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Comparative Life Cycle Assessment of Carbon Emissions and Circular Economy in Conventional and Geopolymer Precast Concrete

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Abstract: The construction sector accounts for approximately 37% of global carbon emissions, largely due to Portland cement production. Accelerated infrastructure development on Lombok Island has surged precast concrete demand, increasing the regional carbon footprint. This study compares the environmental impacts of conventional precast concrete against fly ash-based geopolymer concrete using Life Cycle Assessment (LCA) integrated with circular economy analysis. A cradle-to-gate boundary (Modules A1-A3) with a 1 m^3 functional unit of K-350 concrete was modeled in OpenLCA using the CML-IA method. Primary data came from a West Lombok precast producer; the geopolymer mix was literature-based. Results indicate the conventional precast footprint is 381.71 kg CO_2-eq/m^3, dominated by cement (90.40%). Substituting 90% cement with Jeranjang power plant fly ash reduced emissions by 49.15% to 194.10 kg CO_2-eq/m^3, despite burden shifting to alkali activators (66.86% contribution). Binder circularity achieved 90%, with a fly ash supply-to-demand ratio of ~530%. A 2025–2029 projection shows potential avoidance of 20,027 tons CO_2-eq and absorption of 27,179 tons of fly ash. Sensitivity analysis confirms model robustness (±0.14%). Transitioning to geopolymer concrete is a highly recommended decarbonization strategy for West Nusa Tenggara.

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INTRODUCTION

The construction sector is one of the main pillars of economic development, yet its operations heavily rely on an unsustainable linear economic model. A recent report by the global alliance for buildings and construction indicates that this sector is responsible for approximately 34% of global energy demand and 37% of energy-related carbon dioxide (CO_2) emissions (United Nations Environment Programme, 2022). Cement production, a vital component of concrete, is identified as one of the largest industrial emission sources, contributing around 7% of total global anthropogenic CO_2 emissions (Andrew, 2019; International Energy Agency, 2023). This condition places the decarbonization of the construction sector as an urgent agenda, aligning with Indonesia's commitment to achieving Net Zero Emission (NZE) by 2060 (Kementerian Lingkungan Hidup dan Kehutanan, 2021).

These issues are clearly reflected in Lombok Island, which is currently experiencing massive accelerated infrastructure development. Strategic projects such as the Mandalika Special Economic Zone (KEK Mandalika) and other supporting infrastructures have exponentially increased the demand for construction materials, particularly precast concrete, chosen for its time efficiency, quality control, and production scalability. This surge in demand brings the consequence of an increased regional

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carbon footprint due to Portland cement-based concrete production—an environmental impact that has not been specifically quantified for the Lombok Island context.

The transition towards a circular economy offers a comprehensive solution framework: redesigning industrial systems to eliminate waste and keep materials in high-value use cycles (Ellen MacArthur Foundation, 2021). Geopolymer concrete is a relevant implementation of the circular economy, utilizing industrial by-products like fly ash as an aluminosilicate precursor chemically activated to form a cement substitute binder (Nagaraju et al., 2023). The availability of fly ash from power plants on Lombok Island, such as the Jeranjang Power Plant, presents a strategic opportunity to implement this circular model.

Various global LCA studies confirm the significant emission reduction potential of geopolymer concrete compared to conventional concrete, with reduction ranges varying depending on mix formulation, precursor source, and local energy mix. Bianco et al. (2021) reported a Global Warming Potential (GWP) reduction of up to 70% using waste glass-derived activators; Shi et al. (2021) reported a 62.73% reduction in China; and Meshram & Kumar (2022) achieved a 70% reduction in India using a combination of fly ash and GGBFS. Several studies consistently identify that the emission hotspot shifts from cement production in OPC concrete to alkali activator production (Sodium Silicate and Sodium Hydroxide) in geopolymer concrete—a phenomenon known as burden shifting (Bajpai et al., 2020; Passuello et al., 2017; Salas et al., 2018; Tang et al., 2021). Imtiaz et al. (2021), using the OpenLCA methodology with the CML method identical to this study, reported a 53.7% GWP reduction but also found increased impacts in the Human Toxicity and Ozone Depletion categories due to the chlor-alkali electrolysis process in NaOH production—an important warning that a single evaluation on GWP risks hiding other environmental trade-offs (Sbahieh et al., 2023). In the Indonesian context, Petrus et al. (2022) examined the industrial symbiosis between power plant fly ash and geothermal silica as geopolymer precursors, while Agustiningtyas et al. (2025) published a life cycle inventory of cement and ready-mix concrete production specific to Indonesia, whose OPC cement emission factor (0.910 kg CO_2-eq/kg) is used as a key input in this study.

