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Techno-Economic Perspectives on CCUS Deployment for Reducing Process-Related CO₂ Emissions in Cement-Based Construction

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Abstract

The construction sector, and cement production in particular, is a major contributor to global CO₂ emissions, with a significant share coming from process-related sources which cannot be fully addressed by conventional measures such as efficiency improvements or substitution of materials. As mitigation strategies are reaching their limits, carbon capture, utilization and storage (CCUS) has emerged as a key path to achieve deep decarbonisation of the cement industry, which is being seen as a representative case for the wider hard-to-reach construction sector. This study presents a systematic literature review of CCUS technologies relevant for cement and concrete, based on a screening process informed by PRISMA and drawing on peer reviewed literature, technical reports and industrial case studies. The principal carbon capture pathways include pre-combustion, post-combustion, oxy-fuel combustion, and chemical looping. These pathways are evaluated alongside CO₂ utilization and storage routes such as mineral carbonation, carbonation curing, and CO₂-based construction materials. The review finds that post-combustion capture and mineral carbonation currently exhibit the highest technological readiness for near-term deployment, while emerging approaches offer long-term potential despite higher energy and cost barriers. CCUS-enabled materials also show benefits in durability, resource efficiency, and carbon permanence, though adoption remains constrained by economic, infrastructural, and regulatory challenges. Overall, the findings indicate that CCUS is essential for decarbonizing hard-to-abate construction processes, and its effective deployment will require coordinated technological innovation, supportive policy frameworks, and standardized acceptance criteria for CO₂-modified materials.

Keywords

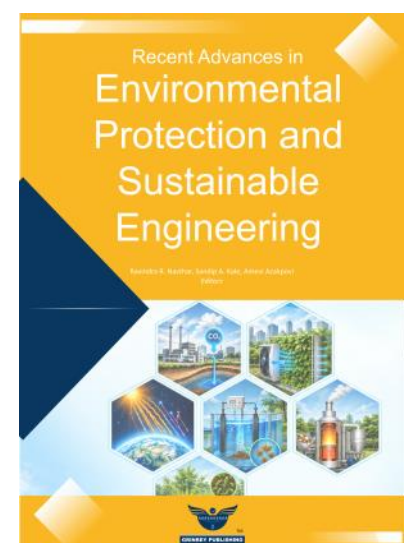
Carbonation Curing; CCUS; Cement De-carbonization; Post-combustion Capture; Sustainable Construction

Received: 15 Feb 2026 | Accepted: 10 Oct 2026 | Online: 22 Oct 2026

Cite this article

Chaithrashree R and Navaneetha Hombali BN (2026). Techno-Economic Perspectives on CCUS Deployment for Reducing Process-Related CO₂ Emissions in Cement-Based Construction. Research Transcripts in Energy, 2, 1-18.

DOI: https://doi.org/10.55084/grinrey/RTE/978-81-996627-6-6_1



1. Introduction

The construction industry plays an important role in global economic growth, but it is also one of the largest sources of climate change because it consumes large volumes of material and energy resources [1]. Cement production is one of the most carbon-intensive industrial processes in terms of its environmental impact among construction-related activities. Latest synthesis analyses suggest that the cement sector contributes about 7-8 per cent of the greenhouse gas emissions in the world, and it is one of the biggest single industrial producers of CO₂ in the world [2]. These gases have two main sources, namely (i) process emissions coming about during the heating of limestone to release carbon dioxide chemically and (ii) energy emissions caused by the burning of fossil fuel and the use of electricity during the production of clinker [2]. Since process emissions are closely connected to the chemical changes of the raw materials, no matter how good the energy efficiency is, they cannot be completely eliminated [3]. Therefore, most commonly, cement production is listed as a hard-to-abate industry in the global plans of de-carbonization.

The issue of deep de-carbonization of industrial fields has now become burning nature in the wider framework of the Paris Agreement and the global commitment to net-zero. However, although the use of renewable energy source and electrification have greatly diminished the emissions in power and transport sector, heavy industries like cement and steel and chemicals still face structural problems associated with high-processing temperatures and process-related emissions. This is opposed to the power generation where the emissions can be diminished by switching the fuel, as cement generation intrinsically emits CO₂ in the process of forming a clinker. This inherent limitation restricts the efficiency of the traditional mitigation strategies and requires the creation of the technological solutions that will be transformative.

The cement industry is considered as a target area in global climatic mitigation agenda and de-carbonization of the industry with respect to the concentration of the sector contributing significant amounts of carbon to the atmosphere [2]. While, supplementary cementitious materials, process improvement, and partial replacement of emitting fuels can reduce carbon emissions, these strategies are not enough to achieve deep reductions in line with net-zero pathways. At that, the Carbon Capture, Utilization, and Storage (CCUS) have become one of the urgent technological ways that can resolve the residual and process-based emissions that are impossible to remove with the help of traditional mitigation methods. CCUS offers a way to achieve significant reductions to the level of the plant through the direct capture of CO₂ to the flue gases and process streams produced at the facilities and releasing them straight into the atmosphere.

