CarbonRe

Three technologies to reduce climate change

Why cement production between now and 2030 matters to all humanity, and what we can do about it

Who we are

We are a company pushing the boundaries of artificial intelligence to accelerate the decarbonization of cement and other foundational materials.

Our first product is Delta Zero, a software platform that embodies cement process expertise and the latest state-of-the-art capabilities in AI. Delta Zero supports operators in managing the complexities of cement production and provides them with clear, actionable recommendations for process set-points, resulting in significantly reduced energy consumption and CO2 emissions.

Delta Zero provides tailored recommendations to plant operators that can reduce energy consumption by 10% and fuel-derived carbon emissions by up to 20%. Our software is compatible with both Expert System operations and manual operator control and achieves gains that cannot be obtained through Expert Systems or operator training.

No capital investment, no new equipment, and no plant shutdowns are needed. Delta Zero enables ongoing cement plant optimization to account for changing process inputs and outside pressures such as volatile fuel market costs and emissions regulations. Substantial savings in energy are achieved by empowering operators to run each plant at its highest possible efficiency levels, resulting in several percentage points of fuel use savings. This equates to very substantial cost savings.

Delta Zero also enables critical secondary benefits, such as helping maintain equipment within operating parameters (e.g. kiln torque) and keeping NOx emissions within control limits. We are further exploring future benefits our technology promises, such as predicting and avoiding kiln blockages.

Find out more at www.carbonre.com/products

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Executive summary

Cement production matters to all humanity. It is the most important area of industrial activity for reducing carbon emissions, the key driver for climate change and global warming. It is responsible for a greater share of carbon emissions than deforestation, global shipping and aviation combined.

Demand for cement will continue with the ongoing trend for urbanization. Cement is the active ingredient in concrete, and concrete is the most widely used material by humans, after water.

Roadmaps to decarbonize cement production rely heavily on Carbon Capture, Utilization and Storage (CCUS) technologies that have yet to be proven at scale and are not yet commercially viable. To make CCUS commercially viable will require; carbon taxes to be well over US$100 per tonne, a stable regulatory environment for carbon, and significant investment in technology development. With these barriers removed, the technology could reach scale in the period 2040 to 2050, leaving emissions from cement production to continue for another 20 years from now.

The delay to any significant improvement until 2040 is too late: achieving reductions by 2030 is more important than achieving net zero in 2050 according to the latest research published by Nature.[1]

This report assesses 20 technologies related to the decarbonization of cement production and models 13 with the potential to make an impact in the next decade. We created a model to assess the potential of each technology to reduce carbon emissions by 2030 and the expected costs of each technology. This report evaluates the results of our model and makes recommendations for cement producers, policymakers and investors.

Our assessment is that the combined impact of the 13 technologies would be to reduce emissions by 0.8 gigatonnes per annum for global cement

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[1] https://www.nature.com/articles/s41598-021-01639-y

production from 2.5 gigatonnes per annum in 2022 to 1.7 gigatonnes per annum in 2030. This is over double the reduction targeted by the International Energy Agency.[2]

As a mature and stable industry, there are barriers to achieving these reductions, such as the capital investment required and operating cost increases. Focusing on the technologies which deliver a cost saving identifies five technologies in three groups that together achieve over 80% of the forecasted benefits for 2030:

1. Substitute Cementitious Materials (SCM) including LC3 Cement
2. Biomass and waste alternative fuels
3. AI for energy efficiency and SCM blending

Common barriers remain including: the commercial structure of vertically integrated cement producers; lack of market demand for low carbon cement; and prescriptive regulations on the specification of cement.

Beyond 2030 we highlight two technologies with longer term potential: "CCUS via oxyfuel" and graphene. Green hydrogen is often seen as a panacea for industrial decarbonization. We reject this as a viable solution for cement production due to the capital investment required in renewable electricity generation and hydrogen production by electrolysis, as well as the high demand from other industries such as steel production.

Whilst we put forward biomass as an opportunity for decarbonization, we suggest caution is required as carbon accounting methodologies may be flawed and incorrectly suggest that it is carbon neutral. Particularly when it is a contributing factor to deforestation.

Our recommendations include:

- Cement producers should focus their resources on the three groups of cost saving technologies listed above to gain cost savings and a strategic advantage over their competitors.
- Policymakers need to remove barriers to decarbonization of cement resulting from poor regulations and policies, including overhauling the design of the European Union's Emissions Trading Scheme, mandating low carbon cement procurement for publicly funded projects, and regularly updating standards for cement quality/performance to reflect new product innovation.
- Investors should support the significant commercial opportunities for existing industry players, new entrants and technology providers.

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[2] https://www.iea.org/reports/cement

Background

Decarbonization of cement is gaining attention among policymakers and governments. Several leading producers have made significant commitments and are investing in new decarbonization solutions; however, there are numerous technological and financial challenges and the path to decarbonization remains uncertain.

This report assesses technologies available today which could help achieve decarbonization in order to limit the expected global rise in temperatures. It provides recommendations for actions that governments can take to help producers accelerate their decarbonization journeys in a financially sustainable manner.

Our aim has been to provide an indicative assessment of available technologies to help:

- Cement producers evaluate attractive areas for further Research & Development
- Technology providers consider how they can best support cement producers
- Policymakers identify where they need to help remove barriers and provide incentives
- Engage with change-makers to feed into crucial emerging policy development
- Steer/ support the cement industry towards definitive action against climate change

We have adopted the convention of referring to the combination of gases responsible for climate change as “carbon emissions”, which includes carbon dioxide (CO2), methane and nitrous oxide. Any reference to ‘CO2’ is a shorthand for “carbon dioxide equivalent emissions” (CO2e).

Decarbonization roadmaps have been developed by cement industry bodies, helping provide leadership and guidance for cement producers on the solutions available. Reports include:

- “Roadmap to Carbon Neutrality” from the Portland Cement Association’s (PCA) in the US, published in October 2021, which covers cement production, building with concrete and the full value chain to end-of life.[3]
- “2050 Roadmap” from Cembureau in Europe with a similar broad scope and focus on net zero by 2050, published in May 2020.[4]
- “UK Concrete and Cement Industry Roadmap to Beyond Net Zero” from the Mineral Products Association (MPA) in the UK, published in Oct 2020.[5]
- “2050 Cement and Concrete Industry Roadmap for Net Zero Concrete” from the Global Concrete and Cement Association (GCCA),[6] and their recognition of the importance of 2030 goals.[7]

In this report, we build on these previous studies to reinforce the importance of decarbonization in cement production with a focus on 2030, and to provide a quantified comparison of technologies available specific to cement producers.

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[3] https://www.cement.org/docs/default-source/roadmap/pca-roadmap-to-carbon-neutrality_10_10_21_final.pdf
[4] https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf
[5] https://www.mineralproducts.org/MPA/media/root/Publications/2020/MPA-UKC-Roadmap-to-Beyond-Net-Zero_Oct20.pdf
[6] GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete
[7] https://gccassociation.org/concretefuture/2020-2030-the-decade-to-make-it-happen/

Why cement production matters

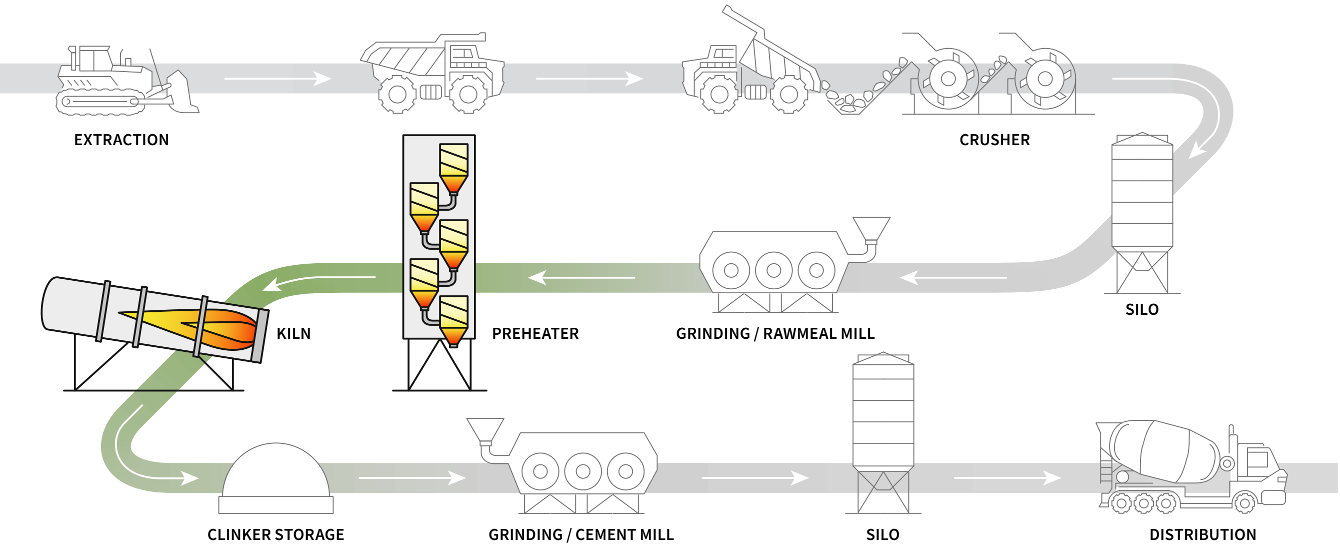
Cement production is the most important area of industry, possibly even of human activity, for reducing carbon emissions and hence minimizing the global temperature increases that are driving climate change.

Cement is the most ubiquitous construction material used in modern infrastructure, and a foundational material on which society is built. Deforestation, shipping and aviation often hit the headlines as root causes for climate change but their combined impact of 2.9 billion tonnes CO2 (5.8% of global emissions)[8] is less than that of cement production.

> “ Versatile and long-lasting, concrete buildings and structures are in many ways ideal for climate-resilient construction. But concrete has a colossal carbon footprint — at least 8% of global emissions caused by humans come from the cement industry alone.
>
> We must decarbonise its production.[9]
>
> NATURE, EDITORIAL, 28 SEPTEMBER 2021

Cement is a simple and well understood commodity product. Cement production is a remarkably complex process with ever-changing inputs (fuels, raw materials), conditions (state of equipment, shift changes), and competing priorities (throughput, control limits).[10]

The raw materials of cement, limestone and clay, are mined at local quarries and crushed in preparation for the preheating kiln. This combined “raw meal” is heated to around 900°C in a process called calcination: a chemical reaction in which the calcium carbonate in the limestone is converted into calcium oxide. Carbon dioxide is released as a part of this reaction. The CO2 produced during calcination accounts for 55% of cement’s carbon emissions. The “calcined raw meal” is then added to a rotating kiln and heated to an extreme temperature (1450°C) to produce “clinker”, the key constituent of cement. Fossil fuels are burnt to produce the high temperatures required in the preheater and kiln. This process accounts for 40% of CO2 emissions in cement



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[8] https://ourworldindata.org/emissions-by-sector
[9] https://www.nature.com/articles/d41586-021-02612-5#ref-CR3
[10] https://www.worldcementassociation.org/about-cement/cement-facts

production, with the remaining 5% for electricity in grinding materials. As such, the amount of cement used in concrete compared to other materials is a key factor in the carbon footprint of concrete.

The significant demand for cement production can be largely attributed to urbanization and the increased need for infrastructure.

Currently, much of the demand for cement is from China, with over 50% of global production of cement occurring there.[11] While China's cement use is expected to decline over the coming decades, globally cement production is expected to increase due to soaring population growth and urbanization in other developing Asian countries, India and Africa. "The unprecedented rate of urbanization that is projected to happen in Africa by mid-century will greatly increase the demand for materials. For example, cement production is expected to more than triple in Africa, and steel production would increase more than sixfold."[12]

A key assumption for this review is that demand for cement will not change by 2030.

This is consistent with the International Energy Agency's (IEA's) forecast that circa 4.3 gigatonnes (Gt) of cement will continue to be produced each year,[13] and that growth in cement production will continue between 2030 and 2050.

In this report, we have not looked at technologies which would reduce the use of concrete, with one exception (graphene). Reducing the use of concrete is one of the most direct ways to reduce the production of cement and technologies that reduce demand for cement are important. These include not building, using alternative materials, reducing waste and creating better engineering designs. Work in this area is being led by organizations such as the 'Useless Group' based at the University of Cambridge in the UK.[14]

Nevertheless, models from the IEA and other organizations forecast stable production levels as they expect demand reduction from these technologies will be offset by increases in demand from other areas. Demand for cement includes increased civil infrastructure being built to protect against rising sea levels and extreme weather events.

The focus of this report is to identify ways to reduce carbon emissions from any concrete and cement that continues to be produced.

The trajectory of emissions from cement production is currently going in the wrong direction.

According to the latest tracking report from the International Energy Agency, "The direct CO2 intensity of cement production increased 1.8% per year during 2015-2020. In contrast, 3% annual declines to 2030 are necessary to get on track with the Net Zero Emissions by 2050 Scenario."

