



Research
Low Carbon Transformation for Conventional Energies—Perspective

The Carbonation Trap: Time Delays and Performance Uncertainty in Cement Climate Accounting



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ABSTRACT

Cement production accounts for 5%–8% of global CO₂ emissions, prompting industry interest in carbonation—the natural reabsorption of atmospheric CO₂ by concrete—as a climate mitigation strategy. Recent studies suggest carbonation could offset approximately 50% of process emissions, positioning concrete infrastructure as vast carbon reservoirs. However, systematic analysis reveals fundamental limitations challenging this assumption. Cement production generates concentrated CO₂ pulses during manufacturing while carbonation proceeds slowly through diffusion-limited processes spanning decades, creating critical temporal asymmetry. When properly accounted for through time-adjusted global assessments, this mismatch reduces claimed benefits by 30%–60% compared to conventional climate warming potential calculations. Moreover, synthesis of published experimental data across 99 scenarios demonstrates that 52% exhibit less than 50% probability of achieving net emission reductions, with compressive strength penalties often requiring additional binder use that erodes nominal carbon gains. Critically, this perspective exposes three systematic failures in current climate accounting: ① temporal frameworks treating decades-delayed absorption as equivalent to immediate emission avoidance, ② selective reporting obscuring widespread performance failures, and ③ policy prioritization allocating resources to slow, uncertain processes while proven alternatives remain underutilized. By integrating sector-scale projections, lifecycle timing analyses, and comprehensive performance distributions under consistent boundaries, this cross-study synthesis reveals patterns invisible when research remains fragmented—establishing evidence-based hierarchies for near-term decarbonization. In contrast, proven alternatives demonstrate superior performance: supplementary cementitious materials offer 11%–34% emission reductions through direct clinker substitution, structural design optimization achieves 18.5% reductions without compromising safety, and service life extension strategies enable 75% total reduction potential by 2100—far exceeding carbonation-dependent pathways. Consequently, while carbonation remains chemically viable, its slow kinetics, performance uncertainty, and temporal misalignment with climate targets necessitate policy recalibration prioritizing transparent temporal accounting and proven alternatives over uncertain future absorption processes.

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1. The evolution of cement's carbon sequestration theory

Cement production stands as one of the largest industrial sources of CO₂ emissions, responsible for about 5%–8% of global

anthropogenic emissions [1] and releasing nearly one ton of CO₂ for every ton of cement produced [2]. The manufacturing process of traditional Portland cement requires heating limestone and clay to temperatures around 1450 °C, where both calcination reactions and fuel combustion create an inherently carbon-intensive industrial footprint [3,4].

In the early 21st century, however, a paradigm shift emerged that challenged this linear view. Researchers found that

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cement-based materials can partially reabsorb atmospheric CO₂ during service life and demolition through carbonation—a slow reaction between hydration products and CO₂ that yields stable calcium carbonate [5–8]. Once viewed primarily as a cause of concrete deterioration and structural concern, has been progressively reframed as a potentially significant CO₂ sink.

The implications of this discovery appeared substantial. Xi et al. [9] estimated that from 1930 to 2013, nearly half of the mineral-sourced CO₂ emissions from cement production had been naturally reabsorbed through carbonation processes. Subsequent studies have reported even more optimistic figures, with annual CO₂ uptake reaching approximately 0.93 Gt and cumulative absorption offsetting roughly 52% of process emissions by 2023 [10].

This emerging “hidden carbon sink” narrative has begun to significantly influence national greenhouse gas inventories, industry decarbonization roadmaps, and even global carbon budget calculations. The concept has offered a seemingly natural solution to one of the most challenging industrial decarbonization problems, suggesting that concrete infrastructure might serve as vast carbon reservoirs rather than simply emission sources.

Yet two foundational questions remain insufficiently resolved. First, while carbonation is a chemical sequestration pathway, its physical realization is governed by diffusion-limited CO₂ ingress, moisture and temperature regimes, pore structure, and exposure conditions—factors that cap practical uptake and slow kinetics. Second, the timing of uptake is profoundly misaligned with kiln emissions: process and energy emissions occur now, whereas carbonation unfolds over decades, creating accounting choices that can inflate near-term climate performance if future, uncertain uptake is netted against present, certain emissions.

Against this backdrop, this perspective critically examines the temporal dynamics, methodological assumptions, and policy implications of incorporating carbonation into cement industry climate strategies. Unlike experimental research articles that generate new data, perspective pieces synthesize existing published evidence to challenge prevailing assumptions and expose systematic patterns obscured when studies are evaluated in isolation. Our contribution lies in cross-study integration of disparate datasets—sector-scale emission trajectories, time-adjusted climate metrics, and comprehensive performance distributions—to reveal how current accounting frameworks systematically misrepresent carbonation’s climate value.

We specifically ① quantify diffusion-limited, use-phase and end-of-life uptake ceilings under transparent boundaries; ② evaluate the climate value of carbonation using time-explicit accounting that respects near-term temperature constraints; and ③ benchmark carbonation against source-side levers—particularly supplementary cementitious materials (SCMs), durability-led demand reduction, and process options (e.g., oxy-fuel variants and synthetic-fuel coupling)—to establish an evidence-based priority order for near-term, auditable abatement.

A preview of our key findings is as follows. First, when boundary choices explicitly include performance penalties (e.g., compressive strength loss and clinker back-addition), logistics, and forced-carbonation energy overheads, the sign and magnitude of carbonation’s net benefit shrink and can invert in realistic contexts. Second, SCM-driven clinker substitution delivers immediate, verifiable cradle-to-gate intensity reductions with lower uncertainty and clearer verification pathways, while carbonation—where demonstrably effective under audited conditions—plays a secondary, conditional role. Third, pathways that appear attractive in theory can underperform in practice: for example, CombOxy-Efuel configurations (and combinations with hydrogen) can yield negative net abatement under non-zero-carbon power mixes due to compounded conversion losses; only under very low-carbon

electricity and high system-coupling efficiency do such options approach parity.

2. Natural carbon Sequestration: Unveiling the temporal, technical, and economic barriers

While cement carbonation has been hailed as a promising natural climate solution, systematic analysis reveals fundamental limitations that challenge its viability as a reliable decarbonization pathway. This section examines four critical dimensions: the temporal mismatch between immediate emissions and delayed absorption, the methodological biases in current climate impact assessments, the practical failures of engineered carbonation technologies, and the economic constraints that limit scalability. Together, these findings demonstrate that carbonation’s apparent benefits often constitute an accounting illusion rather than genuine climate mitigation.

