

Decarbonising Cement: Innovation Pathways to a Sustainable Future



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Concrete is everywhere: it shapes the landscape of our cities and the foundations of our societies. From towering high-rise buildings to the humble pavement, its presence is unmistakable, making it an indispensable role in construction worldwide.

Cement is the powdery binder that holds the sand or crushed stone in concrete together, it makes-up about 10% of concrete but accounts for the majority of its carbon emissions. Alarmingly, cement production alone accounts for 7% of global carbon emissions¹, surpassing aviation 3% and shipping 2% combined². The scale of its manufacture is staggering, with China at the forefront of a relentless surge in production, to fuel their rapid infrastructure development. In fact, just in two years (2020-2021), China has produced more cement (at 4.9 billion tonnes) than the US in the last 100 years (at 4.2 billion tonnes)³. Other countries will also use cement as they too urbanise, expanding their developing infrastructure.

So, addressing the carbon footprint of cement production is essential for achieving net-zero carbon dioxide (CO₂) emissions by 2050, given its close ties to urbanisation and development. Countries experiencing rapid development are expected to increase their cement production, further worsening the emissions issue. While the problem is significant and comprehensive solutions may be challenging to find, collaborative efforts across cements value chain, offers promising pathways for developing emission-free methods of cement production. io consulting, as an energy project architect and systems integrator, would like to share our insights gleaned from our own research and study work conducted for cement manufacturers.

Making Cement⁴

Cement is produced in large, capital-intensive production plants generally located near limestone quarries or other raw carbonate mineral sources as these are the principal raw materials used in the cement production process. The rotating kiln is heated to around 1450°C at the burner end of the kiln and fired almost exclusively by coal or other fossil fuels. Limestone (CaCO₃), clays and other additives termed “raw meal” are dropped into the system at the preheater tower.

CO₂ is released as a by-product during calcination, which occurs in the upper, cooler end of the kiln, or a precalciner, at temperatures of 600-900°C, and results in the conversion of carbonates to oxides.

The simplified stoichiometric relationship is as follows:



At higher temperatures in the lower end or furnace end of the kiln, the lime (CaO) reacts with components of the raw meal i.e. silica, aluminium and iron containing materials to produce minerals in the clinker, an intermediate product of cement manufacture.

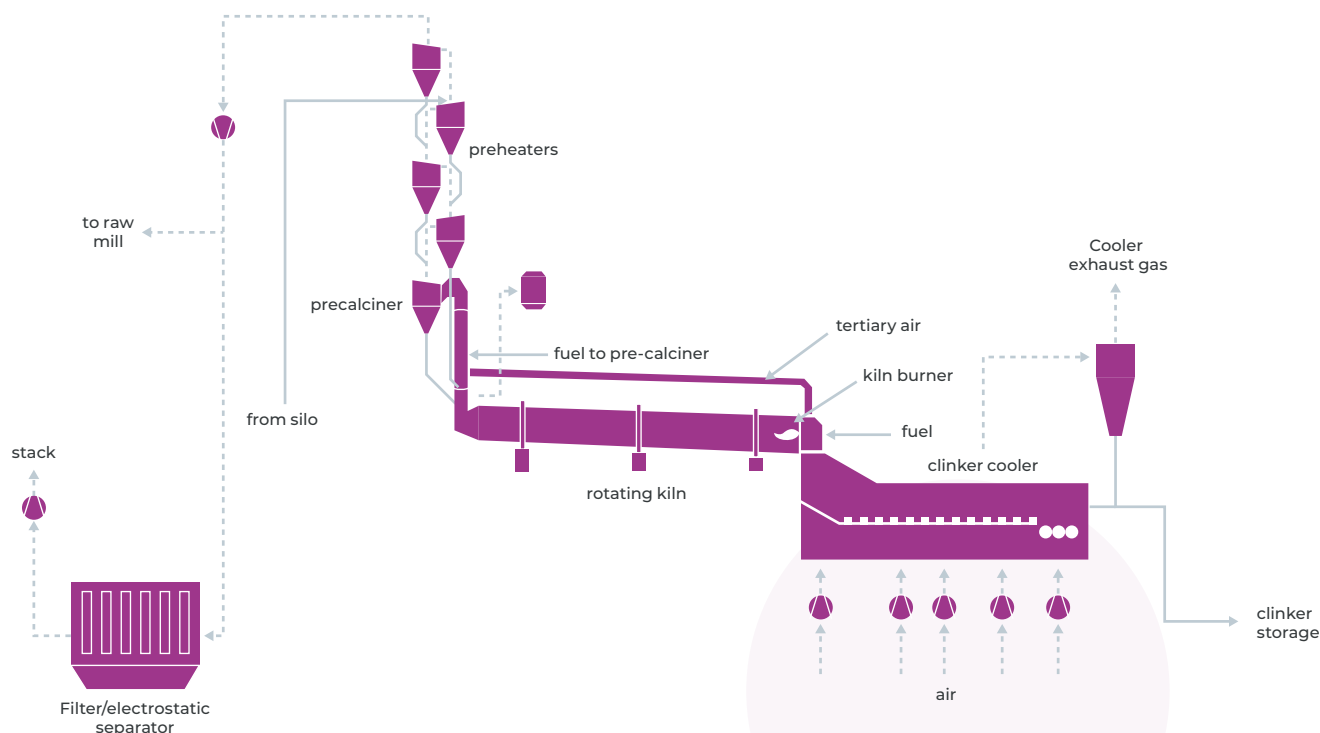
The clinker is then removed from the kiln to cool, ground to a fine powder, and mixed with a small fraction (about 5%) of gypsum to create the most common form of cement known as Portland cement. Masonry cement is generally the second most common form of cement. As masonry cement requires more lime than Portland cement, masonry cement generally results in additional CO₂ emissions.