This review focuses specifically on cement production as a primary sector in construction. Cement production accounts for most process-related emissions in the sector and is the clearest example of a process that is inherently hard to abate, because its main chemical reaction - calcining limestone is inherently releasing CO₂, regardless of energy source or efficiency improvements [2]. This makes cement a representative and technically instructive lens through which the wider application of CCUS in the construction sector can be examined such as: many of the capture technologies, use routes and policy mechanisms discussed (e.g. post-combustion capture, carbon capture and sequestration, carbon pricing instruments) are directly transferable to other high temperature, process-intensive building materials such as steel and glass.[4]

This review will thus (i) monitor the development and technical implementation of carbon capture systems in cement production, (ii) assess emerging CO₂ utilization opportunities in cement and concrete materials and (iii) compare the political and financial environment that will shape large-scale application in the cement industry.

Most technology evaluations show that partial implementation of CCUS can result in a reduction of emission by 60-80% especially with capture systems used on particular kiln or flue gas feeds [5]. Even more developed designs, such as post-combustion amine systems, oxy-fuel combustion, have shown technical feasibility of

capture rates over 90 percent to produce plant level reductions of emissions to around 90-95 percent under optimum operation [6]. In addition to capture and geologic storage, the construction industry has opportunities to integrate CO₂ to aid construction development in a variety of forms, such as mineral carbonation, carbonation curing, and CO₂-based construction materials, which allow long-term carbon sequestration in concrete constituents [7]. But lifecycle assessments point out that the net benefit of utilization pathways in relation to climate is reliant on how permanent the storage is, as well as the generate of carbon intensity of the energy inputs used in processing [8]. As the Indian market is becoming highly urbanized, with the cement demand expected to grow swiftly (aided by infrastructure expansion and general industrial de-carbonization), the role of CCUS in the national strategy of climate mitigation is beginning to gain more and more relevance in national climate strategies and policy discourses.

Despite increasing technological development, the incorporation of CCUS in the construction sector is still affected by economic viability, regulatory frameworks, infrastructure readiness, and market motivations. On the one hand, there are many studies of capture technologies, and as many studies that study policy or material innovation separately, but on the other hand, a synthesis of technology readiness, as well as policy systems and financial effects in regard to the construction sector are not well explored. This paper aims at presenting a systematic evaluation of the current state of CCUS as a potential de-carbonization action plan in the construction sector by considering technical, regulatory, and financial aspects.

2. Literature Review Method

2.1. Literature Search Strategy

Following the identification, screening and inclusion process in PRISMA, a systematic literature review was carried out on carbon capture, utilization and storage (CCUS) applications in the cement and concrete industries. Google Scholar was used as the primary source of literature due to its broad index of peer-reviewed articles, conference papers, and review articles in engineering and environmental science. This single database approach is recognised as a limitation in this review (see section 5). The search terms included combinations of: CCUS in cement industry, carbon capture in cement factories, mineralisation of CO₂ from concrete, carbonation of concrete, decarbonisation of cement industry and CCUS policy and economics. These searches, together with an additional snowball search of key reference lists, resulted in 86 records that were imported into the Zotero reference management software for screening. The timeframe considered for the publications is 2010-25, with an emphasis on 2016, indicating the period of acceleration of research activity and early commercialisation in this area.

2.2. Screening and Selection Requirements

After import, two duplicate records were detected and deleted, leaving 84 unique records for the name and abstract check. Records were screened against the following inclusion criteria: (i) peer reviewed journal articles or reputable conferences, (ii) published in English, or provide a direct link to the CCUS in cement or concrete or provide a basic technical background to related industrial carbon capture applications. At this stage, 10 records were excluded for non-compliance with the peer-review criterion (mainly institutional and agency reports), leaving a total of 74 records for full-text assessment. This resulted in a final set of 45 publications that were included in the summaries and reviews as shown in Fig.1. Additional sources, were found outside the primary survey, which is included in the review to support a specific empirical claim on the results of the policy incentives (section 3.5), bringing the total number of works cited in the review to 54.

