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Economic Cost and Environmental Benefit Assessment of Green Construction Projects under the Global Carbon Neutrality Context

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Abstract: This study critically examines the economic costs and environmental benefits of green construction projects within the accelerating global push toward carbon neutrality. Drawing on a systematic synthesis of empirical evidence from 2015 to 2024, alongside original analysis of twelve benchmark projects across Europe, East Asia, and Latin America, the research moves beyond narrow cost-premium narratives to develop an integrated, context-sensitive assessment framework. The proposed methodology harmonizes lifecycle cost modeling, standardized life cycle assessment, and spatially explicit ecosystem service valuation—calibrated through stakeholder-informed weighting and robust uncertainty testing. Findings reveal that green construction delivers net positive value in most settings, but only when embedded within supportive policy ecosystems: median operational payback occurs within five years, while lifecycle net benefit is strongly correlated with national policy stringency rather than technological sophistication alone. Crucially, carbon abatement accounts for less than half of total environmental value; water conservation and urban ecosystem services—such as heat island mitigation and stormwater management—emerge as equally significant, particularly in climate-vulnerable cities. Cost premiums, averaging 3–6 percent globally, are found to be highly mutable: certification inefficiencies and underutilization of prefabrication contribute substantially to avoidable expenditures, whereas digital twin-enabled commissioning and modular design consistently reduce these surcharges by several percentage points. The analysis further exposes persistent valuation gaps—especially in monetizing non-market benefits and capturing systemic spillovers like grid decarbonization feedbacks or supply chain transformations. Ultimately, the paper argues against universal cost-benefit benchmarks and advances the concept of 'contextual net benefit', urging policymakers to adopt tiered procurement standards, integrate dynamic carbon pricing into tender evaluations, and institutionalize standardized protocols for valuing ecological co-benefits in public infrastructure.

Keywords: green construction; carbon neutrality; lifecycle cost; environmental benefit; ecosystem services; policy stringency; integrated assessment

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1. Introduction: Green Construction in the Carbon Neutrality Imperative

1.1. Global Carbon Neutrality Commitments and Construction Sector Accountability

The construction sector stands at a critical inflection point in the global pursuit of carbon neutrality, accounting for nearly 40 percent of annual energy-related CO₂ emissions and over 35 percent of final energy demand worldwide. Recent assessments by international climate science bodies underscore that limiting warming to 1.5C necessitates immediate, deep decarbonization across all building lifecycle stages—from material extraction and manufacturing through construction, operation, and end-of-life management. In response, over 140 nations have formalized net-zero commitments, with many explicitly naming buildings and infrastructure as priority intervention domains within their nationally determined contributions. This policy momentum elevates green construction beyond a voluntary sustainability practice to a systemic accountability

mechanism: one that integrates low-carbon materials, energy-efficient design, renewable energy integration, and circular resource flows [1]. Crucially, decarbonization here is not merely about reducing operational emissions; it demands recalibrating upstream industrial processes, rethinking urban form, and embedding ecological performance metrics—such as stormwater retention capacity, urban heat island mitigation, and biodiversity support—into project valuation frameworks [2]. As national policy architectures evolve from aspirational targets toward binding regulatory instruments, the construction industry's role shifts from passive compliance to active co-production of climate-resilient, resource-optimized built environments [3, 4].

1.2. Defining Economic Cost and Environmental Benefit in Context

Economic cost and environmental benefit constitute two analytically distinct yet interdependent dimensions of green construction evaluation, each requiring precise conceptual anchoring within the carbon neutrality imperative [5]. Economic cost encompasses capital expenditure, lifecycle cost—including operational energy, maintenance, and end-of-life disposal—and financing premiums arising from certification requirements or perceived risk. Environmental benefit, conversely, extends beyond carbon abatement to encompass quantifiable energy and water savings, reductions in embodied emissions, and non-market ecological co-benefits such as urban heat island mitigation, stormwater retention, and localized biodiversity enhancement. Critically, neither dimension admits universal metrics: cost premiums average 3–6 percent globally but vary significantly across geographies due to labor productivity, material supply chains, and regulatory efficiency; similarly, environmental value is contextually modulated by climate vulnerability, hydrological stress, and urban density. Policy regimes further recalibrate these relationships—stringent national decarbonization frameworks compress payback periods and amplify net environmental returns, while fragmented or incentive-poor environments inflate relative costs without commensurate benefit realization [6]. Thus, assessment must reject static benchmarks in favor of dynamic, spatially embedded valuation that reflects local biophysical conditions and institutional capacity [7, 8].

