35% by 2050 in a circular scenario with some recycling and significant materials efficiency improvement in buildings



Note: Frozen scenario based on constant carbon intensity of cement production; Current practice scenario based on IEA 2DS reduction of cement production carbon intensity; Circular scenario based on 20% cement recycling by 2050, demand reduction in buildings and drop in cement use in infrastructures
Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 6

In Europe, CO_2 emissions from materials used in buildings could be reduced by up to 53% due to greater materials efficiency



Source: Material Economics (2018), The circular economy: a powerful force for climate change

Exhibit 7

3. IMPROVING ENERGY EFFICIENCY

Improving energy efficiency, even within current production processes (making Portland cement from limestone and with heat generated from fossil fuels), constitutes a short-term carbon mitigation opportunity, which can usefully be pursued as other decarbonization options, which would bring cement production closer to net-zero emissions, are still being developed and deployed. Dry kilns have a lower energy intensity than wet process kilns, and state-of-the-art cement production also entails the use of pre-calciners, multistage cyclone heaters and multichannel burners. The IFC/WB have identified about 20 possible technologies (including retrofits) and measures, which together **could deliver 10% energy savings on the typical thermal cement production process**, most of them with a 2-year payback period. The IEA and CSI industry roadmap reaches a similar estimate of 11% potential reduction in global average energy intensity of clinker production by 2050[20]. Retrofitting existing, less efficient plants to best practices could therefore deliver significant emissions reductions.

Many of these energy efficiency improvements could in principle deliver attractive rates of return, thus creating opportunities to abate CO_2 emissions at negative marginal cost and significantly reducing the average abatement cost in the harder-to-abate industrial sectors. However, they often entail high upfront capital costs that individual industry players cannot always bear, especially in developing economies. It is therefore vital to create strong incentives to grasp these opportunities, and the policies required to drive more radical decarbonization – such as carbon pricing – will also help achieve this lower cost abatement potential. However, there are absolute barriers to how much can be achieved without more radical changes in fuel and/or cement chemistry.

[20] IEA & CSI (2018), *Technology Roadmap – Low-carbon transition in the cement industry*

4. DECARBONIZING CEMENT PRODUCTION

To decarbonize cement production, we must reduce and eventually **eliminate both the carbon emissions resulting from energy use to produce intense heat for the kilns and from the chemical processes which convert limestone into calcium oxide**. A wide range of potential decarbonization options are available, but they are likely to be only partially effective in reducing emissions and/or to be costly. This section considers in turn the potential of different decarbonization routes and the implications for the overall cost of decarbonizing cement production.

This section draws on the report by McKinsey – *Decarbonisation of the industrial sectors: the next frontier* (2018) – as well as on the *Technology roadmap: low carbon transition in the cement industry* (2018) jointly published by the IEA (International Energy Agency) and CSI (Cement Sustainability Initiative).

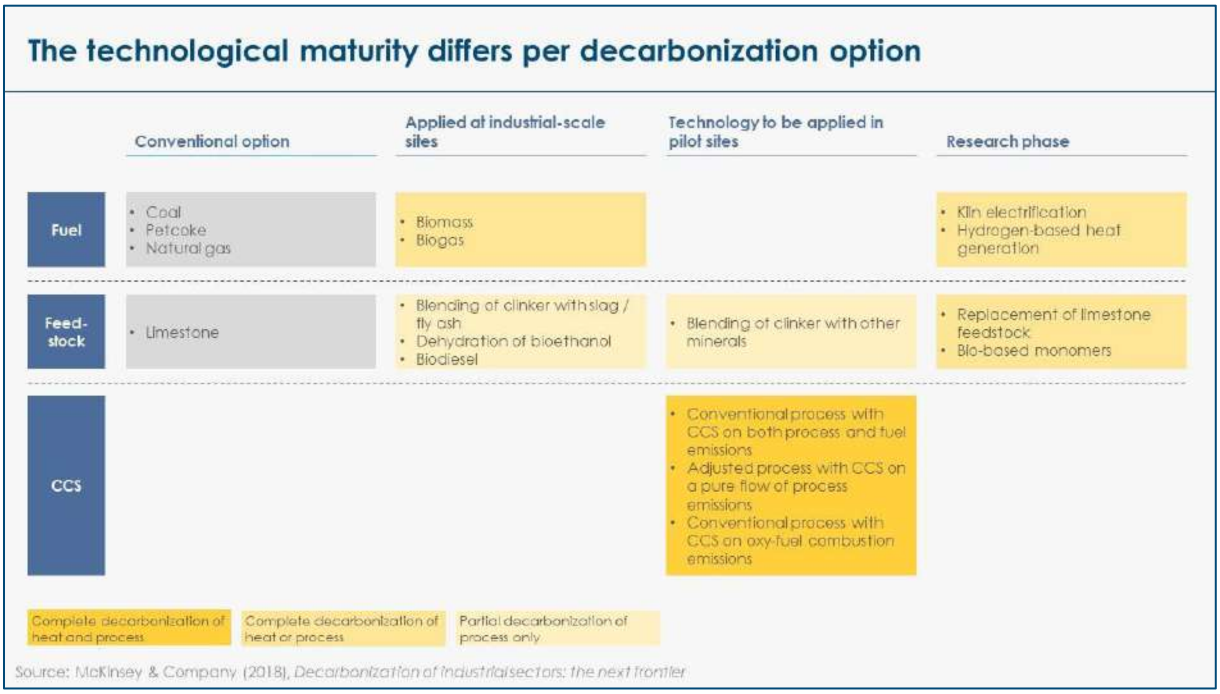


Exhibit 8

A. REACHING NET-ZERO CARBON EMISSIONS FROM HEAT GENERATION

The generation of the intense heat (>1400°C) required to produce clinker results in about 35% of the emissions from cement production[21]. These emissions could initially be reduced by **shifting from coal to gas** as the energy input, which might be a key route to partial decarbonization in China, India and the rest of the Asia Pacific region, which stand out as regions where cement production is most dependent on coal. The potential to achieve this shift will, however, be dependent on the overall economics of gas supply in this region of the world.