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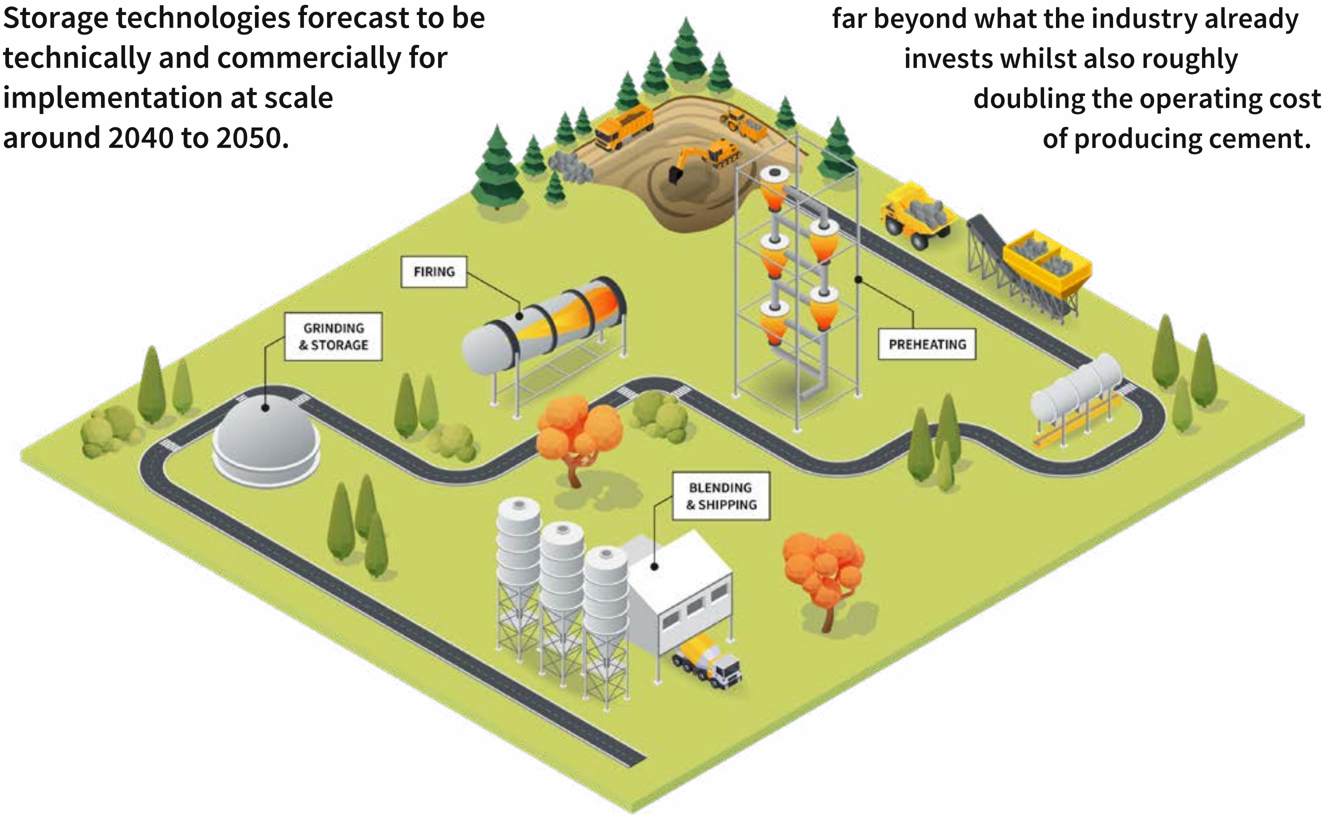
[11] https://www3.weforum.org/docs/WEF_NetZero_Industry_Tracker_2022_Edition.pdf
[12] https://webstore.iea.org/the-future-of-cooling
[13] https://www.iea.org/reports/cement
[14] https://www.uselessgroup.org/files/construction_prospectus_viewing.pdf

The global thermal energy intensity of clinker is estimated to have remained relatively flat over the last five years at 3.4–3.5 GJ per tonne of clinker. This underlying increase in the intensity of emissions from cement production is driven by a 1.6% average annual increase in the 'clinker to cement' ratio. 'Clinker' is the intermediate product responsible for the carbon emissions, and more of it is being used in each tonne of cement. China has the lowest level of clinker in cement, and hence better for the environment, at a ratio of 0.66.[15] This ratio increased from 0.55 in 2015 driven by regulations on cement quality. Europe has the highest levels of clinker in cement globally at 0.75, driven in part by adverse effects of the European Union's "Emissions Trading Scheme" that paradoxically incentivize clinker production..

From research and analysis conducted by Carbon Re in Spring 2022, we found that large cement producers in Europe on average have achieved a 0.9% p.a. reduction in carbon emissions over the last three years. Their published targets to 2030 are to double this performance, aiming to achieve 2% p.a. average reductions, and allowing them to hit the targets set in Paris in 2015.[16] Analysis by others shows that significant reductions were achieved in the period 1990–2010,[17] but have now stagnated and emissions are even increasing.

The roadmap to reduce emissions from cement relies on new Carbon Capture and Storage technologies forecast to be technically and commercially for implementation at scale around 2040 to 2050.

Cement companies recognise this challenge and opportunity. They have driven the cement industry almost to the top of the list of companies announcing pledges to reduce net zero emissions by 2050.[18] To achieve "net zero" as an industry by 2050, cement companies expect limited progress by 2030 and more than any other industrial sector are relying on Carbon Capture, Utilization and Storage (CCUS) technologies expected to be implemented around 2040–2050. This reliance on unproven technologies is due to a lack of commercially-attractive options available today: **CCUS and other technologies will require massive levels of capital investment far beyond what the industry already invests whilst also roughly doubling the operating costs of producing cement.**



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[15] https://www.worldcement.com/asia-pacific-rim/05102021/fine-china/

[16] https://climate.ec.europa.eu/

[17] https://materialeconomics.com/publications/scaling-up-europe

[18] https://www.iea.org/reports/net-zero-by-2050

Achieving reductions by 2030 is more important than achieving ‘net zero’ in 2050

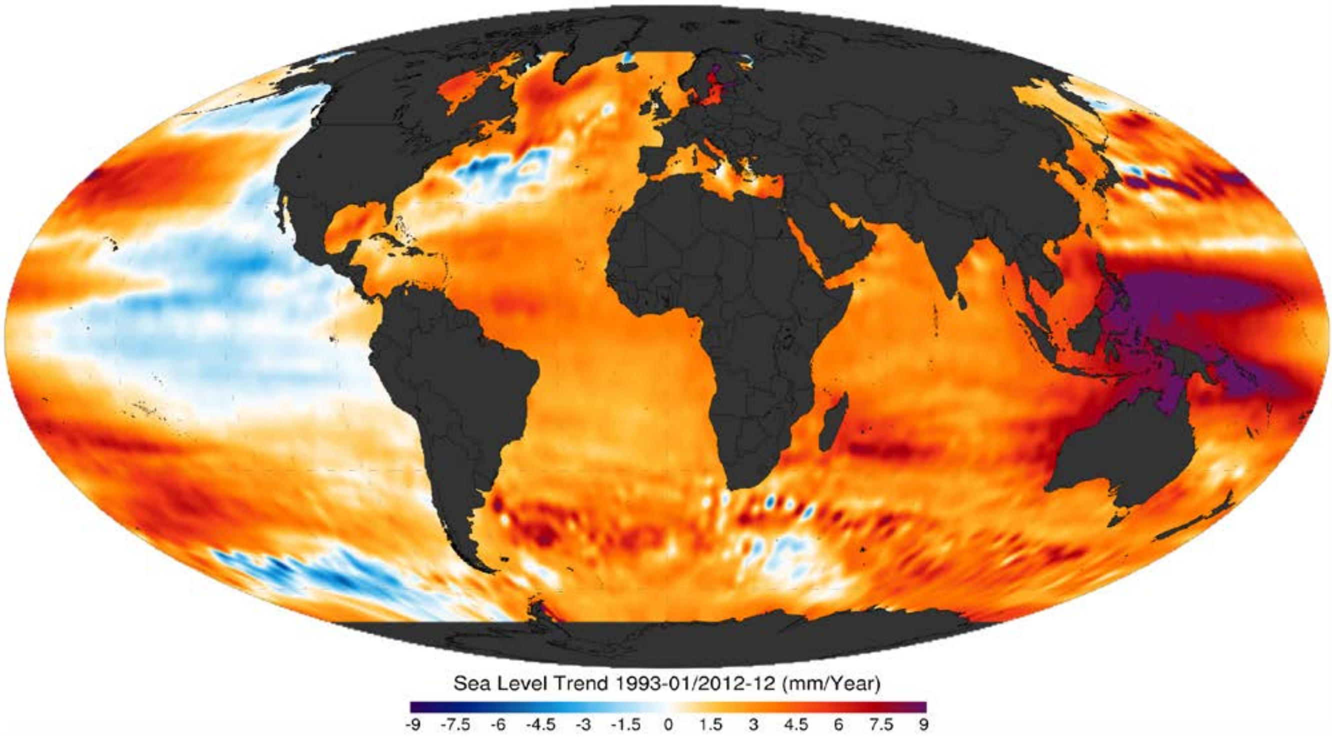
Given the scale and importance of cement production as the largest source of emissions driving climate change, progress to 2030 in reducing emissions is critical due to an often overlooked factor in global warming: the ‘time value of carbon’.

Research published in Nature in 2021 shows that not hitting net zero (but making good progress by 2030) delivers a significantly better result than hitting net zero through a big improvement between 2040 and 2050.[19]

The research in Nature assessed that step changes in 2040–2050 to hit net zero in 2050 actually delivers a significantly worse outcome for global warming than other scenarios they looked at. Instead, keeping the temperature rises to under 2°C is more likely to be achieved by not hitting net zero in 2050, instead focusing on smaller and earlier changes in the period 2020 to 2030.[20]

The chart on page 11 shows the four routes to net zero analyzed by researchers, and two routes (light grey dotted lines) which did not hit net zero in 2050. The chart above on the right shows that these two scenarios led to lower over time temperature rises than many of the ‘net zero in 2050’ scenarios.

The underlying reason for this difference is due to something called the ‘radiative forcing impact’. Emissions we make between now and 2030 will have an extra 20 years in the atmosphere to drive climate change.



Source: www.noaa.gov via wikimedia commons

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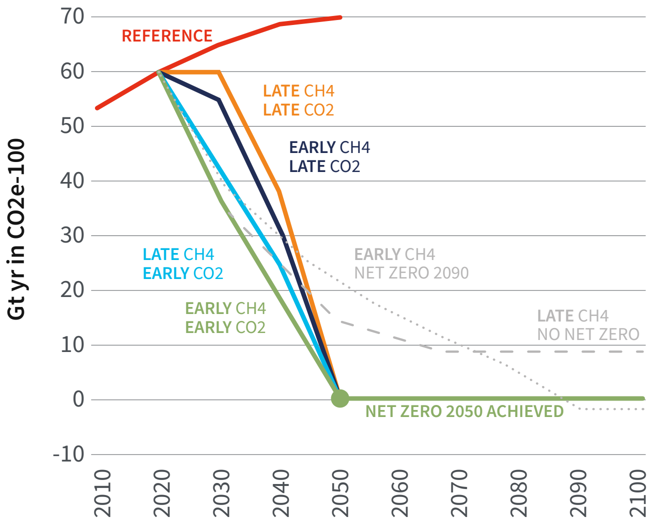
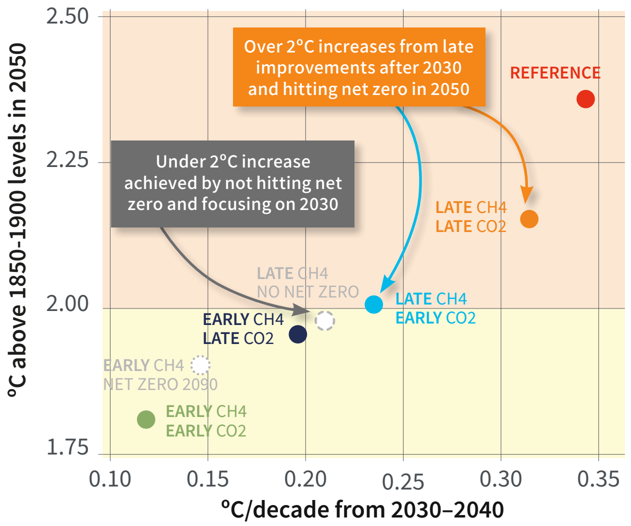
[19] https://www.nature.com/articles/s41598-021-01639-y

[20] https://www.nature.com/articles/s41598-021-01639-y





Evaluating technologies which can make a difference to global warming, now

The purpose of this white paper is to identify and assess technologies with the capability or potential to reduce carbon emissions from cement production by 2030.

We looked for mature technologies which are still being rolled out, technologies currently being deployed that can be scaled further and new technologies due to be viable by 2030.

In this paper, we share how each technology works, the companies and organizations driving them forward and the carbon emission results achieved to date. Using the available data on each of the technologies, we built a model to assess the potential of each in terms of the Gt (“gigatonnes”, or 10^9 metric tonnes) of net carbon-equivalent (“NetCO2e”) emissions reduction that could be achieved between 2023 and 2030:

a. An ‘optimistic’ scenario, where each technology is rapidly and globally scaled by cement producers.

b. A ‘maximum’ scenario, where we have removed commercial and financial constraints, to try and consider the underlying fundamental engineering or physical potential of the technology.

Our review of this research focused on the cumulative gigatonne carbon reduction potential by technology, and the annual gigatonne carbon savings possible by 2030.

The cost of the technology is a critical factor as there is no price premium in the market for low carbon products

Cement production is a competitive market and cement is a commodity product traded at low prices. With significant long-term investment costs to build a cement plant, cement producers have to be very careful with both capital investments and operating costs to maintain profitability. Any investment in technology that lowers carbon emissions needs a business case to justify the cost, putting a significant limit on the options available. In this report we share indicative costs of each technology where they are available.

