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Green Modernisation and Environmental Efficiency in Uzbekistan's Construction Materials Industry: Evidence from Cement Production, Energy Saving and Decarbonisation Indicators

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Abstract: This study examines whether Uzbekistan's expanding construction-materials industry has achieved measurable improvements in energy efficiency and decarbonisation. It analyses official cement-production statistics for 2022–2025, Uzbekistan's First Biennial Transparency Report and regulatory documents using growth rates, intensity proxies, decoupling arithmetic and evidence triangulation. Cement output increased from 11.36 million tonnes in 2022 to 16.01 million tonnes in 2024—an overall rise of 40.9%. Comparable first-half production grew by 59.8% between 2023 and 2025. Meanwhile, sectoral energy consumption and energy intensity reportedly declined by factors of 1.3 and 1.6. An internal consistency check shows that a 1.2-fold production increase combined with a 1.6-fold intensity decline implies an aggregate energy-use reduction of about 25%, close to the separately reported 23.1% decrease. Construction-materials process emissions reached 23.4 Mt CO₂-eq in 2022, of which an estimated 3.42 Mt was associated with cement clinker. The analysis further shows that, with output 40.9% higher, carbon intensity would need to fall by at least 29.0% merely to keep absolute emissions unchanged. Qizilqumsement's modernisation reduced specific gas use by up to 13% and electricity use by 5%. The findings demonstrate credible relative efficiency gains but do not confirm absolute decarbonisation. A digital MRV system, plant benchmarking, verified green financing, clinker-substitution measures and staged deep-decarbonisation instruments are recommended.

Keywords: green modernisation; cement industry; energy efficiency; decarbonisation; Uzbekistan; MRV

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1. Introduction

Construction materials are indispensable to urbanisation, infrastructure and housing, yet their production is energy- and carbon-intensive. Cement is particularly important because emissions arise from both fuel combustion and the calcination of limestone. Consequently, production growth can improve material availability and industrial value added while simultaneously increasing environmental pressure. The policy problem is therefore not whether Uzbekistan should expand construction-materials production, but how expansion can be separated from growth in energy use, resource depletion and greenhouse-gas emissions.

Uzbekistan provides a relevant emerging-economy case. Demand for cement and other materials has expanded alongside public infrastructure, housing and industrial investment. National policy prioritises energy-efficient building materials, dry-process

cement production, heat recovery and the use of secondary resources [1]. The First Biennial Transparency Report (BTR1) states that the country produces 170 types of construction materials, while domestic demand is covered for 97 items. It also identifies construction materials as a major industrial-process emissions source and reports concrete efficiency improvements at selected enterprises (Republic of Uzbekistan, 2024).

The international literature identifies five complementary decarbonisation levers: kiln and process efficiency; substitution of fossil fuels; reduction of the clinker-to-cement ratio; material efficiency and circular use of industrial by-products; and carbon capture, utilisation and storage [2]. However, these pathways depend on country-specific energy systems, raw-material availability, capital costs and regulatory capacity. Evidence for Central Asian construction-materials industries remains limited, and national studies often describe production growth without quantitatively connecting it to energy and emissions outcomes.

This article addresses that gap by linking publicly available production, efficiency and emissions indicators for Uzbekistan. Its purpose is not to claim causal effects from a short time series. Instead, it provides a transparent empirical baseline, tests directional hypotheses through descriptive evidence, identifies where decoupling can and cannot be established, and converts the findings into measurable policy proposals.

The study asks three questions: (1) How rapidly has cement production expanded? (2) Is the expansion accompanied by observable energy-efficiency improvements? (3) Which institutional and technological measures are required to convert relative efficiency gains into verifiable absolute decarbonisation?

Research hypotheses

H1. Cement production in Uzbekistan increased significantly over the observed period, confirming strong industrial expansion.

H2. Green modernisation is associated with measurable reductions in energy consumption and energy intensity, despite production growth.

H3. Plant-level technological modernisation produces material savings in specific gas and electricity consumption [3].

H4. Efficiency improvements alone are insufficient to confirm absolute decarbonisation when output expands rapidly; a consistent emissions-intensity and absolute-emissions monitoring system is required [4], [5].

