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INTEGRATED DECARBONISATION PATHWAYS FOR CEMENT IN ALBANIA AND THE WESTERN BALKANS: AN INDICATIVE CARBON-COST AND FEASIBILITY ASSESSMENT UNDER SCALE AND INFRASTRUCTURE CONSTRAINTS

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Cement-sector decarbonisation must address both calcination and energy-related emissions, while carbon capture adds substantial heat and electricity demand. This study develops a transparent scenario assessment for a data-limited Albanian cement system. ANTEA Cement's published nameplate capacity of 1.4 million tonnes per year is used as a scale reference, and the submitted manuscript's assumed intensity of 0.49 t CO_2 per tonne of cement is retained as a modelling input, giving 686,000 t CO_2 per year. Because plant-level source data are unavailable, the baseline is allocated to calcination/process emissions (55%), fossil-fuel combustion (40%) and purchased electricity (5%). Measures are applied only to the relevant streams. In the integrated base case, clinker substitution, energy efficiency and alternative fuels reduce the direct streams before monoethanolamine post-combustion capture is applied at a 70% rate. Gross capture is 330,426 t CO_2 per year. After accounting for the capture-energy emissions, residual emissions are 255,098 t CO_2 per year, a 62.8% reduction from baseline. Combined low- and high-performance sensitivities yield reductions of 48.8% and 69.8%; neither case reaches net zero. At this scale, the base case would require conditioning and transport of approximately 0.33 Mt CO_2 per year, while no validated storage project or CO_2 transport chain is identified for Albania. Carbon-price calculations are exposure indicators, not estimates of actual CBAM liabilities. The results support a staged feasibility assessment, not investment or competitiveness conclusions.

Keywords: cement, calcination, clinker substitution, carbon capture, carbon-cost exposure, Western Balkans

HIGHLIGHTS

- The assumed 686,000 t CO_2/y baseline is split into process, fuel and electricity streams.
- The integrated base case leaves 255,098 t CO_2/y after capture-energy emissions.
- The base case requires conditioning and transport of 330,426 t CO_2/y of captured CO_2.
- Sensitivity results range from 48.8% to 69.8% reductions and do not reach net zero.

1 Introduction

Cement production emits carbon dioxide from carbonate calcination and from the heat and electricity used to manufacture clinkers and cement. The process stream is released when limestone is decomposed, while fuel switching and efficiency measures mainly affect energy-related emissions. These sources respond differently to mitigation and should therefore be accounted for separately [1,2].

The available mitigation portfolio includes lower clinker-to-cement ratios, thermal and electrical efficiency, alternative fuels, and carbon capture, utilisation and storage (CCUS). Material substitution can reduce both calcination emissions and kiln heat demand; efficiency reduces energy use; and alternative fuels affect the fossil share of combustion emissions. Capture can address residual process and combustion CO_2, but its performance and cost depend on the flue-gas composition, heat supply, electricity mix, retrofit conditions and transport and storage arrangements [3–6].

Much of the published technical and cost evidence is based on large plants or industrial clusters with detailed operating data and planned CO_2 infrastructure. A smaller, data-limited system requires a different analytical emphasis: assumptions must be explicit, mitigation effects must be applied to the relevant emission streams, and infrastructure feasibility must be connected to calculated CO_2 volumes. This paper offers such an indicative assessment for Albania and the Western Balkans. It does not claim to be the first regional study or to represent measured performance at a specific plant.

The study addresses three questions: how do selected mitigation measures affect process, fuel and electricity emissions when applied consistently; what residual emissions and CO_2 handling volumes result from an integrated pathway; and how do resource, cost and infrastructure uncertainties constrain interpretation of that pathway? The contribution is a reproducible scenario calculation with bounded sensitivities and a literature-based CCUS cost comparator. It is intended to support data collection and pre-feasibility work, not investment decisions.

2 Materials and methods

2.1 Scope and baseline emissions

The model uses an annual cement output of 1,400,000 t as a scale reference, equal to ANTEA Cement's published nameplate capacity [12]. It is not treated as a verified annual production figure. The specific emissions input of 0.49 t CO_2/t cement is retained from the submitted manuscript as an assumed benchmark because a plant-specific, independently verifiable emissions intensity was not supplied. Multiplying these values gives a reference total of 686,000 t CO_2/y. The boundary covers calcination/process CO_2, fossil-fuel combustion and purchased-electricity emissions at the cement-production site. Transport, upstream fuel and material supply, and other life-cycle emissions are excluded.

$$E_0 = Q \times I = 1{,}400{,}000 \times 0.49 = 686{,}000 \text{ t } CO_2/y$$

No primary source split is available for the plant. A literature-informed central allocation of 55% process, 40% fossil-fuel combustion and 5% purchased electricity is therefore imposed as a transparent modelling assumption. Sector descriptions place process emissions at approximately one-half, fuel emissions near 40%, and electricity near 5%, with shares varying by plant and boundary [2]. The selected allocation sums to the retained plant-gate total and excludes transport. Alternative allocations are tested separately.