At the material scale, carbonation proceeds via reactions of portlandite and, subsequently, decalcified C–S–H (Ca_xSiO_(2+x)·nH₂O) with CO₂ to form solid carbonates and water [11,12]; the core stoichiometries may be written as:



These reactions are thermodynamically favorable under ambient conditions, but their realization in concrete is diffusion-limited—CO₂ ingress, pore structure, and moisture/temperature regimes control the rate [13]. As a result, the carbonation front depth typically follows a square-root-of-time law:

$$s(t) = k\sqrt{t} \quad (3)$$

$$s(t) = \sqrt{\frac{2D_c c_s}{a_c}} \quad (4)$$

where $s(t)$ is the carbonation-front depth at time t ; D_c is the effective CO₂ diffusivity, c_s the surface CO₂ concentration, a_c the concentration of carbonatable material per unit volume, and k an empirical/effective rate constant. Peak reaction rates generally occur at intermediate relative humidity (commonly ~50%–70%), rather than under very dry or fully water-saturated conditions [14]. Such transport constraints cap practical uptake well below stoichiometric maxima for many cementitious elements, especially at structural depths.

System-level accounting must further debit countervailing flows—energy for accelerated or forced carbonation, transport and processing at end-of-life, potential strength loss that triggers later back-addition of clinker, and possible re-emission under aggressive conditions—so that net sequestration reflects auditable abatements rather than gross uptake. Differences in boundary choices largely explain the wide spread in reported benefits across studies, even when referencing similar cement stocks.

Taken together, these scientific and accounting constraints show that carbonation, although chemically favorable, remains a diffusion-limited and system-dependent process whose benefits are slow, partial, and highly uncertain. To clarify its actual role in cement decarbonization, Section 2 proceeds in four parts: it first examines the scaling dynamics and temporal constraints of the so-called sponge effect (Section 2.1); it then analyzes how temporal asymmetry in climate impact assessments tends to exaggerate benefits (Section 2.2); and it evaluates the methodological and practical limitations of engineered carbonation relative to more robust measures such as SCM-driven clinker reduction (Section 2.3); finally, it offers a summary and implications that

synthesize the evidence from Sections 2.1–2.3 and set accounting and policy guardrails (Section 2.4).

Because the following analysis is based on re-evaluation and data-extraction of published studies rather than new simulations, a brief methodological note is warranted. This perspective synthesizes existing peer-reviewed evidence under consistent analytical frameworks: Fig. 1(a) [15–17] reproduces sector-scale emission trajectories, Fig. 1(b) reinterprets lifecycle flux timing patterns, and Figs. 1(c) and (d) reanalyze Monte Carlo performance distributions across 99 carbon capture and utilization (CCU) concrete scenarios. All results were cross-validated against source data to ensure alignment in magnitudes, probability distributions, and directional trends. This integrative approach reveals systematic patterns obscured in isolated studies, challenging prevailing carbonation accounting assumptions. Detailed source attributions follow in figure captions and section text.

2.1. Scaling dynamics and temporal constraints

Leveraging published sector-scale projections, reanalysis of Cao et al.'s study [15] reveals that the cement industry's sponge effect exhibits distinct time-dependent characteristics. Annual emission flows peak around 2035 at approximately 4.2 (Gt CO₂)-a⁻¹, then

stabilize at 3.5–4.0 (Gt CO₂)-a⁻¹ levels, while carbonation absorption flows show continuous growth from about 0.6 (Gt CO₂)-a⁻¹ in 2015 to 1.7 (Gt CO₂)-a⁻¹ in 2100 (Fig. 1(a)) [15].

However, this dynamic equilibrium reveals two fundamental limitations. First, carbonation primarily occurs during cement use and demolition phases, creating decades of time delay that presents fundamental flaws when addressing urgent climate targets. Second, the purple dashed line showing net emission balance consistently maintains positive values between 2.0 and 3.2 (Gt CO₂)-a⁻¹, indicating that even considering carbonation effects, the cement industry remains a net contributor to atmospheric CO₂.

Historical data supports this concern: from 1930 to 2021, global cement material carbonation cumulatively absorbed approximately 22.9 Gt CO₂, offsetting 55.1% of cement production process emissions [18,19]. More recent analysis shows cumulative absorption of 21.26 Gt CO₂ with an offset ratio of about 46%, with carbon absorption dominance shifting from developed economies to emerging economies like China (38%) and India (9.1%).

Current practices of incorporating carbonation into carbon accounting systems present significant systemic risks. Most critically, directly offsetting long-term, uncertain carbonation potential against current definitive emissions may lead to systematic underestimation of net emissions. In emerging economies, the carbonation benefits of massive new cement infrastructure will