2. Materials and Methods

Research design and data sources

The study uses a quantitative descriptive and documentary research design. All numerical observations are taken from public sources; no survey data are used. The principal sources are the National Statistics Committee of Uzbekistan, Uzbekistan's First Biennial Transparency Report submitted under the UNFCCC, and national regulatory documents. Peer-reviewed international studies are used to interpret the technological and policy implications.

Data block	Period	Indicator	Unit	Status/source
Annual cement output	2022–2024	Output of large enterprises	thousand tonnes	Observed; National Statistics Committee
Comparable half-year output	Jan–Jun 2023–2025	Portland cement output of large enterprises	thousand tonnes	Observed/preliminary for 2025; National Statistics Committee
Industrial-process emissions	2022	Construction-materials IPPU emissions	Mt CO ₂ -eq	Observed; BTR1
Emissions structure	2022	Glass and clinker shares	percent	Observed shares; BTR1
Sector efficiency	recent two-year period	Production, energy use and	multiplicative factor	Reported; BTR1

Data block	Period	Indicator	Unit	Status/source
Plant modernisation	reported project result	energy intensity ratios	percent and kWh	Reported case evidence; BTR1
		Qizilqumsement gas and electricity savings		
Energy-saving potential	energy audits	34 high-consuming enterprises	million kWh/year	Estimated audit potential; BTR1

Note. The public sources use different scopes and periods. Therefore, annual output, half-year output and emissions are analysed separately and are not merged into a single econometric panel.

Analytical procedures

Four analytical procedures are applied. First, year-on-year growth is calculated as $g_t = (Y_t/Y_{t-1} - 1) \times 100$. Second, the compound annual growth rate is calculated as $CAGR = (Y_n/Y_0)^{(1/n)} - 1$. Third, reported multiplicative reductions are converted into percentage reductions. A decline by a factor of 1.3 equals $1 - 1/1.3 = 23.1\%$, while a decline by a factor of 1.6 equals 37.5%. Fourth, an indicative clinker-emissions allocation is derived as total construction-materials IPPU emissions multiplied by the reported clinker share.

The derived allocation is $E_{clinker} = 23.4 \times 0.146 = 3.416$ Mt CO₂-eq. An exploratory process-emissions proxy is then calculated by dividing this value by 2022 cement output: $3.416/11.360 = 0.301$ t CO₂-eq per tonne of cement. This ratio is not a verified plant or product carbon footprint because the numerator concerns an allocated IPPU category and the denominator is cement rather than clinker output. It is retained only as a baseline proxy and sensitivity marker.

Hypothesis assessment protocol

Because the dataset contains only three comparable observations in each production series and one detailed emissions year, inferential regression would be statistically inappropriate. Hypotheses are therefore assessed using pre-declared directional criteria. H1 is supported if both annual and half-year series show positive cumulative growth. H2 is supported descriptively if official evidence shows production growth together with reductions in energy use and intensity. H3 is supported if the plant case reports reductions in both specific gas and electricity use. H4 is supported if the available data cannot establish a declining absolute emissions trend despite efficiency gains. The terms ‘supported’, ‘partially supported’ and ‘not testable’ are used rather than causal language.

Reliability and limitations

Reliability is strengthened by source triangulation and explicit separation of observed, calculated and projected values. Nevertheless, the study is constrained by the absence of a public plant-year panel covering output, clinker ratio, fuel mix, electricity use, waste-derived inputs, revenue and verified emissions. The 2022 emissions figure and source shares do not constitute a time series. The sectoral ‘recent two-year’ efficiency ratios are reported aggregates with no disclosed plant distribution. Finally, the 2025 half-year production value is preliminary. These constraints limit causal inference and prevent a formal test of absolute decoupling.

3. Result

Cement-production dynamics

Period	Output (thousand t)	YoY growth	Index (first year=100)
2022 annual	11,359.5	—	100.0
2023 annual	11,931.3	5.0%	105.0
2024 annual	16,007.3	34.2%	140.9

Period	Output (thousand t)	YoY growth	Index (first year=100)
2023 Jan–Jun	5,731.9	—	100.0
2024 Jan–Jun	7,745.3	35.1%	135.1
2025 Jan–Jun	9,158.2	18.2%	159.8

Note. Annual cumulative growth, 2022–2024: 40.9%; annual-series CAGR: 18.7%. Half-year cumulative growth, 2023–2025: 59.8%; half-year-series CAGR: 26.4%.