Thirteen technologies with potential

Our review identified the following technologies with the capacity or potential to reduce carbon emissions from cement production in the period from now to 2030. They broadly fit into three groups:

GROUP #1: Reducing the use of clinker	**'Clinker' is limestone that has been ground then heated to a very high temperature and is the main 'active' ingredient in cement, as well as being the source of the high-carbon emissions from cement production.**	1. Supplementary Cementitious Materials (SCMs) 2. Artificial intelligence to support SCMs 3. Limestone Calcined Clay Cement (LC3)
GROUP #2: Improving the process	**The process used to create clinker hasn't significantly changed for over 100 years.**	4. Alternative fuels using existing rotary kilns: biomass, refuse derived fuels (RDF) and municipal solid waste (MSW) 5. Alternative fuels using new kilns: green hydrogen 6. New kilns using electricity as the heat source: kiln electrification 7. Artificial intelligence to improve thermal electrical energy efficiency: AI fuel optimization 8. Waste heat recovery 9, 10 & 11. CCUS, including oxyfuel, direct separation and mineralization technologies 12. Calcium looping form of CCUS
GROUP #3: Reducing use of concrete	**Concrete is the primary use for cement, where cement acts as the binder that holds the material together to give it strength.**	13. Graphene

We set out technologies that have not been assessed or ruled out from page 20.

GROUP #1: Reducing the use of clinker

Clinker is limestone that has been ground then heated to a very high temperature and is the main 'active' ingredient in cement, as well as being the source of the high carbon emissions from cement production.

1. Supplementary Cementitious Materials (SCMs)

SCMs reduce the clinker content of cement, replacing it mainly with fly ash (from coal-power stations), ground granulated blast furnace slag, steel slag (waste products from steel production), or volcanic ash. These waste products are "cementitious" and hence less clinker can be used, and their embodied emissions are lower than clinker.

This is one of the most proven of all the technologies, and has been in use for a long time at many cement plants. A key factor affecting their use has simply been their cost, as the price cement producers pay can be quite volatile with changing levels of demand.

Many cement plants already have the necessary infrastructure to incorporate SCMs into the cement mix. Scalability is limited by the availability of these waste materials, and availability is expected to reduce as coal-fired power stations close and steel production processes improve. The substitution rate of SCMs for clinker is also limited: the strength of concrete decreases with increasing use of SCMs.

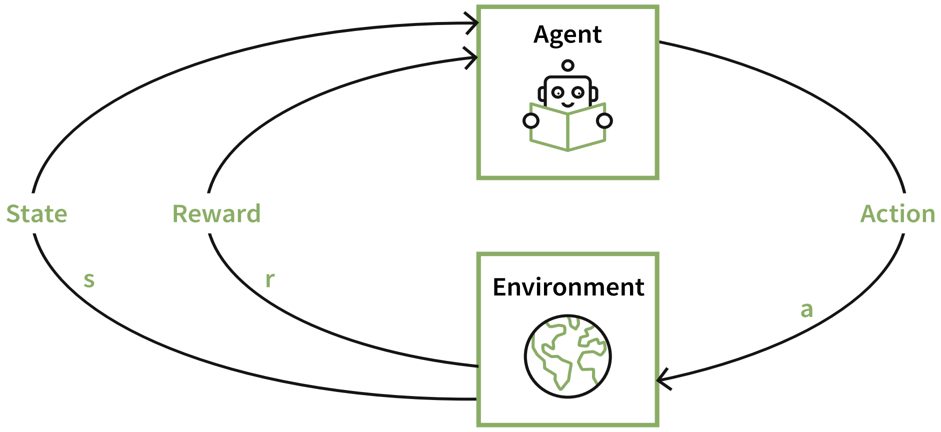
The global leaders in the use of SCMs are Indian-based cement producers Dalmia and Shree. Their access to SCMs has allowed them to reduce their clinker/cement ratios to an industry leading 0.61 and 0.64 respectively. As such Dalmia reported 489 Net kg CO2 per tonne cementitious material in 2021, and Shree 533 Net kg CO2 per tonne cementitious material, well below the average of 622 Net kg CO2 per tonne cementitious material of the world's leading 20 cement producers.

Hot steel slag pouring at a steel plant

2. Artificial intelligence (AI) to support SCMs

An incremental advance in technology in the last three years has been the use of AI-based machine learning tools to support the use of SCMs.

A key challenge with using SCMs is achieving a reliable and standardized cement blend, given the natural variability in their attributes compared to a more regular clinker quality level. AI helps with the challenge of maintaining cement quality strength. Rather than simply creating a cement mix then completing strength tests after 2 days and 28 days, the AI is able to predict the resulting strength of a cement mix from data on the constituent source materials.



Using AI to optimize the process of blending cement mixes is relatively novel and being led by Alcemy, an Austrian firm who have partnered with Spenner, Märker and Rohrdorfer cement producers. Holcim, the global cement producer, has also created a similar tool in-house called CemQ.

3. Limestone Calcined Clay (LC3)

With "LC3", activated clay material and limestone is mixed directly into the cement mix, replacing up to half of the clinker normally used. To 'activate' the clay material, a temperature of around 800°C is required, well below the 1500°C needed for clinker production and with a chemistry that leads to lower carbon emissions.

We have assessed LC3 separately from other SCMs due to the different growth potential and cost profile. The required clay and limestone raw materials are abundant and widely available in locations where most cement is produced such as China and India.

LC3 is a relatively new discovery, with research funded in Switzerland at the École Polytechnique Fédérale de Lausanne in 2014.[21] As such it is a relatively new product in an industry with extremely slow adoption rates to new technologies, driven by concerns about long-term performance and safety. Pilots have been conducted and the resulting cement has been tested to meet requirements.

Production processes need to be updated at each cement plant to introduce the LC3 into the cement mix, and a new line to produce the activated clay. Companies leading this technology are FLSmidth with HeidelbergMaterials and CBI in Ghana.

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[21] https://www.forbes.com/sites/jenniferhicks/2014/06/23/green-cement-to-help-reduce-carbon-emissions/?sh=adb729217097

GROUP #2: Improving the process

The process used to create clinker hasn't significantly changed for over 100 years.

4. Alternative fuels using existing rotary kilns: biomass, refuse derived fuels (RDF) and municipal solid waste (MSW)

Replacing coal as the fuel used in existing cement kilns with alternative fuels is a well-established way to reduce carbon emissions and costs of cement production. The use of fossil fuels to heat ground limestone to 1500°C is responsible for around 40% of the carbon emissions from cement production (the majority is a result of the chemical reaction which occurs producing clinker).

The capital investment required to build a cement plant is in the range of $200 million to $300 million, with a lifespan of over 30 years. As such technologies which exploit existing processes and hardware are much more likely to be adopted in the short term. Minor investment is required in equipment to feed in the biomass and waste-derived fuels to the cement kiln, and controls on the type and moisture content of fuel used to ensure the required high kiln temperatures can be achieved.

Not all 'alternative fuels' are an attempt to reduce carbon emissions. Cement producers can be paid to burn waste materials by government authorities, or be given waste material at no cost to dispose of. Examples include shredded tyres, dried sewage sludge and shredded plastics. Refuse derived fuels and municipal solid waste are made from the combustible components of everyday rubbish. It can be seen as a final chance for waste to be a renewable energy source, as it avoids landfill. An alternative view is that the waste should have been better sorted and recycled instead of burned. Emissions from burning this waste can be harmful to our health and ecosystems, depending on the temperature of the incineration process and the content of the waste.

Biomass as an alternative fuel is seen as being particularly attractive. Biomass is considered a renewable energy source, derived from organic materials such as wood, crops, and waste. It is considered to be carbon neutral because the carbon dioxide emitted when it is burned is roughly the same amount that was absorbed by the plants during their growth. In theory, this means that burning biomass does not add any additional carbon dioxide to the atmosphere, making it a sustainable source of energy. In practice, however, biomass is unlikely to be carbon neutral for two reasons. Firstly, the time difference between the carbon being released during combustion and its recapture over months and years.[22] Secondly, deforestation is a significant contributor to climate change and the increasing trade in biomass creates a demand for wood that is a factor in deforestation.

Biomass and waste are already widely used as alternative fuels, and hence availability may limit its further rollout. Our 'optimistic' model follows the IEA forecast of a global increase in biomass and waste fuel use in cement production from 3% in 2022, to 6% in 2023 and to 14% by 2030.

5. Alternative fuels using new kilns: green hydrogen

By heating a cement kiln with carbon-neutral "green hydrogen" rather than fossil fuels, all thermal carbon intensities can be eliminated. Due to hydrogen producing a flame that differs from that of coal-based fuel mixes, new infrastructure and heating systems are required at each cement plant. In addition, for hydrogen to be "green" it needs to be generated through water electrolysis, powered by a renewable source of electricity. The total capital investment required in a cement plant for hydrogen production and renewable electricity generation is significant.

Cement production through green hydrogen is not the most efficient use of renewable electricity. Each stage of the process incurs efficiency losses that

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[22] https://www.politico.com/news/magazine/2021/03/26/biomass-carbon-climate-politics-477620

drive up the cost to use green hydrogen: generation of the renewable energy, production of the hydrogen, transportation of the hydrogen, and then burning of the hydrogen.

Green hydrogen has high demand as a renewable energy source, being seen as a primary decarbonization route for shipping, aviation, road transportation, chemical production and steel production: fuel prices will be high. Production capacities are low, due to both the availability of renewable electricity to power electrolysis and the capacity of electrolysis plants.

As yet, hydrogen hasn't been commercially used to power cement production on its own, only as part of a fuel blend. CEMEX are using hydrogen in their fuel mix in every European cement plant, although not specifically green hydrogen. Hanson/Heidelberg are running pilots in the UK.

6. New kilns using electricity as the heat source: kiln electrification

Successful pilots of a new kiln design in Finland show how renewable electricity can be used to achieve the high process temperatures required for cement production. By powering the kiln with electricity over fossil fuels, there is the opportunity to eliminate all thermal carbon intensities, if renewable electricity is supplied.

Coolbrook are the industry leaders and expect to have their technology commercially available by late 2024, partnering with CEMEX and UltraTech cement.[23]

Scalability is limited by expensive capital investment, and cost /availability of 100% renewable electricity will be a barrier. There is also doubt in the industry that electricity will supply enough energy for the sintering phase in the kiln.

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[23] https://coolbrook.com/news/2022/cemex-will-use-coolbrooks-rdh-technology-to-cut-co2-from-cement-production/

7. Artificial intelligence to improve thermal electrical energy efficiency: AI energy optimization

Cement production is a complex process with competing demands, controlled manually by plant operators.

Complexity in the process derives from natural variations in the input raw materials and fuels, making the chemical reactions that take place during the heating process difficult to control, ultimately affecting the quality and consistency of the final product. Cement plant kiln ‘control room operators’ need to consider these changing input variables (fuel mix, raw materials), operational process controls (feed rates, kiln speed, cooler fans, exhaust fans, preheaters), and operating constraints (emissions, temperatures, production rates, process stability, quality parameters). All whilst trying to maximize production, reduce fuel consumption and achieve the desired output quality.

With AI and Machine Learning (ML) technology, the many variables of cement production can be controlled, allowing for an optimal and more efficient process, reducing carbon intensities from the fuel and electricity used.

The technology became commercially available in 2022, with active companies including Carbon Re, SIEMENS, ABB, FLSmidth and ThyssenKrupp.

Roll-out of the technology could be fast, with some systems able to roll-out without capital investment, whilst others require installation of new process control systems across the cement plant.

8. Waste heat recovery

“Waste heat recovery” harnesses thermal energy lost through the pre-heater and clinker cooler stages of cement production, generating electricity that can be used elsewhere in the cement production process.

The technology is commercially available and offered by multiple companies. Exergy has 22 plants using their Organic Rankine Cycle system (not just for cement plants), and other companies include Sinoma Energy, Triveni Turbines, Turboden, Korra Energi, and Man.

Demand from cement plants for the technology is not high, due to the capital investment required and the overall cost of the resulting electricity generated. Not all cement plants may be suitable, as newer and more efficient plants have less to gain from the technology.

9, 10 & 11. CCUS, including oxyfuel, direct separation and mineralization technologies

Carbon Capture, Utilization and Storage (CCUS) is the technology of containing CO2 emissions that would otherwise be released into the atmosphere, and then either locking the gases away or using them in some beneficial way. CCUS is seen as the only way to address the carbon emitted during cement production from the chemical reaction when limestone becomes clinker.

There are various methods of capture, as described below. For using or storing the emissions, there are broadly three approaches: permanent storage, non-permanent storage and finally sequestration of the CO2 in concrete.

Permanent storage requires taking the gases from factory chimneys, isolating pure CO2, condensing it, and finally storing it. Non-permanent storage is simply containing the emissions until ready for usage in other industries, typically biological/chemical conversion. The alternative to storage is carbon sequestration: an example being “CO2 curing”: this involves exposing concrete to CO2 gas and steam after pouring, to improve the strength and durability of the concrete. Cost and technology maturity are the key factors in speed of adoption:

- Many technologies are currently being developed and trialled as small-scale experiments to determine the feasibility of an industrial-scale project, no industrial level installations are functioning yet.[24]

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[24] CO2 capture facilities do exist, such as Exxon Mobil’s ‘Shute Creek’ facility in the US, however 97% of the CO2 flowing in the facility is vented to atmosphere. https://energypost.eu/worlds-biggest-carbon-capture-project-shute-creeks-sell-or-vent-business-model-isnt-working/

- Capital investment and operating costs for CCUS are significant and evaluated later in this report. They are predicted by industry experts to more than double the price of cement from around $80 per tonne cement to over $200 per tonne cement.

Some research suggests that the true emission reductions may be limited once emissions associated with the full process of CCUS are factored in.

OXYFUEL

- Oxyfuel uses high purity oxygen to replace atmospheric gases in a specially designed and enclosed kiln. Nitrogen and sulphur containing molecules are no longer produced in the combustion process, hence capturing the carbon in the exhaust gases becomes cheaper and achieves higher capture rates.
- Oxyfuel has been proven on a small-scale pilot plant and is ready for commercial scale pilots: AC2OCEM project; Slite, Lägerdorf plants. Full scale operations are scheduled to begin operating from around 2026.