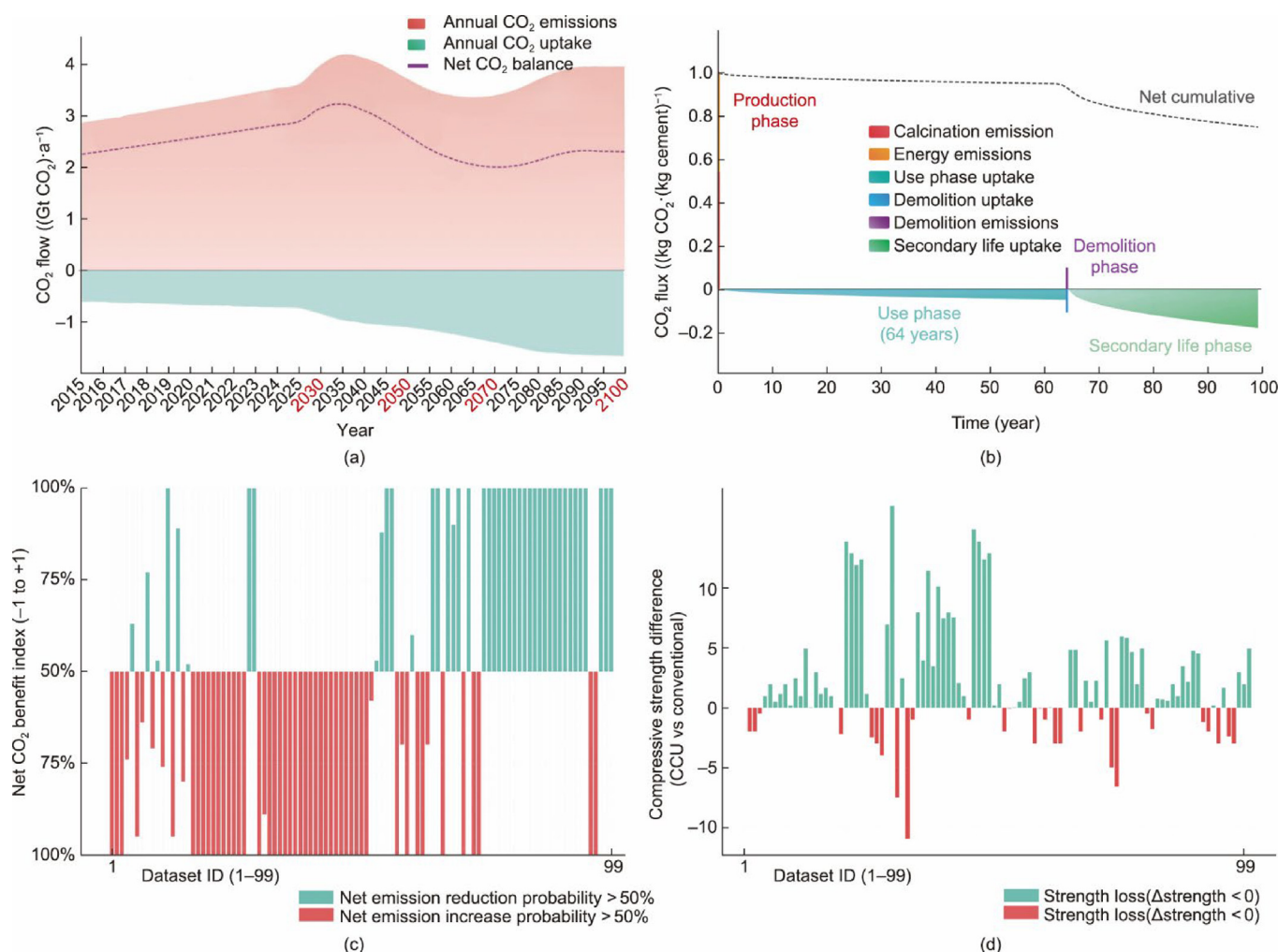


Fig. 1. Cement CO₂ flows, life-cycle fluxes, and performance trade-offs. (a) Annual emissions, carbonation uptake, and net balance (2015–2100). Data source: Ref. [15]. (b) CO₂ flux per kilogram cement over 100 years by production/use/demolition/secondary phases (net: dashed). Data source: Ref. [16]. (c) Probability-based net CO₂ benefit index for 99 CCU scenarios. Data source: Ref. [17]. (d) 28-day compressive strength differences for the same scenarios. Data source: Ref. [17].

only manifest decades later, essentially transferring contemporary emission reduction responsibilities to the future.

Moreover, carbonation efficiency is significantly influenced by regional factors such as climate conditions and building density, showing obvious spatial distribution imbalances. High carbonation rates from mature building environments in developed countries cannot be simply extrapolated to rapid urbanization contexts in developing countries. Even with engineered approaches, natural carbonation processes remain extremely slow and incomplete—in the European Cement Association's 2050 net-zero scenario, negative emission contributions amount to only about 51 kg CO₂·(ton cement)⁻¹ [20].

Under different scenarios, net emissions by 2100 may maintain levels between 1.5 and 3.1 (Gt CO₂)·a⁻¹, far from achieving industry net-zero targets [15]. This indicates that carbonation alone cannot achieve deep decarbonization and excessive reliance on this natural solution may delay investment in fundamental technological transformation such as CCS technology deployment and alternative material development.

2.2. Temporal asymmetry and climate impact assessment

Examining how accounting methodologies affect carbonation valuation, we find serious systematic overestimation of cement carbonation's climate benefits based on Van Roijen et al.'s groundbreaking research [16]. Carbonation is not an instantaneous chemical reaction but a slow diffusion process spanning decades, creating fundamental mismatches with cement production's immediate high-intensity emissions. Traditional global warming potential (GWP) models significantly overestimate carbonation's climate benefits, which should actually be reduced by approximately 60% in positive assessments. In what follows, we use the term comprehensive scenarios to mean cradle-to-grave assessments that include production, use, demolition, and secondary-life phases, and that treat both emissions and uptake with explicit timing rather than assuming they occur concurrently.

Our carbon flux dynamic map clearly illustrates this temporal mismatch (Fig. 1(b)). CO₂ emissions from cement production, including calcination emissions of 0.387 kg CO₂·(kg cement)⁻¹ and energy emissions of 0.367 kg CO₂·(kg cement)⁻¹, complete within the first year, forming intense emission pulses. Meanwhile, carbonation absorption follows diffusion law's square root time relationship, slowly absorbing only 0.05 kg CO₂·(kg cement)⁻¹ during a 64-year service period. This framing reflects the comprehensive scenario definition above, where each life-cycle phase contributes time-stamped flows rather than a single net total.

This time lag effect is supported by time-adjusted warming potential (TAWP) methods, which find that in building lifecycle analysis, equivalent climate benefits considering actual timing are reduced by about 30%–60% compared to traditional GWP [21]. For clarity, TAWP here denotes a timing-aware metric that discounts delayed uptake relative to immediate emissions, providing a closer alignment with cumulative radiative forcing. Leemann et al. [22] found that even with reduced particle size in recycled concrete aggregate under natural storage conditions, CO₂ absorption after months only equaled 5.4%–12.6% of original clinker geological origin emissions.

More concerning is carbonation's rebound effect during demolition phases. While crushing waste concrete can accelerate carbonation, Chen and Yang's scenario simulations [23] show that additional crushing energy consumption and energy supply carbon intensity significantly offset absorption benefits. Under high electricity carbon intensity conditions, 90% carbonation conversion may even shift from net removal to net emissions. Van Roijen et al. [16] similarly found that required additional energy consumption almost completely offsets increased absorption

benefits, with fine particle size crushing only showing net positive benefits when exposed for more than six months post-demolition.

From a dynamic carbon budget perspective, this creates an illusion of carbon absorption rather than true emission reduction. Traditional GWP methods assume total absorption of about 0.33 kg CO₂·(kg cement)⁻¹ over a 100-year lifecycle, but time-adjusted actual climate benefits amount to only about 40% of traditional estimates [16]. From a cumulative radiative forcing perspective, GWP overestimation of carbonation benefits can exceed double actual climate mitigation effects, with this difference particularly evident in the first 50 years when most carbonation remains incomplete while initial emission radiative forcing effects have already fully manifested.

2.3. Methodological limitations in carbon accounting

These temporal limitations raise critical questions about engineered carbonation technologies. Under current global carbon neutrality goals, governments worldwide are introducing policy incentives encouraging the cement industry to adopt CCU or carbon capture, utilization, and storage (CCUS) technologies as emission reduction measures. However, our systematic re-analysis of the comprehensive experimental dataset published by Ravikumar et al. [17] reveals a troubling reality: their analysis of 99 experimental scenarios demonstrates that current mainstream CCU mixing and curing methods not only fail to achieve net emission reductions in most cases, but actually lead to net emission increases due to rising energy consumption and declining material strength.