Table 1. Baseline emissions allocation used in the central case

Emission stream	Share	Baseline (t CO_2/y)	Basis
Calcination / process	55%	377,300	Indicative allocation; not plant-measured [2]
Fossil-fuel combustion	40%	274,400	Indicative allocation; not plant-measured [2]
Purchased electricity	5%	34,300	Indicative allocation; transport excluded [2]
Total	100%	686,000	1.4 Mt/y × 0.49 t CO_2/t cement

The 55/40/5 split is not a measured ANTEA inventory. It represents source categories within the stated boundary. In the supplementary workbook, alternative 50/40/10 and 60/35/5 allocations are evaluated with the same mitigation assumptions.

2.2 Scenario construction and stream-specific effects

Six scenarios are calculated: S0, no mitigation; S1, clinker substitution; S2, energy efficiency; S3, alternative fuels; S4, stand-alone CCUS; and S5, an integrated pathway. S1–S4 are independent comparisons against the baseline. S5 applies measures sequentially to the remaining relevant stream, rather than multiplying aggregate reduction factors across all emissions.

For S1, process emissions fall by 16%. Fuel emissions fall by 5% to represent the associated reduction in clinker-kiln demand; purchased electricity is unchanged. For S2, fuel emissions fall by 15% and purchased-electricity emissions by 10%, while calcination is unchanged. For S3, fossil-fuel combustion emissions fall by 30%; this is a reduction in the fossil CO_2 stream, not a claim that 30% of kiln heat is supplied by alternative fuels. No process or electricity reduction is assigned to S3. The central factors are scenario inputs informed by published mitigation ranges, not plant guarantees [3,4].

For S5, the process stream is reduced by 16%; the fuel stream is then reduced successively by 5% for the clinker-related thermal effect, 15% for energy efficiency and 30% for lower fossil CO_2 from alternative fuels. Purchased electricity is reduced by 10%. The fossil-fuel reduction is applied to the remaining fuel stream after each prior measure. This sequence avoids applying a measure to an unrelated stream and prevents double counting.

The model represents interactions in a limited, explicit way. Clinker substitution lowers calcination and a portion of kiln-fuel demand. Energy efficiency reduces the fuel and electricity streams available before capture. Alternative fuels reduce only fossil combustion CO_2; biogenic accounting and full fuel life-cycle emissions are outside the boundary. CCUS captures the post-mitigation direct process and fuel streams. Lower throughput or a lower flue-gas CO_2 concentration could alter capture-unit size, solvent performance and cost; no process simulator is available to quantify that effect. The capture-energy intensity is held constant per tonne captured, and this limitation is tested through low, central and high energy assumptions [5,6].

2.3 CCUS technology and energy penalty

The CCUS case represents post-combustion monoethanolamine (MEA) capture. The central capture rate is 70% of the direct CO_2 stream remaining after other measures. This is a scenario choice rather than a measured rate or a claim about the technical maximum of MEA. The CEMCAP reference studies report higher capture rates for their modelled plant and provide the energy and cost benchmarks used here [5–7].

The reference capture train uses 3.76 GJ of reboiler heat and 0.521 GJ of electricity per tonne of CO_2 captured. The CEMCAP electricity value is used for capture-train auxiliary power and CO_2 conditioning/compression to the reference delivery pressure; off-site transport and injection energy are excluded. Of the reboiler heat, 96% is

assumed to come from a natural-gas boiler and 4% from waste-heat recovery. The assumed natural-gas emissions factor is 0.057 t CO_2/GJ. A 0.306 t CO_2/MWh electricity factor is used as a European benchmark, not as an Albania-specific grid factor [5,8].

$$e_{pen} = (3.76 \times 0.96 \times 0.057) + (0.521 / 3.6 \times 0.306) = 0.2500322 \text{ t } CO_2 \text{ per t captured}$$

Gross capture is the capture rate multiplied by the post-mitigation direct process and fuel emissions. Direct residual emissions equal those streams less gross capture. Capture-energy emissions equal gross capture multiplied by e_{pen}. Final residual emissions equal direct residual emissions plus remaining purchased-electricity emissions plus capture-energy emissions. Net avoidance attributable to CCUS alone is gross capture minus capture-energy emissions. Total pathway avoidance is baseline emissions minus final residual emissions. This distinction prevents captured mass from being reported as net avoided emissions.