Driving carbon emissions from heat generation towards zero carbon will demand more radical changes in fuels, which currently are at different levels of technology readiness:

[21] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

- The greater **use of waste or biomass** as a fuel input would require only a modest retrofit to existing kilns, but raises issues relating to the total supply of waste and sustainable biomass for use across all sectors. These are considered in Section E below, as well as in Chapters 6 and 7 of the *Mission Possible* report[22].
- **Replacing fossil fuels with hydrogen** (derived from clean electricity) would require significant furnace redesign given the different ways in which heat transfers from hydrogen burners as against fossil fuel burners.
- **Using electricity as the heat source** is theoretically possible and could deliver an eventually zero-carbon fuel source if the electricity itself came from low-carbon sources. But industrial scale electric cement kilns are not yet available, and further research and development as well as operation of pilot plants will be required before this technology becomes commercially viable.

B. NEW CEMENT CHEMISTRIES

New cement chemistries could in principle significantly reduce and perhaps eliminate the process emissions generated during cement production, by reducing or eliminating the carbon content of the mineral feedstock used. **A wide variety of new chemistries are being developed**, and it is highly likely that some of these will play a role in driving cement decarbonization. But, the total potential impact may be limited by the trade-off between the scale of potential CO_2 reduction and the availability of required feedstock minerals. Thus:

- Minerals for making **belite clinker** are readily available, but potential emissions reductions are only about 10%.
- **Calcium sulphoaliminate (CSA) or carbonization of calcium silicates (CACS) clinkers** could deliver more significant emissions reductions (20 to 30%), but the required mineral inputs are somewhat less generally available.
- **Magnesium-silicate-based cement** could eliminate emissions entirely, but the required minerals feedstocks for these chemistries are much less available.
- **Alkali/Geo-polymer-based-cements, in particular, pozzolan-based cements** [Box 1], may be the most promising way forward, as they could eliminate more than 70% of carbon emissions, and pozzolan (volcanic rock) is likely to be relatively more available than other minerals mentioned above.

Beyond new cement chemistries, **new concrete chemistries using less cement input** are also being developed, which can lead to significant reductions in cement use and potentially to cement-less concrete in the longer term.

However, **different types of cement and concrete have different precise characteristics** in terms of speed to harden and final strength, creating barriers to adoption which may in some cases be exacerbated by industry conservativism. Further research and development of new cement chemistries should therefore be a priority. They are likely to be crucial for cement decarbonization in some locations, particularly where carbon capture might be difficult to scale up. But, unless there are major development breakthroughs, **new chemistries seem unlikely to provide a path towards total decarbonization across all locations**.

[22] Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*

Box 1 – Substituting Portland cement: the example of Pozzolan cement

Cement is one of the most complex industry to decarbonize, requiring carbon capture and/or an entirely new chemistry. High Volume Pozzolan Cement (HVPC) can be manufactured blending traditional Portland clinker with pozzolan. It could be one of the most promising alternatives to substitute for conventional Portland cement.

The Energetically Modified Cement (EMC) Technology developed by EMC cement provides an equal or enhanced product that contains 50% fly ash and 50% ordinary Portland cement. Fly ash is usually sourced today from power and industrial plants that burn coal, but, as the economy decarbonizes, it could in the future be produced from pozzolan, a volcanic rock, which may be available across all continents.

This technology was first developed in 2005 and has since been demonstrated at commercial scale, through different projects and applications that include, for instance, both State and Federal highways in the US. These first projects have confirmed the competitive cost structure, technical performance and compliance with materials standards of this new chemistry.

Pozzolan cement can provide up to 70% decrease in CO_2 emissions vs. conventional concrete. It would, have to be combined with carbon capture on the remaining Portland cement production to enable the industry to get close to net-zero emissions[23].

C. CARBON CAPTURE

Carbon capture and storage (CCS) or carbon capture and use (CCU) **could address both the emissions produced from heat generation and from process emissions**. Carbon capture could therefore be used either as a single decarbonization route for all emissions from cement plants, or for process emissions only combined with a switch in fuel to mitigate emissions from heat production. Carbon capture equipment can be fitted on existing kilns. However, current capture technologies only capture up to 90% of the carbon stream, and therefore only constitute a near-zero-carbon solution.

CCS/U is likely to be more expensive in cement than in other industrial sectors. The cost of carbon capture indeed increases when the concentration of CO_2 in exhaust gas streams decreases. With exhaust emissions from cement production only 19% CO_2 – against, for instance, close to 100% in process emissions from ammonia production –, carbon capture costs per tonne of CO_2 are likely to be much higher than in other sectors of the economy. GCCSI estimates for first-of-a-kind plants suggest capture costs of around **US$110 per tonne saved for cement plants**, against US$66 for iron and steel and only US$14 for capturing carbon emissions from steam methane reforming[24] [Exhibit 9].

These costs may reduce over time, thanks to economies of scale and learning curves, or to the development of new technologies increasing the purity of the CO_2 stream to be captured. GCCSI estimates suggest that the "n^{th} of a kind" costs for carbon capture of cement emissions could fall from around US$110 per tonne to US$90 per tonne, but these would still add very significantly to the costs of cement production[25]. Meanwhile, innovative kiln design could separate exhaust gases from fuel combustion (low in CO_2) from the exhaust gases of calcination (almost pure CO_2), allowing the latter to be captured at lower cost. Burning fossil

[23] EMC (2018), *Cement production emissions challenge and solutions*

[24] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

[25] Global CCS Institute (2017), *Global Costs of Carbon Capture and Storage*

fuel input in pure oxygen rather than air (oxy-combustion) would increase the percentage CO_2 in the heat-related emissions. But, these alternative technologies would require more investment and plant redesign.