Dataset structure and experimental design: The 99 scenarios from Ravikumar et al.'s original study [17] span a structured design space with systematic variations along three principal axes: ① CO₂ utilization route (direct injection during mixing versus exposure during curing), ② binder system (neat ordinary Portland cement (OPC) versus OPC blended with SCMs), and ③ SCM allocation approach (mass-based, economic, or system-expansion treatment). Each scenario bundles 13 cradle-to-grave processes covering capture, compression, transport, utilization, upstream energy, and material flows. This factorial diversity was intentionally designed to isolate how process route, binder chemistry, and accounting choices jointly drive net outcomes.

Original methodology: Ravikumar et al. [17] employed Monte Carlo simulation with 10 000 random samplings to estimate net CO₂ benefit distribution for each concrete combination over its lifecycle, setting input parameters as probability distributions to capture uncertainty. Their published results provide: ① probability distributions for net CO₂ benefit across all scenarios, and ② reported compressive strength values for each CCU-conventional concrete pair. We extracted these published values to construct: ① a tendency index visualizing the likelihood of net emission reductions (Fig. 1(c)), and ② a comparative visualization of strength differentials (Fig. 1(d)).

Our re-visualization of their net CO₂ benefit index confirms these concerning findings (Fig. 1(c)): in over half the datasets, Monte Carlo simulations show net emission reduction probabilities below 50%, with multiple cases showing net emission increase probabilities as high as 80%–90%. This means that CCU technologies actively promoted under current policy frameworks lack widespread robustness in emission reduction effects.

Re-analysis of their strength data reveals the underlying mechanism (Fig. 1(d)): In 31 datasets, CCU concrete compressive strength falls below conventional concrete, with some differences reaching –10 MPa. Since structural concrete design must meet minimum strength standards, this strength reduction forces increased cement content in engineering practice, reversely offsetting environmental benefits from carbonation absorption.

This over-using cement to compensate for strength situation reveals the primary driver for net carbon benefits deviating from model predictions.

The original study demonstrates that variables affecting net carbon benefits include not only CO₂ absorption itself, but also energy consumption during production and curing processes, logistics emissions from extended recarbonation curing cycles, and mix proportion adjustments to ensure strength compliance. This series of engineering reaction chains is often simplified or idealized in current LCA models, causing systematic overestimation of carbonation pathway climate benefits.

Furthermore, additional published evidence from Driver et al.'s systematic assessment of 10 global CO₂ mineralization and utilization technologies [24] found that global emission reduction potential under economically viable conditions in 2020 was only 0.39 Gt CO₂-eq (about 15% of that year's cement emissions), primarily constrained by supply bottlenecks of carbonation reaction feedstocks. Unit emission reduction costs vary dramatically across technologies, indicating that without fully considering lifecycle boundaries, feedstock availability, and economics, policy-driven CCU projects may risk resource misallocation or even reverse emission reduction.

Verification approach. We cross-referenced 15 scenarios against the original published figures and supplementary tables to confirm accurate data extraction: our extracted probability values matched their reported distributions; strength differentials aligned with their experimental tables; and our count of 52 scenarios with < 50% net benefit probability matches their cases under system expansion allocation. This verification confirms our visualization accurately represents the source data.

2.4. Summary and implications

The evidence presented in Section 2 reveals a critical disconnect between carbonation's theoretical promise and practical reality. While natural carbonation remains chemically favorable, it is fundamentally constrained by diffusion kinetics, exposure conditions, and methodological boundary choices. These constraints converge to make the realized climate benefit slow, partial, and highly uncertain—characteristics that challenge its role in near-term decarbonization strategies.

Our systematic re-evaluation of published datasets demonstrates this through three interconnected findings, each drawing on established peer-reviewed evidence reinterpreted under consistent analytical frameworks. The sector's sponge effect exhibits strong temporal asymmetry, with emissions peaking early while CO₂ uptake grows slowly, maintaining a net positive carbon balance throughout the century (Fig. 1(a)). This temporal imbalance becomes even more pronounced when examining actual carbon flows: life-cycle flux tracing confirms that large, near-instantaneous production pulses are only partially countered by decades-delayed absorption (Fig. 1(b)). When this timing dimension is properly incorporated into climate assessments, apparent benefits shrink substantially. Time-adjusted warming methods reveal that treating emissions and absorption flows with explicit timestamps rather than as concurrent totals reduces claimed benefits by 30%–60%, a finding corroborated by empirically slow uptake rates during both service life and post-demolition handling. Perhaps most concerning, our re-visualization of 99 carbonation-enabled concrete scenarios from published studies indicates severely limited robustness: more than half demonstrate less than 50% probability of delivering net emission reductions, with many exhibiting compressive-strength penalties that trigger additional binder use, thereby eroding nominal carbon gains (Figs. 1(c) and (d)). These performance variations trace systematically to process route choices (mixing versus curing), binder system composition (OPC versus OPC + SCM), and allocation methodologies for SCMs.

Methodological transparency requires clarification of our analytical approach. The analysis in Section 2 represents comprehensive synthesis of published datasets under consistent presentation frameworks, not original simulation work. We systematically extracted data from source publications, re-visualized outcomes in comparative formats, and verified that our extracted values accurately match the original reported magnitudes, probability distributions, and directional trends. This synthesis approach reveals cross-study patterns invisible when research remains siloed—a core function of perspective scholarship.

These findings carry significant implications for both policy and practice. Carbonation should be treated as conditional and time-explicit in climate accounting, rather than serving as an immediate counterweight to kiln emissions. For meaningful near-term decarbonization, priority must shift toward measures with auditable, present-day impact—including clinker factor reduction through SCM integration, process efficiency improvements, and design optimization for structural durability. Any credited carbonation must satisfy strict criteria: verifiable boundary transparency, explicit temporal accounting, and prohibition of cross-period offsetting that masks immediate emissions with uncertain future absorption. Building on these foundational insights, Section 3 translates these findings into actionable standards, procurement criteria, and policy guardrails that can guide both industry practice and regulatory frameworks.

3. Beyond carbonation myths: Proven pathways for immediate and scalable decarbonization

The analysis in Section 2 exposes carbonation's fundamental limitations as a near-term climate solution. The cement carbonation paradox reveals a fundamental dysfunction in climate governance logic—while cement possesses some reabsorption capacity, it only absorbs a portion of its own emissions with decades of lag time behind concentrated initial manufacturing emissions. These temporal mismatches, methodological biases, and performance uncertainties documented in our re-analysis of 99 experimental scenarios demonstrate that carbonation-dependent strategies cannot deliver the immediate, robust emission reductions required for climate targets.

Rather than continuing to rely on uncertain future absorption processes, evidence demonstrates that immediate, scalable decarbonization requires systematic intervention across manufacturing processes, material substitution, structural optimization, and policy recalibration. This section shifts focus from carbonation's limitations to proven alternatives that deliver measurable emission reductions without the temporal uncertainties and methodological limitations inherent in carbonation-dependent strategies. By examining these established pathways, we demonstrate that the cement industry's decarbonization challenge is both urgent and solvable—but only through abandoning carbonation myths in favor of technologies and strategies with demonstrated, immediate impact.