¹ [mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/cementing-your-lead-the-cement-industry-in-the-net-zero-transition](https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/cementing-your-lead-the-cement-industry-in-the-net-zero-transition)

² World Economic Forum “net-zero industrial tracker”, 2023

³ Hannah Richie- US Geological Survey

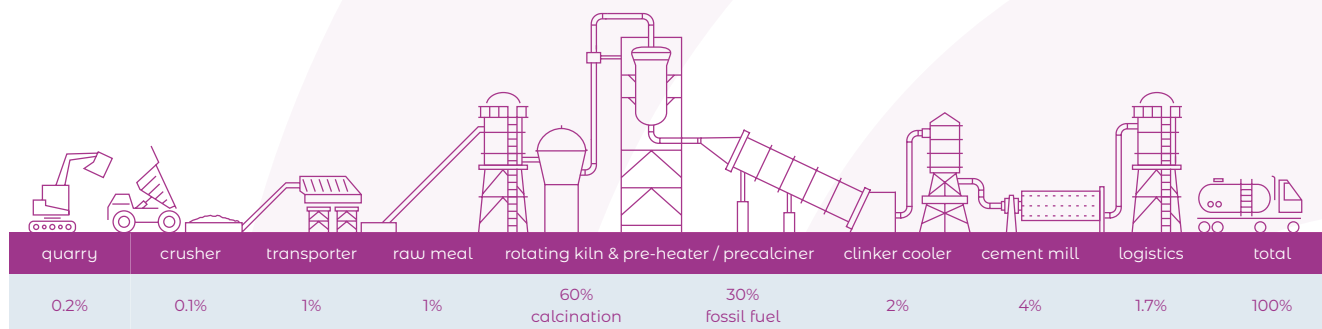
⁴ Michael J. Gibbs, Peter Soyka and David Conneely (ICF Incorporated). It was reviewed by Dina Kruger (USEPA). Entitled “CO₂ Emissions from Cement Production”, 2000



Simplified Clinker Process⁵

Carbon Sources in Cement

Typically, in a cement plant, the furnace (kiln burner), rotating kiln and preheaters are the primary sources of emissions in cement production.



About 30% of a cement plants' carbon emissions come from energy related emissions such as burning fossil fuels to heat the kiln. This process of calcination contributes about 60% of CO₂ emissions from a cement plant and sometimes is referred to as "process carbon" emissions. The remaining 10% of carbon emissions are from other operations including

electricity used to power equipment such as raw meal crushers, dryers, mixing, cement mill and other electrical parts of the plant including illuminating the site. Such electrical related emissions are considered indirect as power is taken from the grid that may not come from a renewable source.