In addition to the cost of CO_2 capture, **the costs of transport and storage for CO_2 captured on cement plants may be significantly higher than in the case of steel or petrochemical plants.** The latter are often clustered in major industrial complexes, in many cases close to coasts, making it possible to achieve economies of scale in the shared development of CO_2 pipelines, and to utilize offshore storage facilities. By contrast, since cement is a heavy low-value product, it is seldom transported more than 250 km from production site to user, and cement plants are therefore dispersed in a way which would complicate, add cost and potentially increase political resistance to the development of transport and storage.

The good news, by contrast, is that **the potential to use CO_2 in other products**, rather than simply store it in underground facilities, seems likely to be greatest in the construction material sector. Currently, absorbing CO_2 into concrete or into aggregates appears to be the most promising CO_2 use option identified across multiple potential applications [Exhibit 10]. In particular, CO_2 can be absorbed into concrete during the curing process, and carbonated concrete demonstrates rapid early strength gains, reduced curing times, overall greater strength, and improved freeze/thaw durability. The US company Carbon Cure has refitted around 50 concrete plants with this CO_2 absorbing technology[26]. The Australian company Mineral Carbonation International is working on similar CO_2 absorption techniques[27].

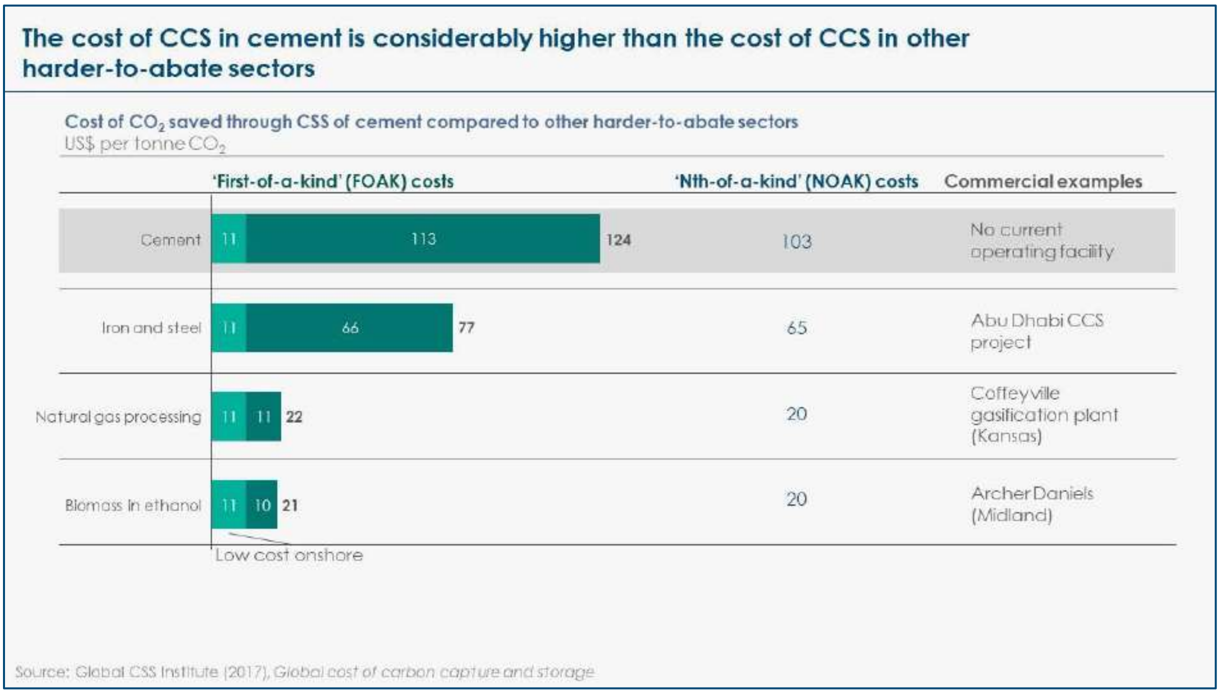


Exhibit 9

[26] Carbon Cure (2017), *Working with waste*
[27] Guardian (2017), *Australian firm unveils plan to convert carbon emissions into 'green' concrete*