Although the scientific consensus on the GWP advantages of geopolymer concrete is well-established, significant research gaps remain. First, the majority of studies have not integrated LCA analysis with quantitative circularity metrics based on ISO 14021 and EN 15804+A2 within a cohesive analytical framework. Second, existing studies are generally conducted in developed countries with generic LCI databases for alkali activators and electricity grids; applying these to developing countries like Indonesia—where the Lombok electricity grid emission factor is 1.610 kg CO_2-eq/kWh, much higher than the European grid—potentially yields inaccurate conclusions. Third, no study has holistically examined the application of geopolymer concrete on Lombok Island from simultaneous LCA and circular economy perspectives across a multi-year projection scenario. This study fills these gaps by integrating LCA and Recycled Content indicators using industrial secondary data from a precast producer on Lombok Island—to the authors' knowledge, the first study to quantify the precast sector's carbon footprint in this region and perform contextual sensitivity analysis to test result robustness.

The novelty of this study therefore lies in three aspects that distinguish it from prior LCA-geopolymer research: (1) it is the first application-level integration of cradle-to-gate LCA with quantitative circularity indicators (ISO 14021) for precast concrete in the Indonesian archipelagic context; (2) it replaces generic European LCI proxies with a site-specific local electricity grid factor

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(1.610 kg CO_2-eq/kWh) and actual industrial mix-design data from a Lombok producer, rather than relying solely on literature-based assumptions; and (3) it links single-unit LCA results to a multi-year regional supply-demand projection, offering decision-relevant evidence for local policy rather than a laboratory-scale comparison alone.

Based on this rationale, this study aims to: (1) calculate the carbon footprint of the cradle-to-gate production cycle of conventional precast concrete on Lombok Island; (2) compare it with the circular economy-based geopolymer concrete alternative; (3) identify emission hotspots in both production systems; (4) analyze the circular economy potential of utilizing fly ash waste; and (5) model the projection of total carbon emissions for the precast concrete sector on Lombok Island under a business-as-usual (BAU) scenario and circular model adoption (CE) over the 2025-2029 period.

RESEARCH METHOD

Research Type and Approach

This research is a descriptive-comparative study employing a quantitative approach based on modeling studies. Descriptively, the study maps the environmental impacts and material flows of the existing conventional precast concrete production process on Lombok Island. Comparatively, the baseline scenario modeling results (conventional concrete/BAU) are compared with the proposed scenario (geopolymer concrete/CE) to evaluate potential environmental and circular economy improvements.

Location and Data Sources

The research location is Lombok Island, with the sample object focused on one medium-to-large scale precast concrete producer facility in West Lombok Regency, selected through purposive sampling based on the depth over breadth principle, considering that detailed operational data access is more challenging to obtain than multi-producer coverage. The fly ash precursor source was obtained from the Jeranjang Power Plant (3×25 MW) in Gerung, West Lombok, which has operated optimally for over 5 years. Fly ash availability data were obtained from two sources for triangulation: institutional secondary data from PLN Indonesia Power (±28,800 Tons/year) and literature secondary data from Dewi et al. (2024) amounting to 24,960 Tons/year. All supply availability analyses in this study utilize the institutional data as a baseline because it originates directly from the facility manager.

Object, Functional Unit, and System Boundary

The material objects of the study focus on structural precast elements U-Ditch and Box Culvert with a grade equivalent to K-350. The functional unit is defined as 1 m^3 of concrete with a compressive strength equivalent to K-350 (30 MPa), serving as an equal basis of comparison across scenarios. The system boundary is set as cradle-to-gate (Modules A1-A3 according to EN 15804), encompassing raw material supply (A1), raw material transportation to the plant (A2), and the manufacturing process at the plant (A3). Modules A4 to D are excluded as they are assumed identical across scenarios and thus do not affect the comparison results. The analyzed impact category is limited to Global Warming Potential (GWP, kg CO_2-eq) using the CML-IA baseline characterization method. Steel reinforcement and chemical admixtures are excluded from the system boundary as they are assumed identical in both scenarios.