DIRECT SEPARATION

- For direct separation, emissions from burning fuel in the kiln are separated from the emissions from the chemical reaction. High purity carbon emissions from the calcination reaction are easily captured.
- This technology is now at the stage of full scale pilots. The LEILAC 2 project is the largest direct separation project using CALIX technology; and it is being piloted at the Lixhe plant in Belgium.

MINERALIZATION

- With mineralization, captured carbon emissions are exposed to concrete during/pre-casting, whereby the CO2 reacts and is sequestered in the concrete material. This technology has the capability to make concrete production a carbon sink, and it is the only technology we looked at with this potential.
- Special trucks are required for concrete used on site, and better results have been achieved in pre-cast concrete.
- The technology is commercially available but is still only active on a small scale: CarbonCure, Amarco, Cementa, and Solidia[25] all offer forms of the technology. It is unclear as to how this technology is expected to scale, and there are still some questions as to how effective it is in terms of true CO2 reduction.[26]

12. Calcium looping form of CCUS

Calcium looping involves the capture of carbon emissions in the flue gases from a rotary kiln, reacting with CaO-based sorbent. The resulting material is Calcium Carbonate which can then be effectively used or recycled e.g. as a limestone filler as an SCM in the cement mix.

The technology is not yet at full scale pilot scheme stage. Examples are the CEMCAP project in Spain, the CLEANKER project demonstration plant in Italy, the Fortera[27] solution, and the HECLOT project which has been in operation since 2013.

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[25] https://www.holcim.com/what-we-do/cement/solidia

[26] CarbonCure aim to scale from 0.08 Mt annual CO2e reduction today to 500 Mt p.a. by 2030. An article in Nature suggests that in total 0.1 to 1.4 Gt will have been saved cumulatively by 2050, and say the real net emission reduction will likely be significantly lower.
Source: https://www.nature.com/articles/s41467-021-21148-w

Even at the top end of the scale with 1.4 Gt cumulative savings, 500 Mta p.a. by 2030 would be unachievable: at the current top performance of 20kg CO2e/m3 concrete the technology would need to be used in more concrete than is currently produced globally (about 14 billion cubic metres).

[27] https://www.globalcement.com/magazine/articles/1230-fortera-low-co2-cement-inspired-by-nature

GROUP #3: Reducing use of concrete

Concrete is the primary use for cement, where cement acts as the ‘binder’ that holds the material together to give it strength.

13. Graphene

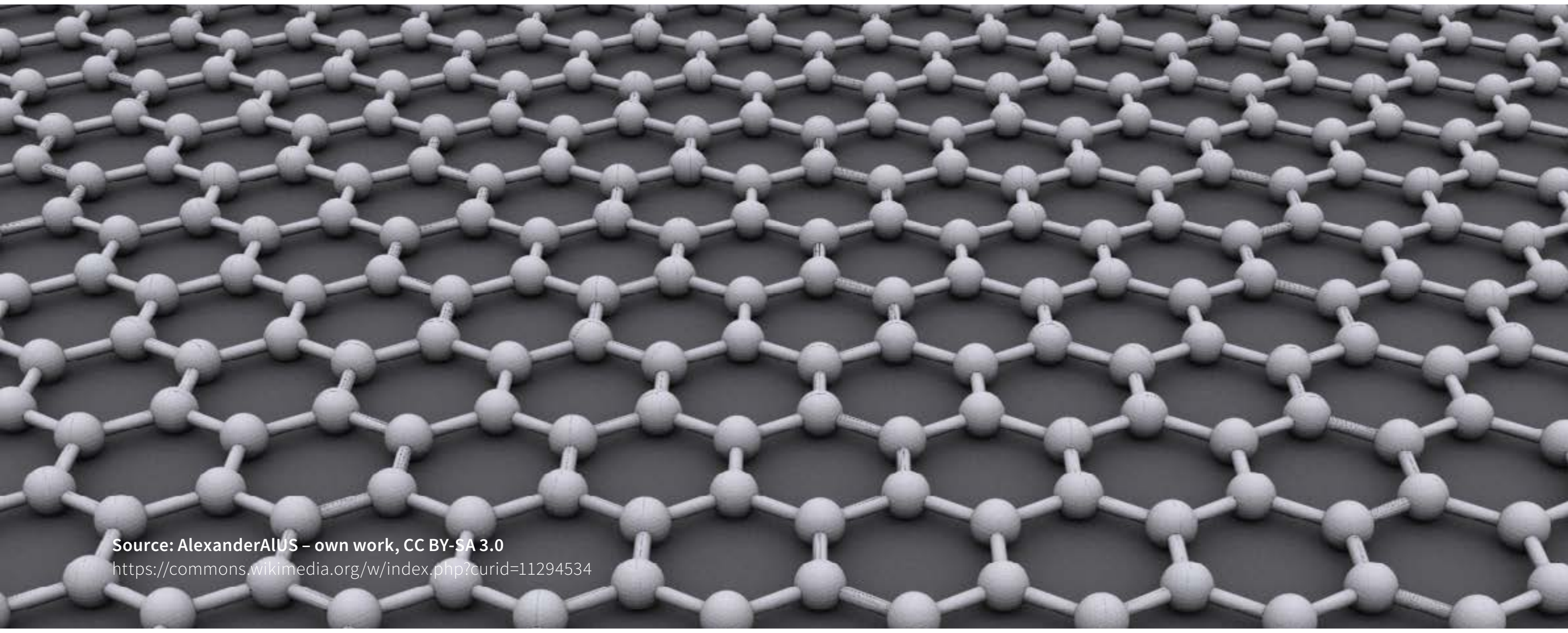
Graphene is a form of carbon that consists of a single layer of atoms arranged in a hexagonal lattice. It is a highly conductive material first identified in 2004 that is also strong and lightweight, making it useful in a variety of applications from pharmaceutical drug delivery to aircraft components.

Graphene can be directly added into a concrete mix, where graphene nanoplatelets strengthen concrete. The graphene decreases porosity, increases crystallinity and acts as a nucleation surface. The resulting concrete is significantly higher strength and hence studies suggest 20% less concrete is required to meet the same load requirements, and up to 50% less cement may be required.

Graphene can be produced through a number of methods, including mechanical exfoliation, chemical vapour deposition, and epitaxial growth. All are complex processes and production is limited. Given demand from other industries, graphene is very expensive, 1 tonne can cost from US$67,000 up to $200,000 compared to just $50 for the same quantity of cement. Trials suggest the use of graphene could be cost effective, as the reduced quantities of concrete needed for the same strength could balance out the high cost of graphene. Only 1.9kg of graphene is reportedly needed for every 20,000 kg of concrete.[28]

Pilots have been completed by one company in the UK, with ‘Concretene’ being used in multiple building projects in Manchester. Nationwide Engineering and Manchester University are both supporting the Concretene product.

We chose to include graphene in the scope of this research as the sole technology which reduces the use of concrete. While there are many other technologies which would reduce or replace the use of concrete, our rationale for including graphene is that it is a technology which also affects both the quantity of clinker required in cement, and the quantity of cement required in concrete. As it will affect clinker production and cement mixing, we propose it is a technology which fits alongside the others in this report and in the decarbonization roadmap for cement producers.



Source: AlexanderAlUS – own work, CC BY-SA 3.0
https://commons.wikimedia.org/w/index.php?curid=11294534

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[28] https://www.nationwideengineering.co.uk/wp-content/uploads/Concretene-Graphene-Enhanced-Concrete.pdf

Alternative technologies not assessed

A number of technologies have been developed with potential to reduce carbon emissions from cement production. For different reasons we have not modelled their potential impact to 2030 as part of this review, as seen below:

Algae-based biocomposite cement alternative

One way to drive innovation is to use nature as a guide, looking at how natural systems function and the ways in which they are sustainable and resilient. For example, ecosystems in nature are able to recycle nutrients and other resources, reducing waste and preventing pollution. By studying these systems and understanding the ways in which they operate we can develop new technologies, products, and practices that mimic these natural processes and are more sustainable and environmentally friendly.

In 2016, a team of biotechnology and engineering professors at the University of Colorado Boulder developed a replacement for traditional cement using 'microalgae' to create cement-free concrete blocks. Whilst the technology is reported to be in commercial production, volumes are limited.[29,30]

Carbicrete

Complete cement alternatives, such as Carbicrete, often use waste materials similar to SCMs. Limited availability of these waste materials, combined with technology immaturity and a different production process means that these complete cement alternatives will not be available on a large enough scale to have an impact by 2030.

Concrete down-cycling

Concrete down-cycling takes old concrete, crushes it and uses it in place of aggregates in new concrete. We rejected this technology as the aggregates are not a significant source of embodied emissions in concrete, and down-cycling concrete may lead to more cement being needed to deal with the lower quality aggregate.

Chemical additives

Chemical additives can be added to both cement and concrete, they decrease carbon emissions in numerous ways including: increased grinding efficiency, less water demand, less clinker and less cement. According to GCP, a leading supplier of proprietary additives, their additives can reduce the emissions by 14%, an effective 150 kg CO2/t cement saving.[31] Information on the specific chemical compounds used is limited, and particularly for our model, their cost, availability and carbon emission reductions.

The commercial sensitivities about chemical formulations and processes mean that objective data is hard to obtain. According to GCP,[32] "*The myriad cement chemistries and morphology variables available – combined with the varying objectives and constraints in each market means there is a vast number of permutations when it comes to choosing which cement additives to use. It can also be difficult to predict the performance of combining multiple additives together.*"

This is an interesting area of technology for further evaluation. It is likely to be enhanced further by AI and machine learning to resolve the complex decisions required on the right additives to use for each construction application.[33]

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[29] https://www.globalcement.com/news/item/14226-prometheus-materials-develops-cement-free-blocks-using-algae

[30] https://www.dezeen.com/2022/06/07/prometheus-biocomposite-cement-blocks/

[31] https://gcpat.com/en/cement-additives

[32] https://gcpat.com/en/about/news/blog/decarbonizing-cement-industry

[33] https://intellegens.com/

Due to the lack of publicly available information on the underlying chemicals or third party studies validating performance which would allow us to assess scalability we have been unable to include them in our assessment.

Electrolysis

Electrolysis is a different approach to clinker production that can replace the heating process altogether, published in a paper by MIT in 2019. Normally, clinker is formed by sintering limestone and aluminosilicates, causing decomposition when CO2 is simultaneously released. Electrolysis, on the other hand, applies a voltage across limestone dissolved in water to form calcium hydroxide. Silicon dioxide is then added to the calcium hydroxide to form alite, one of the four mineral phases in clinker. Whilst CO2 is still produced, the benefit of electrolysis is that fumes are purer making CCUS more effective. Hydrogen is also formed as a side product which could be used as a fuel elsewhere. This chemical reaction avoids the need for high temperatures, but has only been tested in a laboratory.

The main concern regarding this pathway is that it has yet to be proven on any kind of industrial scale and cement production via electrolysis is yet to be trialled outside of the labs at MIT. There is therefore limited knowledge on the cost, scalability, and other potential drawbacks. This process would also be energy intensive, requiring electricity from renewable sources for it to be truly a deep decarbonization. Given the time required to develop and scale this technology it falls outside our 2030 scope.

Limestone fillers

Limestone filler is an attractive technology that is already in use at scale and involves replacing clinker based cement with uncalcined limestone.[34] Although this technology has the benefit of having a potentially fast rollout, it is a less ambitious version of LC3 cement (which also uses uncalcined limestone). In terms of carbon emissions impact it can only save 17.5kg CO2 / cubic metre of concrete (approximately equivalent to 70kg of CO2 per tonne of cement), almost five times less than that of LC3.

Natural pozzolans

“Natural pozzolans” are a specific type of SCM, including rocks of volcanic origin and sedimentary clays and shales. Specific examples used in cement are volcanic ash and calcined clays. Some need processing and calcination whilst some do not. Availability of local supply is a constraining factor due to shipping costs.

The main types of natural pozzolans are covered by our assessment of LC3 (containing calcined clays) and volcanic ash within SCMs. As such we haven’t specifically separated and assessed the alternative, less-used pozzolans.[35]

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[34] https://www.saint-hilaire-industries.fr/en/blog/low-carbon-limestone-filler-for-concrete

[35] https://precast.org/2017/09/scms-concrete-natural-pozzolans/

Our methodology and assumptions

Our methodology

Our methodology to estimate the carbon emission reduction potential of each technology was based on analysis of publicly available information as at August 2022. We reviewed scientific literature, reports from public bodies, listed company annual reports and other industry analysis to obtain performance levels for each technology. Where performance levels were provided by a commercial business we looked for third party assessment and validation of the results.

Taking 2022 performance as the baseline, we then evaluated the potential to scale the technology over the period from 2023 to 2030.

Our carbon emission savings are presented as gross values, and we have not assessed the carbon costs related to installation of the new technology. For example, over the period under review, the net carbon savings for kiln electrification and CCUS, will be lower than presented in this report. This is, due to the large quantity of steel and construction material required for installation of the technology.

Scalability of each technology

Speed of infrastructure roll-out is the limiting factor on scalability for the majority of the technologies that we assessed. Before modelling we had to consider how to quantify this limit.

We aimed to determine the number of cement kilns being installed each year to estimate the absolute limit of kiln-based infrastructure. To do this we considered both the new kilns installed and replaced kilns every year.

For new kilns, we have assumed an arbitrary 30 kilns per year – just 1% of the number of kilns globally. We would not expect this value to be many times higher as production of cement is not expected to increase globally between now and 2030. However, in developing nations, demand will increase, leading to new plants and more kilns.

For the number of kilns being replaced every year, we found the average kiln lifespan to be between 12 and 25 years (IEA). As there are around 3,000 kilns globally, we have estimated a value of 200 for replaced kilns.

