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Salwan F. ALTURKI[1]

TOWARDS GREEN TRANSPORTATION: AN EVALUATION OF STRATEGIES FOR CARBON EMISSIONS MITIGATION IN CEMENT-BASED TRANSPORTATION INFRASTRUCTURE

Summary. The cement industry plays an essential role in the development of transportation and logistics infrastructure, yet it continues to be classified as a major industrial source of global carbon dioxide (CO_2) emissions. The cement production process emits nearly 8% of the total anthropogenic emissions, positioning it as the second-highest industrial source of CO_2 emissions behind power generation. As sustainable transportation systems increasingly become a global priority, the decarbonization of cement-based infrastructure has emerged as an urgent challenge. The primary goal of the current study is to offer a comprehensive evaluation of key CO_2 mitigation strategies applicable to cement production, including the adoption of alternative fuels, reducing the ratio of clinker through supplementary cementitious materials, energy efficiency optimization, and carbon capture and storage technologies. This assessment offers a structured and multidimensional comparative assessment of these strategies in the cement industry. Using real-world cost and performance data for a standard 1-Mt/yr European cement plant, the analysis quantifies capital expenditure, levelized cost of abatement (€/t CO_2), CO_2 savings (kt CO_2/yr), and payback periods for each technology. The outcomes reveal that while operational improvements (e.g., alternative fuels use, supplementary cementitious materials) offer low-cost, short-payback solutions with moderate emission reductions, deep decarbonization requires carbon capture and electrification technologies, which remain cost-intensive and technically demanding. A marginal abatement cost curve and additional visual tools are developed to assist industry stakeholders in identifying optimal pathways. A sensitivity analysis on carbon price, discount rate, and electricity cost is conducted, and their effects on the levelized cost of abatement and the net economic benefit across the valuated technologies are quantified to examine the influence of policy and financing conditions. Based on these findings, a strategic roadmap is proposed that sequences near, mid, and long-term interventions. This work aims to support informed decision-making by plant managers, researchers, and policymakers striving toward net-zero goals in transport-related cement applications.

1. INTRODUCTION

Concrete is widely utilized in the construction and structural integration of transportation infrastructure and its associated connection systems [1]. The durability and resilience of concrete make it ideal for constructing complex transportation structures such as long-lasting roads and bridges. In many countries and regions, concrete is commonly used for road pavements. Given the variable climate in North America and the hot, humid weather in parts of Asia, Portland cement concrete is a primary material used for urban road pavements because of its exceptional durability in resisting rutting caused by heavy traffic loads and volumes, thus extending the service life of pavement.

[1] Budapest University of Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Department of Aeronautics and Naval Architecture; Műegyetem rkp. 3, H-1111 Budapest, Hungary; e-mail: alturki.salwan@edu.bme.hu; orcid.org/0000-0002-8104-8780

Concrete is a composite material that mainly comprises cement, aggregate, water, and additional admixtures that modify the chemical and physical characteristics of the mixture, forming a composite material that solidifies over time [2]. According to a report by the National Concrete Pavement Technology Center, approximately 30% of global cement consumption is dedicated to transportation infrastructure projects [3]. Global cement production reached an estimated 4.1 billion metric tonnes in 2022, with projections indicating a rise to 6.2 billion metric tonnes by 2050 [4]. This growth is primarily due to the rising demand for affordable housing and infrastructure investments, especially in emerging markets [2]. However, projected production growth is likely to complicate CO_2 mitigation unless appropriate measures are implemented to reduce emission intensity.

2. ENVIRONMENTAL IMPACT OF CEMENT PRODUCTION

The cement production sector is estimated to account for 7-8% of all anthropogenic greenhouse gas emissions; therefore, it represents a major emission source within the industrial sector [5]. The most prevalent greenhouse gas associated with cement manufacturing is CO_2 [2]. In fact, cement production is among the largest CO_2-emitting industries, as the production of cement generates no less than 2.1 billion tonnes of CO_2 per year [4]. Fig. 1 illustrates the CO_2 output associated with worldwide cement production spanning from 1990 to 2020, along with the projected emissions for the subsequent years.

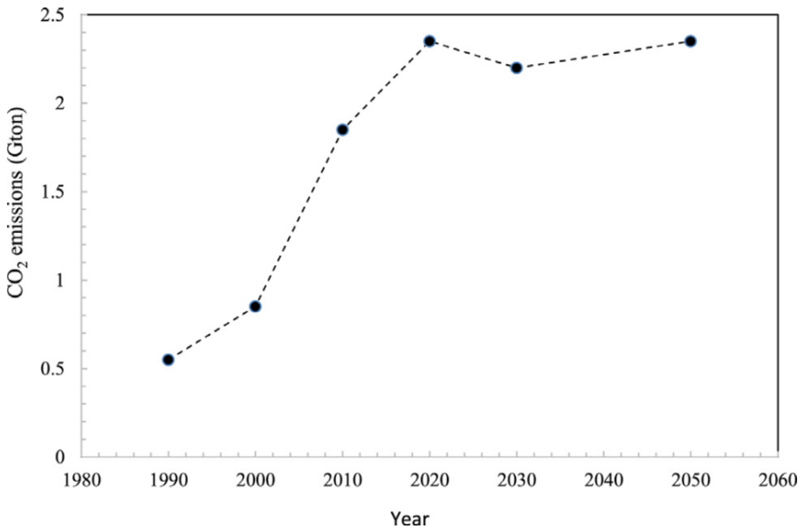

Fig. 1. Trend of the worldwide CO_2 emissions from the cement industry [5]

A comprehensive understanding of emissions and the environmental impacts associated with cement production is crucial for developing effective mitigation technologies. According to [4], throughout the cement production process, CO_2 is released from various sources:

- 50% of CO_2 emissions originate from the thermal decomposition of limestone ($CaCO_3$) into calcium oxide (CaO) and carbon dioxide (CO_2).
- 40% originates from the combination of fossil fuels to generate thermal energy.
- The remaining 10% of CO_2 emissions are attributable to transportation and electricity consumption.