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The CML-IA baseline method and OpenLCA software were selected because both are widely validated, transparent, and reproducible tools consistent with ISO 14040/14044 requirements, and because CML-IA's midpoint characterization for GWP allows direct comparability with the majority of geopolymer LCA studies cited in this paper (e.g., Imtiaz et al., 2021; Shi et al., 2021), facilitating benchmarking of results. The cradle-to-gate (A1-A3) boundary was adopted rather than a full cradle-to-grave analysis because reliable use-phase and end-of-life data (e.g., carbonation uptake, demolition and recycling pathways) are not yet available for Indonesian precast infrastructure, and because the production stage is where the two scenarios differ most significantly. It should be noted that this study relies on secondary data for several inventory items (fly ash characteristics from literature, and generic LCI proxies for chemical activators and aggregates) and on primary data from a single purposively selected producer; these choices, made necessary by current data availability constraints in the region, are discussed further as limitations in the final section.

Data Collection and Inventory Modeling (LCI)

Primary and secondary industrial data were collected through LCI questionnaires and official data request letters to the precast producer, covering standard mix designs, monthly energy consumption (electricity and diesel), total monthly production, and material transportation distances. Table 1 presents the comparison of the K-350 mix design composition for both scenarios.

Table 1. Mix Design Composition Comparison of K-350 Concrete (BAU vs CE Scenarios)

Component	Unit	BAU	CE
Portland Cement (OPC)	kg/m³	370.37	28.29
Class F Fly Ash	kg/m³	–	254.60
Sodium Hydroxide (NaOH), solid	kg/m³	–	25.12
Sodium Silicate (Na_2SiO_3), solid	kg/m³	–	52.92
Water for activator solvent / mixture	kg/m³	200.00	121.96
Fine Aggregate (Natural Sand)	kg/m³	782.63	670.99
Coarse Aggregate (Crushed Stone)	kg/m³	992.00	1.246.12

Source: AHSP Cipta Karya 2026, Appendix VI; geopolymer mix design modeling results based on the regression equation of Pavithra et al. (2016) (CE). AAS = Alkaline Activator Solution.

In the CE Scenario, the geopolymer mix design was developed by substituting 90% of Portland cement with Class F fly ash (ASTM C618) from the Jeranjang Power Plant. The ratio of Alkaline Activator Solution to total precursors (AAS/Precursor) was set at 0.707 based on a regression equation f'c = 20.352 × (AAS/Precursor)^(−1.119) developed by Pavithra et al. (2016) to achieve the target compressive strength of 30 MPa (K-350). The alkaline activator solution consisted of 10M Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) with a mass ratio of 1.5, which falls within the optimal range reported in the literature (Ghafoor et al., 2025; Hardjito & Rangan, 2005; Yahya et al., 2015). The curing process was assumed to occur at room temperature (ambient curing) for both scenarios, utilizing Lombok's tropical climate conditions (29°C-32°C) without artificial heating (Nurruddin et al., 2018).

Secondary data from LCI databases (adapted ELCD/US LCI) and Environmental Product Declaration (EPD) documents were utilized for the production processes of Portland Cement, NaOH, Na_2SiO_3, the Indonesian electricity grid, aggregates, and diesel fuel (Table 2). In accordance with the

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EN 15804 allocation principles, fly ash is categorized as a specific waste (cut-off), meaning the emission burden of coal combustion at the power plant is not allocated to the fly ash product; the system boundary for fly ash begins at the collection point at the power plant, and only its transportation emissions are accounted for.

Table 2. Emission Factors of Key Materials and Processes in LCI Modeling

Material/Process	Emission Factor	Unit	Source
Portland Cement (OPC)	0.910	kg CO_2-eq/kg	Agustiningtyas et al. (2025)
Fly Ash (cut-off principle)	0.000	kg CO_2-eq/kg	ISO 14044; EN 15804+A2
Sodium Hydroxide (NaOH)	1.915	kg CO_2-eq/kg	Turner & Collins (2013)
Sodium Silicate (Na_2SiO_3)	1.514	kg CO_2-eq/kg	Turner & Collins (2013)
Natural Aggregate (sand & crushed stone)	0.005	kg CO_2-eq/kg	EPD Italy No. 0452 (2022); EPD York Aggregates (2025)
PLN Electricity (Lombok local grid)	1.610	kg CO_2-eq/kg	Ditjen Ketenagalistrikan ESDM (2019)
Diesel fuel	3.186 (≈2.68/L)	kg CO_2-eq/kg	IPCC (2006)