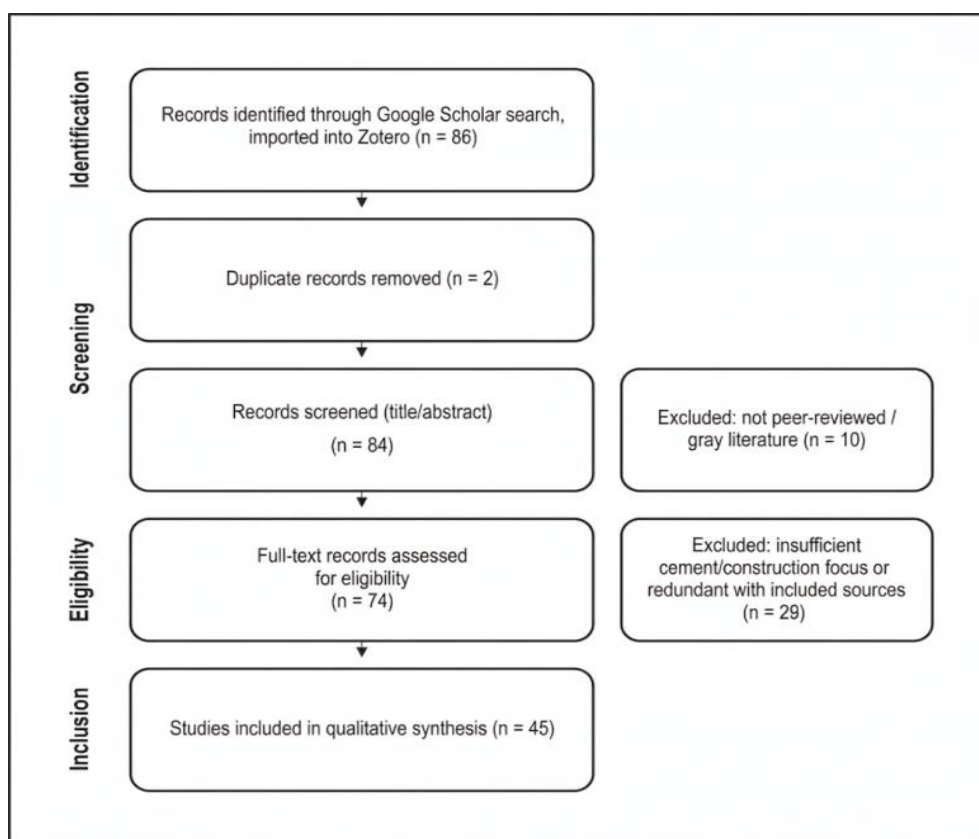


Fig. 1. PRISMA flow diagram of the literature identification, screening, and inclusion process

2.3. Data Categorization and Analytical Framework

The selected literature was then grouped into three thematic areas including (i) carbon capture methods in cement production, (ii) CO₂ use and storage routes in building materials and (iii) policy frameworks and analysis of economic viability of CCUS implementation. This grouping made it possible to compare synthesize the availability of technology, potential of emissions reduction, the mechanism of regulation, and cost implication.

3. Review Findings and Discussion

This part synthesizes the main findings from the literature review and critically reflects on technological improvements, economic factors, and policy changes related to CCUS implementation in the building industry.

3.1. Evolution and Commercialization of CCUS in Construction Industry

Based on a chronological reading of the reviewed literature, this study suggests a three-phase initial period of development of CCUs in the cement and construction industries, characterised by their development from early technological discovery to the present commercialisation efforts.

The review stresses the importance of qualitative synthesis backed by the quantitative results documented in the literature such as capture efficiency ranges, lifecycle considerations as well as cost estimates in order to have a holistic estimate on the CCUS integration in the construction industry.

Since 2010, the development of CCUS in the cement and construction industry can be simplified into three successive stages, namely the screening of technologies and the feasibility of retrofits (early-mid 2010s), the assessment of systems and the lifecycle integration (late 2010s), and the implementation net-zero-oriented approaches and early commercialization (2020s).

Phase I: Retrofit and Technology Screening (Early-Mid 2010s)

In the early 2010s, the main research focused on identifying capture technologies that could be used in cement plants. Treatment of cement was first considered as one of a number of large stationary CO₂ point source with power generation and steel production. Research focused on post-combustion solvent absorption, oxy-fuel combustion, and calcium looping and tested their technical viability and retrofit-ability to existing kiln systems. A seminal review of the literature by [6] found that post-combustion and oxy-fuel systems had the potential to capture approximately 90% of plant-level CO₂ emissions, but most applications were at pilot or demonstration scale.

Simultaneously, the initial research on carbonation curing of cast concrete indicated the technical viability of mineralizing CO₂ in concrete matrices [9]. But at this point, the capture of CO₂ at cement kilns and its use in concrete products were virtually limited to laboratory and demonstration projects.

Phase II: Expansion System-Level and Lifecycle Assessment (Late 2010s)

After the Paris accord in 2015, the focus on research shifted to the assessment of CCUS in the context of decarbonization pathways. Instead of concentrating on capture efficacy, research started to utilize the life-cycle evaluation (LCA) methodologies to evaluate net climate effects. As it has been reviewed, the environmental performance of carbon capture and utilization (CCU) pathways are considerably dependent on carbon intensity of electricity and methodological boundaries that are regularly followed [3].

At the same time, the literature began to view cement as an industry that is hard to abate with CCUS becoming a necessity rather than an option in the case of deep emissions cuts [10], [11]. Integration studies involved combined capture-utilization chains, such as synthetic fuel production and methanol pathways, and highlighted high energy demand and cost sensitivity [3]. It was a conceptual transition to single capture technologies to the analysis of integrated CCUS systems.

Phase III: Net-Zero Framing and Early Commercial Deployment (2020s)

By the 2020s, CCUS in cement has emerged as one of the core points of net-zero industry policies [2]. Studies were broadened in their technical feasibility to techno-economic modelling, regulations, financing systems, and implementation routes. CO₂ mineralization, carbonation curing and CO₂-based construction materials are now being viewed as promising early-commercial technologies in reviews in the civil engineering community [7], [8], [12].

Although capture at integrated cement plants is mostly at pilot and early-commercial stage, it has since the mid-2010s become a more routine part of commercial practice in precast and specialty concrete products. CCUS facilities in all industries worldwide have increased dramatically, but cement accounts for only a small percentage of overall capacity [13]. Carbon pricing and tax incentives (e.g., 45Q in the United States) as policy instruments and green procurement standards have played an essential part in increasing the pace of deployment after 2015 [2], [14].

The general trend of CCUS in cement is that it is now moving towards feasibility of concept to show system-level integration and early commercialization. Nevertheless, full-chain capture, transport, and storage in the production of clinker are only becoming prevalent as opposed to established, and the cost, infrastructure, and regulatory coordination of this technology are still determining its scalability [15].

