The $10 per Tonne Advantage

AI-driven optimisation as a critical enabler for CCS

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Executive Summary

The cement industry is one of the largest industrial sources of CO_2 emissions, making Carbon Capture and Storage (CCS) a critical technology for meeting global net-zero targets. However, it is well established that the energy costs of carbon capture are substantial and present an economic challenge for the industry, often raising production costs by over 50%.

This whitepaper explores how the operational and capital costs of these systems are highly dependent on the efficiency, reliability and control of the underlying cement process, such as kiln performance (particularly the consistency of CO_2 concentration, airflow, and thermal stability). Additional complexity arises with the increasing use of alternative fuels, which introduce further process variability and can degrade capture system performance unless tightly controlled.

In this context, AI-driven process optimisation presents a powerful solution. Already delivering measurable gains in fuel efficiency, clinker quality, and emissions reduction, AI-based control systems, including the one developed by Carbon Re, are already delivering measurable gains. These systems will become essential as cement plants begin to operate with CCS.

Among the many ways that AI can reduce carbon capture costs, the most quantifiable benefit at this stage is the reduction in operational expenditure (OpEx). Based on current plant data and CCS system modelling, **we estimate a $10 per tonne CO_2 saving in OpEx from implementing AI-driven process control.**

This figure represents a conservative, lower-bound estimate and is focused solely on today's measurable operational parameters. It does not yet capture the additional savings from reduced CapEx, such as smaller safety margins in CCS plant sizing, extended solvent lifetimes, minimised downtime, and improved capture efficiency through more stable operations.

Ultimately, the economic rationale is clear: AI optimisation stabilises kiln operation, improves energy efficiency, and increases CCS readiness and allows capture systems to be designed for average rather than peak loads, reducing oversizing costs. These control systems, currently delivering savings of ~$1 per tonne in standalone cement operations, become an order of magnitude more valuable when integrated with CCS infrastructure.

However, the window of opportunity to adopt abatement technologies is narrowing and cement producers must act swiftly to lay the digital foundations necessary for the successful deployment of CCS in the 2030s.

We urge cement producers to act now: early adopters of AI will not only make CCS more viable, they will also gain significant operational and financial advantages as regulations tighten and carbon pricing intensifies.

1. The growing pressure for carbon capture in cement

Cement production is responsible for ~8% of global carbon emissions.[1] To meet climate targets aligned with the Paris Agreement and national net-zero pledges, the sector must deliver rapid and substantial emissions reductions. As such, cement plants are under pressure to improve efficiency, increase alternative fuel use and incorporate substituent materials to lower their process emissions.

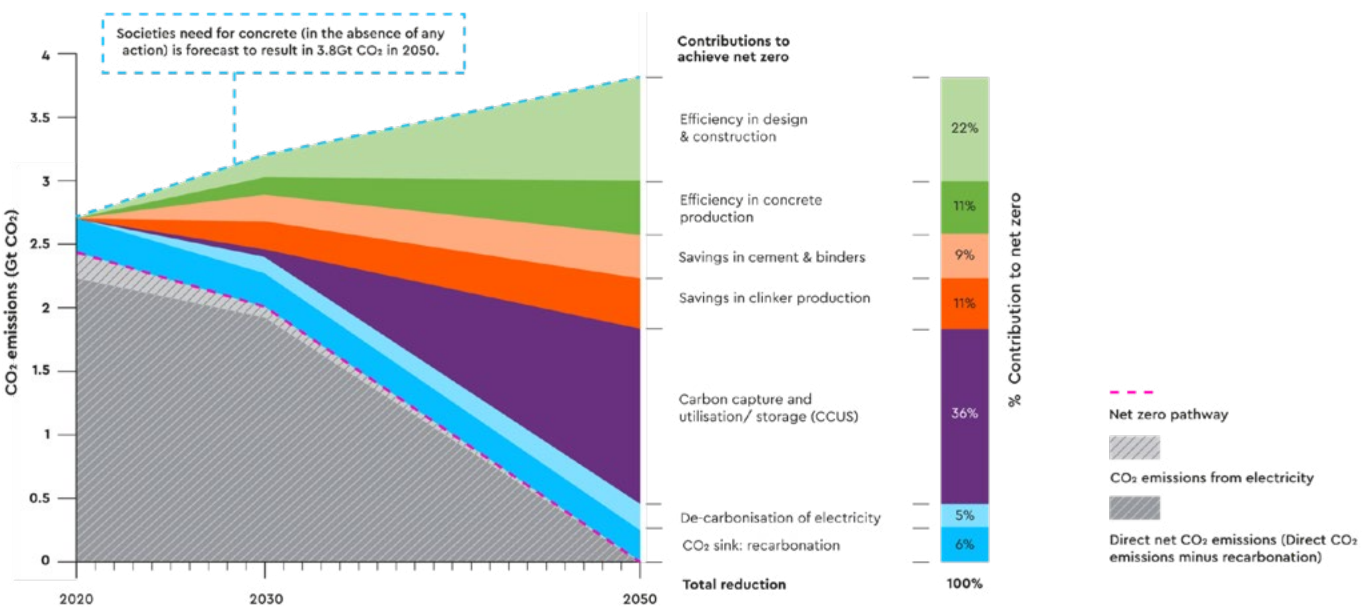
However, a large proportion of cement's emissions cannot be eliminated by switching fuels or improving efficiency alone. This is because a major source of emissions in cement production comes from the chemical process itself: when limestone (calcium carbonate) is heated, it breaks down into lime (calcium oxide) and carbon dioxide (CO_2), meaning that this is a reaction that inherently releases CO_2 regardless of the energy source used.

As a result, industry decarbonisation roadmaps assume widespread adoption of CCS as the only option to fully decarbonise cement production. Nearly all major cement manufacturers have announced 2030 and 2050 emissions targets, many validated by the Science Based Targets initiative.[2] For example, the Global Cement and Concrete Association (GCCA) , which represents 80% of the industry outside China, estimates that CCS will contribute about 36% of total carbon emissions reductions by 2050, making it the single largest decarbonisation lever.