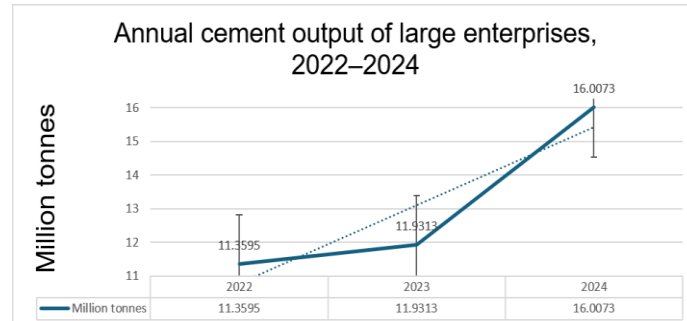


Figure 1. Annual cement output of large enterprises

Annual output increased by 571.8 thousand tonnes in 2023 and by a further 4,076.0 thousand tonnes in 2024. The 2024 increment was more than seven times the 2023 increment. Across 2022–2024, the industry added 4,647.8 thousand tonnes of annual production, equivalent to 40.9%. The CAGR of 18.7% confirms rapid expansion and supports H1 [6].

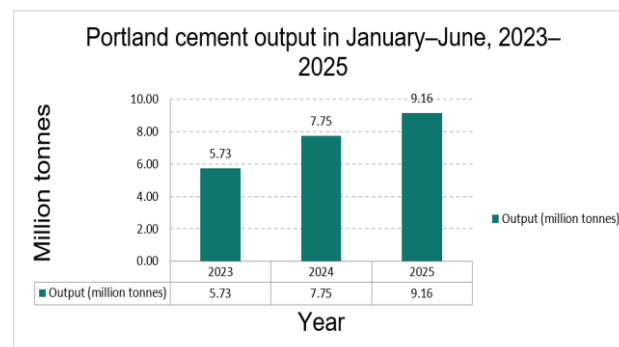


Figure 2. Comparable January–June Portland-cement output

The half-year series corroborates the annual trend. Output rose by 35.1% in 2024 and 18.2% in 2025. The two-year increase was 59.8%, although the growth rate moderated by 16.9 percentage points in 2025. The moderation should not be read as contraction: the absolute first-half increase remained 1,412.9 thousand tonnes [7].

Energy-efficiency evidence

Indicator	Reported change	Converted interpretation	Assessment
Sector production	1.2 times	20.0% increase	Expansion
Sector energy consumption	declined by a factor of 1.3	23.1% reduction	Relative/absolute energy saving as reported
Sector energy intensity	declined by a factor of 1.6	37.5% reduction	Strong efficiency gain
Heat-recovery potential	300 million kWh/year	Across 34 audited high-consuming enterprises	Average arithmetic potential: 8.82 million kWh per

Indicator	Reported change	Converted interpretation	Assessment
Qizilqumsement specific gas use	up to 13% reduction	Per tonne of clinker	audited enterprise; not a plant forecast Plant case
Qizilqumsement specific electricity use	up to 5% reduction	Per tonne of clinker	Plant case
Qizilqumsement annual electricity saving	37 million kWh	12.3% of the audited portfolio potential	Plant case versus portfolio benchmark

Note. The 8.82 million kWh average and 12.3% share are arithmetic derivations. Audit opportunities are heterogeneous, so the average must not be treated as a plant target.

The coexistence of a reported 20% rise in sectoral output and reductions in energy consumption and intensity provides descriptive support for H2. The energy-intensity improvement is especially important because it indicates that energy use per unit of production fell. However, without annual plant-level energy balances, the exact decomposition between technology, capacity utilisation, product mix and temporary operational factors cannot be identified [8].

The Qizilqumsement case supports H3. Modernisation of cyclone heat-exchange equipment reportedly reduced specific natural-gas consumption by up to 13% and electricity consumption by up to 5% per tonne of clinker, with 37 million kWh saved annually. The result demonstrates that process optimisation and heat recovery are not merely strategic intentions; they can generate measurable operational outcomes. Yet one enterprise cannot establish the national average treatment effect.

A useful robustness check can be obtained directly from the reported multiplicative factors. If sectoral output increased by a factor of 1.2 while energy intensity fell by a factor of 1.6, the implied change in total energy use is $1.2/1.6 = 0.75$, corresponding to an approximate 25.0% reduction [9]. This is close to the independently reported reduction in energy consumption by a factor of 1.3, equivalent to 23.1%. The difference of about 1.9 percentage points is small enough to be consistent with rounded sector-level reporting, differences in measurement boundaries or product composition. This internal arithmetic coherence strengthens the descriptive credibility of H2, although it does not identify the causal contribution of individual technologies [10].