3.2. Carbon Capture Technology in Construction Industry

3.2.1 Cement Production and Mechanism and CO₂ Sources.

The average tonne of cement produces around 600-900 kg of CO₂, equivalent to approximately 7-8 percent of anthropogenic CO₂ emissions worldwide [6], [3]. There are two main sources of emissions; the reported ratios vary slightly in the literature depending on the chemical composition of the clinker, the fuel mix and

the kiln technology. The calcification of limestone ($\text{CaCO}_3 + \text{CO}_2$) is an inevitable consequence of the chemical process itself. It accounts for 60-70 percent of emissions, although estimates vary between 50-70 per cent [2], [8]. The remainder, about 30 to 40 per cent, is due to the burning of fossil fuels to maintain the furnace temperature at more than 1450°C [3], [16]. As calcination emissions are chemically inherent in cement production, no amount of energy savings or substitution can fully eliminate them, which makes carbon capture a critical mitigation measure [6].

Carbon capture systems in cement plants are mainly applied to the kiln and precalciner exhaust gases, which contain both combustion and process CO_2 . The CO_2 concentration of the cement combustion flue gas varies considerably (14-33%), showing both the specific point of extraction of the process. The off-gas of the pre-calcification process is usually more CO_2 -rich due to concentrated emissions. Whereas, the main kiln burner exhaust is diluted by combustion of air nitrogen and has wider variability across plants depending on fuel mix, kiln configuration, and use of oxygen enrichment [10]. This range still indicates that the industry is technically well placed to integrate capture with other factory emissions [10].

3.2.2 Pathways of Capture Technology in Cement.

There is post-combustion, oxy-fuel, calcium looping, and direct separation technologies that can be used used in capturing carbon in cement. Post-combustion capture resembles the principle behind the scrubbing process.

a. Post-Combustion Capture (Amine Scrubbing)

The principle of post-combustion capture is similar to the scrubbing process. The most mature and demonstrated capture option is post-combustion solvent absorption. This is done by passing the flue gas through an absorber column filled with chemical solvents (e.g., monoethanolamine), through which CO_2 is selectively absorbed. The solvent is then regenerated by thermal stripping, which emits concentrated CO_2 for compression and storage [6], [10]. It has been reported that the capture efficiencies in treated streams are in the 85-95% range, but energy penalties related to solvent regeneration are large [16]. The main benefit of this method is that it is retrofit-compatible with the existing kilns.

b. Oxy-Fuel Combustion

Oxy-fuel systems substitute air with almost pure oxygen in the combustion process and result in a clean gas that consists mainly of carbon dioxide and water vapour. A stream of high-quality CO_2 is obtained after condensing the water, making the separation complex reduced [3], [6].

Though it can capture at high rates, oxy-fuel needs large kiln redesign and expensive air separation units, which is better applied in new installations or when changing the whole plant [17].

c. Calcium Looping (CaL)

Calcium looping involves using a circulating cycle of CaO/CaCO_3 to absorb CO_2 using flue gases in a carbonator reactor and then release concentrated CO_2 during the calcination process. Because of the chemical compatibility of CaO and cement raw materials, this technology has integration benefits in clinker production [16]. The reported capture efficiencies are greater than 90 percent, and CO_2 purity is high (99 percent), making CaL one of the most promising cement-specific capture methods [6], [16].

d. Direct Separation Concepts

New designs like indirect heating or calciner redesign (e.g., direct separation reactors) are being developed to produce almost pure process CO_2 during limestone calcination and then separate it prior to combustion emissions before it is mixed with them. Although the systems are conceptually appealing in reducing energy penalties, they are current at the laboratory level to pilot [6].

3.2.3 Commercial Deployment and Technology Readiness Level (TRL)

The TRL classifications discussed below are based primarily on one industrial CCUS assessment [13]; while they are broadly in line with the TRL ranges reported elsewhere in the literature on capture technologies, precise attribution of TRL may differ from assessment to assessment depending on the criteria and the industry context used and should be treated as indicative rather than final.

Technology readiness levels (TRLs) offer a systematic way of assessing the maturity of carbon capture technologies between laboratory (TRL 1-3) and commercial (TRL 8-9) operation [18]. According to industrial CCUS evaluations [19], there are capture technologies that can be utilized in cement and they could be classified as follows.

a. Post-Combustion Capture (TRL 8-9)

Solvent-based post-combustion systems are the most mature carbon capture technology that is available at the moment. Having TRLs of 8-9, such systems are commercially implemented in a number of industries. They have a major advantage in that they can be retrofitted to the existing cement kilns. Nevertheless, drawbacks such as high energy penalty for solvent regeneration, solvent degradation, and operational issues driven by corrosion are also significant [19], [20].

Though proven commercially in other industries, large-scale implementation in cement is limited but in early stages of commercial implementation.

b. Pre-Combustion Capture (TRL 7-8)

In pre-combustion systems, CO₂ is captured before combustion in syngas streams (H₂ + CO₂) in pre-combustion devices that recover CO₂ before the combustion process, which in most cases is an integrated gasification combined cycle (IGCC) system. These technologies have been proven to be 7-8 TRLs; however, they are typically not applicable to new plants and can only be integrated into complex plants, which are expensive [6], [19]. Pre-combustion routes are not as prevalent in cement because they do not fit in typical kiln designs.

c. Oxy-Fuel Combustion (TRL 6-7)

Oxy-fuel combustion is located on TRL 6-7 and is associated with pilot and small-scale industrial demonstrations. The flue gas produced is rich in CO₂ when fuel is burned in almost pure oxygen, making it easy to separate. A large air-separation unit, the cost of oxygen production, and material restrictions, however, continue to be serious obstacles to full commercial use [19]. Oxy-fuel in cement is promising but requires major alterations to the kiln.

d. Chemical Looping Combustion (TRL 3-5)

Chemical looping, which uses metal oxides as oxygen carriers to separate CO₂ inherently during combustion, is at TRL 3-5. Development is currently mostly limited to laboratory and initial pilot stages. Some of the challenges include the lifetime of oxygen carriers, the complexity of reactor scale-ups, and the lack of large-scale demonstrations [20].