Pressure to move quickly

Governments and markets are exerting increasing financial pressure on cement producers. In the EU, for example, the price of carbon allowances under the Emissions Trading Scheme (ETS) has risen dramatically — from an average of just €11 per tonne in the 2010s to over €100 per tonne

Getting to Net Zero



https://gccassociation.org/concretefuture/getting-to-net-zero/

1 https://gccassociation.org/concretefuture/getting-to-net-zero/
2 https://www.weforum.org/publications/net-zero-industry-tracker-2023/cement-industry-9931553a33/

by 2023.[3] Although prices dipped to ~€65 in 2024, analysts expect the long-term upward trend to continue.

Moreover, the EU is phasing out free carbon allowances for cement and implementing a Carbon Border Adjustment Mechanism (CBAM), which will require both importers and domestic producers to pay the full carbon price for each tonne of emissions. Under the EU ETS, allowances allocated to cement are set to decline significantly over time and could be eliminated entirely by 2040. Other jurisdictions are adopting similar measures — from Canada's carbon pricing to emerging emissions trading in China and India.[4] Without effective emissions abatement, rising carbon costs pose a serious threat to the profitability of cement producers.

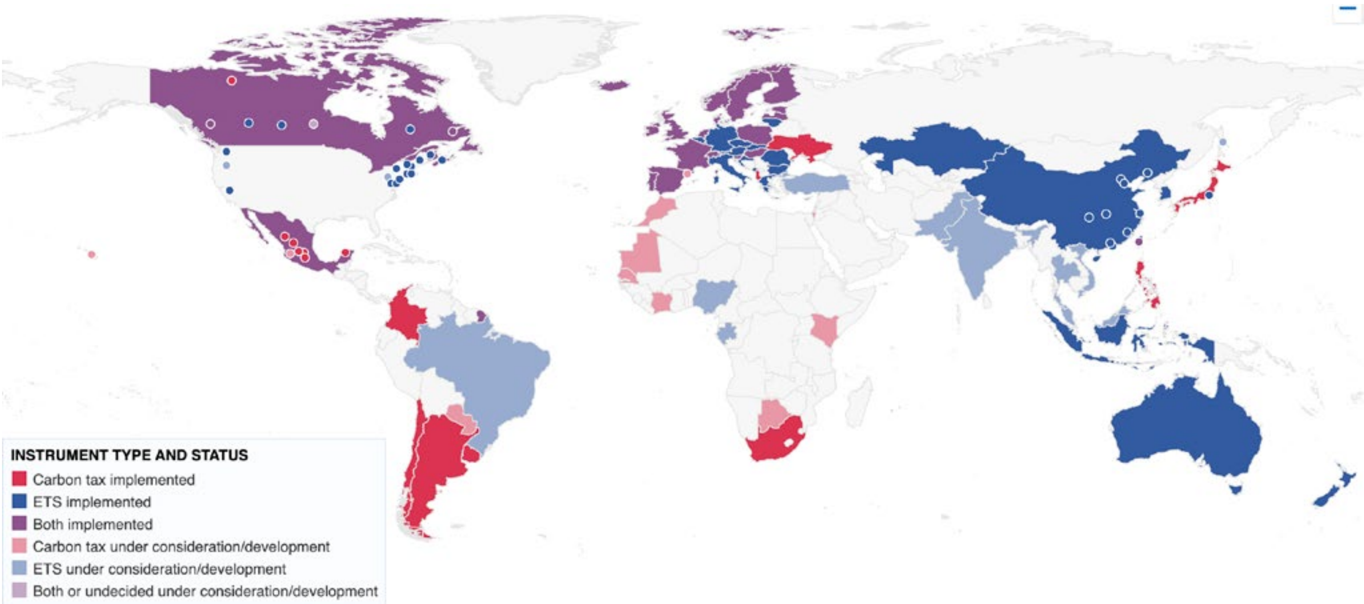
The scale of the challenge

To put this challenge in perspective, the World Economic Forum's Net-Zero Tracker highlights that current CCS capacity in cement is less than 1% of what will be needed by 2050 — therefore, capture needs to scale from near-zero today to roughly 90% of cement emissions by mid-century.[5] Industry initiatives aim for at least 10 commercial-scale carbon capture plants by 2030 as an initial milestone[6] and the most advanced operation today is the Heidelberg Materials CCS project at its Brevik plant in Norway.[7] This plant captured its first CO_2 at the end of 2024 and is designed to capture 400,000 tonnes of CO_2 per year (about 50% of the plant's emissions) for storage under the North Sea.

While CCS is a central pillar of the cement industry's decarbonisation strategy, it remains a complex undertaking. The transport and storage components are relatively mature and well understood, but the capture process varies significantly depending on the technology used. For example, amine-based systems face challenges related to energy demand and operational reliability. Additionally, assessing the economics of CCS requires careful framing: as a waste management solution, its viability depends not on conventional return-on-investment metrics, but on the avoided costs of climate damage and adaptation.

In this paper, we outline some of the key challenges and explore how they might be tackled using digital technologies, including AI.

State and Trends of Carbon Pricing Dashboard



https://carbonpricingdashboard.worldbank.org/compliance/instrument-detail

3 https://www.globalcement.com/magazine/articles/1357-the-future-of-eu-ets-prices
4 https://rmi.org/five-insights-on-the-concrete-and-cement-industrys-transition-to-net-zero/
5 https://www.weforum.org/publications/net-zero-industry-tracker-2023/cement-industry-9931553a33/#:~:text=While%20increased%20use%20of%20alternative,by%202050
6 https://gccassociation.org/wp-content/uploads/2024/11/GCCA-Cement-Industry-Progress-Report-202425.pdf
7 https://www.brevikccs.com/en/node/522705

2. An overview of CCS technologies being explored in the sector

A range of CCS technologies are under evaluation for cement production.

These include post-combustion capture methods (which scrub CO_2 out of flue gases after fuel is burned) and pre-combustion or oxy-fuel approaches (which alter the combustion process itself to facilitate carbon capture).

Each technology comes with different maturity levels (TRLs), examples of deployment, scales achieved, and energy costs per tonne of CO_2 captured.