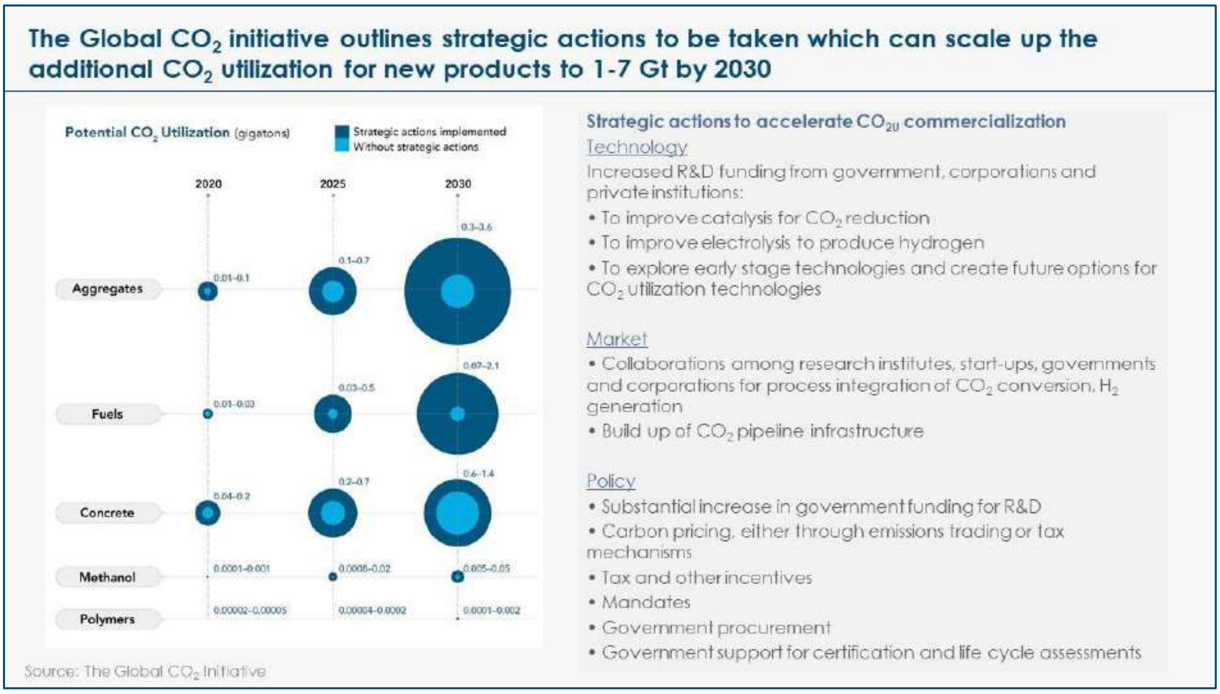


Exhibit 10

While these CO2 usage opportunities cannot reduce the high carbon capture cost on cement plants, they could help **reduce expensive transport and storage costs**, with some concrete production potentially co-located with cement plants. Combined with new approaches to concrete recycling and cement recapture, this implies that there may be **a major business opportunity in the more integrated management of the entire cement, concrete and aggregates value chain**.

D. LEAST COST DECARBONIZATION ROUTE AND ECONOMIC IMPACT

The options discussed above provide many routes to achieve partial or eventual total decarbonization of cement production. **The least cost solution is likely to vary by location, but current estimates suggest that any of the options will add significantly to the cost of cement production and thus to construction costs.**

- In theory, once hydrogen and electrified heat have become deployable technologies, **the most cost-effective way to reduce heat-related emissions will depend on the price of renewable electricity**. McKinsey's analysis suggests that renewable electricity would have to be available at a cost below US$50/MWh for heat electrification to be more economic than CCS for greenfield sites – and US$25/MWh for brownfield sites [Exhibit 11]. Such low electricity prices will almost certainly be achieved in parts of the world with favorable wind and solar resources.
- Even in some locations facing higher renewable electricity costs, electrification may still be the preferred route because of limitations on the local feasibility of CCS deployment. Conversely, there will be **other locations where CCS is likely to be both feasible and cost-effective** to decarbonize the heat input to cement production.
- Whatever the option deployed for heat, however, in the absence of a breakthrough in cement chemistry, **CCS/U will be the only solution to process emissions**.

- In regions with large sustainable biomass resources, **combining biomass with CCS could be the most cost-effective decarbonization route**. However, constraints on the availability of truly sustainable biomass is likely to significantly limit this opportunity, as described below.

The importance of process emissions and the resulting unavoidability of carbon capture to reach net-zero carbon emissions from cement production means that the full decarbonization of the sector will entail a significant cost per tonne of CO_2 saved: McKinsey estimates that **decarbonizing cement will account for circa 57% of all the costs of decarbonizing the harder-to-abate industrial sectors** (in the Reference Case) and as much as 64% if low electricity prices reduce the cost of decarbonizing other industrial sectors like steel. While the cost of decarbonizing steel, and ammonia production will be dramatically reduced if very low-cost renewable electricity is available, the dominance of process emissions in cement means that decarbonization will always impose significant costs, however cheap electricity becomes.