Although post-combustion systems have been commercially demonstrated in some industrial sectors, their use in cement is at early commercial or advanced demonstration phases, oxy-fuel and looping remain in the pilot validation phase. Table 1 outlines the TRL levels, deployment status, and major limitations of major carbon capture technologies relevant to cement production.

The reported capture efficiency of CaL (90%) and CO₂ purity (99%) reflect performance demonstrated in laboratory and pilot studies under supervised conditions rather than commercial-scale operational capability.

TRL is explained because of factors other than chemical performance, including sorbent (CaO) degradation during repeated carbonation-calcification cycles, problems with reactor expansion, and issues in integrating with existing furnace systems. This explains why CaL remains below TRL (3-5) despite the positive performance figures. The difference between demonstrated chemical performance and full system readiness is a common pattern across emerging capture technologies and is not unique to CaL.

Table 1. TRL for different Carbon Capture processes

Capture Process	Technology Description	TRL	Status	Key Limitations
Post-combustion Capture	CO ₂ separation from flue gas using solvents (e.g., amines)	8–9	Commercially deployed	High energy penalty, solvent degradation, corrosion
Pre-combustion Capture	CO ₂ capture from syngas (H ₂ + CO ₂) before combustion in IGCC systems	7–8	Demonstrated, limited to new installations	High capital cost, complex plant design
Oxy-fuel Combustion	Combustion in pure O ₂ yields CO ₂ -rich flue gas	6–7	Pilot and small-scale industrial plants	High oxygen production cost, material constraints
Chemical Looping Combustion	Indirect combustion using metal oxides for inherent CO ₂ separation	3–5	Lab-scale and early pilot testing	Oxygen carrier durability, reactor scale-up, limited demonstration

Source: TRL classifications from [13]; ranges are generally in line with other cited literature on capture technologies but should be considered as indicative and not final.

3.3. CO₂ Utilization in Cement and Concrete

The application of carbon dioxide in the cement and concrete value chain is mainly founded on the mineral carbonation, during which CO₂ combines with calcium- or magnesium-rich phases to produce stable carbonate minerals. As opposed to short-lasting chemical routes of utilization, mineralization pathways provide long-term storage of construction materials and thus high climate mitigation potential in the long term [12], [22].

3.3.1. CO₂ Curing of Precast Concrete

Accelerated carbonation curing applies fresh or young concrete to a condition of higher CO₂ levels in controlled pressure and humidity. The CO₂ dissolves in the pore solution and reacts with calcium hydroxide, unhydrated clinker phases, and C-S-H gel to create stable CaCO₃. This reaction increases the density of the microstructure and promotes early strength development [4], [14].

The uptake of material at the material scale differs greatly with mix design and curing regime. According to laboratory research, uptake of up to 17% of cement mass has been observed in a high-purity CO₂ environment, and in commercial precast, the uptake is more in the 0.01-0.05 t CO₂/ton of concrete range [12], [23]. On a bigger scale, it has projections that, based on high adoption rates, precast carbonation curing has the potential to remove CO₂ at the gigaton level per year [23].

The two figures are not directly comparable: the laboratory value represents the CO₂ content of the proportion of the reactive cement and binder in idealised high purity conditions, while the commercial value represents

the total CO₂ content of the finished concrete unit, which includes the aggregate, water and other non-reactive components diluting the percentage.

Notably, the thermodynamic stability of the carbonates formed is on building time scales, meaning that they store well in the long term [24].

3.3.2. CO₂ Injection during Mixing (Ready-Mix Systems)

Small doses of liquid CO₂ (typically 1.5% of cement mass, roughly 5 kg/m³) are added to the mix by injection. About 50-80 percent of injected CO₂ mineralizes into nano-CaCO₃, resulting in permanent storage of about 2.5-4 kg CO₂/m³ of concrete [8], [25].

The direct mineralized amount is small but the strength benefit provided by the creation of nano-CaCO₃ facilitates cement decreases of about 5 percent, frequently dominating the overall emission sparing [22], [26]. Thus, the climate gain of injection systems is motivated more by that of the reduction of clinker than pure CO₂ uptake.

3.3.3 Mineralization of carbonated Aggregates and Industrial Waste

A further significant route of utilization is ex-situ mineralization of alkaline industrial residues including steel slag, fly ash, red mud and cement kiln dust. The mentioned Ca/Mg-based solids are reacted with concentrated CO₂ in special reactors to produce carbonate-bound aggregates or binder precursors [7], [22].

The uptake is reported to range from around 0.09 to 0.44 t CO₂ per ton of aggregate, depending on feedstock and process conditions [12], [23]. In addition to storing carbon, these pathways increase circularity by diverting industrial wastes from landfills and reducing the need to use virgin aggregates.