⁵ © thyssenkrupp Industrial Solution AG

Innovation Pathways to Emission Abatement

There are multiple ways to lower the carbon footprint of cement at different stages of development. Initiatives are being taken in the industry that consider concrete use optimisation and employing substitute materials such as laminated wood in non-load bearing areas, to deliver carbon conscious designs, that can reduce the carbon footprint by up to 26%⁶. Startups are also pioneering green alternatives to clinker, such as Brimstone Cement⁷, Biozeroc⁸, Maa'va⁹, and ecoLocked¹⁰, however these solutions are undergoing testing and not yet scalable.

Replacing clinker with materials such as steel slag and fly ash, or utilising innovative mixtures like LC3¹¹, has the potential to reduce carbon emissions by 50% while meeting current building codes. However, the scalability of these solutions remains a challenge. Consequently, limestone-derived clinker-based cement continues to be the most prevalent and commercially feasible option for the foreseeable future.

As such, focus is then placed on cement manufacturers taking strides in identifying carbon abatement pathways through plant optimisation, fuel switching and other initiatives to enhance heat integration and recover waste heat to generate electricity. The EU Emissions Trading Schemes' alignment with broader waste management objectives, has provisions to allow cement plants to utilise alternative fuels (such as refuse-derived wastes, biomass from sources like waste wood and sewage sludges and spent tyres) that are excluded from the emissions cap. This incentivises resource efficiency by utilising waste materials' heat value. Complete substitution of coal is not feasible as burning alternative fuels alone does not render the desired temperatures in the kiln, so careful blending of coal and alternative fuels is necessary to reduce emissions whilst achieving clinker production requirements.

As there are no commercially viable alternatives to clinker-based cement, CO₂ emissions from calcination of limestone cannot be avoided. The current thinking in the sector is to apply carbon capture and storage to achieve net zero. Having investment access, such as the EU innovation fund, which was launched as part

of the European Green Deal, has provided major cement players the opportunity to utilise technology innovation to build large scale carbon capture and storage¹².

Five main technologies are being tested to capture and purify CO₂ and include oxy-fuel combustion, amine absorption, Calcium Carbonate Looping (CCL), membranes, cryogenic separation and solid sorbent. These technologies are further described below:

First generation oxy-fuel kiln is a leading technology in cement production, aiming to capture CO₂ emissions from plant exhaust gases. By using pure oxygen instead of air in kiln furnaces, CO₂ concentration in flue gas significantly rises. Ideal for modern clinker kilns, it relies on minimising air ingress, employing heat-resistant seals, and implementing Flue Gas Recirculation (FGR). Increased oxygen levels enhance combustion and flame temperature, moderated by recycling flue gas. FGR in the preheater ensures proper dispersion and heat transfer of raw meal. Waste gas undergoes cooling before entering the clinker cooler to prevent water condensation. However, higher thermal energy for FGR is needed due to CO₂'s heat capacity. Challenges include air ingress and energy input downstream of the kiln. Oxy-fuel combustion's dry flue gas contains over 80% CO₂, with no significant impact on clinker quality based on European Cement Research Academy tests. Despite success in other industries, its adoption in cement production remains limited.

Second generation oxy-fuel kiln is a significant advancement in combustion technology, particularly in cement production. It utilises pure oxygen (O₂) instead of ambient air, resulting in a highly concentrated CO₂ stream in the flue gas, thereby improving energy efficiency and reducing emissions. Unlike its predecessor, this process does not recirculate CO₂-enriched flue gas, eliminating the need for energy-intensive cooling and drying. Oxygen is directly supplied to critical areas such as the cooler inlet, calciner, and main burner. Modifications to kiln design and operation are necessary for optimal performance, including adjustments to thermal energy consumption and installation of smaller cyclones in new clinker plants to accommodate reduced gas volumes.

6 Nature 2033, Paul Fernell et.al

7 www.brimstone.com

8 www.biozeroc.com

9 www.maava.co

10 www.ecolocked.com

11 www.lc3.ch

12 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/innovation-fund-projects_en

Oxy-fuel combustion is a potential solution for decarbonising the cement industry; oxy-fuel firing reduces the volumetric flow of flue gas, and thus facilitates easier capture of CO₂ by concentrating the CO₂ emissions in a smaller volume of gas. This technology requires significant modifications to existing cement production processes to implement i.e. a purpose designed oxy-kiln.