3.1. Sequestration versus temporal displacement

The temporal limitations identified in Section 2 highlight a fundamental challenge: carbonation's slow kinetics and uncertain outcomes cannot meet the urgent timeline requirements for climate action. While cement possesses some reabsorption capacity at the lifecycle level, it only absorbs a portion of its own emissions, with absorption behavior lagging decades behind concentrated initial manufacturing emissions. This temporal mismatch necessitates exploring alternative decarbonization pathways that can deliver immediate, measurable results.

Established decarbonization strategies demonstrate substantially different temporal profiles and certainty levels compared to carbonation approaches. Olsson et al.'s research [25] reveals that concrete industry decarbonization pathways exhibit distinct hierarchical characteristics. Dynamic modeling analysis of global cement emissions from 2015 to 2100 demonstrates that under comprehensive scenarios, up to 76% emission reduction potential could theoretically be achieved through coordinated advancement across four key dimensions: manufacturing process improvement, concrete mix optimization, structural design optimization, and service life extension. These pathways offer the critical advantage of immediate implementation without relying on uncertain long-term natural processes.

From a technology contribution perspective, manufacturing-level emission reduction space remains relatively limited. Even with optimal kiln efficiency, comprehensive low-carbon fuel adoption, kiln electrification, and complete power system decarbonization, total emission reductions amount to only about 20%. This reflects inherent constraints of limestone calcination reactions—CO₂ emissions from this chemical process remain fundamentally unavoidable regardless of optimization efforts.

In contrast, increasing SCMs like fly ash and slag can achieve 11%–34% emission reductions under different scenarios. The core mechanism involves reducing high-emission clinker usage rather than relying on end-of-pipe carbon capture technologies, representing a more direct and reliable approach.

More significant potential lies in structural design optimization. Research comparing American ACI-318, European Eurocode 2, and Indian IS 456:2000 design standards under identical reliability indices found that structural design choices can create 46%–93% emission differences. Since steel reinforcement carries much higher unit volume carbon footprints than concrete, optimizing reinforcement ratios and concrete strength combinations can achieve approximately 18.5% emission reductions without compromising structural safety.

Optimal strategies vary by structural type: column structures benefit from low reinforcement ratios combined with high-strength concrete, while slab structures prove more carbon-efficient with high reinforcement ratios and low-strength concrete. This finding overturns traditional single-parameter optimization approaches.

The most transformative potential emerges from extending service life, delivering up to 47.1% emission reduction effects (cumulative 175.7 Gt CO₂-eq from 2015 to 2100). In coastal chloride intrusion scenarios, increasing SCM usage ratios to 50% can extend building structure lifespans by 3 times and infrastructure lifespans by 4 times, significantly reducing future demand for new cement construction.

Under low population growth scenarios (Fig. 2(a)) [25–27], this integrated strategy can compress 2100 annual emissions from baseline levels of about 3.8 Gt CO₂-eq to less than 1 Gt, achieving nearly 75% total emission reduction—a performance far superior to carbonation-dependent pathways.

Compared to highly uncertain carbonation processes, achieving cement industry decarbonization through SCMs provides a more definitive, reliable emission reduction pathway. Shah et al.'s research [26] demonstrates that industrial byproduct slag and fly ash SCMs could theoretically replace 50% of global cement usage, avoiding up to 1.3 Gt CO₂ emissions in 2018—equivalent to 44% of cement production emissions, or about 2.8% of global anthropogenic CO₂ emissions.

Our analysis reveals strong positive correlations between clinker ratios and unit CO₂ emission intensity (Fig. 2(b)). High clinker ratio countries such as China, Japan, and Republic of Korea show unit cementitious material emissions at global upper levels, while countries with lower clinker ratios such as Brazil, India, and the

United Kingdom still demonstrate potential for absolute emission reductions through increased SCM replacement rates. This analysis validates linear relationships where every 10% reduction in clinker ratios corresponds to approximately 10.6% reductions in CO₂ emission intensity, providing quantitative support for SCM strategy effectiveness.

From supply–demand perspectives, most major cement-producing countries can generate sufficient secondary cementitious materials locally to replace up to 50% of domestic Portland cement clinker demand. Developed countries such as the United States, Germany, and Republic of Korea have industrial byproduct generation exceeding domestic cement production, while rapidly developing countries such as China, the Philippines, and Egypt can achieve higher replacement ratios through international trade despite relatively limited local resources.

Country-specific emission reduction potential shows pronounced differentiation. Brazil can reduce 84.8% of cement production carbon emissions by maximizing SCM utilization, equivalent to reducing national total emissions by 2.9%. Türkiye, Republic of Korea, and China's potential contributions reach 5.5%, 5.4%, and 4.4% respectively, demonstrating the cement industry's crucial role in national carbon reduction efforts. Even supply–demand imbalanced countries like China can theoretically avoid 548 Mt CO₂ equivalent emissions due to enormous production scales—equivalent to South Africa's entire 2018 national emissions.

While SCM replacement and carbonation serve different functions in cement chemistry, their comparative assessment reveals important differences in implementation certainty and temporal characteristics. SCM replacement strategies offer several practical advantages in addressing climate urgency. First, emission reduction effects occur at production stages with immediacy, without waiting for long-term physicochemical processes. Second, adjusting SCM types and contents enables precise emission control, achieving quantified targets with established engineering parameters. From a risk management perspective, secondary cementitious materials have demonstrated technical maturity through decades of engineering validation, whereas carbonation benefits remain subject to the temporal and methodological uncertainties documented in Section 2.

However, the broader landscape of cement decarbonization technologies reveals varying levels of effectiveness and complexity. By contrast, pathways such as CombOxy-Efuel (with or without H₂) suffer from cumulative conversion losses: oxy-fuel operation increases auxiliary loads, CO₂ capture and compression require substantial energy, and synthetic fuel production adds further penalties. Unless all these steps are powered by very low-carbon electricity, the net balance becomes unfavorable, explaining why these scenarios show negative abatement in Fig. 2(c). This spectrum of performance outcomes—from the proven effectiveness of SCM replacement to the energy penalties of complex fuel conversion pathways—illustrates the importance of systematic technology assessment in decarbonization planning.

The optimal approach likely involves strategic deployment of multiple pathways, with SCM replacement addressing immediate emission reduction needs, proven CCS technologies providing substantial near-term abatement, while carbonation research continues to explore its potential role in long-term carbon management alongside careful evaluation of emerging technologies to avoid energy-intensive solutions that may worsen rather than improve net emissions.