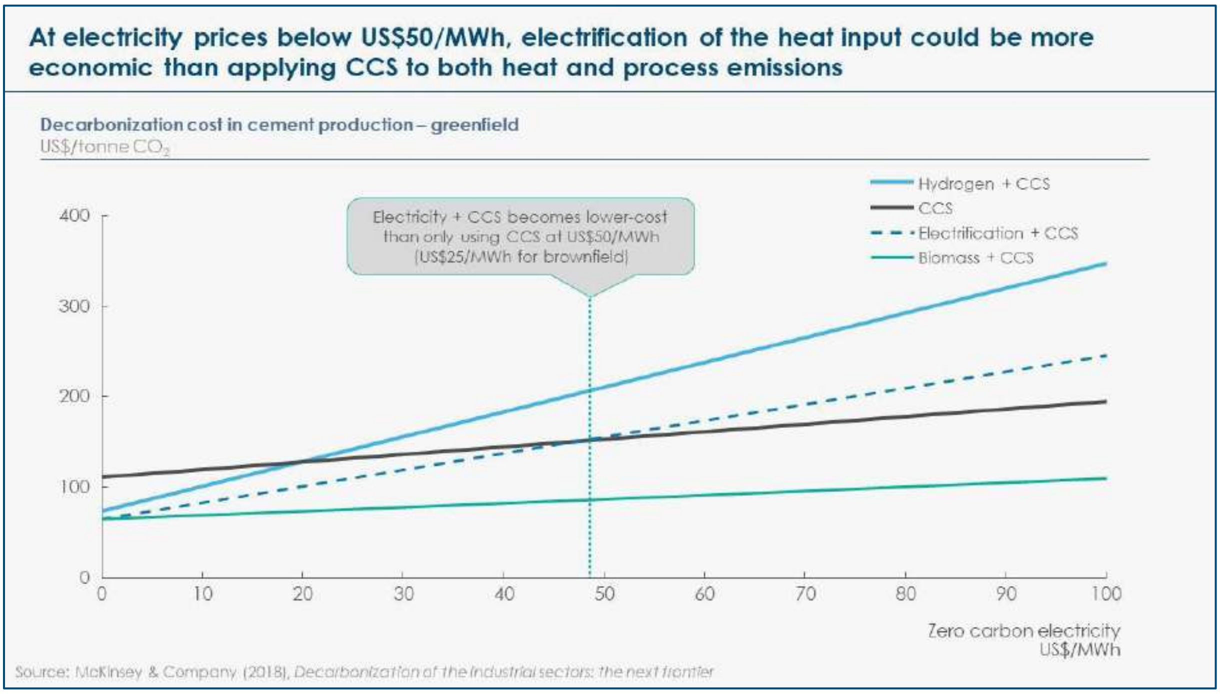


Exhibit 11

E. ISSUES RELATED TO THE USE OF BIOMASS

The IEA and CSI 2˚C scenario estimates that just over 5% of thermal energy used in the global cement industry currently comes from waste and biomass sources, and they forecast that this **could rise to 30% of the total by 2050**[28]. This expansion of biomass or waste energy inputs is in principle attractive since:

- **Cement kilns can use a wide range of biomass and waste inputs**, from old tires to municipal solid waste, effluent sludge from waste water treatment plants, sawdust and other forest residues, providing an end-of-life solution for materials that are difficult to recycle.
- **These resources can be used with some minor preprocessing** and do not have to be converted into the tightly defined biofuels required for transport purposes through production processes, which are often costly and energy-intensive.
- **Increased biomass could be derived from the more sustainable forestry residue and lignocellulosic sources**, placing no reliance on oil plants grown on arable land.
- Using biomass combined with CCS could in principle **make it possible to generate heat with net negative emissions**, since CO_2 would be absorbed during biomass growth.

In deciding the potential for biomass in any sector, however, it is also important to consider **the maximum sustainable supply of biomass and competing demands from other sectors**. The ETC report *Mission Possible*[29] considers these issues across all the harder-to-abate sectors. Key emerging conclusions from Chapters 6 and 7 are that:

- Estimates of the total potential supply of sustainable biomass are inherently uncertain and vary greatly, but the ETC believes that **biomass with energy value of about 70-100EJ could be sustainably harvested each year**. For comparison, IEA analysis usually assumes a 140EJ budget in 2050 in their 2˚C scenario[30].
- **If all of today's annual production of 4Gt of cement were produced from biomass, this would require biomass energy resources of about 14EJ per annum**, making it possible, in principle, to meet all cement industry needs from biomass input[31].
- **However, cement does not constitute a priority sector** for the allocation of scarce sustainable biomass resource, given the availability of other potential decarbonization solutions. Given limited sustainable biomass supply, use of biomass should be concentrated in sectors where there are least alternative decarbonization routes, which we have identified as aviation and bio-feedstocks for plastics production.
- **There might be local exceptions** to this general prioritization rule, in geographies with particularly favorable biomass supply.

In this context, the ETC's indicative pathway presented in *Mission Possible* assumes that **only 20% of the energy needed for cement production could come from biomass by mid-century**, representing a maximum of 6EJ/year[32].

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[28] IEA & CSI (2018), *Technology Roadmap – low carbon transition in the cement industry*
[29] Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*
[30] In the 2˚C scenario from *Energy Technology Perspectives* (2016), IEA forecasts a 138 EJ total primary energy demand from biomass and waste in 2050.
[31] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[32] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

F. ISSUES RELATED TO THE SCALE-UP OF OTHER DECARBONIZATION OPTIONS

Just as the use of biomass in a given sector needs to be considered as part of the broader demands on biomass from the energy and industrial sectors as a whole, the deployment of zero-carbon electricity, zero-carbon hydrogen and carbon capture and storage to decarbonize the cement sector will impact global electricity and hydrogen demand, as well as for global carbon storage requirements.

Chapters 6 and 7 of the *Mission Possible* report present **an aggregated vision of the implications of the full decarbonization of all sectors of the economy on the energy system**[33]. We find that there is no fundamental system boundary constraining the scale-up of critical decarbonization options, with the important exception of biomass, although there might be solvable, transitional and region-specific bottlenecks.

[33] Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*

5. COST OF FULL DECARBONIZATION OF CEMENT

As Sections 2 through 4 argued, although it is technically possible to achieve quasi full decarbonization of the cement sector "within itself" – i.e. without purchasing offsets from other sectors –, **the cement sector constitutes the most challenging of the harder-to-abate sectors**. This fact is reflected in the cost of the full decarbonization of the cement sector and the impact of such a cost must be considered at different levels of the supply chain of cement.

Therefore, this chapter considers in turn:

- The cost to the economy, derived from the abatement cost per tonne of CO_2 saved,
- The implications for the cost of intermediate products purchased by businesses and of end products purchased by consumers.

A. COST TO THE ECONOMY

Actual abatement costs – and the least-cost routes to decarbonization – will depend on future technological developments and cost trends and will vary by region in the light of natural resource endowments. McKinsey's 2018 report[34] gives a reasonable indication of where the higher costs and the cheapest opportunities are likely to lie. The availability of low-cost, zero-carbon electricity would make a slight difference to the cost of cement decarbonization: if zero-carbon electricity was available at US$20/MWh across the world, decarbonizing cement could cost US$110/t$CO_2$ (instead of US$130/t$CO_2$ if zero-carbon electricity is available at US$40/MWh).

The abatement cost on the demand side is also the most expensive of all the industrial harder-to-abate sectors considered in the analysis: Material Economics estimates the demand-side abatement cost of cement at US$48/t$CO_2$, 60% for materials circulation levers (e.g. recycling), 40% for product circulation levers (e.g. sharing economy)[35].