2.4 Carbon-cost exposure and literature cost benchmark

Carbon-cost exposure is calculated as scenario residual emissions multiplied by assumed prices of €50, €80 and €120/t CO_2. These are comparison values, not forecast or an actual CBAM liability. The EU CBAM definitive regime began on 1 January 2026 and covers cement; its certificate price is linked to EU ETS auction prices and the obligation depends on imported goods and verified embedded emissions [11]. The Commission reported a Q3 2026 certificate price of €82.32/t, so the €80 case is a nearby scenario reference, not a substitute for a product- and importer-specific calculation [11].

Because no local energy prices, financing terms, retrofit estimates or plant operating costs are available, the analysis is not a full techno-economic assessment. To give the reader an order-of-magnitude comparator, the CEMCAP MEA reference case is reported without scaling it to Albania: a 3,000 t clinker/day plant, capture-plant capital cost of €76.1 million in 2014 euros, variable operating cost of €55.2/t clinker, fixed operating cost of €23.6/t clinker, total operating cost of €78.8/t clinker, and levelised cost of CO_2 avoided (LCOA) of €80.2/t. The reference used an 8% discount rate and 91.3% capacity factor over a 25-year economic life. These costs reflect the reference plant and its price assumptions; they are not estimates for ANTEA or another Western Balkan plant [6,7].

2.5 Sensitivity analysis and material-flow boundary

Low, base and high cases vary the performance of each measure together with the capture-energy assumptions. The low case uses process reduction 10%, clinker-related fuel saving 2%, efficiency savings of 5% for fuel and 5% for electricity, fossil-fuel CO_2 reduction 15%, capture rate 50%, reboiler duty 3.0 GJ/t, 50% gas-fired heat and 0.10 GJ/t electricity at 0.10 t CO_2/MWh. The base case uses 16%, 5%, 15%, 10%, 30%, 70%, 3.76 GJ/t, 96% gas heat and 0.521 GJ/t electricity at 0.306 t CO_2/MWh. The high case uses 25%, 8%, 20%, 15%, 45%, 90%, 4.5 GJ/t, 100% gas heat and 0.72 GJ/t electricity at 0.60 t CO_2/MWh. These cases are unweighted bounds, not probability distributions or forecasts.

For an indicative materials-flow scale only, a clinker-to-cement ratio of 0.80 is assumed, giving 1.12 Mt/y of clinker-equivalent output at the 1.4 Mt/y cement reference. A 16% clinker-equivalent reduction corresponds to about 179,200 t/y of replacement material if substitution is one-for-one by mass and process emissions scale with clinker output. The 10–25% scenario range corresponds to 112,000–280,000 t/y. This is not a claim that these supplementary cementitious materials (SCMs) are locally available or technically interchangeable; chemistry, strength class, standards, durability and logistics require plant and market data.

3 Results and discussion

3.1 Baseline and stand-alone scenarios

The central baseline is 686,000 t CO_2/y, comprising 377,300 t/y of process emissions, 274,400 t/y of fossil-fuel emissions and 34,300 t/y of purchased-electricity emissions (Table 1). The independent scenarios reduce this total by 10.8% for clinker substitution, 6.5% for energy efficiency and 12.0% for alternative fuels. The results differ from aggregate percentages applied to the whole baseline because each measure now affects only its corresponding stream.

3.2 Recalculated S0–S5 pathway results

Under S4, gross capture is 456,190 t CO_2/y. Direct emissions remaining after capture are 195,510 t/y. The capture train adds 114,062 t/y of energy-related emissions, in addition to the baseline 34,300 t/y of purchased electricity; final residual emissions are 343,872 t/y. The resulting net reduction is 49.9%, not the gross capture rate.

Under integrated S5, the process stream before capture is 316,932 t/y, the fossil-fuel stream is 155,105 t/y and purchased-electricity emissions are 30,870 t/y. Gross capture is 330,426 t/y and direct emissions after capture are 141,611 t/y. Capture requires approximately 1.242 million GJ/y of reboiler heat, including 1.193 million GJ/y from natural gas and 49,696 GJ/y from assumed waste heat, plus 47,820 MWh/y of electricity for the capture train and compression. These energy demands add 82,617 t CO_2/y. The final residual is 255,098 t/y, so total net avoidance against S0 is 430,902 t/y, or 62.8%. Capture itself avoids 247,809 t/y net of its energy penalty after the non-CCUS measures have been applied.