3.2. Alternative pathways and policy recalibration

The temporal limitations documented in Section 2 raise important questions about current policy frameworks that incorporate carbonation as a key decarbonization pathway. Current industry

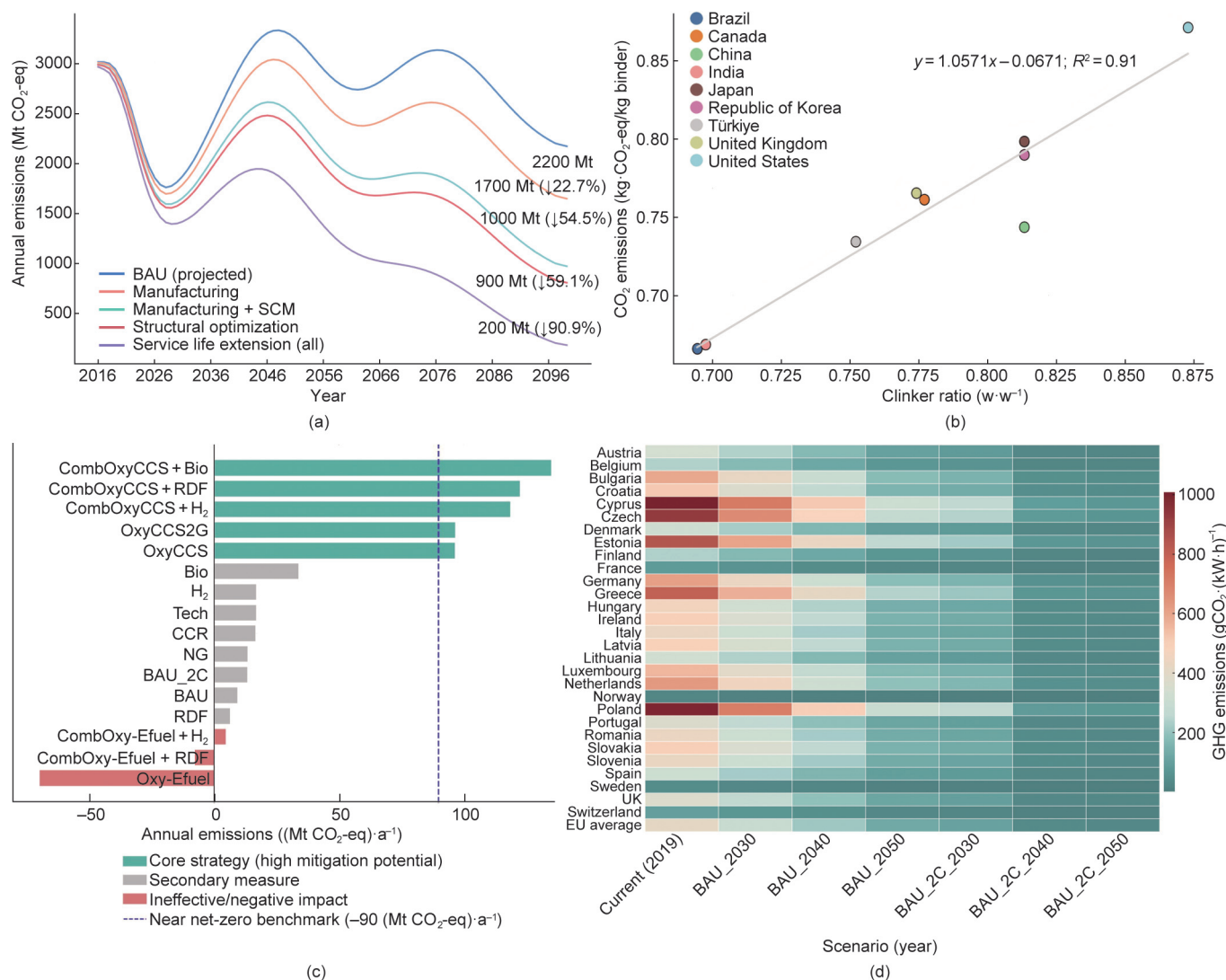


Fig. 2. Cement decarbonization levers from pathway modeling to country signals. (a) Emission trajectories for BAU, manufacturing, manufacturing + SCM, structural optimization, and service-life extension (all). Data source: Ref. [25]. (b) Clinker ratio vs cradle-to-gate CO₂ intensity across nine producers (2018). Data source: Ref. [26]. (c) Mitigation effectiveness of 15 strategies; only CCS-based combinations reach net-zero/negative. Data source: Ref. [27]. (d) European heatmap of reduction trajectories by scenario. Data source: Ref. [27]. The definitions of the acronyms in the figure can be found in Ref. [27].

roadmaps (including Global Cement and Concrete Association (GCCA), International Energy Agency (IEA)) list carbonation as natural carbon removal measures when predicting future emission reduction pathways. However, strategies that inadequately account for lifecycle temporal variables risk creating misleading neutrality [28], potentially reducing investment incentives for pathways with more immediate and certain benefits such as CCS, alternative feedstocks, and electrified kilns. This tendency to incorporate carbonation as a readily available natural carbon sink may inadvertently delay implementation of urgent emission reduction measures that operate on policy-relevant timescales.

The scale of this timing challenge becomes apparent when examining current emission levels against carbonation potential. Cavalett et al.'s systematic assessment [27] of 15 European cement industry pathways reveals this paradox's stark reality: current European clinker production emits 832–1075 kg CO₂-eq·ton⁻¹, with weighted averages of (926 ± 33) kg CO₂-eq·ton⁻¹, totaling approximately 124 MtCO₂-eq·a⁻¹. Against this backdrop of substantial annual emissions, even optimistic carbonation estimates show annual absorption far insufficient to offset continuous production emissions. Studies demonstrate that utilizing demolition

waste for forced carbonation achieves maximum CO₂ capture of only 123–225 kg CO₂·(ton cement)⁻¹ paste, corresponding to merely 0.6%–4.1% absorption per ton aggregate [29].

These quantitative comparisons highlight the scale mismatch between current emissions and carbonation potential. Even under optimistic deployment scenarios—implementing technology modernization, alternative fuel usage rising from 47% to 90%, and CCS deployment reaching 25%—only about 50% emission reduction targets can be achieved by 2050 ((64 ± 1.7) MtCO₂-eq·a⁻¹ reductions) [27]. This analysis suggests that policies treating carbonation as a primary emission reduction pathway may need recalibration to account for temporal and scale constraints.

Alternative decarbonization strategies demonstrate markedly different performance profiles and implementation timelines. As shown in Fig. 2(c), significant differences exist among emission reduction strategies, forming stark contrasts with carbonation's slow processes. CCS technology, as first-tier measures, can achieve approximately 96.7–96.8 MtCO₂-eq·a⁻¹ reductions, equivalent to about 80% emission cuts. Biomass fuel replacement achieves 34.0 MtCO₂-eq·a⁻¹ reductions (28% ± 3%), while technology modernization contributes 17.0 MtCO₂-eq·a⁻¹ (14% ± 5%).