Table 1: CCS Technology Summary

TECHNOLOGY	TECHNICAL MATURITY LEVEL (TRL)	PROCESS DESCRIPTION	USE CASE EXAMPLE	PROS AND CONS
Amine-Based Post-Combustion Capture	TRL 8–9 Commercially proven; ready for full-scale deployment	CO_2 in flue gas is absorbed by an amine solvent (e.g. MEA), then released via thermal regeneration and the solvent is recycled.	**Heidelberg Materials' Brevik plant**	✓ Mature and proven ✓ High capture efficiency ✗ High thermal and electrical energy demand ✗ Solvent degradation and corrosion risk
Oxy-Fuel Combustion Capture	TRL 6–7 Demonstration stage; nearing commercial readiness	Fuel is burned in pure oxygen rather than air, generating CO_2-rich flue gas for simplified separation.	**Oxyfuel cement pilot projects**	✓ High CO_2 concentration stream ✓ Potential thermal efficiency gains ✗ Expensive oxygen production ✗ Complex retrofitting
PSA (Pressure Swing Adsorption) in combination with cryogenic technology	TRL 6-7 Demonstration stage; commercial pilots emerging	Flue gas is first pre-concentrated using PSA, which selectively adsorbs CO_2 under pressure. The resulting CO_2-enriched stream is further purified and liquefied via cryogenic separation.	**Air Liquide's Cryocap FG system**	✓ Produces high-purity, liquefied CO_2 ✓ Suitable for integration into existing CO_2 transport and storage networks ✗ High energy demand for PSA compression and cryogenic cooling ✗ Complex system with multiple integrated units
Calcium Looping	TRL 6–7 Advanced pilot stage; integration in progress	CO_2 is captured by CaO to form $CaCO_3$, then calcined to regenerate CaO and release CO_2.	**CEMCAP pilot project**	✓ Integrates with cement kiln process ✓ Sorbent reusable as raw material ✗ Energy-intensive (~2.5 GJ/t) ✗ Sorbent deactivation risk
Direct Separation (Indirect Calcination)	TRL 6–7 Pilot-to-demonstration stage; cement-specific innovation	Limestone is heated indirectly, allowing pure CO_2 from calcination to be captured separately from combustion gases.	**LEILAC pilot project**	✓ Pure process CO_2 stream ✓ No solvents required ✗ Multi-stage needed for purity ✗ Moderate energy use (~150–250 kWh/t)
Membrane Separation	TRL 5–6 Pilot scale; moderate maturity	Pressurised flue gas is passed through selective membranes that preferentially allow CO_2 to permeate.	**Membrane pilot in cement context**	✓ Compact and modular ✓ No solvents required ✗ Multi-stage needed for purity ✗ Moderate energy use (~150–250 kWh/t)

TECHNOLOGY	TECHNICAL MATURITY LEVEL (TRL)	PROCESS DESCRIPTION	USE CASE EXAMPLE	PROS AND CONS
Hot Potassium Carbonate (HPC) Absorption	**TRL 5–6** Established in other industries; early application in cement	CO_2 absorbed in hot potassium carbonate solution; regenerated using medium-grade heat, often from kiln waste heat.	**Evaluated for cement adaptation**	✓ Uses kiln waste heat ✓ Lower energy than amines (0.55 GJ/t) ✓ Benign solvent ✗ Lower absorption driving force ✗ Larger equipment needed
Cryogenic Separation	**TRL 4–5** Feasibility study phase; early pilot demonstrations	Flue gas is cooled to low temperatures to condense or solidify CO_2 for separation.	**Cryogenic capture feasibility**	✓ High CO_2 purity (99.9%+) ✓ Can remove other pollutants ✗ Very high energy use (500–700 kWh/t) ✗ No full-scale cement demos yet

The table below outlines the key cost drivers for each of these technologies.

It can be seen that across all technologies that CCS would lead to a >50% increase in cement production costs, even assuming the lower bound estimates for capture cost. A small deviation in capture process efficiency will result in a significant cost increase for the overall cement production process. In addition, the potential range of performance is wide, meaning that controlling costs is likely to be a make-or-break factor in the successful and timely adoption of CCS.

In the rest of this paper, we outline what drives the variation in these costs, and what strategies can be adopted to control them.

Table 2: CCS cost drivers

TECHNOLOGY	THERMAL ENERGY REQUIRED (GJ/t CO_2)	ELECTRICAL ENERGY (kWh/t CO_2)	CAPTURE COST ($ per tonne cement)	SOURCE
Amine solvent	**2.0-3.5**	80-120	$36-86	www.mdpi.com/2227-9717/13/1/283
Oxy-fuel combustion	**0-0.5**	200-250	$29-65	www.mdpi.com/1996-1073/12/3/542
Membrane separation	**0**	200-350	$29-72	www.sciencedirect.com/science/article/abs/pii/S1750583614000589
Cryogenic separation	**0-0.2**	350-700	$43-86	www.sciencedirect.com/science/article/pii/S0360544224020188
PSA & Cryogenic	**0-0.2**	350-600	$46-53	netl.doe.gov/sites/default/files/netl-file/22CM_PSC15_Salih.pdf
Hot Potassium Carbonate	**1.0-2.0**	200-400	$29-58	www.shi-fw.com/our-solutions/carbon-capture/sfw-hpcplus/
Calcium looping	**2.0-3.5**	100-150	$22-50	www.sciencedirect.com/science/article/pii/S2949720524000328
Indirect calcination (LEILAC)	**0.1-1.0**	50-440	$20-150*	www.leilac.com/wp-content/uploads/2023/10/2023-10-15-Techno-Economic-Analysis-of-Leilac-Technology-at-Full-Commercial-Scale-EC-Deliverable-PDF-Version.pdf

*only applicable to 60% of emissions, as LEILAC primarily captures process emissions from calcination.

3. Key cost drivers shaping CCS viability

Carbon capture in cement is a major investment, with significant upfront capital expenditure (CapEx) and ongoing operational costs (OpEx) costs.

To reduce these costs, it's important to understand what drives them, and where AI and process optimisation can make an impact.

Many cost factors are linked to how the capture system interacts with the plant's operation (outlined below).