Table 2. Recalculated annual emissions for scenarios S0–S5. Values are rounded to the nearest tonne; the workbook retains formula precision

Case	Process (t/y)	Fuel (t/y)	Electricity (t/y)	Gross captured (t/y)	Direct after capture (t/y)	Capture-energy emissions (t/y)	Final residual (t/y)	Reduction
S0	377,300	274,400	34,300	0	651,700	0	686,000	0.0%
S1	316,932	260,680	34,300	0	577,612	0	611,912	10.8%
S2	377,300	233,240	30,870	0	610,540	0	641,410	6.5%
S3	377,300	192,080	34,300	0	569,380	0	603,680	12.0%
S4	377,300	274,400	34,300	456,190	195,510	114,062	343,872	49.9%
S5	316,932	155,105	30,870	330,426	141,611	82,617	255,098	62.8%

Figure 1 shows the composition of final residual emissions. The capture-energy segment is separate from both the original plant electricity stream and the captured mass. The visual and all scenario totals are generated from the same stream calculations.

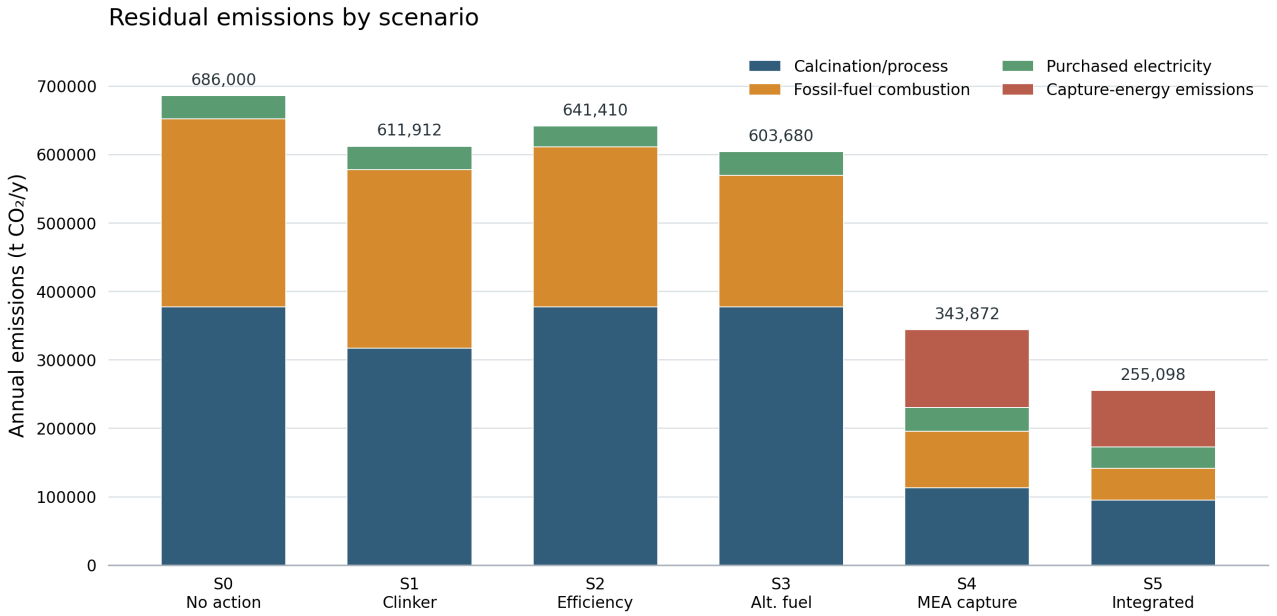

Fig. 1. Residual annual emissions by scenario, separated into remaining process, fossil-fuel and purchased-electricity emissions and capture-energy emissions

3.3 Sensitivity and carbon-cost exposure

The integrated low case leaves 351,303 t CO_2/y, a 48.8% reduction. The base case leaves 255,098 t/y, a 62.8% reduction. The high-performance case leaves 207,281 t/y, a 69.8% reduction despite the higher assumed energy penalty. The high case remains well above zero and should not be interpreted as full decarbonisation. Changing the baseline source allocation to 50/40/10 gives a 60.3% reduction; changing it to 60/35/5 gives 62.2%. The source split matters, but its effect is smaller than the combined uncertainty in mitigation and capture performance.