The recycled concrete aggregates (RCA), which are carbonated, also demonstrate better resistance and a lower water uptake following the accelerated carbonation exposure [8], [12]. On a feasible scale, the annual production of iron and steel slags worldwide is estimated to be more than 400 million tonnes, and the mineralisation of these slags alone yields a potential for global CO₂ savings of ~0.1-0.15 Gt per year, equivalent to a fraction of global anthropogenic emissions. This suggests that mineralisation routes from industrial waste, although valuable for circularity and localised emissions reduction, are unlikely to compensate for the gigatonnes of emissions of the cement sector alone; their main contribution is to complement, rather than replace, capture-based decarbonisation of the cement kiln itself.

3.3.4 CCU to Cement-Integrated Fuels and Chemicals

The CO₂ captured in cement plants can also be used with hydrogen to form methanol, urea, or methane as well as other synthetic fuels in integrated CCU [3], [16]. Nevertheless, the analysis of life-cycle assessment invariably shows that such routes need very low-carbon electricity to yield net reductions in emissions and typically have reduced long-term mitigation efficiency than permanent mineralization pathways [3].

3.3.5 Life-Cycle Assessment Perspective

Life-cycle assessment shows that the use of CO₂ in concrete is not necessarily associated with net climate benefit. A significant part of the captured CO₂ can be compensated by upstream capture energy, CO₂ purification, compression, and transportation [22], [23].

The net benefits are the strongest when:

- Low-carbon energy sources CO₂.
- The distances of transport are insignificant.
- Cement or steam-curing savings are obtained significantly.
- There is high mineralization efficiency.

In many cases, precast carbonation curing systems with clinker reduction can show more apparent life-cycle benefits compared to small-dose injection systems [12], [26].

3.4. Geological Storage of CO₂ from Cement Plants

Geological storage represents the most mature and large-scale option for managing CO₂ captured from cement plants. Unlike utilization pathways, which are constrained by material demand, subsurface storage offers multi-gigaton capacity and is considered essential for deep decarbonization of hard-to-abate sectors [10], [26].

3.4.1 Storage Formations

a. Deep Saline Aquifers

Deep saline formations located at depths greater than ~800–1000 m allow CO₂ to exist in a high-pressure state, boosting storage density. These geological formations are widely distributed globally and are considered the largest potential storage resource [10], [13].

Advantages include:

- Very large potential capacity
- Geographic flexibility
- No dependence on hydrocarbon production
- Strong long-term structural and residual trapping mechanisms
- Saline aquifers are therefore prioritized in long-term CCS deployment strategies.

b. Depleted Oil and Gas Reservoirs

Depleted hydrocarbon fields offer proven caprock integrity, existing infrastructure, and well-characterized geology. In many cases, CO₂ injection can be coupled with enhanced oil or gas recovery (EOR/EGR), generating economic value during early deployment phases [26], [27]. These storage sites are particularly attractive when cement plants are located near mature hydrocarbon basins.

c. Coal Seams and Mafic Formations

Unmineable coal seams enable CO₂ adsorption and methane displacement (ECBM), though total storage potential is smaller and reservoir evaluation is more complex [4].

Mafic and ultramafic formations (e.g., basalts) allow in-situ mineralization, converting injected CO₂ into stable carbonate minerals. While this pathway offers high permanence, it remains more site-specific compared with saline aquifers [28].

3.4.2 Global and Indian Storage Capacity

Geological storage capacity is estimated to be on the order of thousands of gigatons globally. One synthesis reports theoretical global capacity approaching ~11,000 Gt CO₂ across sedimentary formations [13].

The United States alone is estimated to possess >2,400 Gt CO₂ storage capacity across saline aquifers, hydrocarbon reservoirs, and coal seams [13].

As with most assessments of geological storage, the figures for both the world and the US are based on a single synthesis source [13] and reflect theoretical storage capacity rather than the available capacity in practice; actual injection volumes are usually only a fraction of the theoretical volume once geological, regulatory and technical constraints are applied.

For India, latest evaluations estimate geological storage capacities ranging from about 500 to 1,000 Gt CO₂, including sedimentary and basaltic formations [20]. This estimate reflects an assessment at national level; as

estimates of geological storage capacity are highly sensitive to the assessment methodology used (e.g. theoretical versus actual capacity), this figure should be considered as an indicative figure pending more in-depth mapping of the source and sink, rather than an exact or definitive national inventory. This suggests that the availability of storage is unlikely to be a constraint to the long-term de-carbonisation of the cement industry in India, although an in-depth mapping of source and sinks remains to be done.

3.4.3 Operational Deployment and Case Studies

Large-scale geological storage has been operational for over two decades.

Notable examples include:

- Sleipner (Norway), injecting ~0.8–1 Mt CO₂ per year into a saline aquifer since 1996
- Snøhvit (Norway), offshore saline storage associated with gas production
- In Salah (Algeria), deep saline injection project
- Weyburn–Midale (Canada), CO₂-EOR combined with long-term storage

In the United States, CO₂-EOR operations in the Permian Basin have injected millions of tonnes annually, with a significant fraction remaining geologically stored [14].

Recent offshore developments in China, including the Enping 15-1 project, indicate the emergence of hub-scale storage systems [29].

These projects demonstrate that geological storage has reached commercial-scale deployment, particularly in saline aquifers and hydrocarbon reservoirs.