Modeling and Impact Assessment (LCIA)

All LCI data were modeled using OpenLCA software (GreenDelta) with the CML-IA characterization method to calculate the GWP value per functional unit in the BAU and CE Scenarios. Module A2 (transportation) was modeled using a bottom-up approach based on fuel consumption, with a logistics efficiency of 0.03 liters/t.km for truck modes and 0.008 liters/t.km for cargo ship modes (Spielmann et al., 2007). In the BAU Scenario, cement is transported multi-modally over a total of 673.5 km (land-sea-land) from South Kalimantan through Lembar Port, while in the CE Scenario, fly ash only travels 14 km from the Jeranjang Power Plant to the factory. Alkali activators (NaOH and Na_2SiO_3) are assumed to be sourced from chemical industrial zones in East Java, traveling 551-779.5 km via land and sea routes. A hotspot analysis was conducted to identify the processes or materials with the largest emission contributions in each scenario.

Scenario Development and Projections (2025-2029)

Cumulative impact projections were developed for a five-year horizon (2025-2029) by multiplying the impact factor per functional unit (LCIA results) by the projected annual product demand. The demand projection is derived from Lombok Island's population growth rate of 1.435%/year (BPS NTB), assuming precast element demand growth is directly proportional to population growth, with a baseline production in 2025 of 20,746 m^3. Two projection scenarios were modeled separately: the BAU Scenario (entire demand is met by conventional concrete) and the CE Scenario (entire demand is met by geopolymer concrete), to estimate the maximum emission mitigation potential of a full transition.

Circular Economy Analysis

Binder circularity was calculated based on the Recycled Content indicator (ISO 14021:2016; EN 15804+A2), which is the proportion of secondary material (fly ash) to the total binder material mass (fly ash + cement). A supply-demand gap analysis was conducted by matching the fly ash supply data

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from the Jeranjang Power Plant with the projected demand of the precast industry to evaluate the quantitative feasibility of the proposed industrial symbiosis model and identify potential utilization of surplus in other sectors.

Sensitivity Analysis

In accordance with ISO 14044, the validity of the model using partial proxy data was tested through a one-at-a-time sensitivity analysis. The parameter tested was the Portland Cement land transportation distance in the BAU Scenario (baseline 18.5 km), with two extreme scenarios: a +50% distance increase (27.75 km) and a -50% distance decrease (9.25 km), to evaluate the model's robustness against transportation data uncertainties.

RESULTS AND DISCUSSION

Production Profile and Data Inventory

The surveyed producer (hereafter referred to as Producer A) manufactures K-350 grade U-Ditch and Box Culvert with annual volumes as presented in Table 3.

Table 3. Annual Production Volume of Precast Concrete Producer A (m^3/Year)

Year	U-Ditch K-350 (m^3)	Box Culvert K-350 (m^3)	Total (m^3)
2023	14,745.75	4,915.25	19,661.00
2024	4,616.25	1,538.75	6,155.00
2025	15,559.50	5,186.50	20,746.00

Plant energy consumption was recorded at 49,836 kWh of PLN electricity and 60,000 liters of diesel per year for batching plant and heavy equipment operations (Table 4), equivalent to a specific consumption of 2.40 kWh/m^3 and 2.89 liters/m^3 based on the total production in 2025.

Table 4. Annual Plant Energy and Utility Consumption

Type of Energy/Utility	Total Annual Consumption	Specific Consumption
PLN Electricity	49,836 kWh	2.40 kWh/m^3
Diesel fuel (heavy equipment)	60,000 Liters	2.89 Liters/m^3
Operational clean water	–	50 Liters/m^3

Characterization and Emission Hotspots of BAU Scenario

The OpenLCA simulation results show that the total GHG emissions for the BAU Scenario amount to 381.71 kg CO_2-eq per m^3 of precast concrete, dominated by Module A1/upstream material supply (91.21%), followed by Module A2/transportation (5.02%) and Module A3/plant utilities (3.77%). Component-level contribution analysis (Table 5) confirms that the production and transportation of Portland Cement serve as the absolute hotspot, contributing 345.05 kg CO_2-eq or 90.40% of the total emissions—far exceeding the contributions of crushed stone (2.93%), heavy equipment operations (2.76%), natural sand (2.31%), electricity (1.01%), and water (0.59%). These findings align with previous studies that consistently identify cement clinker production as the dominant emission source in OPC concrete (Bajpai et al., 2020; Salas et al., 2018).