Emissions profile and the decoupling constraint

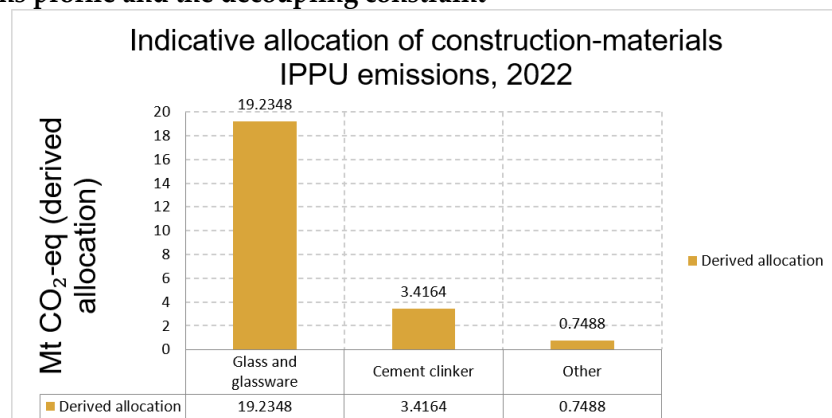


Figure 3. Indicative allocation of construction-materials IPPU emissions

Construction-materials IPPU emissions reached 23.4 Mt CO₂-eq in 2022. The reported source structure assigns 82.2% to glass and glassware and 14.6% to cement clinker. Applying these shares gives indicative allocations of 19.235 Mt CO₂-eq for glass and 3.416 Mt CO₂-eq for clinker, leaving 0.749 Mt CO₂-eq for other sources. These are derived allocations, not facility-level verified emissions.

The exploratory clinker-process proxy equals approximately 0.301 t CO₂-eq per tonne of cement output in 2022. Its main value is methodological: it illustrates the indicator that a future monitoring system should calculate with consistent clinker and cement denominators [11]. It cannot be compared across years until an annual emissions series is published on the same boundary.

Government reporting expects energy-saving dry-process technologies to reduce gas use by approximately 35–40% per tonne of cement and associates their expansion with a potential 0.699 Mt CO₂ reduction. This is an ex ante mitigation estimate, not an observed decline. Since output is rising rapidly and only one emissions year is available, absolute decarbonisation cannot be confirmed. H4 is therefore supported: efficiency progress is visible, but a rebound or scale effect may offset part of the environmental gain.

The scale effect can be quantified without assuming a future emissions value. Let total emissions be represented by $E = Q \times I$, where Q is cement output and I is emissions intensity per tonne of cement. With output increasing by 40.9% between 2022 and 2024, the emissions-intensity multiplier required merely to hold total emissions constant is $1/1.409 = 0.710$. In other words, carbon intensity would have to decline by at least 29.0% over the same period before absolute emissions could stop increasing. For the comparable January–June series, the 59.8% output increase implies an even more demanding break-even intensity reduction of 37.4%. These are decoupling thresholds, not observed carbon-intensity reductions [12].

Applying the same threshold logic to the 2022 clinker-process proxy of 0.301 t CO₂-eq per tonne of cement gives an illustrative break-even level of about 0.214 t CO₂-eq/t cement for 2024 under an unchanged accounting boundary. This calculation is deliberately counterfactual: no verified 2024 process-emissions intensity is available. Its policy significance is that thermal-efficiency gains alone are unlikely to deliver such a reduction because a substantial share of clinker emissions arises from limestone calcination rather than fuel combustion. Therefore, once kiln efficiency and waste-heat recovery are advanced, deeper decarbonisation must increasingly come from lowering the clinker factor, using suitable supplementary cementitious materials, switching to lower-carbon fuels and electricity, improving material efficiency, and ultimately controlling residual process emissions through carbon capture where technically and economically feasible [13].