Table 3: CCS cost drivers linked to plant operations

CATEGORY	COST DRIVER	DETAILS
Capital Cost Drivers	**Scale and Size of Equipment**	Carbon capture units scale with flue gas volume and CO_2 capture percentage. If operational variability requires oversizing to capture peak load, the equipment size and costs increase accordingly. Factors that increase flue gas volume (e.g. high excess air) or lower CO_2 concentration raise capital costs by requiring more gas processing for the same CO_2 output. **Improved process control can help by reducing the oversizing of equipment to deal with peak load.**
	Retrofit Complexity	Retrofitting is more expensive than greenfield projects. Oxy-fuel retrofits are especially complex, requiring major kiln/preheater modifications. Most of the cement production capacity in Europe and the U.S. in 2050 will come from existing plants as very few new plants are being built, making retrofits more relevant, but challenging.
	Auxiliary Systems	Each capture technology brings specific auxiliary equipment, for example: ▪ Solvent-based: Reboilers, heat exchangers, CO_2 compressors ▪ Oxy-fuel: Large Air Separation Unit (ASU) ▪ Membranes: Multiple compressors/vacuums ▪ Cryogenic: Turboexpanders, refrigeration ▪ HPC: Direct contact cooler, heat integration hardware
Operational Cost Drivers	**Energy Consumption**	By far the biggest OpEx driver is the energy required to capture CO_2. Thermal energy may also be needed, such as for solvent regeneration. In a cement plant, some (but not all) of that heat could come from waste heat in the process. Electricity is required for membrane, cryogenic, and in oxy-fuel systems. **Process control becomes essential for operating these interdependent processes efficiently.**
	Solvent/ Sorbent Replacement	Some capture processes incur ongoing costs for consumables: ▪ Amines degrade from oxygen, SOx/NOx and heat — requiring purge and top-up (adds cost per tonne of CO_2). ▪ HPC (potassium carbonate) losses from SOx reaction, but cheaper than amines. ▪ Membranes require periodic module replacement.
	Operating Costs	Running a carbon capture plant is like running a chemical plant alongside the cement plant. It requires skilled operators and regular maintenance (pumps, compressors, heat exchangers, etc.). **Digital twins and plant simulators become important for training and knowledge retention.**
	Downtime & Maintenance Costs	Some technologies have high restart or idle costs, increasing the cost impact of stoppages. Efficient operations and maintenance are critical. **Predictive maintenance, blockage avoidance and process control to balance downtime risk and operational efficiency become increasingly valuable.**
	Transport & Storage Fees	Adds substantial cost per tonne. Planning must include volume forecasting and lifecycle cost estimation, though detailed analysis is beyond this paper's scope.

The link between plant performance and carbon capture effectiveness

The effectiveness of carbon capture depends on the quality and consistency of the flue gas from cement production. But cement plants are complex, and things like feed materials, fuel mix, and kiln temperatures often change. These changes affect the exhaust gas and can make carbon capture systems less efficient, harder to size, and more expensive to run.

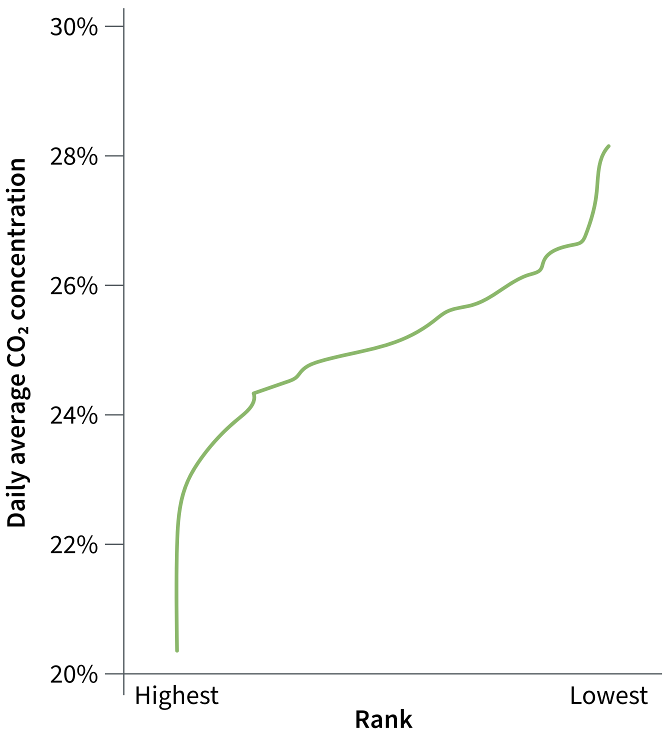
CO_2 concentration variations

The amount of CO_2 in the flue gas is critical for carbon capture performance, and it can range from approximately 14% to 33% across different kilns, depending on the process and the fuel used.[8] Even in a single kiln, different operational conditions can mean variations of 5-8 percentage points, or more, in CO_2 concentration in the flue gas.[9]

Even in a single kiln, different operational conditions can mean variations of 5 percentage points, or more, in CO_2 concentration in the flue gas.

Lower CO_2 levels mean a larger volume of gas must be processed per tonne of CO_2 captured, reducing system capacity or increasing the energy required per tonne. For instance, an amine absorber designed for 25% CO_2 may have reduced removal efficiency if the CO_2 concentration drops to 15%, as the solvent could be under-utilised or the residence time insufficient. If a cement plant's CO_2 output is variable, the capture system may need to be oversized to manage worst-case conditions, or risk low capture rates. Maintaining stable kiln operations helps keep CO_2 levels consistent, allowing the capture unit to operate at an optimal, and cost effective, performance.