In comparison, conventional alternatives show limited effectiveness: refuse-derived fuels (RDF) achieves only 6.5 MtCO₂-eq.a⁻¹ reductions (5% ± 4%), natural gas replacement 13.5 MtCO₂-eq.a⁻¹ (11% ± 3%), and hydrogen fuel 17.0 MtCO₂-eq.a⁻¹ (14% ± 3%). Importantly, these technologies provide immediate, measurable effects that can be validated independently of long-term natural process uncertainties.

However, the analysis also reveals that technological solutions face their own constraints and trade-offs. Fig. 2(c) reveals a subversive finding: Oxy-Efuel strategies not only fail to achieve net emission reductions but actually produce -70.3 MtCO₂-eq.a⁻¹ negative benefits. Even combined with alternative fuels, CombOxy-Efuel + RDF shows -8.0 MtCO₂-eq.a⁻¹ net negative benefits, with only CombOxy-Efuel + H₂ barely achieving 4.7 MtCO₂-eq.a⁻¹ weak positive benefits. This demonstrates that all decarbonization pathways require careful system-level analysis to avoid unintended consequences.

Regional variation adds another layer of complexity to policy design. Fig. 2(d) shows the carbonation paradox exhibits significant imbalanced effects across countries, undermining its credibility as a global strategy. Estonia, Lithuania, and Bulgaria show highest clinker production carbon intensities (approaching 1000 kg CO₂-eq.ton⁻¹) due to energy-intensive technologies and fossil fuel-dependent power structures. Even with massive infrastructure development, these countries' slow carbonation rates cannot offset continuous large emissions from high-intensity production. Conversely, cleaner producers like Norway (832 ± 29 kg CO₂-eq.ton⁻¹), Sweden, and France have limited cement consumption, making carbonation's absolute contributions equally insignificant.

This 243 kg CO₂-eq.ton⁻¹ variation suggests that effective decarbonization strategies must account for regional differences in technology, energy systems, and industrial structure rather than relying on uniform approaches.

4. Discussion: Toward time-symmetric climate governance

Our re-analysis of carbonation's temporal dynamics and performance uncertainty reveals important implications for cement industry decarbonization strategies. The evidence demonstrates that while carbonation remains a legitimate chemical process, its practical contribution to near-term climate targets faces significant constraints that warrant careful policy consideration.

4.1. Synthesis of key findings

The convergence of temporal, methodological, and performance limitations presents a complex picture for carbonation's role in decarbonization pathways. Time-adjusted climate assessments indicate that slow carbonation kinetics reduce claimed benefits by 30%–60% compared to conventional GWP calculations, with most absorption occurring decades after initial emissions. Concurrently, our re-visualization of published experimental data shows that more than half of carbonation-enabled concrete scenarios demonstrate less than 50% probability of achieving net emission reductions, with compressive strength penalties often requiring additional binder use that erodes nominal carbon gains.

These findings suggest that carbonation's contribution to cement industry decarbonization may be more conditional and limited than current policy frameworks assume. The temporal mismatch between immediate emissions and delayed absorption creates accounting challenges for climate targets operating on specific timelines, while performance variability across different process routes and binder systems indicates that carbonation benefits cannot be uniformly applied across all cement applications.

4.2. Policy implications and recommendations

Given these limitations, cement industry decarbonization policy may benefit from recalibration that acknowledges both carbonation's potential and its constraints. Rather than wholesale policy redesign, targeted adjustments could better align carbonation accounting with its actual performance characteristics while strengthening support for alternatives with more immediate and certain benefits.

Enhanced temporal accounting for carbonation claims. Current life-cycle assessment frameworks could incorporate explicit temporal weighting that reflects the timing of emissions versus absorption. This might involve requiring carbonation benefits to be discounted based on absorption timing, similar to financial discount rates, ensuring that claimed benefits reflect their actual contribution to near-term climate targets. Such adjustments would not eliminate carbonation from climate accounting but would ensure its contributions are appropriately weighted against immediate emission reduction needs [30].

Strengthened verification requirements for carbonation projects. Given the performance variability documented in our analysis, carbonation-dependent projects could benefit from enhanced monitoring and verification protocols. This could include mandatory long-term monitoring of actual CO₂ absorption rates, standardized testing protocols for compressive strength impacts, and transparent reporting of boundary conditions that affect carbonation performance. These measures would improve the reliability of carbonation claims while identifying applications where benefits are most robust.

Accelerated deployment of proven alternatives. The analysis demonstrates that SCMs, process efficiency improvements, and structural optimization offer more immediate and predictable emission reductions. Policy frameworks could prioritize these pathways through targeted incentives, streamlined permitting for SCM integration, and research funding focused on scaling proven technologies. This approach complements rather than replaces carbonation research while ensuring near-term progress toward climate targets.

Industry-specific implementation considerations. The cement industry's technical complexity requires nuanced policy approaches that account for regional variations in feedstock availability, energy systems, and demand patterns. Effective decarbonization policies must balance uniform climate objectives with local technical and economic constraints, recognizing that optimal strategies may vary significantly across different markets and applications.

4.3. Research priorities and future directions

This analysis highlights several areas where additional research could strengthen carbonation's contribution to cement decarbonization. Improved understanding of carbonation kinetics under realistic exposure conditions could help identify applications where benefits are most reliable. Similarly, development of accelerated carbonation techniques that can achieve meaningful CO₂ absorption within policy-relevant timescales could address temporal constraints while maintaining the process's fundamental appeal.

Broader integration of carbonation with other decarbonization strategies represents another promising research direction. Rather than viewing carbonation as a standalone solution, future work could explore how it complements other approaches within comprehensive decarbonization strategies that leverage the strengths of multiple pathways while mitigating individual limitations.

Critical gaps remain in understanding the practical implementation constraints of alternative decarbonization pathways,

particularly SCMs. While our analysis demonstrates SCM replacement as a more immediate emission reduction strategy compared to carbonation, the practical deployment of SCMs faces significant regional and technical challenges that require systematic investigation. SCM availability and quality vary substantially across different industrial contexts. High-quality fly ash depends on coal-fired power generation, while slag availability correlates with steel production—both sectors undergoing their own decarbonization transitions that may reduce SCM supply. Research should therefore address SCM quality standardization protocols, alternative pozzolan development from local geological resources, and optimization of regional SCM logistics networks. Understanding how variations in SCM type, fineness, chemical composition, and reactivity affect both immediate emission reductions and long-term performance represents a critical knowledge gap that could inform more robust and resilient deployment strategies across diverse market conditions.