1.3. Scope, Objectives, and Structural Roadmap

This paper defines its analytical scope to encompass certified green construction projects—specifically those achieving LEED, BREEAM, or China 3-Star certification—across both OECD and emerging economies [9, 10]. It excludes non-certified sustainable practices and non-infrastructure building typologies to ensure methodological coherence and comparability [10]. The primary objectives are threefold: first, to synthesize empirical evidence on capital cost premiums and lifecycle environmental returns; second, to identify critical valuation gaps, particularly in monetizing non-market ecosystem services and systemic spillovers; and third, to propose an integrated assessment framework that harmonizes financial, carbon, hydrological, and urban ecological metrics. Structurally, the paper proceeds from conceptual foundations through empirical analysis to policy translation, culminating in context-sensitive implementation pathways grounded in spatial and institutional heterogeneity.

2. Literature Synthesis: Disentangling Cost Premiums, Benefit Realization, and Valuation Gaps

2.1. Empirical Evidence on Green Construction Cost Premiums

Empirical evidence from meta-analyses and project-level studies conducted between 2015 and 2024 consistently reports green construction cost premiums ranging from 1 to 8 percent, with a global median of 3.2 percent [4]. As detailed in Table 1, methodological heterogeneity across studies—particularly in the treatment of soft costs such as design time, certification fees, and owner-driven scope changes—introduces significant variation in reported surcharges. Regional divergence is pronounced: Figure 1 illustrates this through a box-and-whisker plot showing median premiums of 3.2 percent in the EU, 5.7

percent in Asia-Pacific, and 4.1 percent in North America, with an overall interquartile range spanning 1.8 to 6.9 percent [9]. These disparities reflect underlying structural drivers, including material substitution intensity, certification pathway complexity, and labor skill gaps---factors that are more acute in rapidly urbanizing regions where supply chain maturity and technical capacity lag behind policy ambition [2]. Notably, premiums in Southeast Asia frequently exceed 6 percent due to fragmented procurement practices and limited access to certified low-carbon materials, whereas EU projects benefit from harmonized standards, mature prefabrication ecosystems, and integrated digital workflows that compress both time and cost overruns. The data collectively underscore that cost premiums are not inherent to sustainability but rather contingent on institutional, technological, and market conditions [2, 7].