Hypothesis outcomes

Hypothesis	Decision	Evidence	Causal strength
H1: rapid production expansion	Supported	Annual output +40.9%; comparable H1 output +59.8%	Descriptive, high confidence
H2: efficiency improves during expansion	Supported descriptively	Production $\times 1.2$; energy use $\div 1.3$; energy intensity $\div 1.6$	Aggregate association; no causal identification
H3: plant modernisation produces savings	Supported as a case	Gas -13% and electricity -5% per tonne; 37m kWh/year	Single-plant case

Hypothesis	Decision	Evidence	Causal strength
H4: efficiency alone cannot prove absolute decarbonisation	Supported	Only one consistent emissions year; output rising rapidly	Logical and data-availability test

Note. No p-values are reported because the available number of comparable annual observations is insufficient for valid inferential regression.

4. Discussion

Interpretation of the findings

The evidence reveals a dual transition: Uzbekistan is rapidly expanding domestic cement capacity while simultaneously improving operational energy performance. The economic rationale for expansion is clear—cement is a strategic intermediate input for housing, transport, utilities and industrial infrastructure. Yet the environmental test becomes progressively stricter as output rises. The correct benchmark is therefore not whether a plant uses less energy per tonne than before, but whether efficiency gains are large enough to offset the scale effect and place absolute emissions on a declining trajectory. This distinction is central for a fast-growing emerging economy, where successful industrialisation can otherwise overwhelm per-unit environmental improvements.

The reported sectoral pattern is consistent with strong energy decoupling. A 20% increase in output alongside a 37.5% reduction in energy intensity mathematically implies roughly 25% lower aggregate energy use, which closely matches the separately reported 23.1% fall [14]. This consistency is important because it suggests that the direction of the efficiency evidence is not driven by a single isolated indicator. However, energy decoupling is not equivalent to carbon decoupling. Cement-related carbon emissions have at least three distinct channels: process emissions from calcination, direct combustion emissions from kiln fuels, and indirect emissions associated with purchased electricity. Kiln upgrades primarily affect the second and third channels; they do not eliminate the chemical CO₂ released when limestone is transformed into clinker. A monitoring system that aggregates all three channels into one undifferentiated indicator would therefore conceal the mechanism of improvement and weaken policy targeting.

The finding that glass and glassware account for 82.2% of reported construction-materials IPPU emissions also changes the interpretation of sector policy. A cement-only decarbonisation strategy would address a strategically important subsector but would not address the largest reported process-emissions component of the broader industry [15]. The appropriate architecture is therefore a sector-wide construction-materials framework with technology-specific modules: clinker-factor reduction, kiln efficiency and alternative fuels for cement; furnace efficiency, cullet recovery, electrification and low-carbon power for glass; and material-efficiency standards across downstream construction. This portfolio approach reduces the risk of shifting emissions from one material or production stage to another.

Relationship with international evidence

The Uzbekistan evidence aligns with international research showing that kiln optimisation, modern dry-process technology and waste-heat recovery are among the most mature near-term options for reducing energy use, while deep decarbonisation requires a broader technology portfolio. The IEA's net-zero pathway emphasises energy and material efficiency and low-emissions fuels in the near term, but identifies alternative raw materials and carbon capture, utilisation and storage as necessary for deeper reductions in a sector constrained by process emissions. The 2025 Breakthrough Agenda assessment further notes that global cement emissions remain above 2015 levels and that direct emissions intensity has not yet begun the sustained decline required for net zero,

reinforcing the relevance of Uzbekistan's distinction between efficiency gains and absolute decarbonisation.

International studies also emphasise circularity and demand-side efficiency. Fly ash, slag, calcined clay, limestone and other suitable supplementary cementitious materials can reduce the clinker content of cement, but their technical value depends on mineralogy, consistency, logistics and product standards. Uzbekistan's policy documents already encourage secondary resources and large-tonnage technogenic waste; the missing element is a verified mass-balance system linking tonnes received, chemical composition, substitution rate, final product class and avoided emissions [16]. A second missing element is demand creation. International experience increasingly treats low-carbon public procurement, product-level carbon disclosure and performance-based standards as complements to plant investment, because producers have weaker incentives to incur transition costs if low-carbon cement receives no market recognition or price premium. For Uzbekistan, public infrastructure procurement could become an early lead market if carbon-intensity criteria are phased in only after robust measurement and domestic supply capability are established.