Prior to carbon capture and purification, as the kiln is operating with fossil fuels and alternative fuel mixes, the outlet from the kiln (the flue gas) will contain pollutants that need to be removed to meet the CO₂ export specification. Generally, two-stages of gas cleaning are applied, *dry gas cleaning* for the removal of nitrogen oxides (NO_x) and particulates followed by *wet gas cleaning* for the removal of sulphur compounds, hydrogen chloride (HCl) and hydrogen fluoride (HF). Other contaminants that may be present in the flue gas are co-removed with sulphur oxides (SO_x) and NO_x and elsewhere in the overall process. Dependent on the use of the captured CO₂, removal of NO_x particularly to low levels is important to ensure there are no significant metallurgy issues in storage, transportation and/or carbon sequestration sites.

Carbon capture, purification and liquefaction are crucial processes in mitigating CO₂ emissions from industrial sources. Various chemical methods are employed to capture and purify CO₂ to meet export specifications. *Amine Absorbers* utilise liquid solvents such as amine solutions to absorb CO₂ from flue gases, achieving high-purity levels (>99%). While widely used and reliable, amine absorbers are energy-intensive and require solvent management. The *Calcium Carbonate Looping* (CCL) process uses calcium oxide to capture CO₂ by forming calcium carbonate, offering potential energy savings and integration with existing infrastructure. *Membrane Processes* separate CO₂ using selective permeable membranes, known for low energy consumption and scalability. *Cryogenic Separation* captures CO₂ through a phase change process, suitable for oxy-fuel combustion with high CO₂ concentrations (>80%), although it is energy-intensive. Typically coupled with cryogenic separation, the *Adsorptive Processes* utilise Pressure Swing Adsorption (PSA) to capture CO₂ onto solid sorbents under high pressure, enhancing purity levels to over 99%. A cryogenic polishing that includes a distillation column and propane refrigeration loop can be used to achieve export specifications approaching 100%.

With a conventional kiln, and CO₂ concentrations of 15-20% in the flue, a suitable technology is amine absorption or calcium carbonate looping. However, with oxy-fuel combustion processes, the flue at kiln outlet is much higher in CO₂ concentration (up to 80%), therefore lends itself to process schemes that consider alternatives such as membrane or cryogenic separation, with PSA used as a concentrator to achieve export specification. It should be noted that post-combustion CCUS provides opportunities to decarbonise without compromising existing production but requires additional thermal input which is expensive and creates further emissions.

In addition, all technologies require sufficient infrastructure to transport and store or utilise the captured carbon, which could prove very expensive.

How can io help?

io consulting, a joint venture between Baker Hughes and McDermott, specialises in low-carbon solutions in the energy and hydrocarbons sectors. Our mission is to provide techno-economic expertise integrated with access to technology and execution know-how for early-stage projects or portfolio-level initiatives.

io consulting, a specialist energy project architect, excels in guiding clients through the project lifecycle, from feasibility to FID and into execute as owners engineer, and designing complex project developments across hydrocarbon and low-carbon sectors.

We offer a comprehensive range of capabilities, including reservoir due diligence, business case development, field development planning, smartFEED, and more. With over 400 completed assignments for diverse clients, our specialists bring proven skills and significant expertise to project development and execution, particularly in flue gas treatment, CO₂ purification, CO₂ utilisation, CO₂ storage, CO₂ transport and carbon sequestration, making us a perfect project integration partner for our clients.

As systems integrators, we apply "Systems Thinking" and value management approaches to develop concepts and solutions, considering all connected relationships for optimal outcomes. Partnering with GaffneyCline and Houlder further enhances our capabilities, providing expertise in secure geological storage and marine consultancy, respectively.

Leveraging our parent companies' expertise, including project close out costs and schedules, we deliver cost certainty and comprehensive support throughout the project lifecycle. With io consulting, clients benefit from the best-in-class expertise and integrated solutions for sustainable project development.

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