By 2050, the global production of cement is projected to increase by 12 to 23% [4]. On the other hand, CO_2 emissions must be substantially decreased by 24% relative to current levels by 2050 to meet the UN’s 2-degree scenario (2DS). The European Union has also set a target to achieve climate neutrality by the year 2050. This raises a challenge for the cement sector to fulfill production requirements while reducing environmental consequences.

3. METHODS AND SYSTEM BOUNDARY

The system boundary adopted in this study is gate-to-gate, encompassing on-site CO_2 emissions from fossil-fuel combustion and limestone calcination, as well as the associated capital expenditure (CAPEX) and operating expenditure (OPEX) for each mitigation technology. This procedure is in accordance with ISO 14040/44 and the Cement CO_2 and Energy Protocol [6,7]. The choice of this boundary enables high-resolution, operational-level comparisons of decarbonization strategies. The study excludes upstream and downstream emissions, such as raw material extraction, supplementary cementitious materials (SCMs) processing, fuel logistics, and carbon capture and storage (CCS) infrastructure, due to their high variability across regions, supply chains, and energy mixes, which can distort comparative results without harmonized, location-specific datasets [8]. Since calcination and on-site fuel combustion account for approximately 90% of plant-level CO_2 emissions [4], this approach enables a consistent and policy-relevant comparison of mitigation options using marginal abatement cost (MACC), levelized cost of CO_2 abatement (LCOA), and payback period metrics. All cost and performance inputs were normalized to a standardized reference case to ensure a rigorous and equitable techno-economic comparison across decarbonization strategies. This reference scenario represents a typical European cement plant with an annual clinker production capacity of 1 million tonnes per year (1 Mt/yr), operating under a carbon pricing regime of €65 for a tonne of CO_2 and a financial discount rate of 7%.

CAPEX and OPEX data were systematically sourced from peer-reviewed literature and industrial reports published between 2020 and 2025. For each mitigation strategy, the original measurement conditions, including plant size, geographical setting, energy sources, and CO_2 abatement efficiency, were carefully reviewed to ensure consistency with the defined system boundary.

The capital cost estimation for each strategy component was conducted using two complementary approaches. For commercially available systems or materials (e.g., MEA-based CCS units, biomass conversion retrofits), cost data were derived from published techno-economic studies, vendor quotations, and standardized literature reviews. Where capital costs were only available for different-scale applications, cost normalization was applied using the standard six-tenths rule, capacity-scaling law:

$$\mathrm{Cost}_2 = \mathrm{Cost}_1 \left(\frac{\mathrm{Size}_2}{\mathrm{Size}_1}\right)^n . \quad (1)$$

Here, $Cost_1$ and $Cost_2$ are the costs associated with capacities $Size_1$ and $Size_2$, respectively, and n is the scaling exponent (typically 0.55-0.75), which accounts for partial economies of scale across process technologies. In addition, an allowance is included for installation costs, representing site-specific implementation overheads. While every effort was made to validate reported capital costs through triangulation with multiple sources, the estimated uncertainty margin for capital cost data is approximately 25-30%.

The chosen discount rate of 7% reflects a standard midpoint assumption commonly adopted in industrial techno-economic assessments for long-lived infrastructure in Europe. It balances project-level financing risks with public-sector expectations and is consistent with values reported in the literature for cement sector evaluations. The carbon price of €65/t CO_2 represents the average market value within the EU Emissions Trading System (EU ETS) observed in 2024. This value was selected to reflect actual compliance costs encountered by European cement producers and to align the analysis with near-term regulatory and market conditions. All financial figures were converted to 2025 euros (€2025) using standardized inflation indices and exchange rates to maintain consistency across time and geography.

This harmonized methodology enables a transparent cross-comparison of all major and emerging mitigation strategies within a consistent techno-economic framework, offering practical insight for industry stakeholders and policymakers navigating the decarbonization of cement-based infrastructure.

4. MITIGATION STRATEGIES OF CARBON EMISSIONS

The main goal in the cement industry is to identify methods to satisfy rising demand while minimizing the carbon footprint of manufactured cement. Technological approaches, including carbon capture and storage, replacing traditional materials, integrating alternative fuels, and enhancing energy efficiency, are widely recognized as effective strategies for enhancing the sustainability of cement production. A detailed economic-technical investigation was conducted in the present research to evaluate the most dominant methodologies for reducing CO_2 emissions during cement production.