3.4.4 Risks and Monitoring

Long-term risks primarily include:

- Leakage through faults or wellbores
- Groundwater acidification
- Induced seismicity
- Pressure-induced geomechanical effects

However, well characterised sites are expected to retain >99 per cent of the injected CO₂ over a centennial time scale (i.e. ~100 to 1000 years after injection, as typically modeled in geological storage risk assessments) due to structural, residual, solubular and mineral trapping mechanisms, with the latter becoming dominant over time [13].

Effective implementation requires comprehensive Measurement, Monitoring, and Verification (MMV), including:

- Continuous pressure and injection monitoring
- Time-lapse seismic imaging
- Geochemical and tracer studies
- Surface and soil-gas surveys

3.4.5 Geological CO₂ storage Regulatory Framework

Although the technical feasibility of geological storage technologies has been demonstrated, large-scale implementation is mainly limited by regulatory uncertainty rather than technical restrictions. The literature emphasizes that the allocation of long-term liability, the right to own pore space, the right to monitor and verify, and the obligation to maintain stewardship after closure are among the key areas of legal concern [30], [31], [32]. Truncated permit systems and ambiguous environmental compliance criteria in most jurisdictions

extend the project approval process and raise investment risk. Moreover, the lack of uniform international regulations regarding the transportation of cross-border CO₂ and offshore storage is an added legal complication. Such regulatory uncertainty significantly affects investor confidence and the bankability of the project, especially for first-of-a-kind cement CCUS installations.

3.5. Carbon Pricing and Economic Instruments

The key factor in influencing the implementation of CCUS in the cement industry is carbon pricing. According to empirical and modeling research, moderate or fluctuating carbon prices are generally not high enough to motivate significant capital investment in capture and storage infrastructure [33], [34]. Evidence from emissions trading schemes indicates that carbon prices are stable and sufficiently high when complemented by complementary schemes, including tax credits, investment subsidies, contracts for differentiated services, and carbon border adjustment schemes. Examples of policy instruments such as the 45Q tax credit in the US and the Innovation Fund in the EU have demonstrated the importance of some financial incentives to drive industrial de-carbonisation at an early stage. In the US, the 45Q loan was linked to more than 150 proposed CCS projects covering electricity generation, cement, chemicals, gas processing, and the concrete sector; sector-specific analyses estimated significant related employment and economic impacts linked to projects that would not have been undertaken without the loan [35]. Cement producers will not invest heavily in the CCUS until price certainty is guaranteed in the long term [36].

3.6. Governance of infrastructure, Transport Networks and Storage

Beyond capture economics, unit costs are reduced through the development of shared CO₂ transport and storage facilities, which demand industrial clustering. Hub-and-cluster models, in which several emitters use pipelines and storage reservoirs, improve economies of scale and decrease risks associated with single projects. Infrastructure planning, however, requires policy support, collaboration between the government and businesses, and government intervention to ensure regulatory transparency on third-party access rights, tariffs, and inter-sector integration to create effective CO₂ transport networks. Poor characterization of storage site information and restricted geological surveys also delay infrastructure planning, especially in developing economies.

3.7. Policy Environment and Business Obstacles in India

CCUS implementation in India is also at an early stage, and its adoption is mostly facilitated by strategic roadmaps and pilot projects rather than a full regulatory statute. Policy deliberations at a national level, such as reports by NITI Aayog and sectoral decarbonization pathways, note that CCUS is an infrastructure-level technology that can be fundamental in reaching long-term net-zero goals within sectors like cement, which are hard-to-abate. Commercialization is, however, limited by barriers such as high capital costs, a lack of specific financial incentives, inadequate transport infrastructure, and a lack of well-established frameworks of long-term liability [4], [37], [38]. Besides, the changing carbon market structure in India remains in an initial phase, and the lack of a well-established mechanism to price carbon decreases economic incentives towards the use of CCUS. Although pilot mineralization and utilization projects are coming into place, full-scale geological storage governance structures are still not institutionalized. These structural and financial gaps will require attention to move to commercial application in the cement sector in India.

4. Future Direction

The shift of the CCUS in the cement industry out of pilot demonstrations to a system-wide implementation will need co-ordinated technological, infrastructure, governance, and digital integration progressions. Recent literature shows that conceptual feasibility is no longer the major bottleneck; instead, cement-specific scale-up, system integration, and market structuring have become the critical bottlenecks.

4.1 Scale-Up of technology and Cement-specific integration

One of the most significant research gaps is the development of capture systems (TRL 5-6) to commercial systems (TRL 7-9) operating in cement-specific routes including oxy-fuel combustion systems, calcium looping systems, and indirect calcination systems (e.g., LEILAC) [3], [6]. Mass retrofit engineering, kiln-capture heat integration, space considerations and sequential renovation of plants are areas that are not explored enough. Further improvement with the help of waste heat recovery and low carbon integration is needed to further reduce the 10-20 percent energy costs associated with solvent recovery in post combustion amine-based capture systems [39].

In addition to capture units, system level design is not well researched. Small studies assess committed transport networks to deliver cement clusters, source-sink compatibility, policy uncertainty, and connections to local storage centers [7], [10]. Region-specific evaluations of CCS versus CCU versus combined routes under realistic grid carbon intensities are also limited [25], [40].

4.2 Usage Patterns and Market Creation

Carbonation curing, CO₂ mineralization, and CO₂-based binders are additional avenues of utilization that need to be further legitimized over the long term; nonetheless, the durability, kinetics, and performance of these materials on waste streams and mix-designs need to be validated [12]. There should be harmonized approaches to the lifecycle accounting to prevent the cases of the duplication of counts and healthy claims on carbon removal [40]. As a way of scaling up utilization markets, market-pull mechanisms such as green public procurement, product standard of low-carbon cementitious materials are viewed as crucial [24].

