

Implementing CCUS in the Cement Industry: Challenges and Solutions





Introduction

The global cement industry is said to be responsible for 8% of global CO₂ emissions, but what often gets lost in this statistic is the work the industry had done over a significant period of time. CEMBUREAU states that since 1990 there has been a 15% reduction in relative CO₂ emissions from the European cement industry¹ and the Global Cement and Concrete Association (GCCA), which represents 80% of the World's concrete industry outside of China, states there has been a "proportionate reductions of CO₂ emissions in cement production of 20% over the last three decades"². **The cement industry understands the need to decarbonise.**

However, there remains a lot of work to do:

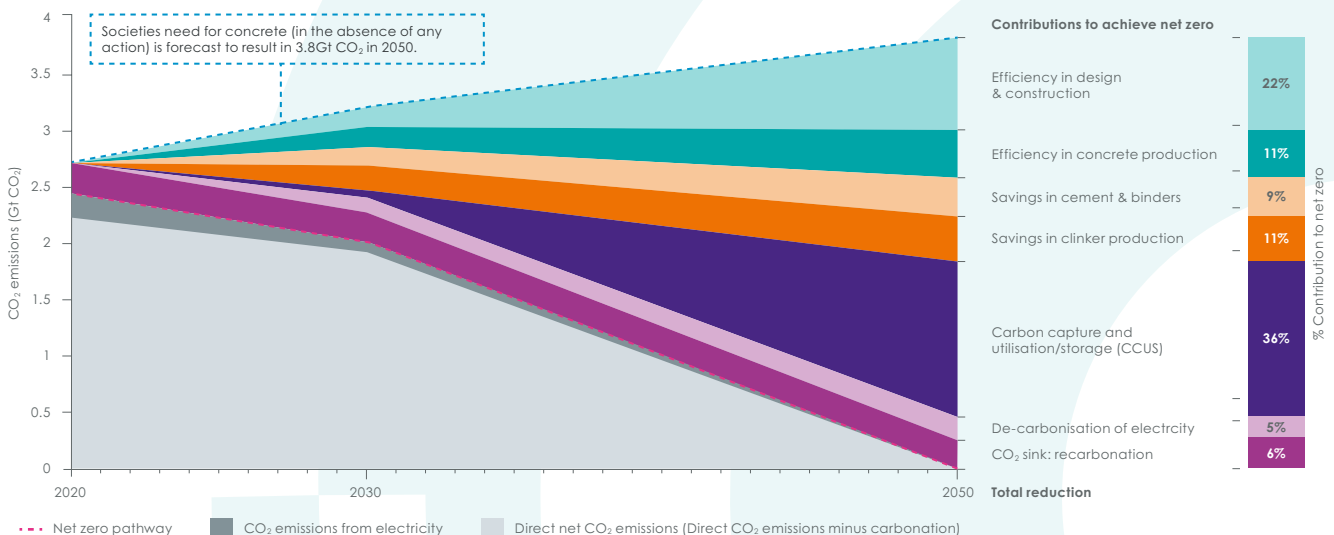
- Global demand for cement is predicted to increase by almost 50% by 2050³
- The IEA states that to meet the Net Zero Emissions by 2050 (NZE) Scenario, cement industry emissions must fall by an average of 3% annually through to 2030 and this requires annual CO₂ intensity reductions of 4% through to 2030⁴.
- The Paris Climate Agreement requires the global concrete industry must reduce emissions by 16 percent by 2030 and 100 percent by 2050 to stay within the 1.5°C warming carbon budget⁵

The cement industry recognises this challenge and the GCCA has both a commitment to achieve net zero by 2050 and a roadmap for how the industry will get there:

This roadmap from the GCCA shows four distinct areas that are within the control of the cement producers:

1. Efficiency in concrete production (11% contribution)
2. Savings in cement and binders (9% contribution)
3. Savings in clinker production (11% contribution)
4. Carbon Capture and Utilisation / Storage (CCUS) (36% contribution)

Each area presents significant challenges, but perhaps the most significant challenges are within CCUS. As this is an area that needs to contribute more than the other three combined, it is imperative there is a concerted effort to overcome these challenges. The following paper articulates the challenges and presents solutions for the mass implementation of CCUS across the cement industry.