Other important figures in our model are the production capacities of integrated plants and their kilns. We took average kiln capacity as 1.2 million tonnes per annum (Mt p.a.) of clinker and 1.8 Mt p.a. of cement for the integrated plant capacity. With these numbers we were in a position to estimate the CO2 savings from such infrastructure changes. Our model could also be very easy to be adjusted if different circumstances were required or our number turned out to be incorrect.

Key assumptions in our model

In order to establish our model and scenarios we have made the following key assumptions:

- **100% of electricity used in an electric kiln will be renewable**

  Actual availability of renewable energy is lower, we have assumed only renewable electricity will be sourced.

- **All biomass is carbon neutral and fully renewable**

  Biomass can actually be worse than coal for climate change, and may be a significant factor contributing to deforestation. Our optimistic scenario increases from 6% to 14% following IEA's 'Net Zero Scenario'.

- **Sufficient quantities of graphene are available in a suitable quality**

  More research is needed on the graphene quality required to deliver the performance result, and production significantly expanded.

- **CCUS will be commercially available by 2025**
  For the 'optimistic' model we assumed by 2030 there will be 15 full scale systems for each of the respective types.
- **Average kiln life span is 12–25 years**
  Some kilns can operate for 50 years, others are mothballed very early in their life.
- **LC3 roll out will be possible on a large scale in India and China**
  Both India and China have access to the required volume of clay and so are likely to be the lead adopters of LC3.
- **Waste Heat Recovery systems generate enough electricity to fully supply the integrated cement plant with all electricity needs**
  The resulting CO2e saved is the average carbon intensity of this amount of electricity.

Estimating the carbon emission reduction potential of each technology requires a specific model in each case to assess the impact

More details on the specific assumptions and calculations made for each of the technologies, together with the primary sources used, is included in the Appendix.

Summary of our assessment: ‘optimistic’ scenario

Our findings are that three technologies available today can have a material impact to drive down carbon emissions from cement production by 2030: SCMs, Biomass/Waste Fuel and AI.

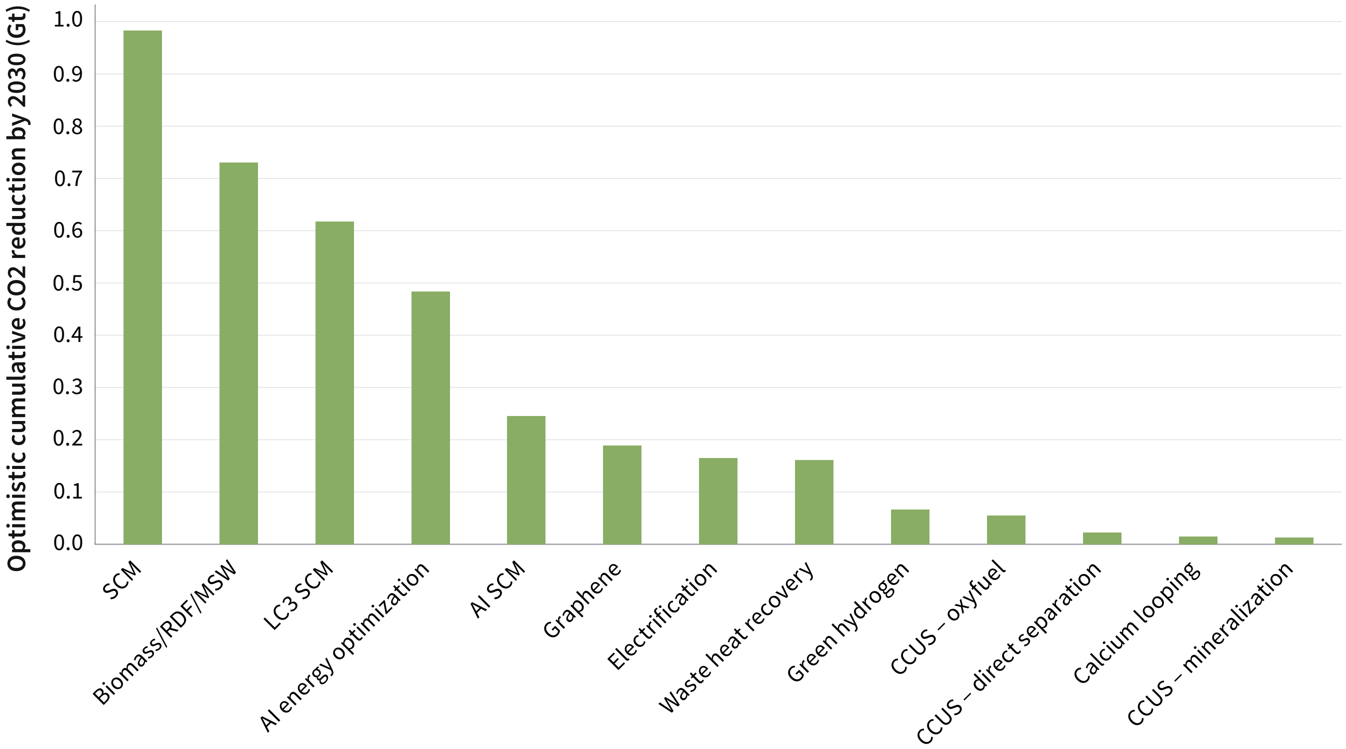
Our review focused on estimating the cumulative net CO2 reduction potential of each technology by 2030, as shown in the chart and table below. The technologies are ranked in order of their cumulative gigatonne impact.

The chart below shows SCMs are the highest impact technologies, followed by the replacement of fossil fuels with alternative fuels in the existing rotary cement kilns (biomass/RDF/MSW). Both of these technologies are mature and well established, having played a significant role in reducing carbon emissions from cement production over the last 30 years. Our ‘optimistic’ model suggests that the LC3 form of SCM and AI process controls are the two technologies which will join them with over 100 Mt p.a. CO2 impact by 2030.

In this ‘optimistic’ scenario there is not much interplay (positive or negative) between the different technologies. For example, in this scenario biomass increases from 3% in 2022, to 6% in 2023 and then to 14% of thermal fuel use by 2030, which allows plenty of scope for kiln electrification and new kilns using 100% green hydrogen. We believe it is fair to assume that each cement company or plant will implement different technologies that do not cannibalize each other.

In total the technologies under review in this scenario would have a 19% cumulative impact on carbon emissions from cement production over the period. In terms of annual performance, achieving all the combined savings from the technologies listed would reduce emissions from 2.5 Gt CO2 in 2022 down to 1.7 Gt CO2 in 2030, a 34% reduction.

Chart 1: Cumulative CO2 reduction from 2023 to 2030 (Gt) in the ‘optimistic’ scenario



The IEA has set a target for cement to achieve 2.1 Gt CO2 in the year 2030, a 16% reduction, broadly in line with the reductions targeted by listed European cement companies. As such there is a good reason for optimism that the IEA's target can be achieved, or even exceeded.

Nevertheless to achieve this result a concerted effort is required by all cement companies to implement all the technologies available today. Whilst there are significant cost barriers to consider (discussed further below), selecting just the technologies with low or no capital investment requirements and low operating costs can deliver a 26% annual reduction in CO2 emissions.

To compare the barriers to implementation of each technology, we assessed ease of adoption for each of these technologies according to these three factors:

- **Maturity of the technology**

  Is the technology at pilot stage, with early adopters or well understood in the market?

- **Commercial availability**

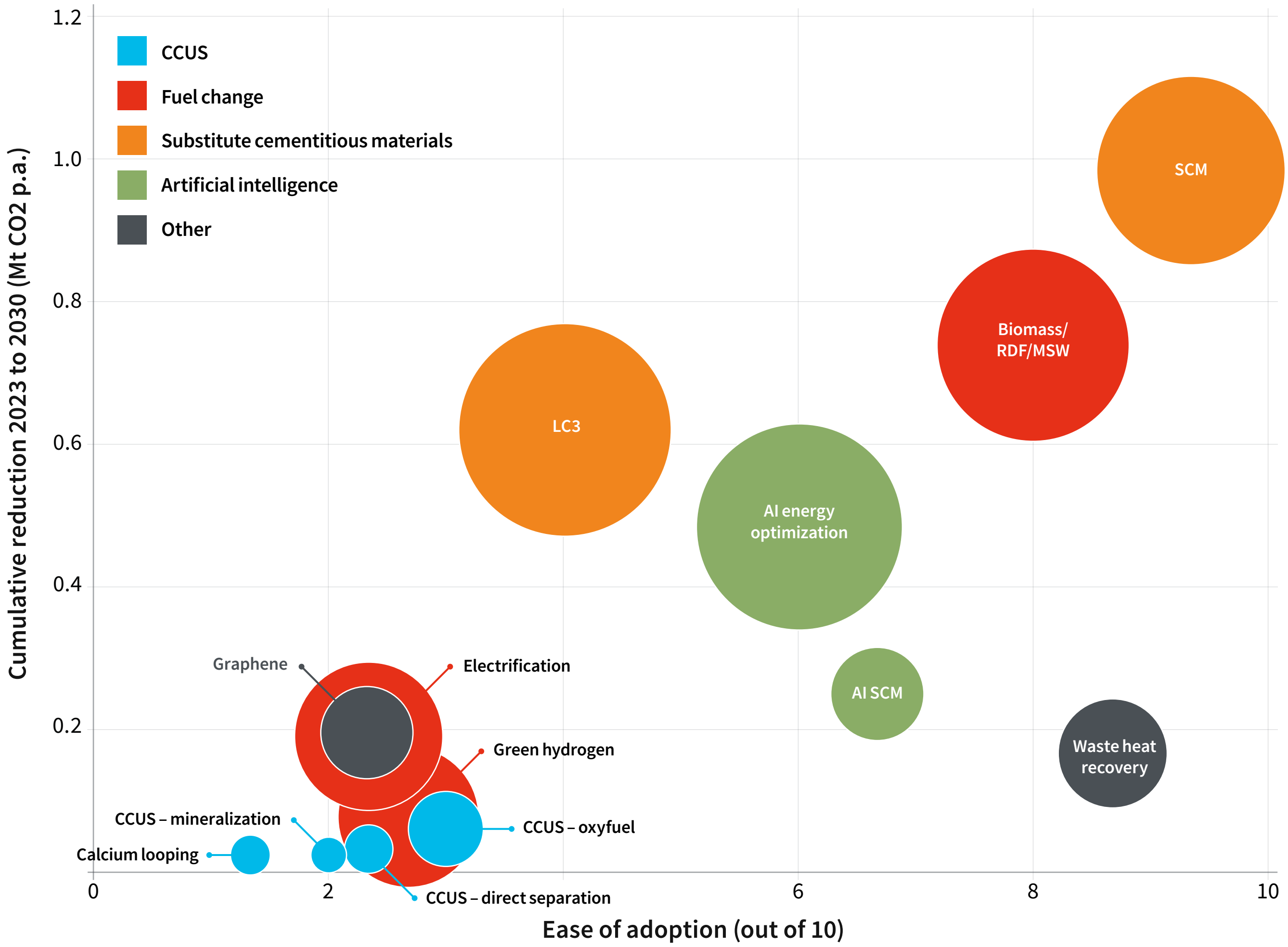
  Is the technology commercially available by just one provider or a number of providers?

- **Degree of change to current industrial processes**

  Does the technology require a new production process, significant changes to the current process, or no change?

As shown in the chart below, technologies with the largest cumulative impact over the period, and the largest annual impact in 2030, are also the ones with the greatest ease of adoption.

Chart 2: Cumulative CO2 reduction from 2023 to 2030 (Mt p.a.) in the 'optimistic' scenario compared to current Ease of Adoption in 2023



Size of circle represents the annual carbon saving potential in 2030 in gigatonnes.

Common barriers to achieving the carbon emission reductions estimated in the ‘optimistic’ scenario

Significant barriers will need to be overcome to achieve the ‘optimistic’ scenario:

- **Commercial interest of cement companies due to cost, competitive position etc.**

  For example, sunk costs for capital investment in clinker production capacity create a disincentive to switch to LC3, graphene or SCMs.

- **Focus on new tech for 2050 undermines efforts to make change now**

  Current plans are focused on CCUS-based technologies from 2040, which removes some of the pressure to deliver changes in the short term.

- **Market demand for low carbon cement**

  To date there has been no commercial demand from clients or price-based opportunity for low carbon cements beyond an occasional ‘showcase’ project, although this may be starting to change.

- **Regulations on cement quality and specification**

  The time and effort required to gain approval and industry acceptance for new cement formulations is significant. Concrete needs to perform well over decades, so long-term studies are required.

- **Availability of finance for capital investment**

  Many of the technologies require significant capital investment above the normal levels seen in the cement industry. Given the limited financial business case for capital investment, availability of finance will be limited.

- **Technology performance matches pilot performance when scaled**

  We have assumed that successful pilots can be scaled across cement plants and regions.

- **Perception of ‘carbon neutral’ e.g. biomass**

  We have taken industry norms regarding calculation of the carbon savings. Re-evaluation of these norms, such as considering the impact of biomass on deforestation, would change the findings.

- **Competition for scarce resource e.g. renewable electricity, green hydrogen, SCMs, biomass**

  Many of the resources needed for decarbonisation are scarce and in significant demand from other industries also moving to reduce carbon emissions.

Evaluating the underlying physical and technical limits to each technology

Our investment in technology now should look beyond current limitations and also consider the underlying potential.

To further understand and compare technologies we created another ‘maximum’ scenario, to consider what could be achieved if we removed commercial and financial constraints. As shown in the table below, in most cases we found that the technologies could have 5 to 10 times the cumulative impact if these constraints were removed. This model helps compare the longer term potential of each technology beyond 2030.