An initial estimate of the maximum annual cost to the global economy of achieving net-zero CO_2 emissions within the cement sector (with no use of offsets) can be generated by multiplying these abatement costs with the volume of CO_2 emissions projected by mid-century in a business-as-usual scenario. This indicative "cost for the economy" is the highest of all industrial sectors, but still very low compared with an indicative 2050 global GDP: running a fully decarbonized cement industry could amount to less than 0.07% of global GDP in 2050, or less than US$250 billion per annum [Exhibits 12 and 13].

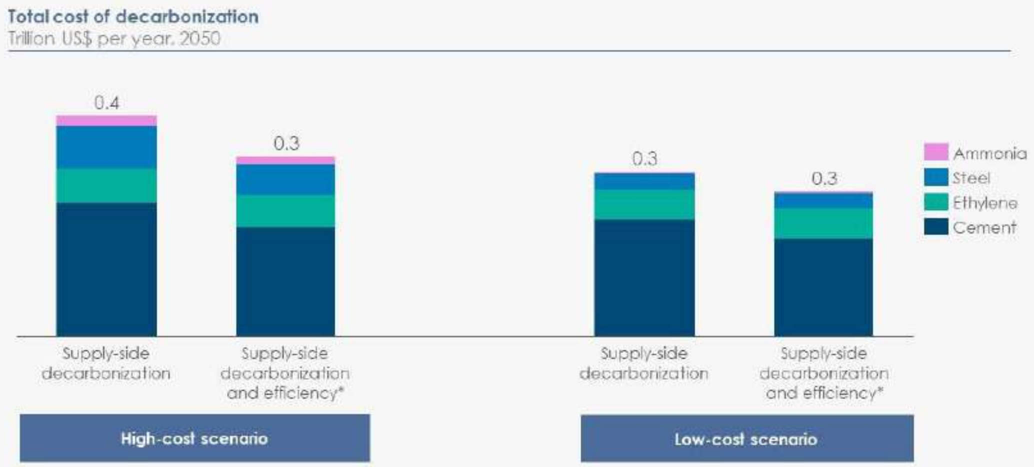
This could be significantly reduced by three factors:

- **Lower renewable energy costs**: if zero-carbon electricity was available at US$20/MWh instead of US$40/MWh, the cost of decarbonizing cement would be reduced by more than 10-15%.
- **Demand management**: greater recycling and reuse of material could reduce the total decarbonization cost of cement by 15-20%, bringing it to lower than 0.05% of global GDP.
- **Future technological development**: the cost of decarbonization could be dramatically reduced or even eliminated by new and unanticipated technologies. For instance, if technological improvements make pozzolan-based cement (or other

[34] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[35] Material Economics (2018), analysis for the Energy Transitions Commission

substitutes to Portland cement) cost-competitive, the cost of cement decarbonization could be driven down even more.

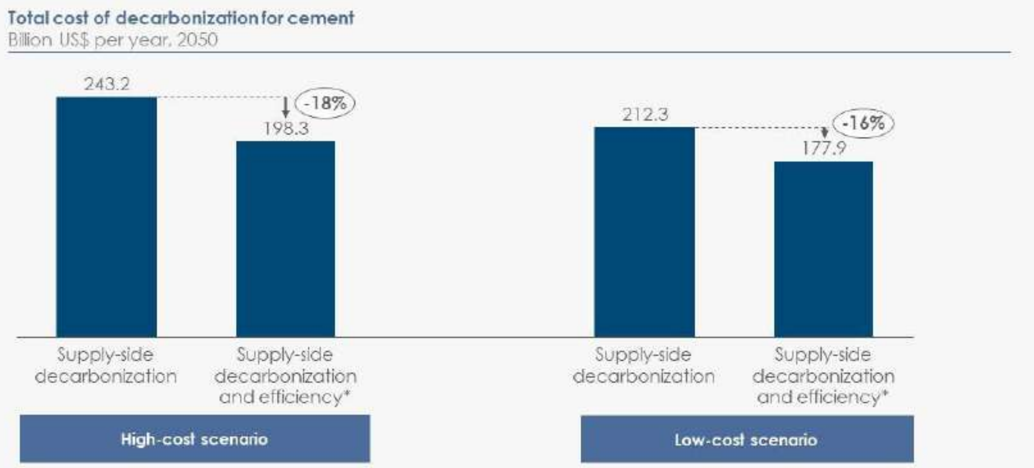
Cement is the costliest of all harder-to-abate sectors



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 12

Decarbonizing cement would cost significantly less if pursuing demand management and energy efficiency improvement opportunities



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 13

B. B2B COST AND END-CONSUMER COST OF DECARBONIZATION

Decarbonizing cement production will have a significant impact on the costs faced by the construction industry, **adding more than US$100 per tonne of cement, which means roughly doubling its cost.** This would then translate into a 30% increase in the cost of concrete, with a material impact on the construction value chain.

However, **the maximum impact on the price faced by the buyers** of a typical house priced US$500,000 **would only be around a 3% increase** (using an assumption of 2tCO_2 per tonne of cement and the high-range abatement cost of supply-side decarbonization of US$130/tonne of CO_2). The additional cost of cement would indeed be diluted in the multiple other sources of costs faced by the end buyers. This makes it likely that consumers could be willing to support policies and initiatives which would drive decarbonization. In particular, it implies that public procurement could play a significant role in driving demand for zero-carbon construction materials without significantly adding to the total cost of these operations.

The key challenge in cement decarbonization is therefore not cost to the global economy, nor the implications for the end consumer prices, but **how to deal with the extra-cost faced by intermediary stakeholders in the construction value chain**, especially during the transition period.