4.1. Carbon Capture and Storage (CCS)

CCS represents a promising method for reducing greenhouse gas emissions in the cement sector. The cement production process involves burning fossil fuels and limestone calcination, resulting in significant CO_2 emissions. Therefore, carbon capture technologies are particularly crucial because a substantial portion of cement emissions is process-related and cannot be mitigated through energy efficiency or fuel switching alone. Post-combustion monoethanolamine (MEA) capture, oxyfuel combustion, indirect calcination (LEILAC), and calcium looping (CaL) are considered the most effective carbon capture technologies. These technologies can reduce CO_2 emissions by capturing about 90% carbon from flue gases [9]. Table 1 summarizes key parameters of each CCS technology in the cement industry.

Table 1

Key parameters of the CCS technologies in the cement industry

Technology	CAPEX (€M)	OPEX (%CAPEX/yr)	Payback (Years)	CO_2 Savings (kt CO_2/yr)	CO_2 Reduction	Levelized Cost (€/t CO_2)	References
Post-Combustion (MEA)	95-130	6-12	12-18	750-900	85-95%	95-150	[9-11]
Oxyfuel Combustion	35-55	5-12	4-9	850-1000	90-95%	35-45	[11,12]
Indirect Calcination (LEILAC)	25-45	3-6	4-7	550-700	60-70%	30-45	[13,14]
Calcium Looping (CaL)	120-180	8-12	12-25	850-950	90-98%	50-70	[11,15]

Notes: Data are for a 1-Mt/yr cement plant in Europe. Percent reductions refer to a comparison with a fossil-fuel baseline. Levelized costs (LCOA) exclude transport/storage. Payback periods assume a CO_2 price of €65/t CO_2 and a 7% real discount rate.

4.2. Alternative Fuels (AFs)

At present, one of the major global challenges is determining how to minimize energy consumption from fossil fuels, given their negative economic, social, and environmental consequences. The primary energy source used in traditional kilns is fossil fuels, like coal, petroleum coke, and natural gas [4]. The reliance on fossil fuels is a primary source of on-site CO_2 emissions. The environmental challenges associated with fossil fuels support the potential deployment of low-carbon AFs in the cement sector. The dominant alternative fuels commonly utilized in cement manufacturing include refuse-derived fuel (RDF), biomass (such as wood, biogas) and tire-derived fuel (TDF).

Economically, the system installation cost of AF depends on several factors, including the type of AF, required modifications to existing infrastructure, and the economic benefits from reduced fuel costs and emissions. The transition from conventional fossil fuels to AFs requires careful consideration of both the initial investment and the long-term operational savings. Table 2 summarizes key parameters of AFs in the cement industry.

Table 2

Key parameters of AFs in the cement industry

Technology	CAPEX (€M)	OPEX (€/t Fuel)	Payback (Years)	CO_2 Savings (kt CO_2/yr)	CO_2 Reduction	Levelized Cost (€/t CO_2)	References
Refuse-Derived Fuel (RDF)	12-35	12-18	5-8	45-90	5-10%	-20 to 20	[16,17]
Biomass (Wood, Biogas)	2-10	5-12	3-5	200-270	20-30%	0-30	[1,18]
Tire-Derived Fuel (TDF)	0.5-2	15-23	3-6	108-135	12-15%	-10 to 0	[16,19]

Notes: Data are for a 1-Mt/yr cement plant in Europe. Percent reductions refer to a comparison with a fossil-fuel baseline. Levelized costs (LCOA) exclude transport/storage. Payback periods assume a CO_2 price of €65/t CO_2 and a 7% real discount rate.

4.3. Energy Efficiency Optimization (EEO)

Various technologies and systems have been developed to minimize the consumption of energy in the cement industry. Waste heat recovery (WHR) systems represent a cost-effective solution for improving energy efficiency. WHR enhances operational efficiency while lowering greenhouse gas emissions by extracting and reusing excess heat produced during cement production. This process is essential because the cement industry has a high energy demand. Furthermore, many studies have suggested that the adoption of high-efficiency motors and variable-speed drives (VSDs) can directly lower operational expenses and extend the lifespan of equipment. Table 3 summarizes key parameters of EEO in the cement industry.

Table 3

Key parameters of EEO in the cement industry

Technology	CAPEX (€M)	OPEX (%CAPEX/yr)	Payback (Years)	CO_2 Savings (kt CO_2/yr)	CO_2 Reduction	Levelized Cost (€/t CO_2)	References
WHR	50-60 (for 20 MW)	2-3	3-7	30-70	3-8%	50-100	[20,21]
High-Efficiency Motors	0.5-1	$\lesssim 1$	1-3	1-2	0.1-1%	10-20	[22,23]
Variable-Speed Drives (VSD)	0.5-1.2	$\lesssim 1$	1.3-1.7	1-2	0.25%	50-70	[24,25]

Notes: Data are for a 1-Mt/yr cement plant in Europe. Percent reductions refer to a comparison with a fossil-fuel baseline. Levelized costs (LCOA) exclude transport/storage. Payback periods assume a CO_2 price of €65/t CO_2 and a 7% real discount rate. Aggregate Motor Capacity for VSD Implementation: 10 MW.

4.4. Supplementary Cementitious Materials (SCMs)

The incorporation of supplementary cementitious materials (SCMs) into cement production has gained increasing attention for its potential to mitigate environmental impacts while offering economic benefits. Replacing a portion of clinker with SCMs offers a viable solution to mitigate CO_2 emissions generated by limestone calcination and the energy-intensive clinker production process. Table 4 summarizes key parameters of SCMs in the cement industry.