Decoupling arithmetic and transition risk

The decoupling-threshold calculations add a more demanding interpretation to the descriptive evidence. With annual cement output 40.9% higher in 2024 than in 2022, emissions intensity must decline by at least 29.0% simply to prevent absolute emissions from rising. This creates a 'moving target' for green modernisation: the faster the industry expands, the faster carbon intensity must fall. A policy that celebrates a 10–15% efficiency gain during a 30–40% production surge may therefore record technological progress while still allowing total emissions to increase. This is the core scale-risk facing rapidly industrialising construction-materials sectors [17].

The same logic also clarifies why the sequencing of mitigation matters. Energy-efficiency projects are attractive early measures because they often reduce production costs and natural-gas demand. However, their marginal abatement potential diminishes as plants approach modern thermal-efficiency benchmarks. At that point, continued emissions reductions depend increasingly on structural measures: a lower clinker-to-cement ratio, alternative fuels, low-carbon electricity, industrial symbiosis, material-efficient concrete design and, for residual process emissions, carbon capture. The transition is therefore best understood as a progression from operational efficiency to material substitution and finally to deep process decarbonisation, rather than as a single technology choice.

A staged green-modernisation pathway for Uzbekistan

For Uzbekistan, a staged pathway is more credible than a uniform requirement imposed simultaneously on all plants. Stage 1 should establish measurement discipline: plant-level MRV, metering, common system boundaries and disclosure of electricity intensity, thermal intensity, clinker factor and Scope 1–2 emissions. Stage 2 should prioritise commercially mature efficiency investments, including preheater and cooler optimisation, high-efficiency motors, waste-heat recovery, digital process control and preventive maintenance. Stage 3 should scale clinker substitution, alternative fuels and renewable electricity through standards, testing infrastructure and long-term supply contracts. Stage 4 should prepare for deep decarbonisation by assessing carbon-capture readiness, transport and storage options, and the financing architecture for technologies whose costs exceed conventional production.

This sequencing also has an institutional advantage. It links each policy instrument to the maturity of the relevant technology. Information and benchmarking are appropriate where measurement is weak; concessional finance is appropriate for proven but capital-intensive efficiency investments; standards and public procurement are appropriate when lower-carbon products are technically validated; and risk-sharing instruments become necessary for first-of-a-kind deep-decarbonisation projects. Such differentiation reduces

the probability that public support finances equipment purchases without verified performance and helps shift policy from input-based subsidies toward measured environmental outcomes.

A further consideration is energy security. Uzbekistan's wider climate strategy emphasises reducing energy intensity and pressure on natural-gas resources. In this context, gas savings from cement modernisation have a system value beyond plant-level cost reduction: saved gas can ease seasonal supply pressure or be redirected to higher-value uses, while waste-heat recovery can reduce electricity demand from the grid. Consequently, the economic appraisal of green cement projects should include not only avoided CO₂ but also avoided fuel use, peak-system relief, local air-quality co-benefits and resilience to future energy-price reform.

Scientific contribution and transferability

The article makes five contributions. First, it creates a transparent quantitative baseline from fragmented public evidence and prevents incompatible periods and accounting boundaries from being combined. Second, it distinguishes energy decoupling from carbon decoupling and shows why the two should not be treated as interchangeable in a clinker-based industry. Third, it introduces a simple decoupling-threshold calculation that converts production growth into the minimum carbon-intensity decline required to stabilise absolute emissions; for Uzbekistan's 2022–2024 output trajectory this threshold is 29.0%. Fourth, it performs an internal consistency check on reported output, energy-use and energy-intensity factors, strengthening the credibility of the descriptive evidence without claiming causality. Fifth, it translates the identified data gaps into an operational measurement and policy architecture that can be replicated in other emerging economies where industrial growth is rapid but plant-level environmental data remain incomplete.

Uzbekistan's cement industry expanded rapidly: annual output of large enterprises rose from 11.360 Mt in 2022 to 16.007 Mt in 2024, while comparable January–June Portland-cement output increased from 5.732 Mt in 2023 to 9.158 Mt in 2025. Official evidence simultaneously reports lower energy use and intensity, and the Qizilqumsement case demonstrates tangible plant-level savings. The reported energy indicators are internally coherent: a 1.2-fold rise in production combined with a 1.6-fold fall in energy intensity implies about 25% lower aggregate energy use, close to the separately reported 23.1% decline. Green modernisation is therefore producing credible efficiency benefits. However, output growth of 40.9% means that carbon intensity would need to decline by at least 29.0% merely to keep absolute emissions constant. Since 23.4 Mt CO₂-eq of construction-materials IPPU emissions were reported for 2022 and no consistent annual emissions series is available, absolute decarbonisation has not yet been demonstrated.