6. CONCLUSIONS AND POLICY IMPLICATIONS

Cement is almost certain to be the most difficult and costly sector of the economy to decarbonize. This high cost is driven by (i) some marginal economic gains from demand-side management including circular economy approaches, (ii) the importance of process emissions, which cannot be easily removed (unlike with the use of hydrogen as a reduction agent in the case of steel production), and therefore will most probably require carbon capture, (iii) a higher cost of carbon capture than in other sectors due to the low concentration of CO_2 in the exhaust gases, and (iv) the likely high cost of carbon transportation and storage due to the dispersed locations of cement plants.

No one dominant route to decarbonization can be defined, as different options are likely to be most cost-effective in different locations, reflecting different electricity prices, biomass resources, and feasibility of carbon storage solutions.

But some overall conclusions and policy implications can be drawn from the analysis:

- **There are important opportunities to reduce demand for cement through improvements in material efficiency within the building sector combined with greater recapture and reuse/recycling of cement.** It is vitally important to grasp these demand reduction opportunities given the high cost that production decarbonization will impose on the economy. Regulation may play a useful role in supporting demand constraint, but a carbon price, reflected in higher cement and concrete prices, would also greatly increase the incentives to economize on cement/concrete use.
- **The substitution of timber for cement could play a major role in emissions reductions over the very long-term**, and major afforestation programs, which would in any case support carbon sequestration, should be a priority (with the caveat of considering the related land use trade-offs and sustainability issues).
- **New cement chemistries – and concrete chemistries – could play a significant role in driving emissions reduction**, with uptake varying by location in line with local mineral resources but would be more likely to become economic if standard limestone-based cement faced a carbon price.
- **It is certain that carbon capture will have to play a role in the full decarbonization of cement production**. In this context, maximizing the potential role of carbon use in concrete and aggregates would decrease high cost of transport and storage, and could make a tangible difference to the overall cost of cement decarbonization.
- Applying carbon capture or, using hydrogen or electricity to decarbonize heat production will add a significant cost (except perhaps in locations with exceptionally cheap renewable electricity sources).
- This implies that **an explicit or implicit carbon price of roughly US$100 per tonne of CO_2 will be necessary to drive cement decarbonization.** A carbon price at that level would **significantly increase the price of cement and concrete**. But since cement, unlike steel or plastics, is too heavy or low value to be extensively internationally traded, a high carbon price could be imposed on cement production without inducing large-scale competitiveness problems or the relocation of production – although there may be some impact on clinker production localization.
- Higher prices for cement and concrete should therefore be accepted as the necessary consequence of cement decarbonization. **They may in turn unleash material efficiency improvements, which will significantly reduce the total cost to customers and the economy.**

7. EXISTING INDUSTRY INITIATIVES

The **Cement Sustainability Initiative (CSI)** (which sat under the World Business Council for Sustainable Development umbrella until 2018 and has now joined the Global Cement and Concrete Association) has been driving tangible progress across the industry for the past 20 years. The CSI aims to address the environment and social impacts of cement manufacturing. It currently convenes 24 cement companies established across 100 countries, including major Chinese, Indian, European and US players. This initiative has proven useful to raise the sustainability and climate change agenda in the cement sector, reach alignment across the industry on key areas of focus, share best practices, and develop common guidelines and reporting mechanisms. It encouraged the deployment of energy-efficient technologies and could indeed partly explain the relatively limited remaining potential for energy efficiency improvement in the sector (about 10% as described in Section 3).

Most notably, CSI developed its first **decarbonization roadmap** alongside the IEA and the World Business Council for Sustainable Development, laying out a joint vision of the carbon reduction pathway for the industry in 2009[36] and recently updated this exercise in collaboration with the IEA to define a pathway compatible with a 2˚C scenario[37]. This joint platform also constitutes a powerful tool to advocate for a favorable policy framework.

This exercise, however, presents two major limits: first, **it doesn't yet propose a pathway to full decarbonization** of the cement sector; then, being driven by the industry, **it is by nature rather cautious on the potential to slow down demand growth**, in particular, through materials substitution.

[36] IEA, WBCSD & CSI (2009), *Global Cement Technology Roadmap*

[37] IEA & CSI (2018), *Technology Roadmap – low carbon transition in the cement industry*

8. RECOMMENDATIONS

Considering the numerous challenges inherent in decarbonizing this low-margin, high-demand-growth industry, the Energy Transitions Commission recommends the following key innovation, industry and policy actions to accelerate decarbonization of the cement industry.

A. RESEARCH AND DEVELOPMENT

There is no single route currently available to achieve deep-decarbonization of the cement industry. While R&D support could expand decarbonization options in all industry sectors, **the cement industry is particularly dependent on the emergence of innovative technologies, which are further away from commercial readiness than in other industrial sectors**. The search for these technologies will primarily be driven by individual companies but should also be supported through public R&D spending and could even be partly shared between companies through joint R&D projects for early-stage technologies not yet representing a stake in terms of industrially-relevant intellectual property.

Key R&D priorities will include:

- Development of electric and hydrogen kiln furnaces to commercially-feasible scale;
- Reduced capital costs of hydrogen electrolysis equipment to drive down hydrogen production costs;
- Development and reduced cost of new industrial processes (for instance oxyfuel-based ones) enabling a purer CO_2 stream which can be captured at lower cost;
- Development of alternative cement and concrete chemistries – including carbon use innovations in the cement, concrete and aggregate value chain;
- Development and accelerated uptake of innovations enabling better recycling/reuse of both cement and concrete, in particular digital technologies enabling better tracking, collection and sorting of materials;
- Development of new construction materials fit for both buildings and infrastructure – including but not limited to expanding the range of technical uses of timber.

B. PUBLIC POLICY

Policy is crucial to align incentives in a fragmented cement industry and drive both (i) the search for medium-to-long term full decarbonization solutions and (ii) the short-term uptake of available technologies and practices that enable energy efficiency in the production process and materials efficiency at use stage. Such a policy-framework should combine **push levers**, such as carbon pricing and regulations on cement production, with **pull levers**, such as public procurement and regulations on the construction sector.