Table 4

Key parameters of SCM technology

Technology	CAPEX (€M)	OPEX (€/t SCMs)	Payback (Years)	CO_2 Savings (kt CO_2/yr)	CO_2 Reduction	Levelized Cost (€/t CO_2)	References
SCMs	1.4-22	4-20	0.12-1.96	70-345	10-60%	6-20	[26,27]

Notes: Data are for a 1-Mt/yr cement plant in Europe. Percent reductions refer to a comparison with a fossil-fuel baseline. Levelized costs (LCOA) exclude transport/storage. Payback periods assume a CO_2 price of €65/t CO_2 and a 7% real discount rate. A clinker CO_2 emission factor of 0.693 t CO_2/t clinker is applied. A reference thermal substitution rate of 25% is applied for SCMs (e.g., fly ash, GGBS, calcined clay) relative to a fossil-fuel baseline.

4.5. Electrification and Innovative Technologies

In recent years, considerable attention has been directed toward three emerging decarbonization approaches – kiln electrification, hydrogen firing, and solar-thermal calcination – each of which has unique environmental and economic advantages. Although these technologies have yet to be widely adopted in the cement industry, they merit rigorous investigation and scholarly attention. Table 5 summarizes the key parameters of electrification and innovative technologies in the cement industry.

Table 5

Key parameters of Electrification and innovative technologies

Technology	CAPEX (€M)	OPEX (€M/yr)	Payback (Years)	CO_2 Savings (kt CO_2/yr)	CO_2 Reduction	Levelized Cost (€/t CO_2)	References
Kiln Electrification	150-300	10-20	10-15	400-500	40%	50-80	[28,29]
Hydrogen Firing	100-300	3-5	5-15	50-560	3-28%	75-1560	[30,31]
Solar Thermal Calcination (14-30% Heat)	120-160	1.2-1.6	6-8	90-150	12-25%	74-118	[32]

Notes: Data are for a 1-Mt/yr cement plant in Europe. Percent reductions refer to a comparison with a fossil-fuel baseline. Levelized costs (LCOA) exclude transport/storage. Payback periods assume a CO_2 price of €65/t CO_2 and a 7% real discount rate. Capital costs are expressed as total initial investment (CAPEX), with an assumed economic life of 20 years. Electricity is sourced from the existing national grid without renewable integration. Operating costs (OPEX) include electricity consumption and routine maintenance but exclude CO_2 transportation and downstream infrastructure.

The production of green hydrogen through electrolysis is currently expensive due to the high costs of renewable electricity and the electrolysis process. This economic barrier limits the widespread adoption of green hydrogen in cement production. Additionally, the adoption of green hydrogen requires extensive infrastructure development, including hydrogen production facilities, storage, and distribution networks. These infrastructure requirements pose logistical and financial challenges [33]. However, policy interventions and collaborative efforts are crucial to overcoming these challenges for achieving deep decarbonization in the cement industry.

5. COMPARATIVE TECHNO-ECONOMIC ANALYSIS

Fig. 2 illustrates the generated MACC and presents a comparative analysis of various CO_2 mitigation strategies from earlier in this study. The analysis reveals that TDF and RDF offer the lowest abatement costs, with TDF exhibiting a saving cost of about -10 €/t CO_2 and an abatement potential of about 122 kt CO_2/yr, making it one of the most cost-effective early-action solutions. In contrast, hydrogen firing presents the highest marginal cost, reaching up to 1560 €/t CO_2, albeit with a wide abatement range (up to 305 kt CO_2/yr), reflecting elevated abatement costs despite its high technical potential. SCMs exhibit attractive economic performance (6-20 €/t CO_2), while delivering a considerable annual mitigation potential of approximately 208 kt CO_2/yr. Among carbon capture technologies, MEA post-combustion capture delivers large-scale mitigation (825 kt CO_2/yr) but at a higher cost (95-150 €/t CO_2), whereas oxyfuel combustion achieves similar abatement (925 kt CO_2/yr) at a lower cost (35-45 €/t CO_2).