1 [cembureau-2050-roadmap_final-version_web.pdf](#)

2 [Our path to net zero \(gccassociation.org\)](#)

3 <https://energypost.eu/concrete-8-of-global-emissions-and-rising-which-innovations-can-achieve-net-zero-by-2050>

4 <https://www.iea.org/energy-system/industry/cement#tracking>

5 <https://rmi.org/with-concrete-less-is-more/#:~:text=In%20accordance%20with%20the%20Paris,%C2%B0C%20warming%20carbon%20budget.>

Challenges

CCUS Projects: Complex in three dimensions

There is complexity and uncertainty within all major projects, however CCUS projects are complex in three dimensions. This complexity comes from the nascent nature of the developing CCUS industry, and it brings uncertainty. Taking decisions in a context of this complexity and uncertainty complicates an already difficult decision-making process as is described below.

Scope Complexity

CCUS projects are composed of multiple distinct sub-projects. These can be broadly grouped as capture, process and treatment, transportation and storage, utilisation, and sequestration. Within each of these there is technical complexity, including selection of capture technology; dehydration and purification of the captured CO₂; the phase of transportation, gas, liquid, dense and the associated risks; the mode of transportation and any interim storage requirements; the decision whether the CO₂ will be utilised or sequestered.

The complexity is compounded by the interdependencies between each sub project. The decision whether to utilise or sequester impacts the CO₂ specification for transportation, which impacts design of the capture system and CO₂ treatment, it also impacts material selection decisions throughout the value chain; the distance to the user of sequestration also impacts the phase of transportation, which has impacts on design throughout the chain.

No decision can be made in this system of sub-projects without impacting the other elements. To ascertain the optimal project architecture there needs to be a holistic understanding of each element and their relationships with one another.

Organisation Complexity

CCUS projects are rarely executed end to end by any one entity, different parties undertake different sub-projects within the whole. Even so, given the nascent nature of the CCUS value chain, it is common that the execution of these sub projects is not the core business of the executing entity.

Cement companies excel at making cement; they have less expertise in the capture and subsequent treatment of the CO₂. The same applies across the CCUS value chain. For example, transportation, whether by pipeline, barge, rail or marine, is rarely the core business of the operator of the vector. This organisation complexity is compounded by the need for all of these projects to align with one another: no one sub-project in the chain can take a Final Investment Decision (FID) without some certainty that the other sub-projects will also take FID in the required timeframe.

The chain of projects relies on the alignment of execution schedules of technically complex projects executed by entities for whom they are not core expertise.

Strategic Complexity

The third dimension of complexity relates to the strategic drivers for these projects. Beyond the common societal stakeholder need to reduce CO₂ emissions, CCUS projects must serve a complex landscape of internal and external stakeholders. On the internal stakeholders there is a need to balance corporate commitments to net zero with commercial and productivity needs, the process must maintain economic efficiency while the net zero goals are pursued. External stakeholders beyond wider society include government legislation and incentives, the carrot and stick of decarbonisation. There are also less obvious external stakeholder considerations such as regional restrictions regarding the disposal of CO₂. Germany, for example, prohibits onshore sequestration of CO₂. This means CO₂ captured from German process facilities must be transported to either the coast of a neighbouring country, this has implications on the internal stakeholder economic

requirements: what is the most economically favourable solution: pipeline, barge or railcar? Similarly, the export route has an impact on the technical choices: are the risks associated with transportation in the dense phase appropriate for areas of high population density?