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Table 5. GWP Emission Contribution of BAU Scenario (Conventional Concrete) per Component

Component	Emissions (kg CO_2-eq/m^3)	Contribution (%)
OPC Cement (production + transportation)	345.05	90.40
Crushed stone (production + transportation)	11.19	2.93
Heavy equipment operations (diesel)	10.52	2.76
Natural sand (production + transportation)	8.83	2.31
Operational electricity	3.86	1.01
Water	2.25	0.59
Total	**381.71**	**100.00**

Characterization and Emission Hotspots of CE Scenario

Substituting 90% of cement with fly ash in the CE Scenario reduced total emissions to 194.10 kg CO_2-eq per m^3, with Module A1 remaining dominant but shrinking in proportion to 85.06% (Module A2: 7.52%; Module A3: 7.41%). The component contribution analysis (Table 6) reveals a fundamental shift in hotspot composition: Sodium Silicate became the largest contributor (81.17 kg CO_2-eq; 41.82%), followed by Sodium Hydroxide (48.61 kg CO_2-eq; 25.04%), bringing the combined contribution of both alkali activators to 66.86% of total emissions. The remaining 10% OPC cement contributed 13.58%, while fly ash itself—treated as a burden-free material (cut-off) according to EN 15804—only contributed 0.21%, entirely derived from transportation over 14 km. Figure 1 visualizes the comparison of component contributions in both scenarios.

Table 6. GWP Emission Contribution of CE Scenario (Geopolymer Concrete) per Component

Component	Emissions (kg CO_2-eq/m^3)	Contribution (%)
Sodium Silicate (production + transportation)	81.17	41.82
Sodium Hydroxide (production + transportation)	48.61	25.04
OPC Cement 10% (production + transportation)	26.36	13.58
Crushed stone (production + transportation)	14.05	7.24
Heavy equipment operations (diesel)	10.52	5.42
Natural sand (production + transportation)	7.57	3.90
Operational electricity	3.86	1.99
Water	1.55	0.80
Fly ash (transportation only)	0.41	0.21
Total	**194.10**	**100.00**

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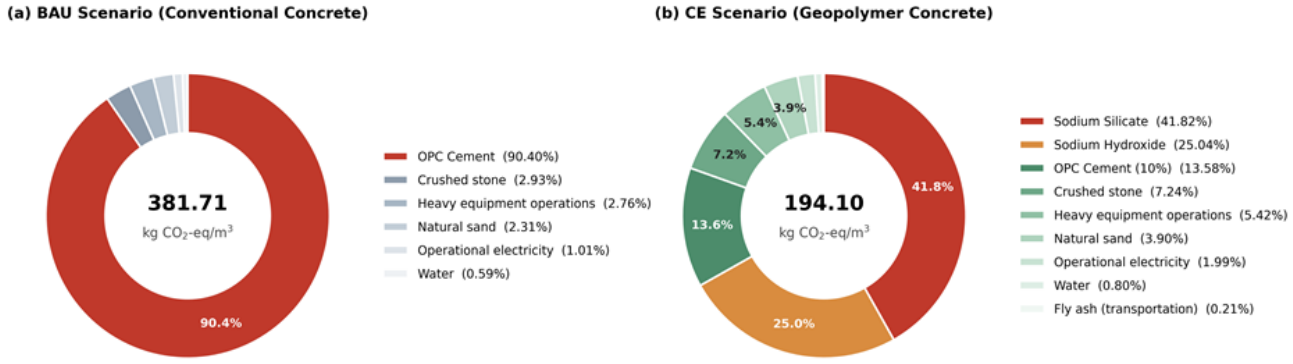

Figure 1. Component contribution to GWP emissions per 1 m³ precast concrete: (a) BAU Scenario, (b) CE Scenario.

Comparative Analysis and Burden Shifting

Table 7 summarizes the direct comparison of both scenarios per component. The transition from BAU to CE reduced emissions by 187.61 kg CO_2-eq/m³ or 49.15%, primarily driven by a 318.69 kg CO_2-eq reduction in cement emissions (-92.36%). However, this reduction was offset by the emergence of a new burden from alkali activators amounting to 129.78 kg CO_2-eq. Figure 2 shows the emission comparison per life cycle module, confirming that the emission decrease primarily occurs in Module A1 (348.16 → 165.11 kg CO_2-eq), Module A2 decreases moderately (19.15 → 14.60 kg CO_2-eq) due to a shorter binder supply chain, while Module A3 remains unchanged as plant energy consumption is assumed identical in both scenarios.