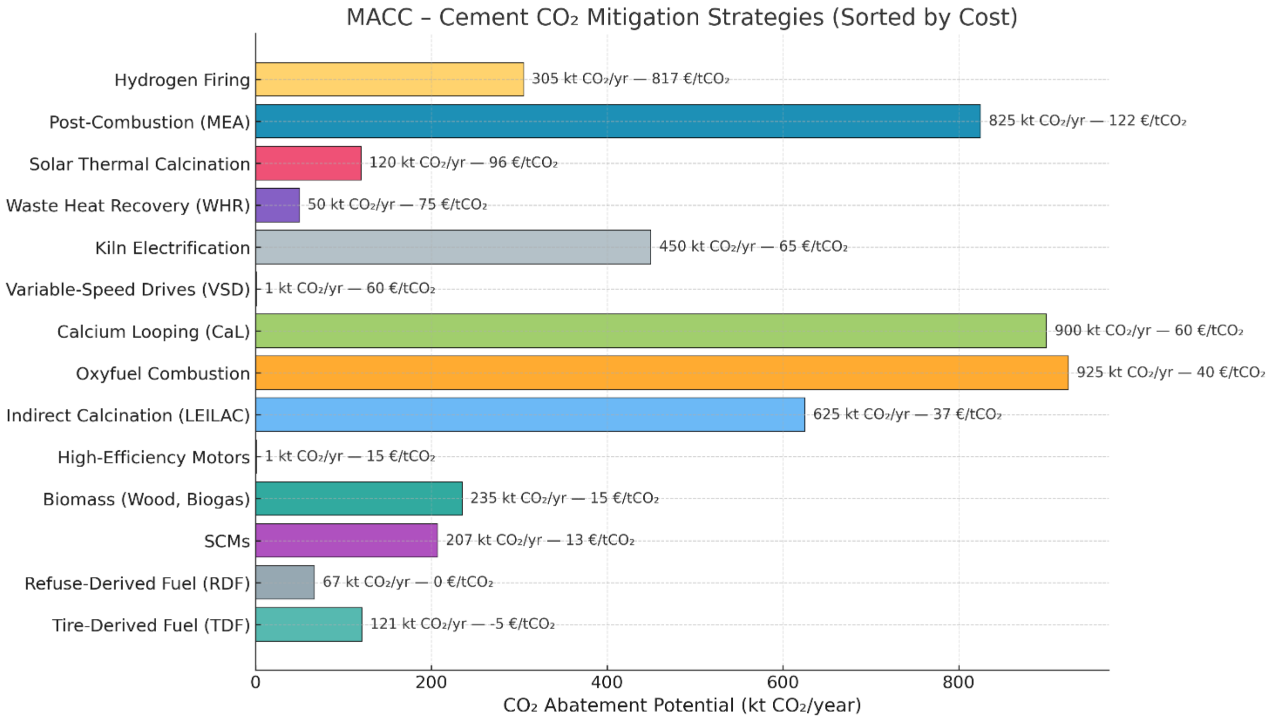

Fig. 2. MACC-CO_2 Cement Mitigation Strategies

Fig. 3 shows the CO_2 abatement potential of each technology. CCS technologies lead to efficient CO_2 reduction, whereas operational measures, such as energy efficiency upgrades, typically achieve only modest reductions.

The payback distribution plot (Fig. 4) demonstrates that low-cost measures such as SCMs incorporation, VSDs, and high-efficiency motors recover their investments within 0.1-3 years, while alternative fuels like RDF, TDF, and WHR exhibit longer payback durations of 3-8 years. In contrast, deep-decarbonization technologies, including hydrogen firing (5-15 years), MEA CCS (12-18 years), and calcium looping (12-25 years), require substantially longer investment horizons.

This comparison indicates that operational efficiency improvements, waste-fuel substitution, and clinker reduction can substantially reduce CO_2 emissions at a relatively low cost. In contrast, carbon capture and storage (CCS) entails high capital expenditure per ton of CO_2 captured, making large-scale deployment economically challenging. Electrification and hydrogen firing offer promising pathways to further decarbonization but are at an early stage of development and require substantial up-front investment.

In practice, cement producers should first pursue “easy-win” measures, such as adopting alternative fuels, incorporating SCMs, and enhancing energy efficiency with multi-year return on investment. Once these initial strategies are established and have yielded measurable emission savings, companies can then scale up carbon capture technologies to achieve more substantial emission reductions. Indeed, industry roadmaps envisage roughly a 30% reduction in emissions by 2030, through changes in fuel and energy sources. However, reaching net-zero by 2050 will ultimately depend on widespread CCS deployment or a breakthrough in alternative binder technologies.

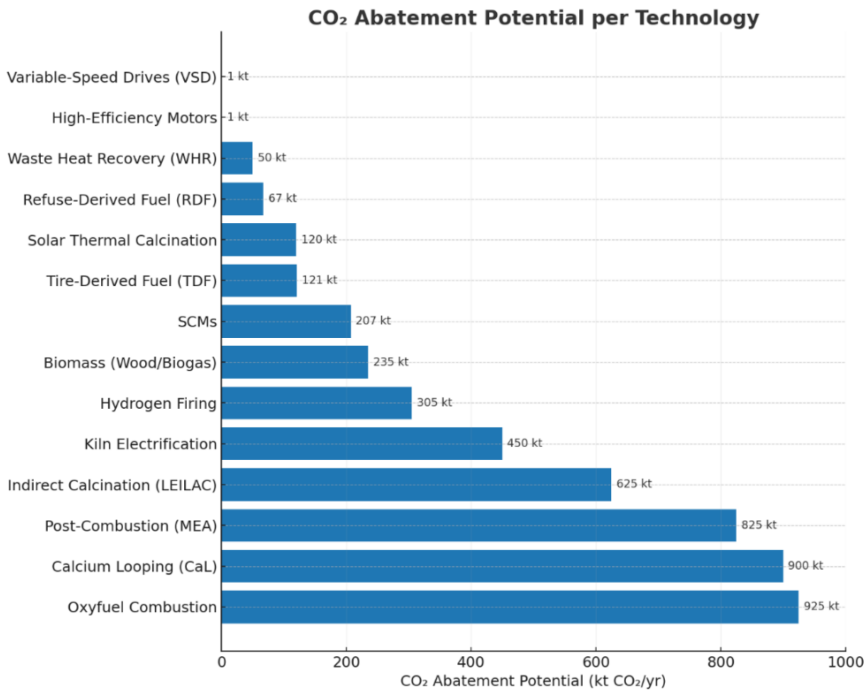

Fig. 3. CO_2 Abatement Potential for CO_2 Mitigation Strategies

It is important to emphasize that the techno-economic performance of the evaluated mitigation strategies is highly context-dependent. Factors such as local carbon-pricing policies, regional fuel and electricity markets, plant-specific configurations, geographic location, raw material availability, and environmental regulations can considerably influence the feasibility and effectiveness of each technology. Therefore, any implementation plan should be preceded by a detailed, site-specific assessment that considers the operational, economic, and regulatory conditions unique to each cement plant.

6. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on three critical parameters—carbon price, discount rate, and electricity cost—to evaluate the influence of key techno-economic variables on the economic viability of CO_2 mitigation options. These ranges reflect realistic market scenarios across EU and global decarbonization trajectories. The analysis quantifies the variation in net economic benefit (NEB) and LCOA across mitigation strategies for the cement sector. The sensitivity analyses were performed by varying the carbon price from 30 to 100 €/t CO_2, the discount rate from 5% to 10%, and electricity cost from 90 to 140 €/MWh.

The net economic benefit (NEB) is calculated as

$$NEB = P_{CO_2} - LCOA, \tag{2}$$

where P_{CO_2} is the prevailing carbon price (€/t CO_2) and LCOA is the levelized cost of abatement for each strategy.

Fig. 5 shows that strategies with low or negative LCOA values—such as TDF, RDF, biomass, and SCMs—yield a high NEB, even at CO_2 prices below 50 €/t. For example, RDF achieves an NEB of up to 100 €/t CO_2 at a CO_2 price of 100 €/t. Conversely, high-cost technologies, such as MEA post-combustion and solar thermal calcination, require prices of more than 110 €/t CO_2 to become economically feasible. Mid-range technologies such as oxyfuel combustion, LEILAC, and CaL, shift from negative to positive NEB in the range of 50-70 €/t CO_2. These results highlight the pivotal role of CO_2 pricing in determining the feasibility of mitigation.

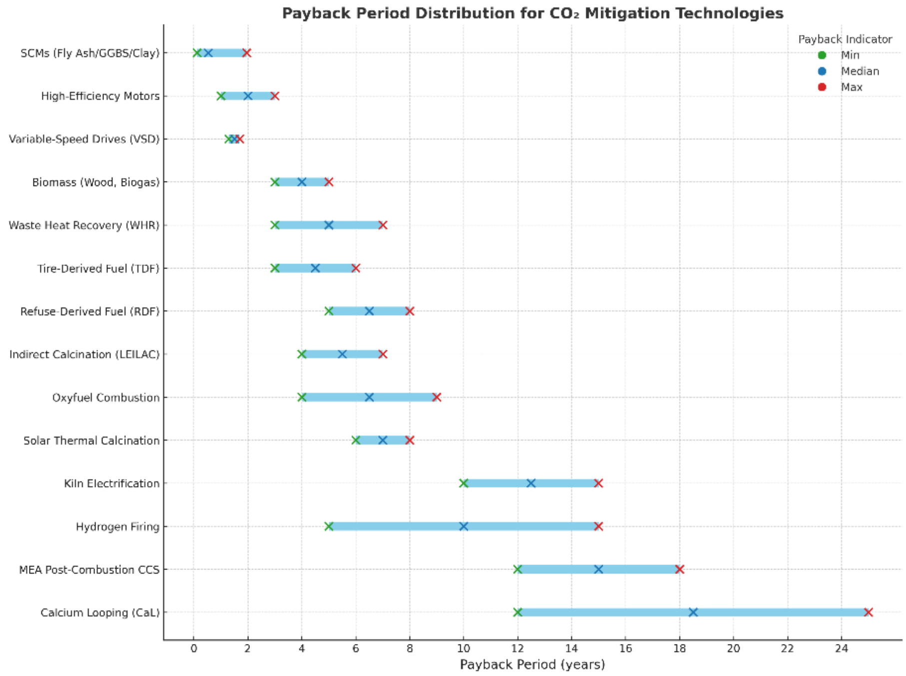

Fig. 4. Payback Period Distribution for CO_2 Mitigation Technologies

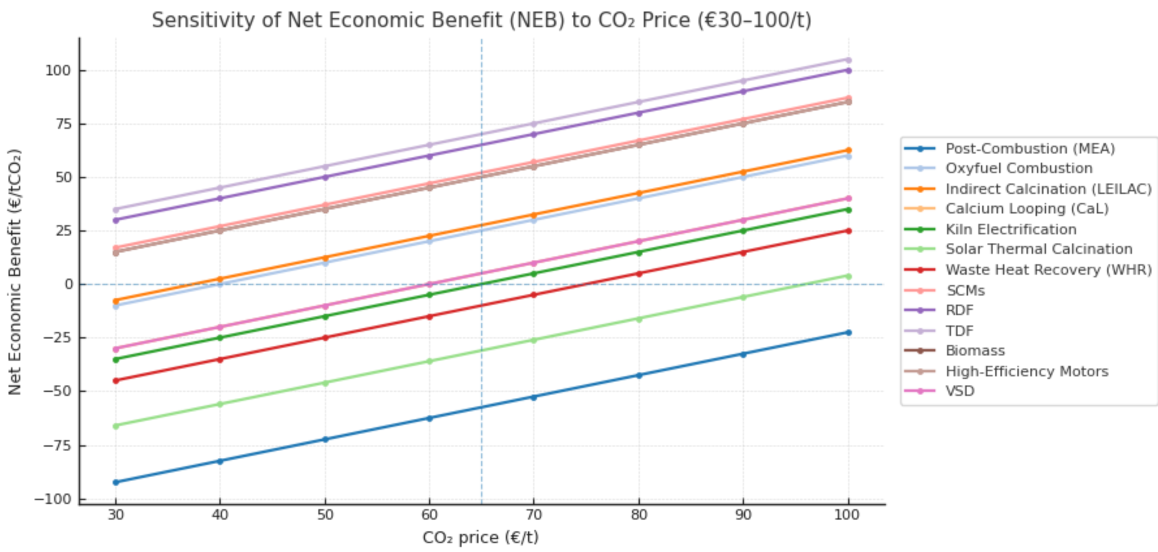

Fig. 5. Sensitivity of Mitigation Strategies to CO_2 Price (€/t CO_2)