The interplay between internal and external stakeholders also manifests in the decision whether to sequester or utilise the CO₂. In many geographies, there is a difference between incentivisation for the utilisation and sequestration of CO₂. In some instances, this presents an opportunity for the previously waste stream to be monetised through utilisation. For example, can the CO₂ be sold or used to make a recycled carbon fuel (RCF). This is particularly the case in the European Union where if the CO₂ can be classified as biogenic, it can be used to produce Renewable Fuels of Non-Biological Origin (RFNBO) and access the associated incentive schemes. This dynamic may be the difference between a CCUS project being economically viable or an impact on a company's bottom line.

Industry Specific Challenges: Unique nature of cement

As is the case with all industries, there are unique aspects of the cement industry that need to be considered, and each of these have implications for the complexity dynamic described.

The primary source of CO₂ emissions in the cement process is in the clinker process, where limestone, clay and sand are heated to produce clinker. In this process, in addition to any emissions from the fuel used to generate the heat, CO₂ from the limestone is released. While there is work ongoing to reduce emissions from the clinker process, there is a need to capture the CO₂. As described above, the choice of capture technology is impacted by the upstream and downstream processes. Each capture technology has its own strengths and weaknesses, which manifest in diverse ways for applications in the cement industry.

Amine Absorber

This technology involves using a liquid solvent, typically an amine solution, to absorb CO₂ from flue gases. It is effective across a wide range of gas streams, from low concentrations of CO₂ to levels of high purity CO₂ (99%+). The major advantage of this technology is its maturity and reliability, as it has been widely used in various industrial applications for decades. However, it can be energy-intensive and requires careful management of solvent degradation and emissions.

Calcium Carbonate Looping (CCL)

CCL utilises calcium oxide (lime) to capture CO₂ from flue gases by forming calcium carbonate. One key advantage is the potential for lower energy consumption compared to amine-based processes. Additionally, it can be integrated with existing infrastructure, such as cement kilns, reducing implementation costs.

Adsorptive Processes (TSA, VPSA)

Temperature Swing Adsorption (TSA) and Vacuum Pressure Swing Adsorption (VPSA) technologies capture CO₂ by adsorbing it onto solid sorbents. They can be energy-efficient and offer flexibility in operation. However, they may require high-pressure or high-temperature conditions and suffer from lower capture efficiencies compared to liquid solvent-based methods.

Membrane Process

Membrane-based carbon capture separates CO₂ from flue gases using selective permeable membranes. It is often regarded for its low energy consumption and scalability. However, membrane materials need to be optimised for high selectivity and permeability to achieve commercial viability.

Cryogenic Separation (CPU)

Low temperature CO₂ capture technologies, often referred to as cryogenic carbon processing, are based on a phase change in which the CO₂-rich gas stream is separated from the residual gas by several process stages. It can achieve high purity and is suitable for large-scale applications. However, it typically requires significant energy input for refrigeration through a Cryogenic Processing Unit (CPU). The energy requirements of a CPU are such that it is only efficient if the exhaust gas stream has an increased CO₂ concentration greater than 70-75%. The design of the CPU is based on ensuring the captured CO₂ meets the purity requirements of the CO₂ transport and storage sub-projects. As such, the design of the CPU must be bespoke to the flue gas conditions and downstream purity requirements.

Sorbent Processes (Double Absorber Hot Gas System)

Sorbent-based processes use solid materials to adsorb CO₂ from flue gases. The Double Absorber Hot Gas System, for example, involves two sorbent beds operating alternately to capture and release CO₂. These processes offer potential for lower energy consumption and can be tailored for specific applications.

With a conventional kiln, and CO₂ concentrations in the range of 15-20% in the flue, the technology that may be selected is amine absorption or calcium carbonate looping. However, an alternative kiln technology can offer significant benefits.

Oxy-Kiln: the solution for cement?