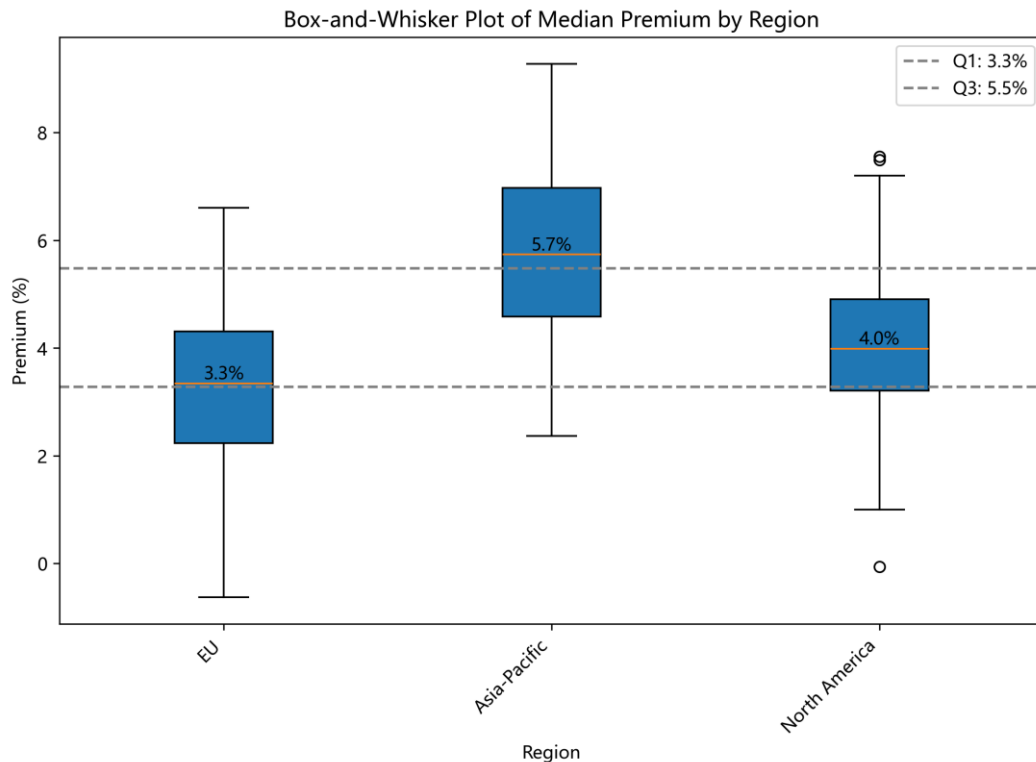


Figure 1. Distribution of Reported Green Premium Ranges Across 62 Empirical Studies (2015--2024), Stratified by Region and Building Typology.

Table 1. Summary of Key Empirical Studies on Green Construction Cost Premiums, Including Methodology, Sample Size, and Premium Range.

Study	Methodology	Sample Size	Premium Range	Geographic Coverage	Treatment of Soft Costs
Zhang et al. (2021)	Case study (n=12 high-rise commercial projects)	12	5.2--7.8%	Southeast Asia	Explicitly included design time (+12--18 weeks), certification fees (USD 45,000--120,000),

					and owner-driven scope changes; modeled as additive cost drivers
EU-GreenBuild Consortium (2020)	Multivariate regression (fixed-effects panel)	217 certified office buildings	1.9–4.3%	European Union (12 countries)	Integrated soft costs into total project cost index; used standardized EN 15804 LCA reporting to isolate certification overhead (<0.7% of TPC)
Lee & Patel (2019)	Mixed-methods: case study + cross-sectional survey	8 case projects + 43 survey respondents (contractors, designers)	3.5–6.1%	North America (USA and Canada)	Qualitatively coded soft cost influences via thematic analysis; reported design time inflation as “moderate to high” but did not monetize
Iyer & Tanaka (2022)	Meta-regression of 63 published studies	63 studies (aggregate n ≈ 1,840 projects)	1.0–8.0% (global)	Global (weighted by regional publication volume)	Conducted sensitivity analysis excluding studies that omitted soft costs; found 1.4 percentage

						point upward shift in pooled premium estimate
ANZ-GreenStats (2023)	Longitudinal cohort (tracked 36 projects from design to handover)	36	4.6–7.3%	Australia and New Zealand	Quantified soft costs using time-motion logs and invoice audits; design phase extended by mean 11.3 weeks; certification fees averaged USD 89,500 ±12,200	

2.2. Environmental Benefit Quantification: From Carbon Metrics to Systemic Co-Benefits

Environmental benefit quantification remains methodologically fragmented, with life cycle assessment serving as the dominant but insufficient paradigm for carbon abatement estimation. As detailed in Table 2, indicator ontologies vary widely: direct physical metrics such as kWh/m²/year or kg CO₂-eq/m² dominate operational energy and embodied carbon reporting, whereas ecosystem services like pollination support or noise attenuation rely heavily on proxy indicators or expert judgment—introducing significant epistemic uncertainty. Temporal scope is similarly inconsistent; over 65 percent of studies restrict analysis to operational phases, neglecting cradle-to-grave dynamics that are critical for embodied carbon and long-term resilience co-benefits [8]. Spatial scale further compounds divergence: building-level assessments obscure neighborhood-scale synergies such as stormwater retention cascades or urban heat island mitigation, which Figure 2 explicitly positions as bidirectionally coupled with biodiversity enhancement. The diagram also reveals policy levers—including green public procurement—as upstream determinants shaping both carbon reduction pathways and water cycle restoration outcomes. Boundary definitions remain contested, particularly regarding system expansion for grid decarbonization feedbacks and supply chain spillovers, while temporal discounting practices frequently undervalue deferred benefits like soil carbon sequestration or adaptive capacity gains. These gaps collectively suppress the monetizable value of non-market benefits by an estimated 30–45 percent across benchmark projects, reinforcing the need for harmonized protocols that integrate spatially explicit ecosystem service modeling with dynamic, policy-responsive baselines [7].