Figure 1: Day to day variation of CO_2 concentration in flue gas at a cement kiln

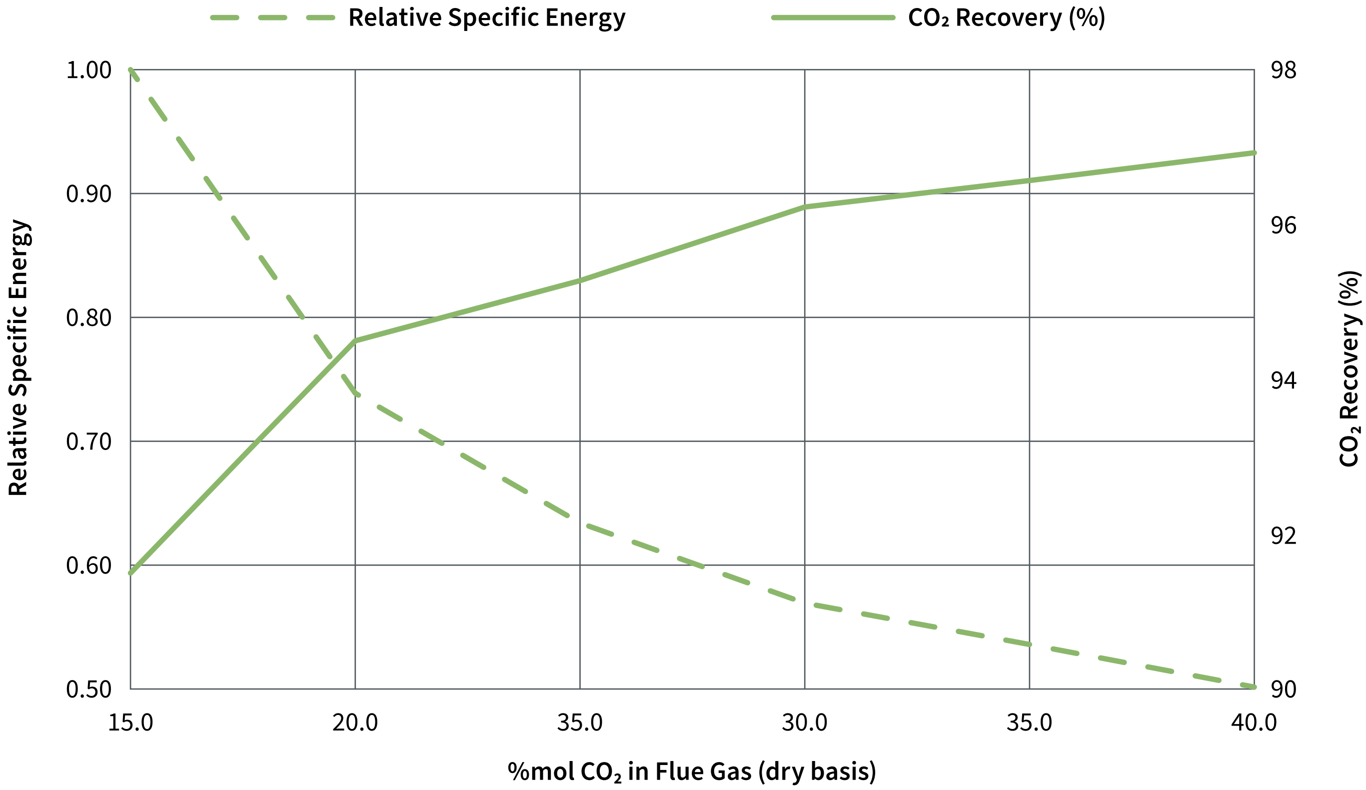


8 https://blog.sintef.com/energy/the-cemcap-framework-public-and-ready-for-use/#:~:text=CO2%20capture%20in%20the%20European,Therefore%2C%20a%20reference

9 Summerbell, D. L. (2018). Environmental Performance Improvement in the Cement Industry https://www.repository.cam.ac.uk/items/318d94f4-c9b6-4ef2-a660-0b7b44c00759

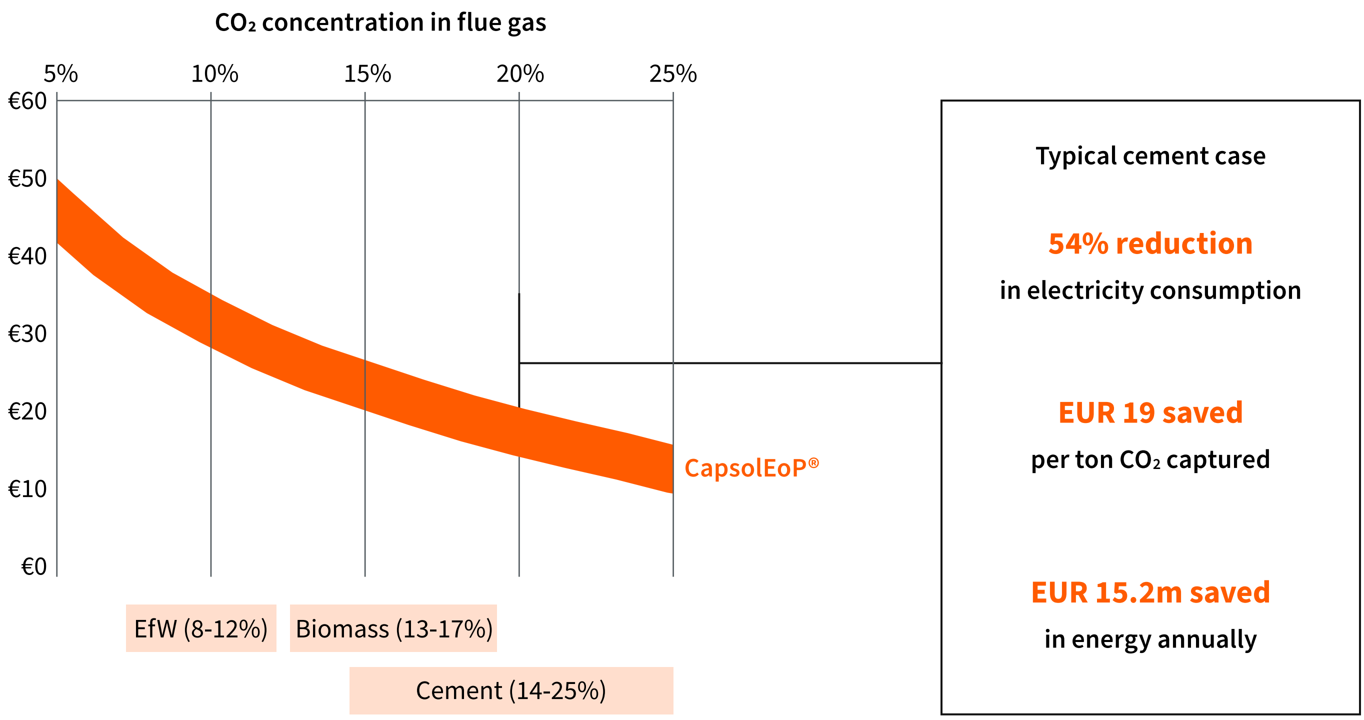
Figures 2 and 3 below, show the sensitivity of cryogenic and HPC capture units to CO_2 concentration: if the CO_2 concentration drops from 20%-15% in the flue gas, the CCS energy requirements could increase by as much as 33%.