The findings also underscore the importance of developing accounting frameworks that can accommodate the temporal complexity of industrial decarbonization. As industries increasingly rely on processes that operate over different timescales, climate policy will need sophisticated tools for evaluating and comparing interventions with varying temporal profiles and uncertainty characteristics.

5. Conclusions: Breaking the carbonation orthodoxy

This perspective challenges three prevailing assumptions that have shaped cement industry climate policy over the past two decades, revealing systematic patterns invisible when research remains fragmented.

First broken assumption. Carbonation reliably offsets 50% of cement emissions. Industry roadmaps (GCCA, IEA) and national greenhouse gas inventories increasingly credit carbonation as a dependable carbon sink based on lifetime uptake estimates. Our cross-study synthesis exposes this as an accounting artifact. By integrating sector-scale temporal projections [15], time-adjusted climate metrics [16], and comprehensive performance distributions [17], we demonstrate that this 50% offset conflates three distinct timescales: immediate manufacturing emissions (complete within year one), decades-delayed service-life absorption ($0.05 \text{ kg CO}_2 \cdot (\text{kg cement})^{-1}$ over 64 years), and uncertain end-of-life uptake contingent on energy-intensive processing. When temporal asymmetry is properly incorporated through TAWP methods, claimed benefits shrink by 30%–60%—a magnitude sufficient to misguide multi-billion-dollar investment decisions. The sector's net positive carbon balance of $2.0\text{--}3.2 \text{ Gt CO}_2 \cdot \text{a}^{-1}$ persists through 2100 even under optimistic carbonation scenarios, fundamentally contradicting the vast carbon reservoir narrative.

Second broken assumption. CCU concrete technologies uniformly deliver climate benefits. Policy incentives worldwide promote carbon capture and utilization in concrete as emission reduction measures, supported by selective reporting of high-performing laboratory cases. Our systematic reanalysis of 99 experimental scenarios reveals a starkly different reality: 52% exhibit less than 50% probability of achieving net emission reductions, with many scenarios yielding 80%–90% probability of increasing lifecycle emissions. This performance uncertainty traces systematically to compressive strength penalties (31 scenarios show $\Delta \text{strength} < 0$, some reaching -10 MPa) that trigger compensatory clinker additions, eroding nominal sequestration gains. Crucially, this failure mode remains largely invisible in current policy frameworks because: ① LCA studies report mean values rather than probability distributions, masking high failure rates; ② boundary choices often exclude energy penalties from CO_2 curing (up to $38.8 \text{ kW} \cdot \text{m}^{-3}$) and post-demolition processing; and ③ allocation

methodologies for SCM co-products create 15%–30% swings in computed net benefits without changing physical reality. The policy implication is stark: technologies promoted under current frameworks lack the robustness needed for climate compliance at scale.

Third broken assumption. All decarbonization pathways deserve equal policy support. The temporal urgency of climate targets (50% reduction by 2030, net-zero by 2050) demands prioritization, yet current frameworks treat carbonation, SCMs, CCS, and emerging technologies as parallel options. Our comparative pathway analysis establishes a clear hierarchy. SCMs deliver 11%–34% immediate emission reductions through direct clinker substitution, with established supply chains and decades of engineering validation. Structural design optimization achieves 18.5% reductions through reinforcement-strength optimization without material substitution. Service life extension—enabled by 50% SCM ratios in chloride environments—delivers 47.1% reduction potential by cutting future construction demand. Combined, these proven pathways achieve 75% total reduction by 2100, far exceeding carbonation-dependent scenarios. In contrast, carbonation contributes only 0.6%–4.1% absorption per ton aggregate even under forced demolition conditions [29], while complex pathways like CombOxy-Efuel show negative net abatement ($-70.3 \text{ MtCO}_2 \cdot \text{eq} \cdot \text{a}^{-1}$ in European analysis [27]) due to compounded energy penalties. The evidence base for prioritization is unambiguous.

The unique contribution of this perspective lies not in generating new experimental data, but in cross-study pattern recognition that exposes systematic failures in current climate accounting orthodoxy. Individual studies report carbonation uptake rates, CCU concrete performance, or alternative pathway effectiveness—each valuable but insufficient for policy design. By synthesizing sector projections, lifecycle timing analyses, and comprehensive performance databases under consistent boundaries, we reveal three interconnected failures: ① temporal accounting that treats decades-delayed absorption as equivalent to immediate emission avoidance, inflating climate value by 30%–60%; ② selective result reporting that obscures 52% failure rates in CCU technologies, creating false confidence in unproven approaches; and ③ policy frameworks that allocate resources to slow, uncertain processes while proven alternatives (SCMs, structural optimization, service life extension) remain underutilized despite delivering 75% reduction potential. This synthesis function—identifying patterns invisible in isolated studies—constitutes the core scholarly contribution of this paper.

These findings demand fundamental recalibration of cement climate governance along three dimensions. First, temporal symmetry in accounting: carbonation credits must be discounted based on absorption timing, with explicit prohibition of cross-period offsetting that masks immediate emissions with uncertain future uptake. Second, performance-based verification: CCU projects must demonstrate net emission reductions through probability-weighted lifecycle assessment, with mandatory reporting of compressive strength impacts and energy overheads currently excluded from boundaries. Third, evidence-based prioritization: policy incentives should scale with demonstrated reliability and immediacy—prioritizing SCM deployment (11%–34% immediate reductions, established supply chains) and structural optimization (18.5% reductions, no material substitution) over carbonation (0.6%–4.1% uncertain uptake, decades-delayed) and energy-intensive conversions (negative net benefits under realistic power mixes). The optimal pathway combines immediate clinker reduction through SCMs, proven CCS for residual process emissions, and structural design optimization—relegating carbonation to a conditional, long-term role subject to strict verification protocols.

The carbonation trap is ultimately a governance failure, not a chemical one. Carbonation reactions remain thermodynamically favorable; the problem lies in policy frameworks that credit future, uncertain absorption against present, certain emissions without temporal discounting, accept laboratory performance claims without field-scale verification, and allocate scarce resources to slow processes while immediate alternatives languish. Breaking this orthodoxy requires recognizing that climate targets operate on policy-relevant timescales (2030, 2050) where temporal asymmetry matters profoundly, that performance uncertainty demands probability-weighted assessment rather than selective mean reporting, and that decarbonization prioritization must follow evidence hierarchies rather than treating all pathways as equivalent. The cement industry's decarbonization is achievable through proven pathways—but only if policy recalibration occurs before temporal misalignment and false confidence in unverified technologies lock in another decade of inadequate progress.

CRedit authorship contribution statement

Haoxuan Yu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration. **Jilong Pan:** Writing – original draft, Validation. **Izni Zahidi:** Writing – review & editing, Validation, Supervision. **Chow Ming Fai:** Writing – review & editing, Validation, Supervision. **Dongfang Liang:** Writing – review & editing, Writing – original draft, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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