Table 3. Integrated-pathway sensitivity results

Case	Process share	Capture rate	Gross captured (t CO_2/y)	Capture-energy emissions (t/y)	Residual emissions (t CO_2/y)	Reduction
Low performance	50%	50%	262,923	23,210	351,303	48.8%
Base	55%	70%	330,426	82,617	255,098	62.8%
High performance	60%	90%	365,303	137,537	207,281	69.8%

Case	Process share	Capture rate	Gross captured (t CO_2/y)	Capture-energy emissions (t/y)	Residual emissions (t CO_2/y)	Reduction
Alternative source split A	50%	70%	310,257	77,574	272,282	60.3%
Alternative source split B	60%	70%	337,022	84,266	259,575	62.2%

At the €50/€80/€120 per t CO_2 proxy prices, baseline exposure is €34.30/€54.88/€82.32 million per year. S5 exposure is €12.75/€20.41/€30.61 million per year. The difference reflects multiplication by residual emissions only. It excludes CBAM product benchmarks, embedded-emissions verification, free-allocation phase-in, import quantities, contractual pass-through, abatement costs and any carbon price already paid in the exporting country.

3.4 Literature-based MEA cost comparator

Table 4. CEMCAP MEA reference-cost indicators; these values are not Albania-specific estimates

Indicator	Reference value	Interpretation
Reference kiln	3,000 t clinker/day	CEMCAP model plant
Capture-plant capital cost	€76.1 million (2014)	Reference capture unit; not scaled
Variable operating cost	€55.2/t clinker	Reference plant with MEA capture
Fixed operating cost	€23.6/t clinker	Reference plant with MEA capture
Total operating cost	€78.8/t clinker	Whole reference plant with capture
LCOA	€80.2/t CO_2 avoided	Reference MEA case; depends on energy and finance assumptions
Financial basis	8% discount; 91.3% utilisation; 25 years	CEMCAP reference assumptions

The cost comparator helps establish the likely order of magnitude and the sensitivity of capture economics to plant conditions. It does not establish a positive business case for an Albanian plant. Recent business-case analysis also finds that carbon prices alone may be insufficient to make cement CCS viable under its model assumptions [9].

3.5 Interpretation and interactions among measures

The results show why source-specific accounting changes the interpretation of the pathway. Clinker substitution reduces process emissions directly and provides a smaller fuel benefit. Efficiency does not reduce calcination, and alternative fuels do not reduce process or purchased-electricity emissions. In the integrated case, those measures reduce the direct stream available to CCUS from 651,700 t/y at baseline to 472,037 t/y before capture. The 70% capture assumption therefore yields 330,426 t/y gross capture rather than an aggregate reduction applied to all baseline emissions.

Capture energy materially changes net performance. The base case's 330,426 t/y gross captured becomes 247,809 t/y net avoided by CCUS after the estimated 82,617 t/y energy emissions. Purchased electricity remains a separate stream. Waste-heat recovery supplies only 4% of the reference reboiler duty in this calculation. A local heat-integration study could improve or worsen the result. Likewise, changes to clinker ratio, fuel composition and flue-gas concentration may change capture-unit size and specific cost; the scenario model does not resolve these process-level effects [5,6].

The integrated reduction is 62.8% in the central case, while the bundled sensitivity range is 48.8–69.8%. Neither the central nor high result demonstrates net zero. The analysis also does not support a claim of improved export competitiveness, because no cement-price, product-quality, investment, trade-flow or importer-specific CBAM model is included.

3.6 Scale, infrastructure and resource constraints

The S5 gross capture flow of 330,426 t/y corresponds to a calendar-year average of about 37.7 t/h. The S4 stand-alone case would require about 456,190 t/y, or 52.1 t/h. These are the quantities that would need capture, conditioning, transport and storage if the scenarios were implemented. At 70% capture, the residual direct stream is still 141,611 t/y in S5, before the purchased-electricity and capture-energy components are added to final emissions.

ANTEA's plant is reported to be about 45 km from the Port of Durrës in an IFC project snapshot [13]. That distance is a geographic reference only; it is not an engineered pipeline route. The existing port and cement terminals are

not CO_2 export terminals. A potential pathway could involve a short pipeline to a newly developed CO_2 conditioning and shipping terminal, a shared regional pipeline and storage hub, or eventual connection to a wider European CO_2 network. Each option would require engineering, permitting, commercial agreements, monitoring and a verified storage site.