Fig. 6 illustrates that capital-intensive options such as solar thermal calcination, kiln electrification, and waste-heat recovery are highly sensitive to the discount rate. For example, the LCOA for solar thermal increases from 79 to 122 €/t CO_2 as the discount rate rises from 5% to 10%, while kiln electrification increases from 58 to 76 €/t CO_2. In contrast, cost-effective and low-CAPEX options, such as SCMs, RDF, and TDF, show negligible sensitivity, maintaining LCOAs below 20 €/t CO_2 across all rates. These findings underscore the importance of stable, low-cost financing in enabling the deployment of CAPEX-heavy mitigation technologies.

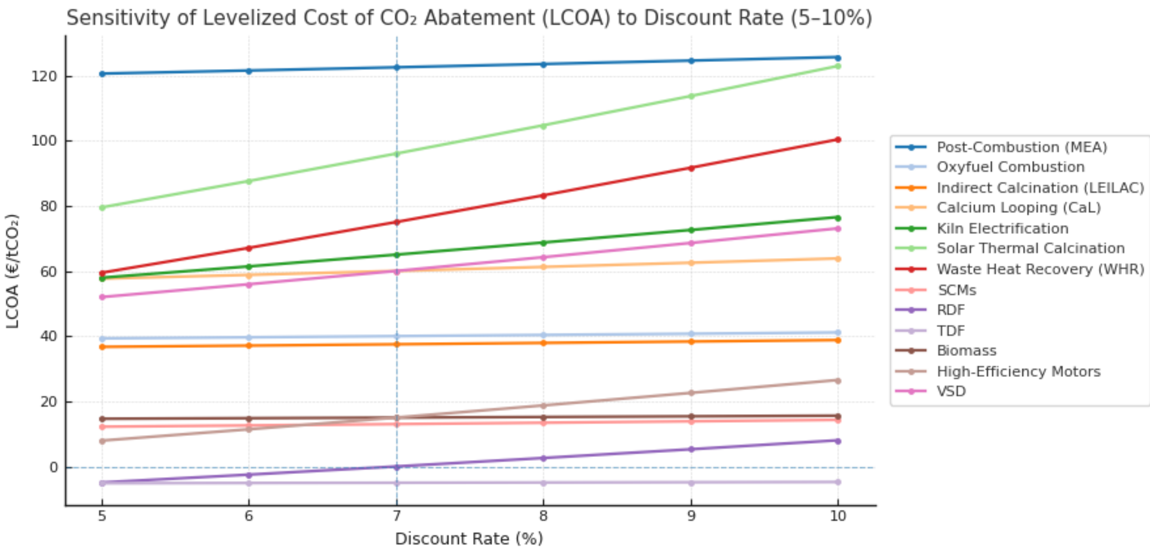

Fig. 6. Sensitivity of Levelized Cost of CO_2 Abatement (LCOA) to Discount Rate (5-10%)

Electricity price fluctuations critically influence the operating costs of electrified or electrically assisted options. As shown in Fig. 7, increasing the electricity price from 90 to 140 €/MWh raises the LCOA by approximately 22.5 €/t CO_2 for kiln electrification and 17.5 €/t CO_2 for MEA, with oxyfuel and calcium looping exhibiting moderate increases of about 9 and 6 €/t CO_2, respectively, while LEILAC and solar-thermal auxiliaries show only modest changes of 3-4 €/t CO_2. Electricity-saving or electricity-neutral measures are omitted for clarity.