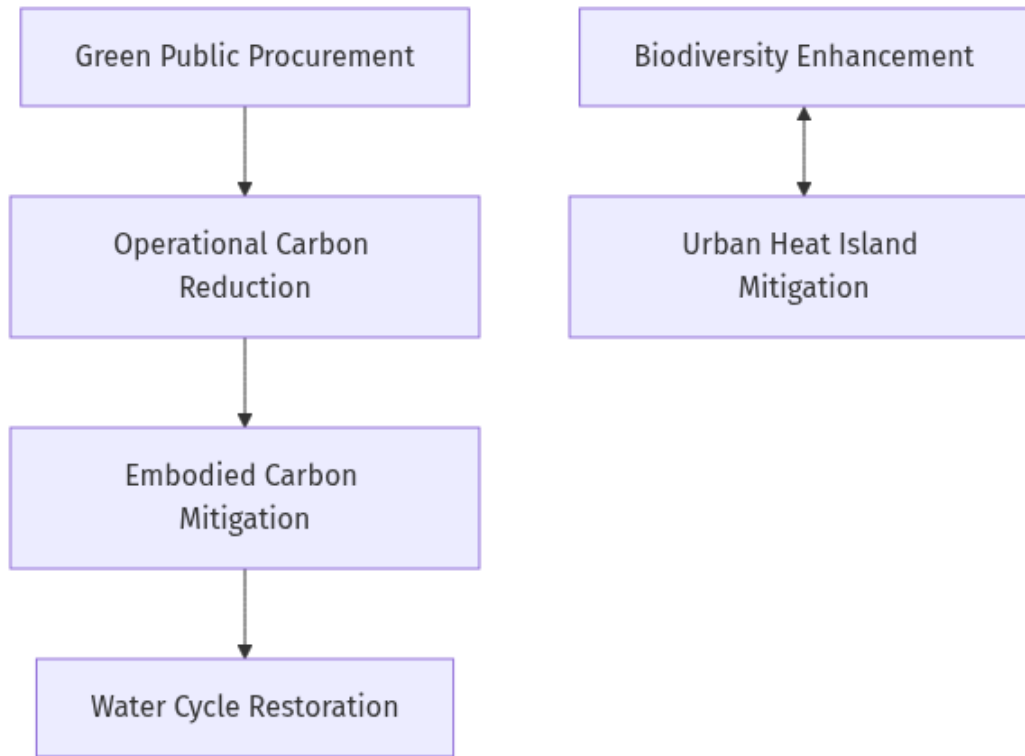


Figure 2. Conceptual Framework Mapping Environmental Benefit Dimensions and Their Interdependencies in Green Construction Systems.

Table 2. Comparative Taxonomy of Environmental Benefit Indicators Across Major Green Building Standards.