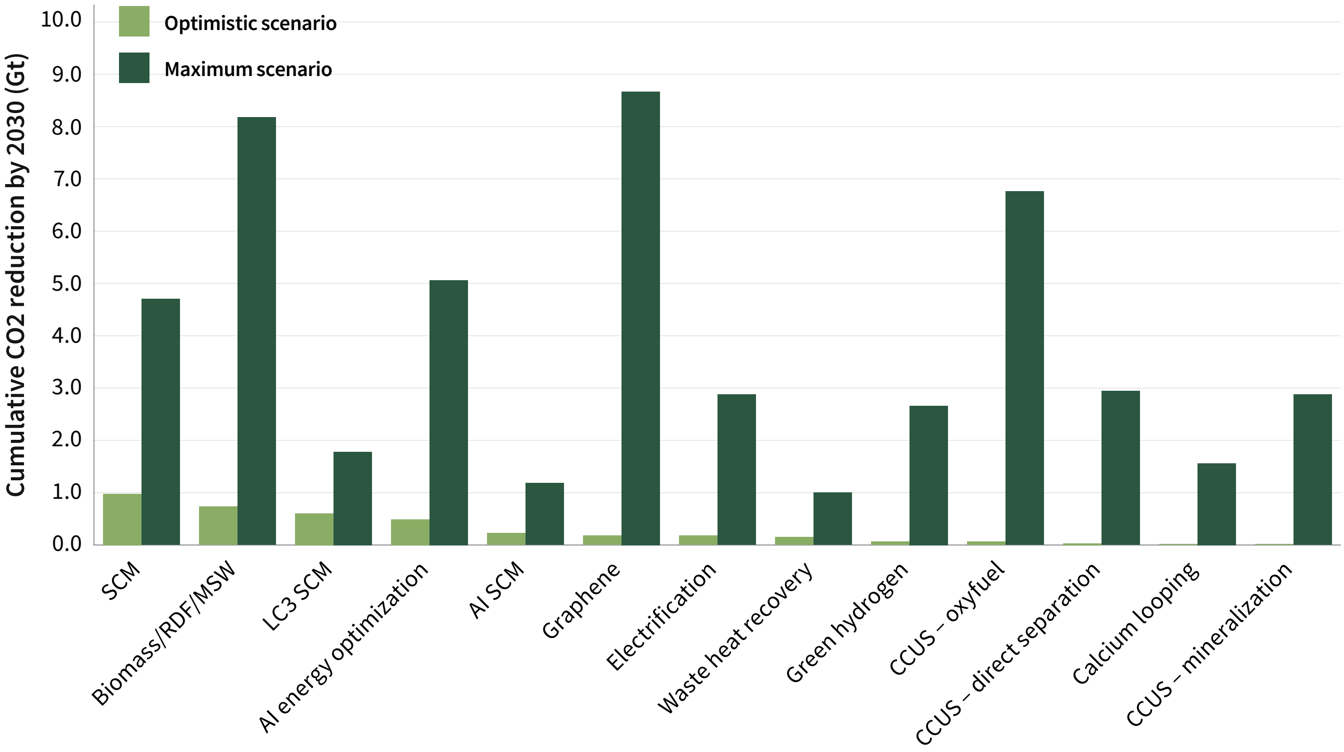
This ‘maximum’ scenario highlights a few key elements:

- From results achieved to date, oxyfuel, CCUS, graphene and LC3 have the greatest longer term potential.
- CCUS-based technologies could have over 100x the impact if financing barriers were removed for both the capital investment and increased operating costs.
- Waste heat recovery has limited upside potential.

Interplay between these technologies is critical beyond 2030

In the ‘maximum’ scenario the total carbon reductions achieved when added together total 256%, and as such the interplay between technologies becomes critical. For example, the 8.1 Gt CO2 saving from biomass and alternative fuels is not achievable at the same time as the 8.7 Gt CO2 saving from reducing the amount of concrete used via graphene.

Chart 3: Cumulative CO2 reduction by 2030 (Gt) in the ‘maximum’ scenario



Complementary effects between the technologies include:

AI ALTERNATIVE FUELS	AI models for the kiln pyro-process can help optimise and accelerate use of alternative fuels e.g. biomass/MSW
ELECTRIFICATION AND CCUS DIRECT SEPARATION	By tackling both fuel and process emissions, this combination could make cement production close to net zero.

Dilutive effects between the technologies include:

WASTE HEAT RECOVERY vs AI ENERGY OPTIMIZATION vs ELECTRIFICATION	Increased energy efficiency in the kiln will reduce heat loss to the stack, and hence reduce heat that can be recovered there. Electrification is an alternative to both.
AI vs CCUS	AI will increase efficiency, increasing costs of CCUS for the same carbon capture.
LC3 vs AI OR ALTERNATIVE FUELS	The ‘greener’ cement production becomes, the smaller the pay off from using LC3 .

The evolution of the use of SCMs in cement production

SCMs have been widely used in cement production for some time. In our ‘optimistic’ model we have assumed that in 2023 all SCMs that currently go to waste in landfill are used for cement production, increasing the quantity from 0.37 Gt p.a. at current levels by another 0.12 Gt p.a.

Once this step change has been achieved, limited further improvements can be made by using SCMs, as they are waste products from other processes which are in long-term decline: coal-fired power plants and steel-producing blast furnaces. In our ‘optimistic’ scenario we have assumed that there is no increase or reduction in the availability of SCMs by 2030. In the ‘maximum’ scenario we evaluate next, we have assumed that all SCMs are diverted from their other uses and wholly being deployed for cement production.

Biomass and green hydrogen-based technologies should be approached with caution

Evaluating the net impact of increased biomass production on climate change

In both 'optimistic' and 'maximum' scenarios, biomass and waste-derived alternative fuels have a significant positive impact. Using biomass as a 'carbon neutral' fuel is already a controversial point in climate change discussions, and further expansion of the use of biomass is likely to significantly raise concerns further.[36] In general models, biomass is evaluated as being fully renewable. However in practice, biomass is considered as a significant factor in deforestation. Global transatlantic shipments of biomass also contribute to a carbon footprint that isn't identified in most simple models of industrial fuel sources.

The role of hydrogen as a fuel in cement production

Hydrogen is already established as an alternative fuel for use in existing rotary cement kilns: Cemex have recently rolled out use of hydrogen as part of their fuel mix in all their European cement plants.[37] The carbon savings from this small scale use of hydrogen may be limited both due to the proportion of hydrogen used in the fuel mix as well as the carbon emissions from any hydrogen which isn't "green".

"Green" hydrogen produced by electrolysis powered by renewable electricity is the only carbon neutral form of hydrogen as a fuel. Three changes will be required for green hydrogen to become a scalable and attractive major fuel source for cement production:

- Redesign and capital investment in new special rotary kilns,
- Significant increase in the availability of renewable electricity to power its production, and
- Significant increase in the production capacity of hydrogen through electrolysis.

Even with these three changes, hydrogen may not be available to cement production in sufficient volume and at the right cost: many industries are looking to green hydrogen as their 'fuel of choice', which is likely to mean high demand and hence high prices. At current prices of US$5 to $6 per kg, green hydrogen is 2x to 3x times more expensive than coal for the same amount of energy used. This leads to a high abatement cost of over $200 per t of CO2 saved, well over current carbon prices which remain under $100 per t CO2.

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[36] https://www.bbc.co.uk/news/business-59546278

[37] https://www.cemex.com/-/cemex-to-introduce-hydrogen-technology-to-reduce-co2-emissions-in-four-cement-plants-in-mexico

Evaluation and limitations of our model

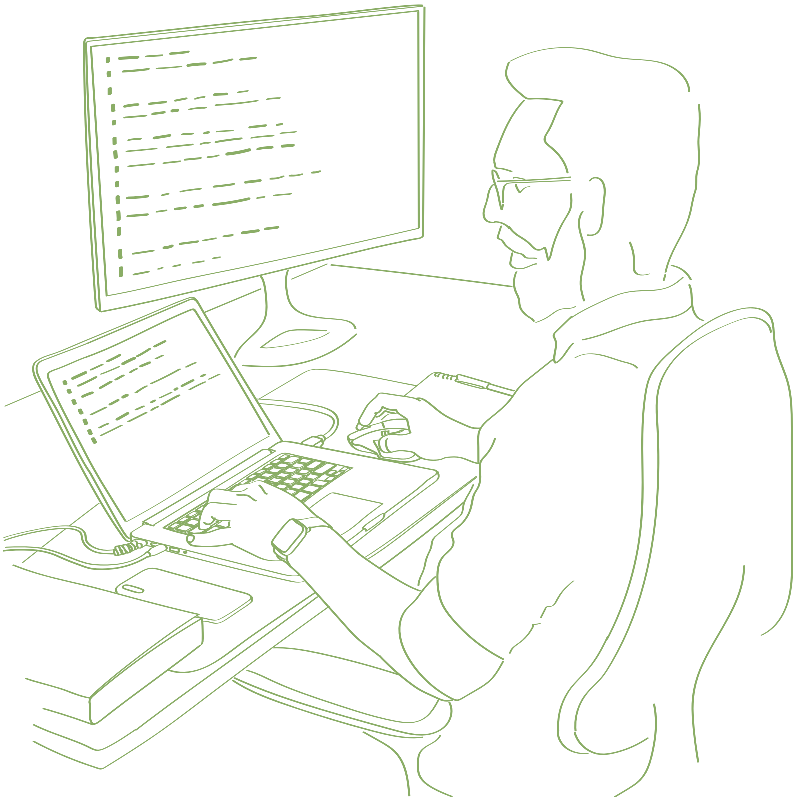
Whilst there are many potential takeaways from our findings, it is important to remember that it is a model with limitations. It fails to account for some complex factors that could have great impact on which technologies succeed and which do not. For example, our model has limited ability to factor in the comparative financial costs of the different technologies. Even with government subsidies and incentives, cost will have a major impact on the rollout. The investment case for each technology will be affected by the unexpected volatility in fuel prices such as experienced in 2022.

A particularly difficult part of our research was predicting the scalability of technologies that are still new, in development and require huge capital investment. This suggests that our model is best used in a comparative fashion and that there may be disparity with the non-infrastructure (biomass, AI optimization, SCMs) and infrastructure requiring (electrification, green hydrogen, CCUS) technologies.

One way our model could be improved would be by providing a range of values for figures; however, this would require set and justified bounds and greatly increase the complexity of our model. We considered using a minimum and maximum figure instead of likely and maximum savings. However, for several of the technologies the minimum would be zero or insignificant, providing little information about the future of the technologies. Another reason for switching to a range is that figures on the cement industry occasionally had to be taken from 2018 data due to a lack of public availability of more current figures. Whilst we would expect these figures not to have changed drastically in this time, it decreases the accuracy of our model.

Our model simplifies the many ideas and current projects for CCUS. These include oxyfuel technology, direct separation, amine scrubbing, calcium looping, polymeric membrane separation on top of the utilization and storage options: mineralisation, methanol production, e-fuels, fertilizers, stimulating microalgae growth farms or simply permanent storage. The potential savings will be determined by which combinations of technologies are chosen. This kind of complexity cannot be factored in.

Our model also fails to account for current regulations slowing down the adoption of new/alternative technologies by the cement industry. For example, although there is the opportunity to increase the supply of SCMs included in cement, the class of the cement is defined by the substitution rate. This is an example of a regulation that is likely to hinder decarbonization. Due to this regulation only certain levels of substitution are allowed to keep the cement in a certain class. A higher substitution rate may be in a different class making it less attractive to consumers. There continues to be concern for how SCMs will affect the long-term mechanical properties of the concrete and this classing system. According to Chatham House, "Unfortunately it can take decades for a new standard to be approved and implemented in the EU."



Capital and operating costs will be a critical factor in technology adoption

Technologies with low capital expenditure and operating costs are naturally the ones which will be prioritized by the cement industry and their technology providers. In the current market there is no competitive advantage or price premium for low carbon cement productions in any global region.

In some global markets, ‘Emissions Trading Schemes’ put an external value on the amount of carbon emitted, and some companies have an ‘internal cost of carbon’ that allows them to create a business case for investment in carbon emission reduction projects. In the absence of these two factors, carbon reduction technology needs to deliver an attractive cost saving.

As shown in the table below, our assessment is that technologies with the highest gigatonne CO2 impact between now and 2030 have no or low capital requirements, and typically deliver operating cost savings.