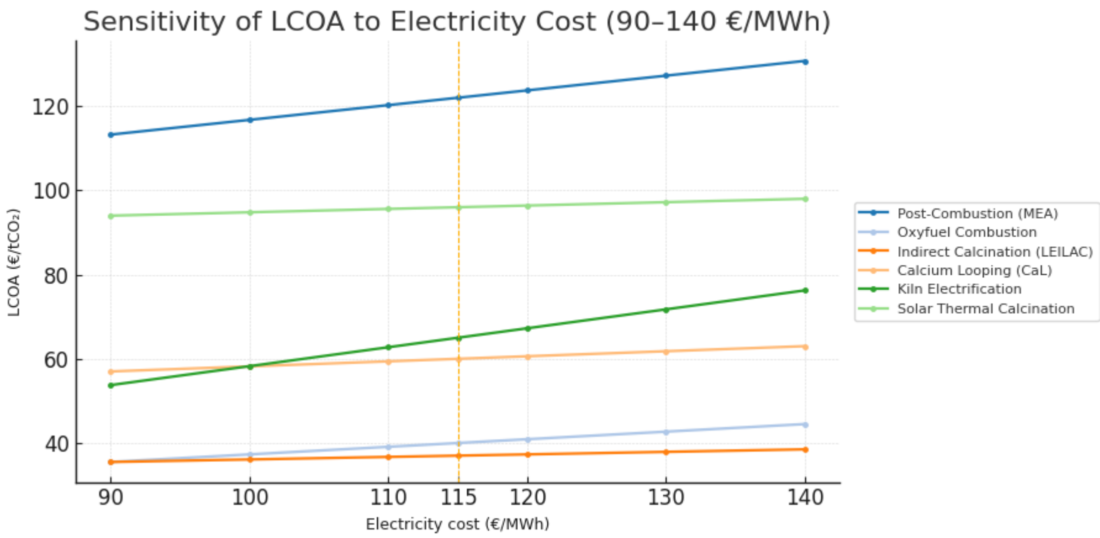

Fig. 7. Sensitivity of Levelized Cost of CO_2 Abatement (LCOA) to Electricity Cost (90-140 €/MWh)

7. STRATEGIC ROADMAP FOR THE DECARBONIZATION OF THE CEMENT INDUSTRY (2025-2050)

A phased implementation roadmap grounded in techno-economic realism and aligned with evolving EU and global climate objectives is proposed to operationalize decarbonization in the cement industry. The roadmap segments implementation into three key milestones: immediate action (2025-2030), medium-term deployment (2030-2040), and long-term deep decarbonization (2040-2050), as detailed in Table 6. This structure and sequencing are consistent with recent sectoral roadmaps and guidance issued by CEMBUREAU and the International Energy Agency (IEA) [34,35]. Each milestone targets a specific CO_2-reduction range and is supported by context-specific strategies based on technological maturity, financial feasibility, and policy relevance.

From 2025-2030, priority will be given to commercially available, low-CAPEX measures with rapid return on investment (ROI), namely the use of SCMs to lower the clinker factor, fuel substitution with RDF and biomass, WHR, plant-wide energy-efficiency upgrades, and robust monitoring, reporting and verification (MRV), collectively delivering about 20-30% abatement. In the transition to Phase 2, the program scales to moderate CAPEX options whose feasibility is policy-driven, including kiln electrification, hydrogen (H_2) co-firing, the deployment of digital twins for optimization and predictive control, and improved AF sorting and preparation to raise substitution rates. These measures typically yield 40-50% abatement when supported by carbon pricing and favorable electricity markets. From 2040-2050, the roadmap targets net-zero readiness through high-impact technologies that are infrastructure-dependent and capital-intensive, CCS, full H_2 firing, solar-thermal calcination, and the procurement of renewable electricity through green power purchase agreements (PPAs), with expected abatement above 80% contingent on CO_2 transport and storage networks, large-scale hydrogen supply, and reliable low-carbon power. Together, this sequencing captures “no-regret” reductions first, then scales maturing options, and finally closes the residual-emissions gap with deep-decarbonization technologies.

Table 6

Milestone-Based Decarbonization Framework for Cement Infrastructure (2025-2050)

Phase	Period	Key Technologies	Abatement Potential	Implementation Characteristics
Phase 1	2025-2030	SCMs, RDF, biomass, WHR, energy efficiency, MRV	20-30%	Commercially available, low CAPEX, rapid ROI
Phase 2	2030-2040	Kiln electrification, H_2 co-firing, digital twins, AF sorting	40-50%	Moderate CAPEX, maturing technologies, policy-driven
Phase 3	2040-2050	CCS, full H_2 firing, solar calcination, green PPAs	>80%	High CAPEX, infrastructure-dependent, long ROI

8. CONCLUSIONS

Modern transportation systems are inconceivable without the supporting infrastructure, in which concrete—and, by extension, cement—plays an indispensable role. However, cement production is a major contributor to global CO_2 emissions, emitting billions of tons annually, a trend expected to continue without substantial intervention. This study reviewed and compared a wide range of CO_2 mitigation strategies that fall under four main pillars: carbon capture and storage, alternative fuel substitution, energy efficiency improvements, and clinker ratio reduction using supplementary cementitious materials (SCMs). The findings based on a series of techno-economic evaluations – including MACC curves, CO_2 abatement potential comparison, and payback period analysis – show that SCMs and alternative fuels (like RDF and biomass) are the most accessible and cost-effective short-term solutions. These options are characterized by relatively low capital requirements, high feasibility, and short payback periods. In contrast, electrification and CCS technologies offer much higher CO_2 abatement potential but are capital-intensive, involve longer implementation timelines, and depend on robust policy support. Their adoption is expected to grow in the long term as part of deep decarbonization pathways, especially after more cost-effective measures have been implemented. Sensitivity analyses on carbon price, discount rate, and electricity cost show that levelized abatement costs and net economic benefits for capital-intensive options are highly contingent on financing and energy-price assumptions, whereas low-CAPEX measures remain comparatively stable.

In conclusion, while improving process efficiency, switching to low-carbon fuels and SCMs can deliver cost-effective CO_2 reductions in the short to medium term, achieving full decarbonization in this sector by 2050, in line with EU and global climate goals, will not be feasible without the large-scale deployment of high-impact technologies like CCS. Despite their financial and logistical challenges, these systems are essential for mitigating the inherent process-derived emissions associated with clinker production. The findings of this study offer valuable guidance for industry stakeholders, investors, and policymakers aiming to align cement infrastructure with climate targets. A future cradle-to-grave LCA with region-specific inventories is proposed to capture broader life-cycle impacts.

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