Figure 2: Energy requirements for CO2 recovery vs flue gas concentration



https://netl.doe.gov/sites/default/files/netl-file/24CM/24CM_PSCC_6_Sarkar.pdf#:~:text=,1000%20kWh

Figure 3: Electricity costs for fully electric capture systems



https://www.capsoltechnologies.com/cement-decarbonization#:~:text=The%20main%20portion%20of%20the,energy%20savings%20increases%20with%20higher%C2%A0CO%E2%82%82%C2%A0concentrations

At a typical kiln these fluctuations in CO_2 concentration could add up to tens of millions of dollars per year in additional carbon capture costs, meaning that CO_2 concentration in the flue gas (which is not currently measured by most existing kilns) becomes a **critical performance parameter** for cement operation.

The flow rate of flue gas varies with production levels, fuel input, and excess air. Frequent stops, starts, or load-following reduce the efficiency of capture systems, which are less effective at partial load. For example, an amine unit running at half capacity may still consume 70% of the energy used at full flow (due to fixed reboiler duty to keep solvent hot, etc.), making the cost per tonne higher if the kiln isn't running at full rate.

Temperature also matters. Most post-combustion technologies require flue gas to be cooled before entering the capture unit. Inconsistent exhaust temperatures, which is common in cement kilns, complicate system design and control. Similarly, oxygen concentration and excess air are crucial, as while excess oxygen ensures combustion, it also degrades solvents (especially amines) through oxidation, and dilutes CO_2, impacting the capture performance. Oxy-fuel systems, in particular, are highly sensitive to air ingress and require precise airflow control to remain cost-effective. Given the impact of airflow on capture efficiency and operational cost, CCS adoption requires continuously matching the airflow to the exact requirements of the fuel mix is essential.

Additionally, contaminants in the flue gas, such as dust, SO_x, NO_x, moisture, and trace elements, can damage or degrade capture technologies. High dust loading clogs membranes and consumes solvents, while SO_2 and NO_2 form heat-stable salts that reduce capture efficiency and drive up operational costs. Moisture fluctuations can impair membrane and cryogenic systems, and chloride or alkali imbalances increase the risk of blockages and forced outages.

Therefore, maintaining consistent kiln operations, with tightly controlled airflow, stable temperatures, and minimal contaminants, is essential for efficient and cost-effective carbon capture. However, achieving this level of control becomes more challenging with the introduction of alternative fuels, a topic we explore in the next chapter.

4. How alternative fuels complicate the carbon capture challenge

Cement plants increasingly use alternatives to petcoke and coal to reduce both fuel costs and fossil carbon emissions. These alternative fuels range from refuse and tyre-derived fuel (RDF & TDF), industrial waste such as solvents, to biomass, such as sewage sludge and agricultural waste.

When cement plants use waste-derived fuels, particularly biomass, they not only reduce fuel costs and operational expenses but also lower emissions. They can also benefit from a Bio-CCS or BECCS (Bioenergy with CCS) approach — biomass produces biogenic CO_2, which can count as negative emissions if captured and stored. This is especially significant in cement production, where a large proportion of CO_2 comes from the calcination of limestone. By using 50% biomass and capturing 90% of total CO_2 emissions, a plant could offset the CO_2 released from limestone, potentially achieving net-zero or even net-negative emissions. This approach may also make the plant eligible for additional regulatory or financial incentives.


AI-generated image

However, these benefits come with technical and economic trade-offs and introduce additional complexity for carbon capture systems.

Alternative fuels are notoriously inconsistent in composition, moisture, and calorific value, which leads to unstable kiln temperatures and fluctuating gas compositions when compared with steady coal firing. Intermittent feeding further disrupts O_2 and CO levels, complicating CCS performance. Many waste fuels also contain higher levels of contaminants, like chlorides, increasing the burden on gas pre-treatment and bypass systems. Without advanced control systems, alternative fuels can make it much harder for capture plants to maintain stable operation. These challenges are particularly acute in oxy-fuel combustion systems, where fuel volatility and inconsistent burn characteristics can destabilise the flame and affect recirculated CO_2 streams.

While alternative fuels can reduce fuel costs, poor fuel quality or supply disruptions can erode these savings, especially if plants must revert to more expensive fossil fuels or suffer efficiency losses in the CCS process. For instance as alternative fuel supply chains are often less reliable, CCS-enabled kilns must be designed with flexibility as a plant optimised for 50% RDF firing, may need to switch back to coal, or substitute a different alternative fuel, for a period due to RDF shortage causing an abrupt change in the flue gas composition and thus CCS performance.

Real-world experience is still limited on mixing high alternative fuel rates with carbon capture, since no cement plant has both in full-scale as of 2025. But we can learn from similar industries or pilots:

- The National Carbon Capture Center (NCCC)[10] in the U.S. has tested amine-based CO_2 capture on flue gas from coal power plants, including those co-firing biomass. While variations in CO_2 levels and SOx were observed, systems could handle moderate co-firing. However, high biomass content increased moisture and oxygen, requiring adjustments in capture operations.
- At its GeZero[11] pilot in Germany, Heidelberg Materials found that using varied waste fuels during solvent-based CO_2 capture introduced more impurities, making solvent management more complex.

In summary, the cement plant's operational performance (stability, consistency, and control of emissions) is tightly intertwined with CCS technical and economic performance. If the baseline process is erratic, the CCS system must be over-engineered or will suffer inefficiency.