The 2025 CO_2 Storage Resource Catalogue's Albania chapter reports limited public storage data and identifies regulatory and assessment gaps [10]. This does not establish that geological storage is impossible; it means that this study cannot assign a validated storage capacity, injection rate or permitting schedule. Regional cooperation may improve scale economics, but the volume from one modeled plant alone does not prove that a shared transport or storage chain is commercially feasible.

The illustrative clinker-equivalent SCM requirement of 179,200 t/y in the base case, with a scenario range of 112,000–280,000 t/y, makes the material constraint tangible. The calculation assumes a clinker-to-cement ratio of 0.80 and one-for-one mass substitution. It does not measure local slag, fly ash, calcined clay or pozzolan supply. The alternative-fuel case is expressed as a reduction in fossil CO_2, not tonnes of fuel, because kiln heat demand, fuel lower heating value, moisture and fossil/biogenic fractions are unavailable. A regional resource map and product-testing programme are prerequisites to converting these scenario assumptions into plant targets.

3.7 Carbon-cost exposure and implementation sequence

The carbon-cost proxy falls in proportion to modeled residual emissions, but it is not an investment return or a CBAM invoice. Current CBAM obligations attach to covered imported goods and verified embedded emissions; the model's annual cement emissions cannot be multiplied by a certificate price and interpreted as the producer's legal payment without trade and product data [11]. The €80/t scenario is close to the Q3 2026 published certificate price, but prices and applicable rules can change.

A practical sequence would first measure annual output, clinker ratio, kiln fuels and their fossil fractions, specific thermal and electrical use, and process emissions using a plant inventory protocol. The next step would verify SCM and alternative-fuel quantity, quality and logistics. A capture pre-feasibility study could then test heat integration, capture rate, compression specification, route options, storage appraisal and shared infrastructure. This sequence would replace the current scenario assumptions with site data before investment decisions are considered.

3.8 Limitations

The main limitations are the retained assumed emissions intensity, the literature-informed but unmeasured stream allocation, scenario reduction factors, the fixed capture-energy intensity, and the absence of plant-specific fuel, electricity, SCM, waste-heat, CAPEX and OPEX data. The model excludes upstream and transport life-cycle emissions, construction emissions, non-CO_2 greenhouse gases, CO_2 transport and injection energy, storage leakage risk, and product-specific CBAM calculations. The high and low sensitivities are structured bounds rather than probabilistic results. The workbook makes inputs and calculations editable so that verified plant data can replace these assumptions.

4 Conclusions

This study recalculates cement-sector mitigation scenarios for an Albanian scale reference using separate process, fossil-fuel and purchased-electricity streams. With an assumed baseline of 686,000 t CO_2/y and a transparent 55/40/5 allocation, the integrated base case leaves 255,098 t CO_2/y after capture-energy emissions, corresponding to a 62.8% reduction. The pathway captures 330,426 t CO_2/y gross, but capture energy adds 82,617 t CO_2/y. The low and high-performance sensitivities produce reductions of 48.8% and 69.8%; no modeled case reaches net zero.

At the base capture rate, approximately 0.33 Mt CO_2/y would require conditioning, compression and a permitted transport and storage route. The plant-to-port distance offers a geographic reference for future study, but existing cement logistics do not establish CO_2 handling capability. Material replacement may require roughly 0.18 Mt/y of clinker-equivalent SCMs under the stated illustrative assumptions. These quantities connect regional resource and infrastructure constraints to the modeled pathway.

The cost analysis is limited to carbon-price exposure indicators and published MEA benchmarks. It does not establish plant-specific CAPEX, OPEX, investment viability or export competitiveness. The results support data collection and regional pre-feasibility work, particularly measured emissions accounting, SCM and alternative-fuel mapping, capture heat integration, and shared transport and storage appraisal.

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7 Conflict of interest statement

The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this manuscript.

8 Author contributions

Hasimin Keçi led the study, developed the scenario calculations, and prepared the original manuscript draft. Majlinda Alcani supervised the work and contributed to review and editing. Both authors reviewed and approved the final manuscript.

9 Data availability statement

The supplementary calculation workbook contains model inputs, source notes, formulas, scenario results and sensitivity calculations. No primary plant measurements were generated for this study.

10 Supplementary materials

The supplementary calculation workbook is provided with the manuscript and contains the model inputs, source notes, formulas, scenario results, and sensitivity calculations.

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