Table 1: ‘Optimistic scenario’ CO2 reduction over the period 2023 to 2030, and indicative cost factors for capital investment (‘capex’) and operating costs (‘opex’)

Technology	‘**Optimistic**’ CO2 reduction Cumulative from 2023 to 2030		Cost factors	
	Gt	%	CAPEX	OPEX
SCM (without AI)	**1.0**	**4.9%**	Low	Saving
Biomass/RDF/MSW	**0.7**	**3.7%**	Low	Low
LC3	**0.6**	**3.1%**	Low	Saving
AI energy optimization	**0.5**	**2.4%**	Saving	Saving
AI SCM	**0.2**	**1.2%**	Low	Saving
Graphene	**0.2**	**1.0%**	Low	HIGH
Electrification	**0.2**	**0.8%**	HIGH	HIGH
Waste heat recovery	**0.2**	**0.8%**	Low	Saving
Green hydrogen	**0.1**	**0.3%**	Low	HIGH
CCUS - oxyfuel	**0.06**	**0.3%**	HIGH	HIGH
CCUS - direct separation	**0.02**	**0.1%**	HIGH	HIGH
Calcium looping	**0.02**	**0.1%**	HIGH	Low
CCUS - mineralisation	**0.02**	**0.1%**	HIGH	HIGH
Total	3.8	19.0%		

Low	a low capital investment or increase in operating costs
HIGH	a significant capital investment required, or significant increase in costs
Saving	no capital investment or a reduction in operating costs

Indicative cost evaluation of CCUS technologies

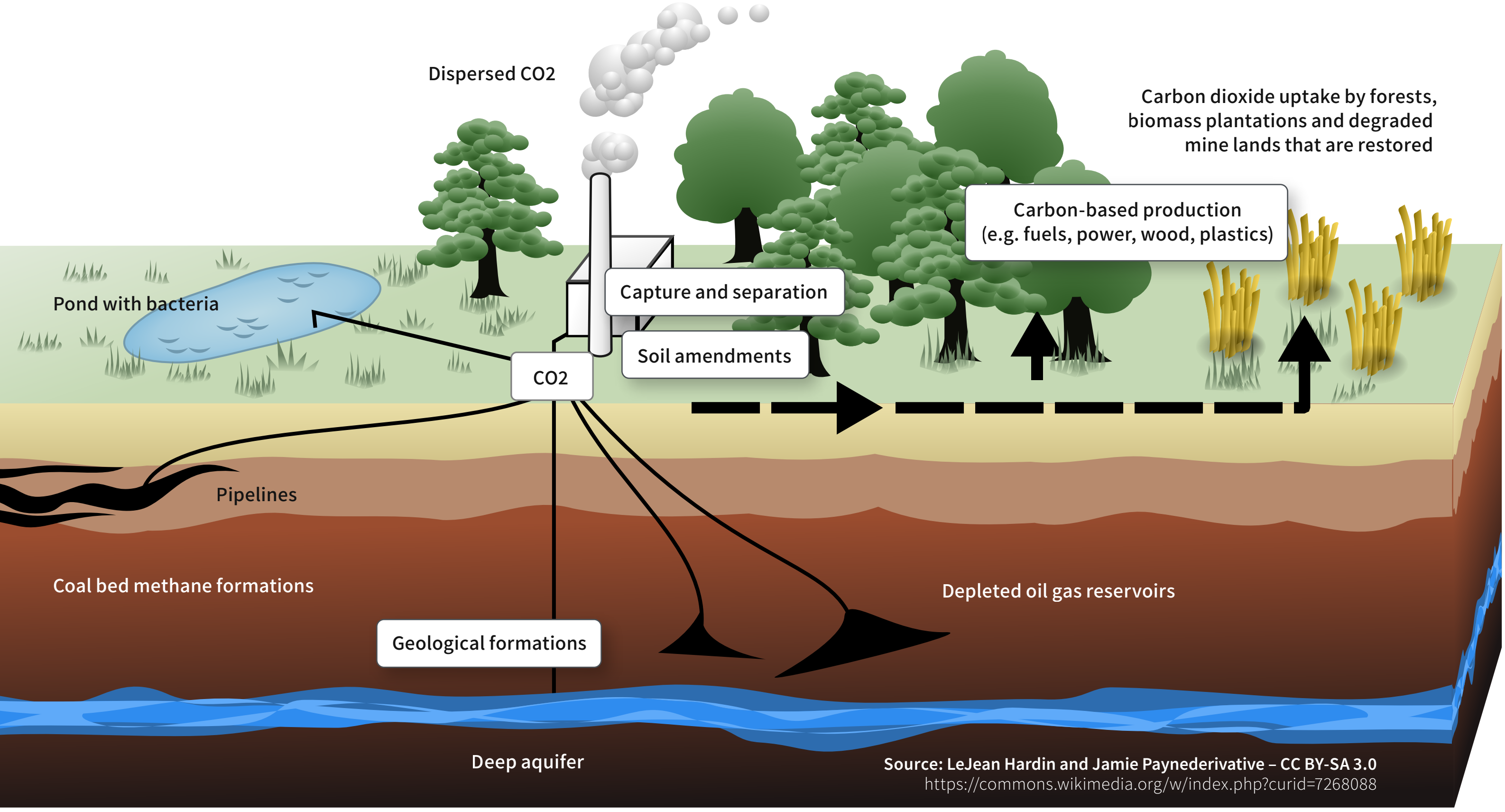
The only technologies evaluated in our review that tackle the chemical reaction-based carbon emissions from cement production are the CCUS technologies. As described below, these are expected to double the production cost of cement from under €100 per tonne to over €200 per tonne. Overall the cost of cement is not a key factor in the cost of construction of a building, however we should expect this cost increase to make alternative construction materials more cost effective and attractive. This could lead to oversupply in the industry, with the winners being those with the lowest cost and most efficient processes.

The necessary infrastructure on top of existing cement plant operations is what makes CCUS so expensive. Material Economics suggest that the capital investment for a CCUS system is approximately 1.25x the investment made in the cement production. e.g. a plant to produce 2.0 Mt p.a. of cement requires €300 million[38] to build the plant and will now need an additional €375 million investment for the CCUS equipment. This estimate at €600 million investment for carbon capture at a single plant is significantly lower than the current actual cost of pilots to date, where costs are 60% higher than this estimate.

Typical operating costs for a cement plant are €50 per t cement. Assuming flat line depreciation over 20 years, circa €20 million depreciation each year would add a cost of €10 per tonne of cement. At this level, US$250 to 500 million of capital investment will be required for every 1 Mt p.a. CO2 saving. The cost to operate CCUS equipment is estimated at an additional €30 to €50 per t cement, with an extra €10 per t cement depreciation of the investment on top.

Our modelling suggests the resulting effective cost to abate carbon emissions would be in the range of €60 to €135 per tonne CO2 once the technology is mature.

This is within the range of expectations for carbon prices for markets with an Emissions Trading Scheme in place, such as the European Union, South Korea and California, suggesting that the technology may be commercially viable in the long term.



Source: LeJean Hardin and Jamie Paynederivative – CC BY-SA 3.0
https://commons.wikimedia.org/w/index.php?curid=7268088

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[38] https://cembureau.eu/about-our-industry/key-facts-figures/

Indicative cost evaluation of graphene

Large quantities of graphene (particularly higher qualities) are expensive: costs range from $60,000 to $200,000 per tonne of graphene (cement typically only costs $50 per tonne to produce). Tests suggest that very small volumes of graphene are required, and that they can reduce the volume of concrete required by 20% to achieve the same strength (and a 50% reduction in the cement).

Depending on the cost of graphene, the overall cost of the concrete required for a structure could be a saving or a marginal increase of up to 4%.

The resulting effective cost to abate carbon emissions would either be a net saving or a cost of up to US$85 per tonne CO2 depending on the quality grade of graphene used.

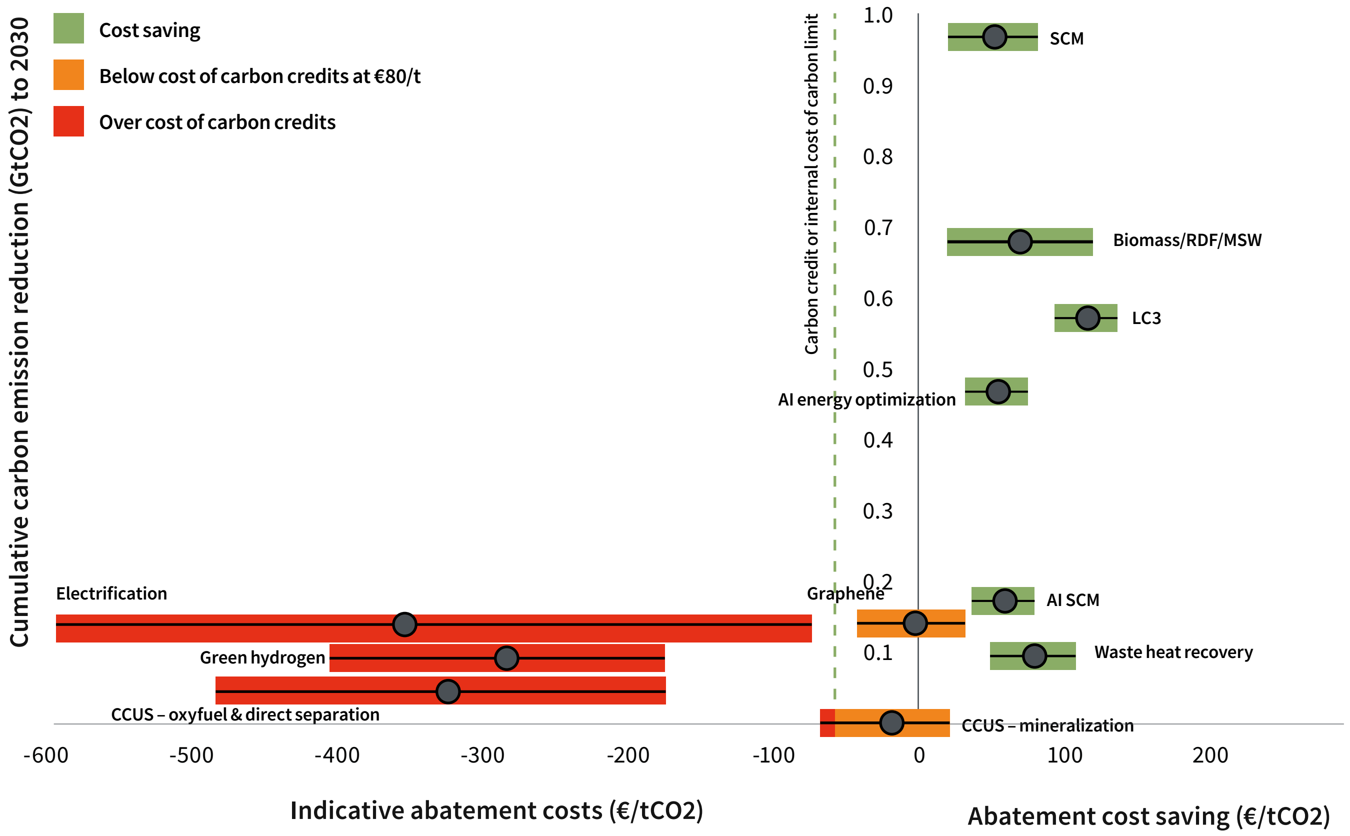
Comparing carbon saving potential and cost

Chart 4 evaluates the carbon emissions saving potential of each of the thirteen technologies under review against the combined capital and operating costs expected for each technology.

Reviewing chart 4 we can group the technologies into three that combined deliver 81% of the total 3.8 gigatonne CO2 saving in the 'optimistic' scenario, and are also cost saving opportunities:

1. SCMs: standard and LC3
2. Biomass, RDF and MSW alternative fuels
3. AI improved process controls, covering Energy optimisation and SCM blending

Chart 4: Indicative carbon emission abatement costs compared to the cumulative carbon emission reduction potential from 2023 to 2030



Our recommendations

From our work on this paper, we recommend the following:

Recommendations for cement producers

Reducing the impact of cement production on global temperature rises means taking action to reduce carbon emissions before 2030, and three available families of technologies could achieve a significant gigatonne-level reduction self-funded through cost savings.

1. Substitute Cementitious Materials (SCMs): standard and LC3
2. Biomass, RDF and MSW alternative fuels
3. AI improved process controls, covering energy optimization and SCM blending

These three groups combined deliver 81% of the total 3.8 Gt CO2 saving in the 'optimistic' scenario.

The competitive advantage for cement producers from adopting these three technologies in the short-term will be limited, other than the immediate cost savings (to varying degrees) to drive profitability. Over the coming years, we expect changes in government policies and carbon taxes to make them the primary driver of adoption of these technologies. Additionally, we expect to see significant commercial and reputational pressure on producers who don't move as quickly as the rest of the market.

In parallel, producers need to continue to develop and invest in new technologies to hit net zero in 2050 such as either CCUS to make the current process carbon neutral, or new innovative technologies for new production processes or materials. Investment in, and development of, new technologies is critical to find a way to produce cement without emitting harmful carbon emissions. Beyond the scope of this report, some technologies being developed now such as algae-based cements and production by electrolysis look promising. Nevertheless these technologies will face significant challenges in replacing current production processes, and are difficult for existing industry players to adopt.

Recommendations for policy makers

Cement production is a critical industry for reducing global carbon emissions. It is often classified as a 'hard to abate' sector due to the complexity of the industry. Policy makers should be aware that there are established technologies which can be applied to cement production today to significantly reduce carbon emissions in the short term.

As explained in our previous whitepaper, "Carbon taxes set to revolutionize cement production" in Spring 2022, policies addressing cement production need care and attention. For example, the Emissions Trading Scheme in the European Union has incentivised cement producers to increase clinker production and clinker content of their cements over the last 15 years. As a result, cement production is more carbon intensive in Europe than most other markets.

In this review we have identified a number of barriers to technology adoption, and policy makers are in a strong position to address these.

In the coming months we will research and evaluate these policy opportunities and challenges further. At headline level they are:

- Emission Trading Scheme / Carbon Tax design: recalculating how free carbon credits are allocated to cement producers, and/or removing the free issue of credits through the introduction of a Carbon Border Adjustment Mechanism.
- Establishing demand and a price premium or low carbon cements via the public procurement process.
- Establishing a certification process for the carbon content of cement.

- Encouraging a move from ‘prescriptive’ cement product standards to ‘performance based’ cement product standards to enable better use of SCMs.

Recommendations for investors

It has been around 80 to 100 years since the innovation of Ordinary Portland Cement redefined the product and process for cement production. Since then it has been broadly seen by investors as a low interest commodity sector with low levels of innovation. Eric Trusiewicz at Stanford University describes the challenges faced by ‘start-ups’ including $1 trillion of sunk-cost investment in the large cement producers, very low marginal cost of production at $20 to $40 per tonne of cement, vertical integration in the industry, aggressive competition and the influence of legacy regulations and standards.[39]

We are now entering an era where basic commodity materials are being reimagined, driven by the impact of applying a cost of carbon. Carbon taxes are forecast by industry experts to more than double the price of cement, creating a significant opportunity to create value in a large global industry.