This is precisely why cement producers are looking at AI-driven process control as an enabler for CCS: by reducing the variability and improving the predictability of kiln operation, AI can de-risk CCS integration.


AI-generated image

10 Source: NCCC Technical Papers
11 https://www.heidelbergmaterials.com/en/sustainability/we-decarbonize-the-construction-industry/CCS/gezero

5. The $10 per tonne advantage: AI-driven optimisation as a critical enabler for CCS

Given the complexities for CCS that we have outlined in this whitepaper, including the need for steady operations, tight control of O_2, consistent clinker quality, and integration of alternative fuels, it's clear that advanced process control will be essential for cement plants planning to implement CCS. Based on our analysis, implementing AI-driven process control can deliver significant operational benefits, with an estimated OpEx saving of $10 per tonne of CO_2 captured.

Existing control systems, ranging from human operators making manual adjustments to PID (Proportional-Integral-Derivative) loops — feedback control mechanisms that automatically regulate process variables — to Advanced Process Control (APC) systems using model predictive control, have limits in managing the highly interdependent and nonlinear dynamics of a cement kiln. This complexity will become much more difficult, perhaps impossible, for these systems to manage under the additional constraints and tradeoffs that CCS imposes.

This is where AI comes in.

These technologies are being successfully applied to cement process control today, delivering significant improvements in stability, fuel cost, and emissions. This is not only of immediate benefit for kiln operators successfully using these technologies today, but also provides evidence of how some of the challenges described in this whitepaper might be addressed using AI-driven process control.

Carbon Re has developed an AI-powered platform for the cement pyroprocess — the high-temperature phase of cement manufacturing where raw materials are chemically transformed in the kiln to form clinker, the key ingredient in cement. Our system uses plant data to train predictive models and AI-based controllers. The insights from these models, and the recommended setpoints (target values for key process variables that control systems aim to maintain) are fed into existing APC systems such as ABB's AbilityTM Expert Optimizer[12] or FLS PXP,[13] or directly into the Distributed Control System (DCS). This gives closed-loop, AI based control of the process, with substantial improvements to kiln performance.

As an example, in Heidelberg Materials' Mokra plant (Czechia), Carbon Re was deployed to optimise the kiln.[14] Within the first month of continuous operation, the plant saw impressive gains:

- A **3.2% increase in thermal substitution rate** by controlling the air-fuel ratio, enabling the plant to use more, cheaper alternative fuels.
- A **33% reduction in clinker quality variation**, as measured by the standard deviation of Free Lime and C3S (tricalcium silicate, the primary compound responsible for early strength development in cement) content of the clinker.
- A **4.5 kg reduction in CO^2 per tonne of clinker**, equating to a 2% reduction in fuel-derived emissions.

How AI lowers CapEx/OpEx for carbon capture

The value of the benefits outlined above will be substantially increased if similar process improvements are made at

12 https://new.abb.com/cement/systems-and-solutions/advanced-process-control/abb-ability-expert-optimizer-cement
13 https://www.flsmidth-cement.com/products/ecs-processexpert-advanced-process-control-software
14 https://carbonre.com/heidelberg-materials-improves-performance-by-integrating-carbon-re-ai

a kiln integrated with a carbon capture system. It is most straightforward to estimate impact on OpEx, where the estimated cost impact of poor control is ~$10 per tonne of CO_2. This gives a lower-bound estimate value for the value of AI control. The additional benefits, detailed below, are likely to add to this value. However the data available from existing cement-CCS combined operations are limited, and so the benefits are hard to quantify at this stage.

- **Smaller safety margins (CapEx savings):** If the kiln is AI-controlled to stay within tight bounds of total emission production, the carbon capture system can be designed closer to average load rather than worst-case.

  AI can "shave the peaks" off operations that would otherwise force over-design of the capture unit, saving capital cost.

- **Energy Efficiency (OpEx savings):** A more efficient kiln means less fuel per tonne clinker, **which means less CO_2 generated to capture in the first place.**

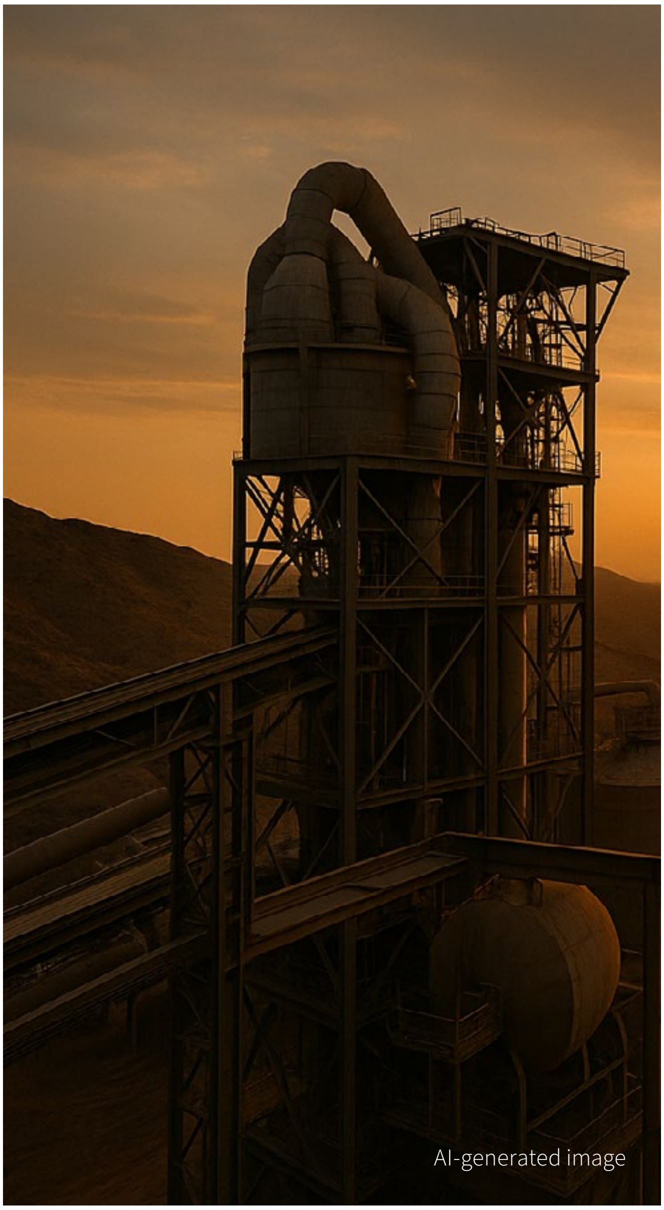
  Furthermore, controlling the air-to-fuel ratio leads to reduced capture volumes and higher CO_2 concentrations, improving carbon capture efficiency. **The estimated impact of this is on the order of ~$10 per tonne** (see **Section 2**). The reward function in the controlling algorithms can be adjusted to account for the relative costs of operating the carbon capture system, balancing the trade-off with kiln operation and fuel costs.