EXPLICIT OR IMPLICIT CARBON PRICING

A sufficiently high carbon price **of US$100 per tonne** could play a crucial role in driving both decarbonization of primary cement production and a decentralized demand-led search for least-cost solutions to build greener buildings and infrastructure. Such a price signal could stimulate the R&D necessary in search of innovative new technologies, as well as incentivize cement recycling/reuse initiatives and indeed cement substitution. Incidentally, if the cement industry perceives a greater risk for materials substitution in the buildings sector, it might be encouraged to move faster towards the decarbonization of cement production. The benefit of this lever is that **carbon pricing is unlikely to induce large-scale competitiveness problems** or the relocation of cement production, although there might be a limited impact on clinker production.

In addition to enforcing carbon pricing at production level, governments should ideally **impose product regulations which require major cement users (e.g. in the construction industry) to use a minimum, rising percentage of low/zero-carbon cement**, thus effectively imposing a carbon tax on cement use within an economy irrespective of the location of production, and creating demand for low/zero-carbon cement.

REGULATION TO DRIVE INCREASED MATERIAL EFFICIENCY

Governments should develop strategies explicitly focused on the need for increased recycling/reuse and improved material efficiency. Specific regulatory policies which might achieve this could include:

- **Setting international standards for measuring embodied carbon and upstream emissions on building materials**, which should be integrated into sustainability rating building codes;
- **Establishing building codes** which:
    - Require improved efficiency in the use of materials, and
    - Are performance-based rather than specification-based, to facilitate access to market of new chemistries and new materials;
- **Pushing regulations on building demolition,** which require rigorous separation of different materials;
- **Increasing landfill taxes** to discourage unseparated landfill;
- **Introducing producer responsibility regulations,** which increase incentives for buildings/infrastructure design compatible with complete recycling.

PUBLIC PROCUREMENT

Governments should use public procurement to favor – and indeed create initial demand for – lower-carbon cement and a broader set of lower-carbon materials, for instance by requiring a minimum percentage of low/zero-carbon materials to be used in all publicly funded construction (based on metrics on embodied and upstream carbon emissions) and setting targets for this percentage to increase over time, thus creating long-term incentives for both demand- and supply-side action.

R&D AND DEPLOYMENT SUPPORT FOR NEW TECHNOLOGIES

The role of governments to support the R&D priorities described above will be more specifically to:

- **Support R&D** in technologies which are currently further away from commercial readiness;
- Support specific projects designed to achieve early decarbonization for a country's cement industry by way of **large-scale demonstration projects and pilots** (e.g. China plans to scale clinker substitution with fly ash and blast furnace slag);

- **Support technology cooperation agreements between countries** on lower-carbon cement and concrete use (e.g. ensuring deployment of lower-carbon use in infrastructure deployment as part of the China Belt and Road initiative);
- Establish a deployment strategy and support investment in **carbon transport and storage infrastructure.**

REGIONAL SPECIFICITIES

These public policies are relevant to governments across the world. But some **country-specific priorities** can also be outlined, for example:

- **Europe could set ambitious retrofit, reuse and recycling targets** for the construction sector in the EU's "Circular Economy Package" (building on guidelines being developed for sorting, processing and recycling waste from construction and demolition), as well as set targets for embodied energy and carbon for new builds, building on the work done relating to energy efficiency for buildings in the "Energy Performance of Buildings Directive".
- **In China,** it is vital to develop the regulations and other policies, which will **drive increased recycling/reuse** in a country now approaching developed country cement stocks per capita, and vital also to ensure that **Belt and Road Initiative investments favor the use of lower-carbon materials** through ambitious procurement practices.
- **Cities should work together to build the market for low-carbon cements and construction materials** by aligning their goals via the C40 and ICLEI-Local Governments for Sustainability and Urban Leadership Council. This could include collective city pledges and common principles for low-embodied-carbon buildings and infrastructure procurement, as well as guidelines to inform planning, design, construction, operations and end-of-first-life of public buildings.

C. ACTION FROM CEMENT PRODUCERS AND USERS

Beyond ongoing efforts coordinated by the Cement Sustainability Initiative to share best-practices and develop decarbonization roadmaps, **the cement industry can accelerate decarbonization by:**

- **Establishing clearer targets**, either individually or collectively across the industry – for the steady reduction in carbon intensity per tonne of cement – these could be developed as science-based targets, but would have to aim for zero-carbon emissions in the second half of the century rather than only align with a 2˚C scenario by mid-century;
- **Supporting the design and implementation of standards,** which make it possible to track and certify embodied carbon, and therefore open the scope for a demand for "green cement" and potentially get a price premium for it;
- **Proposing and supporting** regional and local agreements to impose significant **carbon prices**, to create a level playing field for all cement players in a given geographical area.

In addition, a broader set of players across the construction value chain can facilitate decarbonization progress:

- **End-users of cement** – i.e. purchasers of buildings and infrastructure – could play a major role in driving decarbonization by **procuring decreasingly carbon-intensive**

cement and construction materials. This is true particularly for public procurement, but equally applies to businesses across multiple sectors which are committing to reducing their direct and indirect emissions. These carbon-intensity targets would ideally be generic to leave space for material substitution and could purposefully support the use of novel products in smaller projects.

- Beyond this, **the construction sector** should endeavor to achieve a significantly **lower material input for building/construction services** by developing a more circular approach to cement consumption, aiming in particular to:
    - Addressing the barriers to higher recycling rates by designing for disassembly, durability and flexibility and keeping records of building content by use of digital technologies;
    - Improving material productivity and reducing construction over-specification.

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