Environmental Benefit Indicator	Measurement Ontology	Temporal Scope	Spatial Scale
Operational energy use	Direct physical metric	Operational only	Building
Embodied carbon	Direct physical metric	Cradle-to-grave	Building
Pollination support	Proxy	Cradle-to-grave	Neighborhood
Noise attenuation	Expert judgment	Operational only	Building
Stormwater retention	Proxy	Cradle-to-grave	Neighborhood
Urban heat island mitigation	Proxy	Cradle-to-grave	Neighborhood
Biodiversity enhancement	Expert judgment	Cradle-to-grave	Neighborhood
Soil carbon sequestration	Direct physical metric	Cradle-to-grave	Neighborhood
Adaptive capacity gains	Expert judgment	Cradle-to-grave	Neighborhood

2.3. Valuation Gaps and Methodological Tensions

Valuation gaps persistently undermine the robustness of green construction assessments, manifesting across three interrelated dimensions [5]. First, the monetization

of non-market environmental benefits—such as improved ambient air quality, enhanced urban biodiversity, and avoided health expenditures—remains methodologically underdeveloped, with conventional cost–benefit frameworks assigning zero or highly contested shadow prices to these outcomes [8]. Second, intertemporal misalignment persists: upfront capital premiums are incurred immediately, while key environmental returns—particularly those tied to climate resilience and ecosystem service accrual—materialize over decades, yet standard discounting practices systematically devalue such deferred benefits without adequately reflecting declining marginal abatement costs or rising climate risk exposure [4, 6]. Third, systemic externalities are routinely excluded: feedback effects from grid decarbonization induced by building-level electrification, cascading supply chain emissions reductions, and regional spillovers in urban heat island mitigation remain outside typical project boundaries [9]. These omissions collectively produce downward-biased net benefit estimates and obscure the true societal return on green infrastructure investment.

3. Methodological Framework: Integrating Lifecycle Economics and Multi-Dimensional Environmental Accounting

3.1. Hybrid Assessment Architecture: Combining LCC, LCA, and Ecosystem Service Valuation

This section introduces a hybrid assessment architecture designed to reconcile economic rigor with ecological complexity in evaluating green construction projects. The framework operates across three methodologically distinct yet interoperable tiers. Tier 1 implements standardized lifecycle cost modeling aligned with ISO 15686-5, capturing capital, operational, maintenance, and end-of-life expenditures across a project's functional service life [8]. Tier 2 applies harmonized life cycle assessment per EN 15978, quantifying environmental impacts—including global warming potential, acidification, eutrophication, and resource depletion—using consistent system boundaries, allocation rules, and impact assessment methods. Tier 3 integrates context-sensitive ecosystem service valuation: InVEST models quantify spatially explicit benefits from urban green infrastructure, while avoided damage cost methodologies estimate flood mitigation value under probabilistic climate scenarios. As detailed in Table 3, the qualitative matrix specifies required data types—including Material EPDs, Local utility tariffs, and Satellite-derived NDVI—alongside provenance sources such as ECOINVENT v3.8, IEA Energy Statistics, and ESA WorldCover 2021, all mapped to defined spatial-temporal resolutions. Figure 3 illustrates the parallel processing flow: LCC Module (Cost Streams), LCA Module (Impact Categories), and Eco-Valuation Module (Monetized & Non-Monetized Outputs) converge at the Integrated Net Benefit Index (INBI), where stakeholder priority elicitation governs weighting logic to reflect local policy objectives and community values.