Given the interplay between the capture technology and the flue gas stream from the clinker process, it is important to consider this as a system to understand if changes to the clinker process can address some of the inherent challenges of the capture technologies. One such option that is proving to be significant benefit to cement production is the use of oxy-combustion in the kiln. The benefit of oxy-combustion is that when fuel is combusted in pure oxygen the flue gas contains mainly CO₂ and water vapour with only trace amounts of other combustion products, mainly in the form of NO_x, SO_x, and PM). Capture of the CO₂ from this highly pure stream is significantly easier than from flue gas produced in conventional combustion, which contains significantly more impurities (e.g. mainly nitrogen from the air). Yet, as is often the case in systems problems, the gain of easier to capture CO₂ comes with trade-offs in other areas of the process. Based on laboratory tests performed by the European Cement Research Academy (ECRA), oxy-fuel combustion has no considerable effects on the quality of clinker⁶. However, while already established in various industries, the application of oxy-combustion in cement production remains nascent.⁷

First Generation Oxy-kilns

This method is most suitable for clinker kilns that are in excellent condition and equipped with modern features like a tertiary air duct and a calciner. Conversion of the kilns to enable this approach includes utilising heat-resistant seals and linings to minimise air ingress, which reduces the oxygen purity and is known as 'false air'; the implementation of flue gas recirculation (FGR), which is used to moderate the higher temperatures caused by combustion in pure oxygen.

FGR is especially important in the preheater to ensure proper dispersion and heat transfer of the dropped raw meal. By adjusting the exhaust gas volume returned to the process, the oxygen content can be maintained at the optimal level. In this process, the recirculated waste gas undergoes energetic cooling and drying before entering the clinker cooler to ensure both rapid cooling for clinker quality and prevent water condensation. However, the specific heat capacity of CO₂ requires higher thermal energy for FGR compared to conventional kilns using air humidification. Thus, the benefits are weighed against an increased energy demand. Nevertheless, the resulting dry flue gas concentration of Oxyfuel 1st Generation technology can exceed 80% CO₂.

Second Generation Oxy-Kilns (without FGR)

These units are designed to burn fuels in a pure O₂ environment with O₂ provided by a new ASU. There is no recirculation of the CO₂-enriched flue gas and thus no energy-intensive cooling and drying of it. O₂ is supplied via the cooler inlet and at the calciner and main burner. Only for the transport of the solid fuels to the burners is a partial flow of the CO₂-rich gas stream separated in a CPU used.

With this type of kiln, the total amount of combustion gases drawn through the kiln, calciner and preheater are significantly reduced. To ensure the optimal ratio of clinker/ CO₂ in the preheaters the new clinker plant has pre-heater cyclones with smaller diameters and therefore smaller volumes than in conventional kilns with the same production capacity. The calcination and sintering process at the main burner takes place at significantly different atmospheric and partial pressures than in the conventional kiln and deviates from the first-generation concept. Limiting the amount of false air is also important with this new kiln technology to operate

⁶ Oona Katajisto Calcination of Calcium Carbonate based Materials in Electric Heated Rotary Kiln, 2020

⁷ It should be noted other solutions to the clinker process are in development, including Calix's LEILAC which uses indirect heating to produce a separate CO₂ stream. This, and other alternatives, come with their own strengths, weaknesses and multidimensional complexities, which need to be managed.

the subsequent CO₂ separation in the CPU as efficiently as possible. To minimise the amount of false air, special kiln inlet and outlet seals with a temperature resistance of > 1,000°C are necessary. Separation of the gas flow in the cooler is also mandatory to ensure that the cooling air in the rear area is not drawn into the kiln and that the purest possible O₂ atmosphere is maintained. To ensure this separation, pendulum plates or a lower shaft guide, where the clinker forms the gas barrier, are being considered. The heat generated at the cooler can be used directly to dry raw materials or fuels. The resulting flue gas concentration (dry) of the Oxyfuel 2nd generation technology can be ≥93.5% CO₂, with a moisture content of 27-28%.

Air Separation Unit

Regardless of the generation of technology deployed, oxy-kilns require a source of oxygen. This can be achieved by implementing an Air Separation Unit with the process. ASUs are a mature and proven technology having been used in industrial gas operations for decades. However, it is another new technology for the cement industry and the different physical principles available, such as membranes, pressure-swing-adsorption (PSA), vacuum-PSA or cryogenic separation must be evaluated to select the most appropriate. PSA/VPSA is ideal for low volumes and low purity oxygen requirements, while cryogenic separation is preferred for high flow rates and applications requiring high purity oxygen.