The following proposals convert the findings into measurable actions:

1. Create a mandatory digital measurement, reporting and verification (MRV) platform by 2027. Every cement and glass plant above a defined capacity threshold should report monthly clinker/cement output, fuel by type, electricity, heat recovery, direct process emissions, combustion emissions, waste inputs and water use. Annual data should be independently verified and published in aggregated and plant-benchmark form.
2. Adopt plant-level benchmarks. For cement, publish kWh of electricity per tonne of cement, GJ of thermal energy per tonne of clinker, t CO₂ per tonne of clinker, t CO₂ per tonne of cement, clinker-to-cement ratio and alternative-fuel rate. For glass, add energy per tonne of glass and cullet share.
3. Launch a 34-enterprise heat-recovery programme based on the reported 300 million kWh annual potential. Require investment-grade audits, prioritise projects by cost per saved kWh and verify savings for at least 24 months. The portfolio target should be staged—30% captured by 2028, 65% by 2030 and at least 90% by 2032—subject to technical validation.

4. Link concessional green finance and tax preferences to verified performance. Eligibility should depend on metered reductions rather than equipment purchase alone. A suggested threshold is at least a 10% reduction in specific energy use or a verified decline in carbon intensity against a three-year baseline.
5. Introduce a clinker-substitution roadmap. Establish standards and testing protocols for slag, fly ash, calcined clay and other locally suitable supplementary cementitious materials; publish the national clinker factor annually; and set differentiated targets after material-availability and quality studies.
6. Develop an industrial-symbiosis register. Record the origin, chemical characteristics, volume and destination of large-tonnage industrial by-products used in construction materials. This would create the missing quantitative basis for future circular-economy research.
7. Apply a two-part decarbonisation KPI: relative efficiency and absolute emissions. Sector performance should be judged simultaneously by declining t CO₂/t product and an emissions trajectory compatible with national climate commitments. This prevents rapid output growth from masking increases in total emissions.
8. Expand disclosure from cement to glass. Given the reported 82.2% share of glass and glassware in construction-materials IPPU emissions, furnace modernisation, cullet recovery, electrification and low-carbon power procurement require a dedicated programme.

Proposed monitoring scorecard

Indicator	Baseline requirement	Suggested 2030 direction	Responsible actors
Electricity intensity	kWh/t cement by plant	Continuous annual decline; ≥10% versus verified baseline for financed projects	Enterprises; energy regulator
Thermal intensity	GJ/t clinker by plant	Benchmark against best available domestic dry-process plants	Enterprises; industry association
Carbon intensity	t CO ₂ -eq/t clinker and t cement	Annual verified reduction	Enterprises; climate/environment authority
Absolute emissions	Scope 1 and Scope 2 t CO ₂ -eq	Published annual trajectory	Climate/environment authority
Clinker factor	t clinker/t cement	Declining, subject to product standards	Industry association; standards body
Secondary-material rate	t secondary inputs/t total inputs	Annual increase with quality control	Enterprises; waste authority
Recovered electricity/heat	kWh or GJ recovered	Capture audited technical potential	Enterprises; financing institutions

Note. The suggested directions are policy design proposals, not reported government commitments. Numeric plant targets should be finalised after a verified baseline audit.

5. Conclusion

Future studies should construct a plant-year panel for at least 2018–2030 and apply fixed-effects or difference-in-differences models to major modernisation projects. The dependent variables should include energy intensity, carbon intensity, absolute Scope 1–2 emissions, operating cost, productivity and profitability. Explanatory variables should include dry-process adoption, waste-heat recovery, alternative-fuel rate, clinker factor, renewable-electricity share and verified green-investment expenditure. A Logarithmic Mean Divisia Index (LMDI) or related index-decomposition framework could additionally separate activity, structural, energy-intensity and fuel-mix effects, making it possible to quantify how much of observed emissions change is attributable to production growth versus genuine technological improvement. Where installation dates are available, event-study specifications could test whether efficiency gains persist after modernisation rather than reflecting temporary capacity-utilisation effects. Such a panel would allow the relationship between green modernisation, environmental performance and firm competitiveness to be estimated causally rather than descriptively.

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Author contributions: To be completed according to the target journal's CRediT requirements.

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