- **Solvent lifetime and consumption:** By keeping O_2 low and preventing large swings in NOx/SOx, AI-based control can extend solvent life. In addition, soft sensors (software-based models that estimate hard-to-measure process variables using easily accessible data) can estimate and even predict the concentrations of contaminants (such as SO_3 which is difficult to measure in the presence of NH_3), allowing for more precise holistic process control.

- **Maximising capture uptime:** AI-control can reduce the chances of cyclone blockages (obstructions caused by the build-up of materials such as kiln feed, dust, or alkali salts, which disrupt the flow of hot gases and raw meal) or other causes of downtime. More uptime means more CO_2 captured, diluting the fixed costs of shutdowns.

Carbon Re's partnerships with leading automation providers — ABB and FLS Cement — position our AI as a powerful enhancement to existing control systems and a key component in the future of cement plant operations.

For cement companies planning carbon capture: we believe that adopting AI optimisation now — during the planning stage — is critical as it will deliver immediate cost and CO_2 savings in support of interim climate targets and enable reinvestment. Crucially, it also prepares the plant to be "capture-ready." By the time the carbon capture system is in place — after years of planning and construction — the kiln will already be operating in a tightly controlled, optimised state. This lowers scale-up risks and can significantly reduce the capture unit's commissioning time.



AI-generated image

6. Conclusion: The case for urgent action and industry collaboration

The cement industry stands at a crossroads. One path sees companies delaying transformation, risking rising carbon costs, stricter regulations, and scrambling to retrofit solutions under duress. The other path involves acting early, embracing digital innovations and preparing for technologies like carbon capture, gaining both competitive and environmental advantages.

Why the urgency?

- **Climate commitments are imminent:** 2030 is less than one kiln-rebuild cycle away. **The GCCA's 2030 milestone calls for at least 10 industrial-scale CCUS projects and 25% emission intensity reduction.** Implementing AI control is something that can be done in months, not years, and can start chipping away at emissions immediately, while laying the groundwork for faster and more efficient CCS integration.

- **Digital readiness for CCS:** To adopt CCS at scale by the 2030s, cement plants must be digitally mature. This means having robust data infrastructure, integrated control systems, and the ability to deploy and maintain advanced digital tools, including AI-driven optimisation, real-time monitoring, and predictive maintenance.

  CCS operations will generate vast amounts of data from sensors monitoring solvent concentrations, temperatures, valve positions etc. To effectively manage the integrated cement and CCS processes, plants will need both modern digital infrastructure and skilled personnel.

  Implementing AI systems today serves a dual purpose: it acts as a "data audit," identifying gaps and inconsistencies, and helps build organisational capabilities. Importantly, successful AI control of a cement requires several years of historical data. If data is not available, it is better to start collecting it now.

- **Economic advantage of early integration:** Early adopters of AI optimisation will accrue savings and efficiency gains year on year. **The benefit of AI-based control above existing control systems is of the order of $1 per tonne of cement.** Over a period of 5–10 years prior to carbon capture, this could result in fuel savings and avoided carbon liabilities amounting to several million dollars (particularly as carbon prices rise and thresholds fall). These financial gains can directly enhance profitability or be allocated to capital investments such as carbon capture infrastructure.

- **Advanced control is essential:** The impact of CCS integration will be to increase the cost of cement production by a factor of 1.5-2, while **the value of improved process control increases by an order of magnitude — from $1 per tonne today to ~$10 per tonne in a combined CCS/Cement system.** This is a lower bound estimate, based on the cost per tonne impact of varying CO_2 concentrations, without including the additional benefits of solvent management, CapEx control and minimising downtime.

The window of opportunity is now. Cement companies have a chance in the mid-2020s to lay the groundwork for the massive changes coming in the 2030s. Adopting AI process control is one of the most cost-effective investments to future-proof plants. It drives immediate profit and performance improvements while positioning the kiln for the radical shift in operating procedures that carbon capture integration requires. Every kiln optimised with AI today is a kiln that can more smoothly integrate carbon capture tomorrow. The industry can thus move from being seen as a "hard-to-abate" problem to a leader in deploying innovative solutions for a sustainable, profitable future. The message to decision-makers is clear: act now — implement AI, stabilise and optimise your process, and be ready to capture carbon.

The climate, and your company's competitive future, cannot wait.

About Carbon Re

Carbon Re is an Industrial AI company on a mission to reduce carbon emissions at gigatonne scale. Our flagship product helps cement producers cut up to 5% of fuel-derived CO_2 emissions by optimising the pyroprocess, the most carbon-intensive stage of cement production.

Carbon Re works seamlessly works seamlessly with existing Advanced Process Control (APC) systems such as ABB Ability™ and FLSmidth ECS/ProcessExpert®. Our adaptive AI models operate in closed-loop control, continuously optimising fuel usage and managing fuel-mix variability in real time.

By integrating Carbon Re, plants unlock greater value from their process, lab, and chemical data. Our machine learning models dynamically adjust process targets, reduce reliance on manual intervention, and free up engineers to focus on higher-impact optimisation.

Carbon Re requires no capital expenditure, no new equipment, and no production downtime. It continuously adapts to changing inputs and external pressures to deliver sustained energy savings and cost reductions.

Learn more: **carbonre.com/product**

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