Pollution Control Technologies

While the flue gas from an oxy-kiln can exceed 93% CO₂, it will benefit from addition of a cleaning stage before being captured. The main combustion pollutants from fossil fuels and alternative fuel mixes used in clinker kilns are:

- Oxides of nitrogen (NO_x)
- Oxides of sulphur (SO_x)
- Particulates
- Total organic compounds (TOC) including volatile organic compounds (VOC)
- Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD and PCDF)
- Metals and their compounds
- Hydrogen fluoride (HF)
- Hydrogen chloride (HCl)
- Carbon Monoxide

In other industries, two-stages of gas cleaning are normally applied:

- dry gas cleaning for the removal of NO_x and particulates
- wet gas cleaning for the removal of sulphur compounds, HCl, HF.

Dependent on the use of the captured CO₂, removal of NO_x in particular is important to ensure there are no significant metallurgy issues in storage, transportation and sequestration.

Carbon Capture: Cryogenic Processing Unit (CPU)

Having achieved a highly pure stream of CO₂, the oxy-kiln process lends itself well to the cryogenic separation using a CPU. Cryogenic separation is a low temperature CO₂ capture technology, based on a phase change in which the CO₂-rich gas stream is separated from the residual gas by several process stages to achieve higher purity (>95%).

However, the thermodynamics of the cryogenic separation process are such that it is only efficient if the inlet stream is >80% CO₂. This makes the cryogenic process well suited for oxy-fuel combustion processes as it delivers a flue gas stream containing 85% CO₂ and is suitable for large-scale applications. In CPUs, a pressure swing absorber can be integrated to capture CO₂ after cryogenic separation, enhancing purity levels by removing remaining impurities. This cyclic process ensures efficient CO₂ capture while minimising energy consumption, making it a crucial component in carbon capture technology. It is possible to achieve CO₂ purity >99% using this approach.

However, this remains an energy intensive process, and steps should be taken to improve the efficiency. This may include the integration of waste heat recovery technology with the oxy-kiln.

Solution

What can be done in this decade of “making it happen” to manage this complexity and deliver the critical decarbonisation of the cement industry?

CCUS projects are complex mega projects, through the lessons learned in other industries it is well understood that investment in the early phases through Front End Loading (FEL) is critical to establishing the strongest possible foundations for success. Given the multidimensional complexities of CCUS projects for the cement industry, it is recommended that a systems approach to the project architecture is taken in the earliest phases. This is best done through the formation of an integrated team that not only possesses deep technical expertise in project management and systems engineering, but also demonstrates a nuanced understanding of the complex economics and stakeholder dynamics associated with CO₂ capture utilisation and sequestration projects.

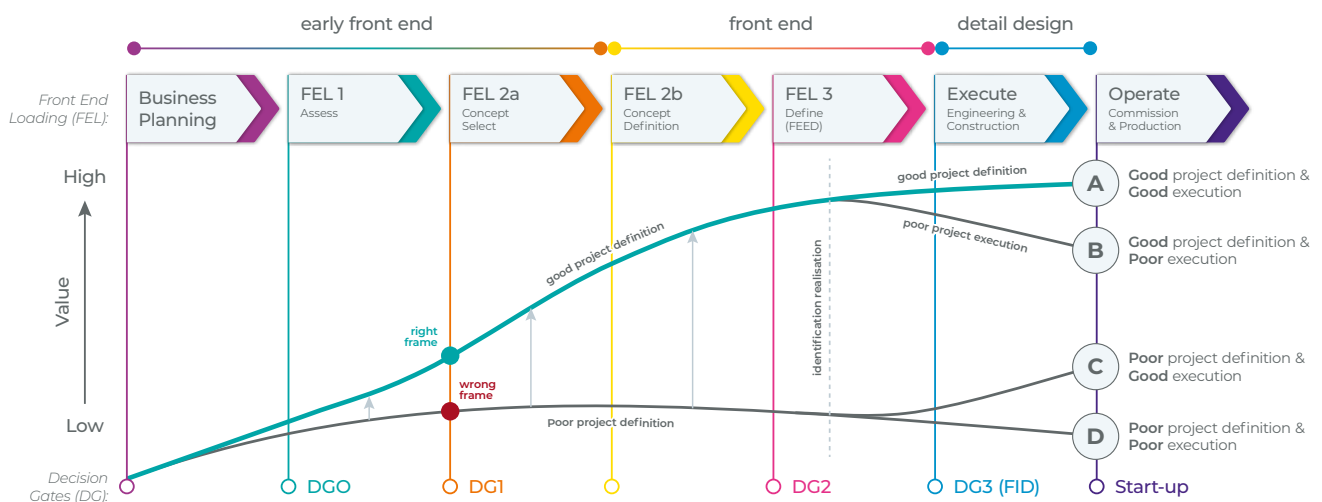
A more detailed analysis of the key success enablers, and io consulting's unique expertise in each follows below.