Table 7. Comparison of Emission Components Between BAU vs CE Scenarios and Burden Shifting Indications

Component	BAU (kg CO_2-eq/m³)	CE (kg CO_2-eq/m³)	Difference	Remarks
OPC Cement	345.05	26.36	-318.69	Reduction
Alkaline activator (NaOH + Na_2SiO_3)	–	129.78	+129.78	New burden
Crushed stone	11.19	14.05	+2.86	New burden
Heavy equipment operations	10.52	10.52	0.00	Unchanged
Natural sand	8.83	7.57	-1.26	Reduction
Electricity	3.86	3.86	0.00	Unchanged
Water	2.25	1.55	-0.70	Reduction
Fly ash (transportation)	–	0.41	+0.41	New burden
Total	**381.71**	**194.10**	**-187.61**	**49,15% Reduction**

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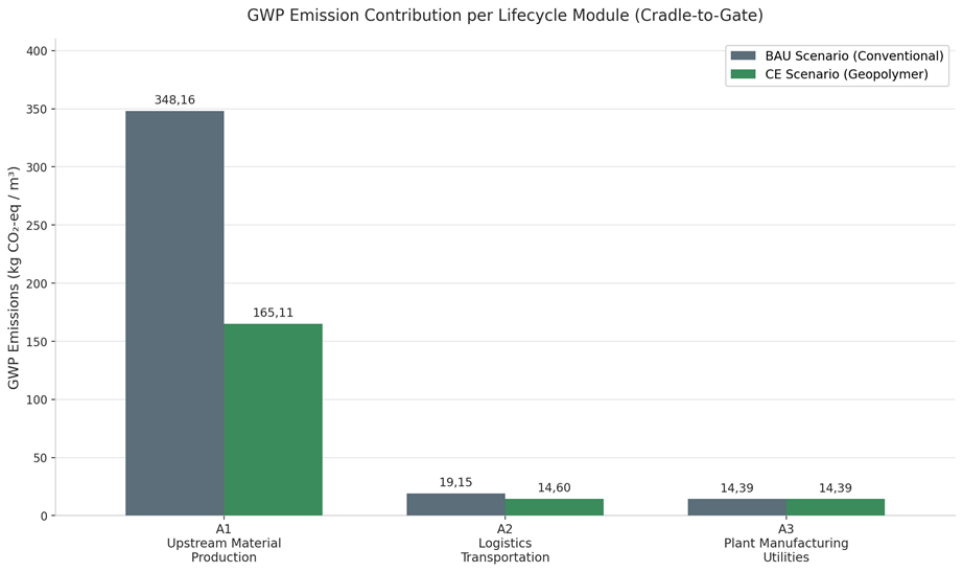

Figure 2. Comparison of GWP emissions per life cycle module (cradle-to-gate) between BAU and CE Scenarios.

This 49.15% reduction value falls below the ranges reported by international studies, such as Shi et al. (2021) who reported a 62.73% reduction in China and Meshram & Kumar (2022) who achieved 70% in India. This difference can be explained by two contextual factors: first, this study utilized a 90% partial substitution (instead of 100%) to ensure mechanical performance under ambient curing conditions without external heating; second, the sea transportation emissions of alkali activators over 503 km from Java added a burden not found in studies with geographically integrated chemical industry infrastructures. Thus, the 49.15% figure reflects a realistic and relatively conservative estimate for the Indonesian archipelagic context.

The burden-shifting phenomenon found in this study is consistent with global findings (Bajpai et al., 2020; Passuello et al., 2017; Salas et al., 2018; Tang et al., 2021). Findings by (Imtiaz et al., 2021) indicating increased impacts in the Human Toxicity and Ozone Depletion categories due to the electrolysis process of NaOH production suggest that evaluations limited to GWP risk presenting an incomplete picture of sustainability—a limitation inherent to this study that constitutes an important direction for future research.