4.3 Policy Innovation and Business Model Development

Further studies also need to deal with cement-specific business models that connect capture facilities with transport and storage networks. Risk-sharing schemes, contracts-for-differences, price stability in relation to carbon prices, and liability systems continue to be key factors behind the decision to invest [33], [41], [42]. Models of a carbon hub cluster and a staged infrastructure implementation are broadly suggested as the ways to lower the price per tonne captured [43], [44].

Emerging literature also focuses more on sociotechnical aspects of the topic, such as social acceptance, environmental justice, and transparency in governance, which are less represented in studies on the cement sector [41], [45].

4.4 Optimization of Systems and Digitalization.

A major but unexploited opportunity by cement CCUS is presented by digital technologies. Hybrid models that use AI and model predictive control have also proven to increase the energy efficiency of cement plants and have the potential to optimize kiln-capture [46], [47]. Machine learning applications are useful for predicting solvent performance, real-time process optimization, and detecting faults in capture systems [29], [48].

In the case of geological storage, digital twins that combine both reservoir dynamics simulation and real-time observation of data enable dynamic injection control and early leak identification [49]. AI-enhanced lifecycle assessment systems also enable adaptive assessment of the environment to changing operating conditions [50], [51]. Nevertheless, all-inclusive digital CCUS systems that suit cement plants are mostly abstract.

4.5 Cement Industry in India Strategy.

Synergising projections across national policy plans [28], [29] the development would be gradual: pilot and cluster development in the 2020s, infrastructure development in the post-2030s and, depending on policy and

financial incentives, more extensive integration into industrial de-carbonisation trajectories from 2035 to 2050.

The implementation of CCUS in India will proceed slowly. At present, work remains limited to demonstrations and use-oriented projects [37], [38]. Short-term obstacles include capture costs, the lack of transport infrastructure, and the changing regulatory framework [52], [53]. However, modeling research indicates that CCUS will also be essential to reduce the cement industry's process emissions in India by mid-century, especially under net-zero 2070 pledges [54].

5. Conclusion

The cement industry is also one of the most problematic industries to decarbonize because it has a dual emission profile, consisting of energy-related and unavoidable process emissions from limestone calcination. Although incremental changes in energy efficiency, clinker replacement, and the use of alternative fuels can reduce carbon emissions, they cannot meet deep decarbonization goals on their own. Carbon Capture, Utilization, and Storage (CCUS) is thus not a peripheral solution, but a structural requirement towards long-term net-zero solutions in the cement industry.

As evidenced by the review, capture technologies including post-combustion absorption, oxy-fuel combustion, calcium looping, and indirect calcination have developed considerably in the technology readiness spectrum, with several pilot and demonstration programs preparing to scale up to early commercialisation. Nevertheless, these technologies are still limited by large-scale integration issues, energy penalties, infrastructure reliance, and cost uncertainties, which inhibit rapid adoption. Storage routes are technically well-developed, yet they need coordinated transport network development and clear regulations. The Use method, in particular CO₂ mineralisation, shows good prospects for circular economy synergies, although the net climate benefit varies greatly between them. In some cases, notably for CO₂ injection into a ready mix; significant proportion of the reported emission benefit is due to the associated reduction of the clinker in the composition rather than the CO₂ itself, which points to the need for a standardised lifecycle accounting to separate these two contributions and allow for long-term verification of the carbon sequestration claims.

CCUS feasibility is increasingly influenced by policy and governance structures. The major facilitators include stable carbon pricing systems, financial de-risking instruments, and infrastructure models, as well as clusters and harmonized monitoring-reporting-verification (MRV) systems. In India, with cement demand expected to rise further as a result of infrastructure development, CCUS is expected to play a decisive role in residual process emissions under the national net-zero commitment in 2070. Nevertheless, preliminary pilots, positive regulatory tools, and industry clustering plans should be accelerated to close the demonstration and deployment periods.

Future research directions should focus on cement-specific system integration, cost-reduction avenues through modularization and scale learning, digital optimization schemes, and regionally specific techno-economic analyses. There will be a need for greater interdisciplinary coordination between materials science, process engineering, infrastructure planning, digital analytics, and policy design. Finally, technology maturity will be key not only to the viability of CCUS in cement alone, but also to the concerted actions taken at technical, economic, and institutional levels.

CCUS is, in this regard, a disruptive but multidimensional course of action: one that, when wisely implemented, could bring together the essential contribution of the sector to the growth of the global economy with the goal of climate stabilization.

Abbreviation

CaL	: Calcium Looping
CCS	: Carbon Capture and Storage
CCU	: Carbon Capture and Utilization
CCUS	: Carbon Capture, Utilization, and Storage
ECBM	: Enhanced Coalbed Methane recovery
EGR	: Enhanced Gas Recovery
EOR	: Enhanced Oil Recovery
IGCC	: Integrated Gasification Combined Cycle
LCA	: Life-Cycle Assessment
LEILAC	: Low Emissions Intensity Lime and Cement (project)
MMV	: Measurement, Monitoring, and Verification
MRV	: Monitoring, Reporting, and Verification
PRISMA	: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TRL	: Technology Readiness Level

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