Front End Loading (FEL)

FEL is about investing time and effort to ensure projects are viable before significant amounts of CAPEX are committed. At the core, the FEL process ensures a project is correctly defined and planned. The decisions taken in the early phases of the project set the pathway to success or failure: no matter how well you execute, it counts for little if you execute the wrong project.

At io, we are passionate about the front end of projects. Front End Loading (FEL) is our area of expertise, we work with our clients to create value in the front end and support them by protecting value through the subsequent phases. It is in these early phases that a project is defined, defining the correct project is the biggest influence on the subsequent outcome.

Our internal cost estimating database has been developed through successful execution of many CCUS projects, across industries. It has been benchmarked against outturn data from our parent companies and includes McDermott's extensive experience in EPCIC (Engineering, Procurement, Construction, Installation and Commissioning). If required, we can embed McDermott's expertise directly into our project execution, this allows for superior construction management, procurement strategies, and installation services, and enables greater certainty in our execution schedules.



Holistic Project Integration

It is critically important to align the disparate elements of the CO₂ value chain, from capture and purification to transportation and storage, and subsequent utilisation or sequestration. This integration is critical in ensuring project feasibility and allowing each of the sub-projects to take FID.

This is best done with a systems approach to project execution, where the technical aspect of each sub-project is connected with the organisational and economic realities, ensuring that all components work harmoniously.

io has pioneered a systems approach to energy transition projects, including CCUS projects incorporating multi-industry emitters capturing and transporting CO₂ for onshore and offshore sequestration. Our Systems Optimiser tool enables us to integrate technical, cost and economic variables into a single environment and rapidly undertake multivariable optimisation. This not only enables us to optimise projects but also identify emergent properties from the complete value chain and identify the value levers.

Technical expertise

CCUS projects have technical complexity throughout the value chain. No one entity has expertise in all areas. It is important to select the correct partner when developing CCUS projects to ensure project phase appropriate expertise is applied to each element of the value chain.

io has deep domain expertise in CO₂ including phase properties, equations of state, static and dynamic simulation, and flow assurance. This expertise is such that io has designed a CPU that enables export specification compositions to be achieved without the need for an external refrigeration plant and associated infrastructure, thus presenting a significant advantage compared to other technologies for the application.

Our experts have also developed transportation projects covering all fluid phases and transportation mechanisms, including onshore and offshore pipelines, in extreme environmental conditions and terrains; rail and barge systems, including loading and unloading systems, and transportation logistic; and marine shipping, again with loading and unloading systems.

io consulting, as a joint venture between Baker Hughes and McDermott, has access to the subsurface expertise within the Gaffney Cline Associates business. This expertise includes all subsurface resource development technical disciplines (geology, geophysics, petrophysics, reservoir engineering, drilling and completion and development planning / facilities engineering). The team of specialists has decades of experience in subsurface geology, process and injection of CO₂. By integrating this expertise into the io team, we can provide technical expertise from CO₂ source to sink.