The opportunities to invest are significant, and the businesses who achieve success in sustainability and reduction in emissions are also likely to be those that take the most profits from the sector. Opportunities to invest include:

- Cement producers with the lowest carbon intensity through their innovations and technology adoption to date
- Cement producers positioned to achieve the lowest carbon intensity, say through access to low cost carbon storage, or access to low cost SCMs and alternative fuels
- Technology providers with scalable solutions for existing cement producers
- Technology companies creating new cements to disrupt the industry and value chain

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[39] https://co2.docsend.com/view/c834kaakb6r2f5wq

Summary of our technology review

Below is a summary of our six key findings from this review:

1. **CCUS will not be here on the required scale by 2030.**
2. **Clinker reducing technologies (SCMs) along with new LC3 cement blends are likely to have the greatest impact.**
3. **Biomass has the greatest potential in the short term, after SCMs, however its impact on the climate may be limited or even negative depending on the source and wider impact of using these alternative fuels.**
4. **AI has the potential to have a significant impact in a short timescale, as it adapts to existing processes and delivers significant cost savings.**
5. **Not all technologies can be used together, some will reduce the impact and/or effectiveness of others.**
6. **Capital investment costs will hold back many of the technologies: kiln electrification, green hydrogen, carbon capture (CCUS) and calcium looping.**

Appendix

Estimating the carbon emission reduction potential of each technology required a specific model in each case to assess the impact.

AI: fuel and process optimisation

AI and ML can improve the efficiency of the full production process, directly reducing the carbon emissions from the chemical process, the fuel burnt, and electricity used.

For energy optimization of fossil fuels in the kiln, due to lack of information from companies offering similar technology, our model is based on Carbon Re's figures and projected CO2 savings as well as predicted scalability in terms of market rollout. Additional companies are working on the energy optimization of grinding raw materials and clinker.

Current AI models are focused on thermal fuel carbon intensity. By 2030, electrical, fuel and process carbon intensity are forecast to be reduced by the technology. For the 'maximum' scenario, all cement production would be using the technology from 2023. For the 'optimistic' scenario we assumed 45% of cement production using AI energy optimization technology by 2030.

Key sources

- https://planet-a.com/portfolio/carbon-re/
- https://www.carbonre.com/
- https://link.springer.com/article/10.1007/s00202-021-01409-z
- https://www.researchgate.net/publication/242393661_Cement_grinding_optimisation

Biomass

Biomass doesn't require any new infrastructure and is already used in many current fuel mixes. Therefore, the only limiting factor is the availability and potential cost of biomass over fossil fuels. For the 'maximum' scenario, we assumed that all the global industry biomass consumption would be used in cement production by 2025. This would be more than enough to fuel all clinker production. For the 'optimistic' scenario, we used the IEA's net zero scenario for the cement industry.

There was some confusion on the rate of renewable fuels currently used by the cement industry as weight percentage and thermal energy percentage are very different due to the greater energy density of coal and other fossil fuels. However, in conclusion we used the IEA's figures.

Key sources

- https://www.buzziunicem.com/documents/20143/0/Our%20Journey%20to%20Net%20Zero.pdf/acc52af1-8f28-bb30-6863-62da57c704e6?version=1.0
- https://www.sciencedirect.com/science/article/pii/S1364032120309758
- https://en.wikipedia.org/wiki/Biomass
- https://ee-ip.org/en/article/deep-decarbonisation-of-industry-the-cement-sector-1773
- https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/

CCUS: oxyfuel, direct separation and mineralization

Carbon Capture, Utilization and Storage (CCUS) is chemically capturing CO2 from flue gas that would otherwise be emitted and released into the atmosphere. Then either using the CO2 in industry or permanently storing it. In the cement industry, predominantly post combustion carbon capture is being considered.

This was one of the most challenging parts of our model, here we tried to estimate both the capture rates and the scalability of this new and slowly developing technology. We also had to consider the different approaches to CCUS. Whilst there are many current proposals for CCUS methods we decided to focus on the cement specific technologies, namely oxyfuel and direct separation.

Oxyfuel involves replacing the atmospheric conditions inside the kilns with high purity O2, this removes nitrogen and sulphur containing compounds making the capture process cheaper and more efficient. Direct separation isolates the high purity CO2 produced from the decomposition reactions for easier capture. The CO2 emissions from the burning process are not captured.

To model oxyfuel we based our average plant reduction figures on the Lägerdorf cement plant pilot and commitments. We used the same scalability model of infrastructure for the ‘maximum’ scenario with rollout commencing in 2025. There are no cement specific full scale CCUS projects planned before the end of 2024 (Norcem Brevik). For the ‘optimistic’ rollout, we chose an arbitrary scale of growth, with 15 plants using the technology by the start of 2030. This is generous but realistic, especially if oxyfuel was chosen as the stand alone best CCUS technology by 2025.

For direct separation, we assumed 99% of the process emissions were capturable, there are no published figures from full scale operations. It is believed this high rate is achievable but the extra percentage points may be more costly than worth capturing. This is 99% of only the process carbon emissions. We chose the same scalability for direct separation as oxyfuel for the same reasons.

It should be noted that for both technologies we have assumed CO2 captured is equal to CO2 saved. This is unrealistic due to emissions produced in capturing, transporting, and creating the necessary infrastructure.However, it is extremely unclear what the ratio of CO2 captured to CO2 saved is, and how this varies with what is done with the captured CO2.

We also considered mineralisation in the cement industry, a technology which is still being developed and evaluated, this is the sequestration of CO2 in concrete. It has the potential to improve mechanical properties. It is difficult to estimate the potential for rollout, however even at its maximum the total CO2 savings are still small relative to other technologies.

Key sources

- https://calix.global/co2-mitigation-focus-area/calix-and-boral-to-develop-carbon-abatement-project/
- https://wikimapia.org/38403707/Holcim-Lägerdorf-Cement-Plant
- https://www.researchgate.net/publication/319194132_Feasibility_Assessment_of_CO_2_Capture_Retrofitted_to_an_Existing_Cement_Plant_Post-combustion_vs_Oxy-fuel_Combustion_Technology
- https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/

Calcium looping form of CCUS

Calcium looping is a method of CCUS that we chose to model separately. It uses calcium oxide sorbent to react with CO2 forming calcium carbonate which then has many uses, some in the cement industry. Our model used a Taiwan pilot scheme and their 2025 target capture rates as a basis. We used a similar rate of growth to the other CCUS technologies.

Key sources

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- https://core.ac.uk/download/pdf/82149798.pdf
- https://pdf.sciencedirectassets.com/277910/1-s2.0-S1876610209X00020/1-s2.0-S1876610209000216/main.pdf
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- https://www.zkg.de/en/artikel/zkg_Trends_in_the_performance_management_of_cement_plants_1984227.html
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Electrification

Electrification of cement rotary kilns in combination with renewable electricity can remove the carbon emitted due to burning fossil fuels.

Calculations were quite simple once we had decided on the measure of scalability of infrastructure. For the 'maximum' we had 232 electric kilns being installed every year and an arbitrary scale for the 'optimistic' scenario with a total of 182 kilns by 2030. Electric kilns by Coolbrook will not be available commercially until 2024 so this is when we assumed rollout of the technology in our model. Savings were estimated by removing the carbon fuel intensity. This of course assumes we would be using renewable electricity. There was no information on the potential energy efficiency of this heating system and how it compares to a conventional kiln, so we assumed equivalent energy intensity for clinker production.

Key sources

- https://bulb.co.uk/carbon-tracker/
- https://wikiwaste.org.uk/Aberthaw_Cement_Kiln
- https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded_clm_bref_1201.pdf
- https://www.iea.org/data-and-statistics/charts/age-profile-of-global-production-capacity-for-the-cement-sector-kilns

Graphene

Graphene nanoplates are added to improve the strength of concrete. This allows for less cement usage and less concrete overall.

There were many figures that we could have used to estimate the potential of graphene in concrete. Unfortunately, all figures came from one source, the Nationwide Engineering and Manchester University project. We originally chose to work with the claim that 1.9kg of graphene in a 20t of concrete allows for up to a 50% cement reduction. However, using a different statistic on the reduction in emissions directly yielded an answer 15% smaller than our original figure. This is a clear example in the limitations of our model, the numbers can vary greatly depending on how our model is approached.

Our 'optimistic' CO2 saving required 1% of global graphene supply used in concrete, whilst the 'maximum' had the assumption of all the global graphene production being used. For our model we had to predict the growth of global graphene production: we optimistically estimated that it would be ten times greater by 2030, based from 1.1 Mt in 2019. This would mean by 2024 there would be sufficient graphene to supply the entire global supply of concrete.

Another assumption we had to make was that all graphene produced was of significant quality and negligible carbon footprint from its production. Graphene comes in a range of quality with lower qualities not being suitable in concrete. We were unable to find the quantitative quality of the graphene needed to allow for a 50% cement reduction.

Key sources

- https://www.nationwideengineering.co.uk/wp-content/uploads/Concretene-Graphene-Enhanced-Concrete.pdf
- https://gccassociation.org/concretefuture/cement-concrete-around-the-world/
- https://www.statista.com/topics/8769/graphene-industry-worldwide/

Green hydrogen

Green hydrogen, produced by electrolysis with renewable electricity, can also replace fossil fuels. Green hydrogen burns differently to coal hence requiring new heating systems when used in large volumes.

This part of our model had very similar calculations to electrification, just needing to also factor in the availability of green hydrogen. 'Maximum' assumes the rollout of infrastructure will be the limiting factor, that green hydrogen is sufficiently available. 'Optimistic' uses the IEA's numbers for the green hydrogen demand by 2025 and 2030, we interpolated these values to complete our model.

Our model assumes cement production uses 10% of global demand. This is a very generous assumption due to other needs for green hydrogen such as ammonia and methanol production as well as fuel in other industries.

Key sources

- https://www.iea.org/articles/could-the-green-hydrogen-boom-lead-to-additional-renewable-capacity-by-2026
- https://www.iea.org/reports/hydrogen
- https://rmi.org/run-on-less-with-hydrogen-fuel-cells/

LC3

Limestone Calcined Clay Cement (LC3) is an alternative to Ordinary Portland Cement (OPC), it replaces a significant amount of clinker with limestone and activated clays.

To be able to model its potential for decarbonization, we first had to estimate the savings that LC3 could provide per tonne of cement produced. We used FLSmidth's model on the savings that LC3 could offer, then standardized it to fit the average cement emissions rather than fossil fuel burnt OPC. It should be noted that the more efficient/green the OPC production becomes, the smaller the reduction in carbon emissions when using LC3.

Next, we had to predict the likely and maximum scalability of this technology. For the maximum rollout, all of India and China's cement production would be using LC3 from 2023. This was chosen as both countries have large cement production capacity and have easy access to the required clays (see source 2). The optimistic scenario estimated a rate of growth in these two countries with 30% of cement producers using LC3 over OPC by 2030. This is still ambitious; the infrastructure required to mine and transport the clays would not be quick to introduce. However, it would be cheaper than CCUS or other capital intensive technologies. India's cement production is also expected to double by 2030, making a large-scale switch to LC3 more feasible.

Large-scale roll out may require regulation changes to create the demand for LC3 cement over OPC.

Keys sources

- https://www.flsmidth.com/en-gb/discover/cement-2021/revealing-the-numbers-behind-calcined-clay
- https://lc3.ch/wp-content/uploads/2020/10/2019-LC3FinancialAttractiveness-WEB.pdf
- https://www.researchgate.net/publication/330249714_China%27s_cement_demand_and_CO2_emissions_toward_2030_from_the_perspective_of_socioeconomic_technology_and_population/figures
- https://www.kanvic.com/grey-matter/building-a-new-india

SCMs and AI optimization of SCM blending

SCMs also work to replace clinker in cement. They include fly ash, ground granulated blast furnace slag (GGBS) and steel slag (SS).

The SCMs in our model are all produced as waste from other industrial processes. Therefore, we used the reduction of OPC to calculate the CO2 abated. Sourcing values from the internet we were able to find the CO2 saved per tonne of cement with each SCMs used. We also had to source the common substitution rates for the different SCMs.

To estimate the scope of this technology we had to evaluate the limiting factor, the availability of these SCMs: fly ash, GGBS and SS. For the maximum we assumed we could access all the fly ash, GGBS and SS produced globally for use in cement: this is an aggressive assumption due to demand from other industries.

Another factor is that SCM production is declining in certain countries as the processes become more efficient and burning coal is reduced. We have assumed this will not have an impact before 2030.

For our ‘optimistic’ model, we used all the SS, fly ash and GGBS currently being landfilled/not recycled. It should be noted that both these figures are assuming the current values will stay constant between now and 2030, although this is unlikely, we were unable to find any statistics on the forecasted availability of the waste materials.

These figures are both increased savings in CO2, as SCMs are already currently in usage.

There is also strong potential for the use of AI optimization working with SCMs, we factored this into our model by suggesting only an arbitrary 80% of the emission savings would be achievable without AI working in combination. The AI works by producing higher quality cement allowing for higher substitution rates and hence further reducing the clinker content.

Key sources

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- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9525259/

Waste heat recovery

Waste heat recovery (WHR) uses the hot flue gases to produce electricity and improves the energy efficiency of the plant.

Our model used the main assumption that is source backed, that WHR can provide enough electricity to power an integrated plant. Therefore, we assumed the electricity carbon intensity would be eliminated in installing a WHR system at an integrated cement plant. The main issue is that not all cement plants are suitable for WHR, more efficient plants wouldn’t benefit enough from this technology. Therefore, the pool of cement plants that would consider installing a WHR system is smaller than the 2400 cement plants our model assumes.

Key sources

- https://ppweb-publications.s3.eu-west-1.amazonaws.com/pdf/world-cement/2022/July/WCTju30.pdf

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To discuss this paper, its findings and implications, please get in touch.

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