Binder Circularity and Supply Chain Resilience

Based on the Recycled Content indicator (ISO 14021:2016), the BAU Scenario has a 0% circularity rate as it entirely relies on Portland cement, while the CE Scenario achieves a 90% binder circularity, with 254.6 kg of fly ash per m^3 replacing the need for cement previously imported to Lombok Island. This transition also alters the binder supply chain characteristics from vulnerable (import-dependent, 673.5 km multi-modal) to regionally resilient (locally-resilient, 14 km land-based), reducing binder transportation emissions by 94.88% (from 8.01 to 0.41 kg CO_2-eq). This supply chain resilience is a strategic added value not captured in GWP figures alone but highly relevant for infrastructure planning in archipelagic regions like West Nusa Tenggara.

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Practical Implications and Implementation Challenges

These findings carry direct implications for the local construction industry. From a practical standpoint, precast producers on Lombok Island could adopt fly ash-based geopolymer mix designs without additional raw-material sourcing risk, given the substantial local fly ash surplus identified in this study, potentially positioning early adopters competitively as regional carbon-reporting requirements tighten. However, several implementation challenges remain. First, geopolymer concrete typically requires more stringent quality control of activator dosing and mixing time than OPC concrete, which may require additional operator training and process adjustment at the plant level. Second, the absence of an Indonesian National Standard (SNI) specifically governing geopolymer concrete design and testing creates regulatory uncertainty for structural applications, particularly in government-funded infrastructure projects that mandate SNI compliance. Third, the alkali activators remain sourced from outside the region (East Java), so their price volatility and supply-chain exposure should be considered when evaluating economic feasibility alongside the environmental benefits demonstrated here. Addressing these barriers through pilot-scale trials, activator supply-chain localization studies, and engagement with standardization bodies would support wider industrial adoption of the circular model proposed in this study.

Macro Projections and Fly Ash Supply Gap Analysis (2025-2029)

Assuming a precast demand growth of 1.435%/year, full adoption of the CE Scenario during the 2025-2029 period is projected to prevent an accumulation of 20,027.40 Tons CO_2-eq and absorb 27,179.29 Tons of fly ash waste from the Jeranjang Power Plant (Table 8; Figure 3). From a circular economy perspective, this fly ash volume indicatively substitutes the need for 36,517.49 Tons of imported cement during the projection period.

Table 8. Projected Production Volume, Emission Reduction, and Fly Ash Supply Balance (2025-2029)

Year	Precast Concrete Demand (m^3)	Avoided CO_2 Emission (Ton)	Utilized Fly Ash (Ton)	FA Supply Surplus (Ton)*
2025	20,746	3,892.13	5,282.02	23,517.98
2026	21,044	3,948.03	5,357.90	23,442.10
2027	21,346	4,004.69	5,434.79	23,365.21
2028	21,652	4,062.10	5,512.70	23,287.30
2029	21,963	4,120.45	5,591.88	23,208.12
Total	106,751	20,027.39	27,179.29	116,820.71

**The surplus is calculated from PLN Indonesia Power's institutional supply of ±28,800 tons/year minus the projected absorption by the precast industry.*

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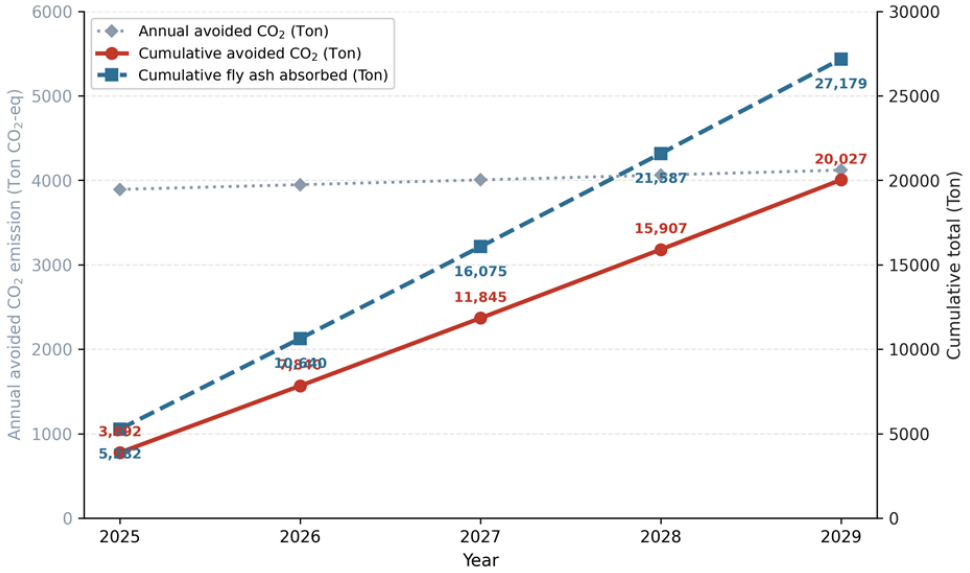

Figure 3. Cumulative projection of CO_2 emission reduction and fly ash absorption for the 2025-2029 period.