Economic and Regulatory Expertise

The economics of CCUS projects are challenged, there is often a need for external financial support. In addition to economic modelling, io's energy economists have expertise in project financing. We have a 100% record in applying for government funding for energy transition projects and offer support to our clients including grant application, grant management and joint execution of grant funded projects. This success comes from a combination of our credibility as subject matter experts and our ability to effectively communicate the technical and environmental benefits of projects to a non-expert audience.

In addition to our economic expertise, our environmental and social experts have deep domain knowledge of the regulations and legislations surrounding all aspects of CCUS projects. We include these assessments in the earliest phases of projects to ensure the risks and implications are included in the holistic assessment of project architecture and prevent unnecessary project recycle.

Stakeholder Management and Advocacy

For these highly integrated projects with multiple stakeholders, each controlling various segments of the value chain, it is critical to have robust stakeholder management. There is a need for each party to understand the value drivers of the other to enable alignment of the sub-projects in a way that facilitates each party to take FID at the required time.

It is common for io to work in complex stakeholder landscapes such as this. Drawing on aspects of Decision Quality, a framework that mitigates cognitive bias and enables higher quality decisions when working with uncertainty, and has decision dialogue as a key element, we have developed an approach to stakeholder management that allows us to identify, align and manage diverse stakeholder interests.

Our expert facilitators work to ensure continual communication of project benefits and needs and provide comprehensive support for clients throughout the project lifecycle.

Strategic Execution, End-to-End Support & Execution Excellence

A decision is only as good as the commitment to implement it. The same applies for the FEL process, once the correct project has been defined it still must be executed effectively otherwise the value created in the front end will be lost.

At io we aspire to work with our clients beyond FID, to help our clients protect the value created in the front end. Acting as the owner's engineer, io ensures continuity and consistency, reducing risks associated with transitioning between project phases and different contractors. We provide oversight and technical guidance during the execution phase, safeguarding the owner's interests and ensuring project specifications and performance criteria are met. This integrated approach enhances operational efficiency, and it increases project reliability, safety, and compliance.

Should a client's contracting strategy prefer an end-to-end execution, io can leverage top-tier EPCIC services from McDermott, to delivering large-scale, technically complex projects that drive forward the goals of decarbonisation and sustainable industrial practices.

Circularity / Sector Coupling

An emerging trend in the energy transition is circularity, where the waste product from one part of the systems is a feedstock for another. In the context of the CCUS challenge for the cement industry, this concept is particularly interesting as the cement industry develops alternative fuels, including those from biomass and municipal solid waste. Depending on the genesis of these alternative fuels, an element of the CO₂ produced by cement facilities may be classified as biogenic. Under current EU classifications for renewable fuels, biogenic CO₂ is a premium product with value for producers of e-fuels and e-SAF (sustainable aviation fuel). As a leader in the development of e-fuels projects, io can support cement companies identify and leverage opportunities to convert a waste stream into a value stream while delivering emission reduction targets.



Conclusion

As described above, CCUS projects are multi-variant and correct definition requires a thorough understanding of the interdependences between these dynamic elements. By applying our expertise as a project architect and systems thinker we ensure the sub-projects come together to serve the whole.

We have successfully delivered value on projects for some of the World's leading cement companies, helping them conceptualise and design their decarbonisation solutions. We bring subject matter expertise in major project development, including cost and schedule estimation; carbon capture, processing, transportation, storage and utilisation; advanced simulation and flow assurance; safety and risk; environmental and social; and project economics and financing. We also recognise where others are more expert and work collaboratively with domain experts to ensure CCUS projects do not adversely impact the cement manufacturing process.

The GCCA considers the decade from 2020-2030 as the "decade to make it happen" and the period from 2030-2050 the time for "full deployment of technologies to get to net zero". In this we see analogy with the FEL process, the decisions made in the next five years are fundamental to achieving the 2050 target. Our role in this critical journey is to bring our expertise to support the Global cement and concrete industry make net zero happen.



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