The supply-demand gap analysis shows that precast industry fly ash requirements range from 5,282-5,592 Tons/year, far below the available supply of ±28,800 Tons/year from the Jeranjang Power Plant, generating an average supply-to-demand ratio of ±530% and a cumulative surplus of ±116,821 Tons during the projection period. These findings confirm that the implementation feasibility of the CE Scenario on Lombok Island is not threatened by raw material shortage risks, while indicating opportunities to utilize surplus fly ash in other construction sectors such as soil stabilization, mortars, and non-structural concrete.

Sensitivity Analysis

Varying the cement land transport distance by ±50% (from a baseline of 18.5 km to 27.75 km and 9.25 km) only shifted the BAU Scenario's total GWP by ±0.14% (Table 9), from 381.71 kg CO_2-eq to 382.24 kg CO_2-eq (+50% scenario) and 381.19 kg CO_2-eq (-50% scenario). These results prove that the research model is robust against uncertainties in land transportation data, meaning the conclusion regarding the CE Scenario's superiority over BAU—a 49.15% emission reduction—remains undeniable even under conditions of significant logistical inefficiency.

Table 9. Sensitivity Analysis Results of Cement Transportation Distance Parameter

Scenario	Land Transportation Distance (km)	Total GWP (kg CO_2-eq/m^3)	Deviation from Baseline (%)
Baseline	18.50	381.71	0.00
Distance +50%	27.75	382.24	+0.14
Distance -50%	9.25	381.19	-0.14

Research Limitations

Several important limitations must be considered when interpreting and generalizing these findings, and readers are advised to treat the results as indicative of one representative facility rather than the entire regional industry. First, primary industrial data were sourced from a single, purposively

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selected producer rather than a multi-producer sample; while this choice enabled data depth (detailed mix designs, energy records, and transport logistics), it also means the results are not statistically representative of all precast producers on Lombok Island and should be validated against additional facilities in future work. Second, the characteristics of Jeranjang Power Plant's fly ash are based on literature secondary data (Dewi et al., 2024) without direct XRF/XRD testing. Third, this study utilizes adapted proxy LCI databases (ELCD/US LCI), given the absence of comprehensive Indonesia-specific databases. Fourth, the analysis is limited to the GWP impact category and production phase (cradle-to-gate), thus excluding other impact categories (acidification, eutrophication, abiotic depletion) as well as environmental benefits during the use phase (carbonation) and end-of-life.

CONCLUSION

This study concludes with three main findings. First, regarding the emissions comparison, the cradle-to-gate carbon footprint of conventional precast concrete (BAU Scenario) on Lombok Island is 381.71 kg CO_2-eq/m^3, dominated by Portland cement (90.40%); substituting 90% of cement with fly ash (CE Scenario) reduces this footprint to 194.10 kg CO_2-eq/m^3, a 49.15% reduction, despite an emerging burden shift to alkali activators (66.86% combined contribution). Second, regarding the circular economy contribution, the CE Scenario achieves 90% binder circularity and is supported by a local fly ash supply-to-demand ratio of approximately 530%, confirming that surplus fly ash from the Jeranjang Power Plant can sustain full industrial adoption without material shortage risk over the 2025-2029 projection period, during which 20,027 tons of CO_2-eq could be avoided and 27,179 tons of fly ash absorbed. Third, regarding implications for low-carbon construction development, these results position fly ash-based geopolymer precast concrete as a technically feasible and locally resilient decarbonization pathway for West Nusa Tenggara, supporting Indonesia's 2060 Net Zero Emission target; future research should prioritize optimizing activator molarities to reduce the identified burden-shifting effect, developing Indonesia-specific LCI databases, and integrating Life Cycle Cost Analysis to evaluate economic feasibility alongside the environmental benefits demonstrated here.

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