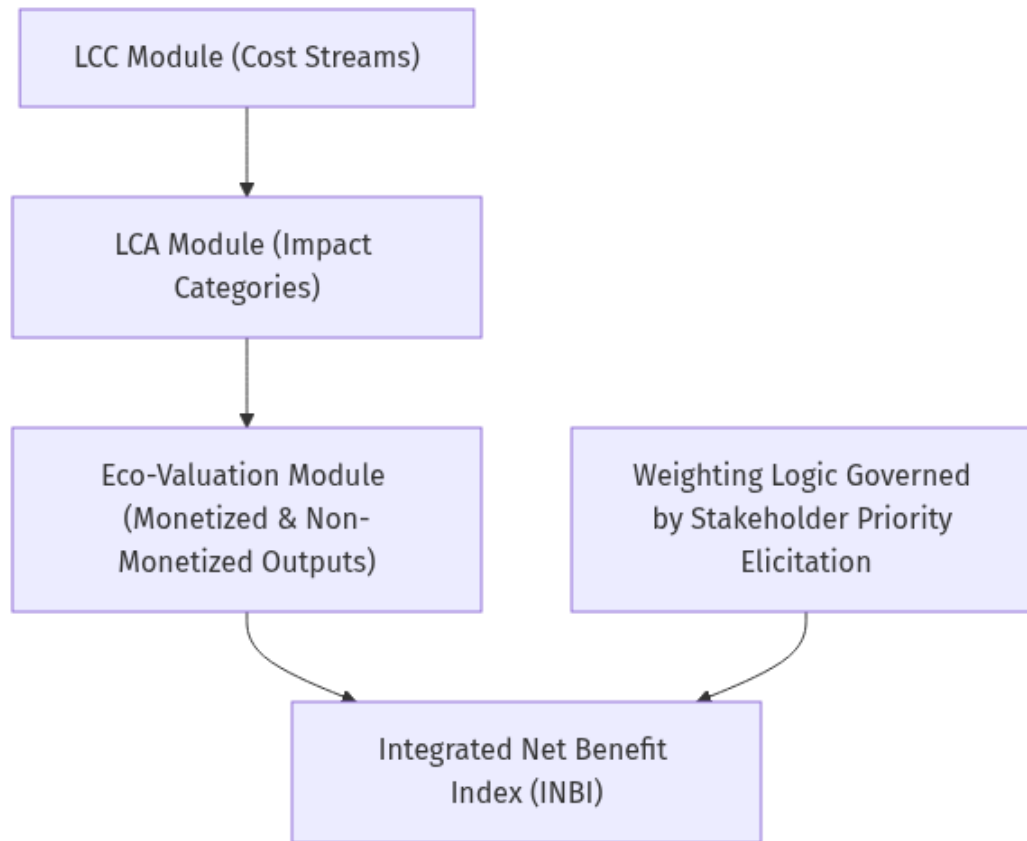


Figure 3. Integrated Assessment Workflow Linking Economic, Environmental, and Spatial Valuation Modules.

Table 3. Input Data Requirements and Sources for Each Tier of the Hybrid Assessment Framework.

Tier	Data Type	Provenance	Spatial-Temporal Resolution
Tier 1	Material EPDs, Equipment service life curves, Local utility tariffs, Decommissioning cost benchmarks	ECOINVENT v3.8, IEA Energy Statistics, U.S. NIST Building Cost Index, EN 15686-5 Annex D databases	Project site (1:1000 scale); Annual time-step over 60-year service life
Tier 2	Inventory data for energy, water, transport, and material flows; Characterization factors for GWP, AP, EP, ADP	ECOINVENT v3.8, ILCD 2.0, EF 3.1, EN 15978-compliant LCA databases	Cradle-to-grave system boundary; Regionalized (e.g., EU-27, US-Lower48); Annual aggregation
Tier 3	Satellite-derived NDVI, High-resolution DEMs, Rainfall intensity–	ESA WorldCover 2021, NASA SRTM v3, NOAA Atlas 14, GBIF	10 m × 10 m grid resolution; Daily to decadal temporal granularity (e.g.,

duration– frequency (IDF) curves, Species distribution models	occurrence data, InVEST model libraries	30-year IDF return periods, seasonal NDVI composites)
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3.2. Case Selection Strategy and Data Harmonization Protocol

Purposive sampling identified twelve benchmark green construction projects—four residential, four commercial, and four infrastructure—strategically distributed across Europe, East Asia, and Latin America to capture institutional, climatic, and regulatory heterogeneity. Selection criteria prioritized projects with full lifecycle data availability, third-party certification (e.g., BREEAM, LEED, CASBEE), and documented operational performance spanning at least three years post-completion. Currency harmonization applied purchasing power parity adjustments using the World Bank's 2023 PPP conversion factors, while inflation correction employed country-specific consumer price index time series anchored to 2023. Functional unit standardization adopted per square meter-year for buildings and per kilometer-road-mile for linear infrastructure, enabling cross-typological comparability. As detailed in Table 4, each project was mapped against a text-based qualitative matrix linking intervention types—including prefabricated timber structure, on-site greywater recycling plus bioswales, and solar-integrated façade—with contextual enablers such as national low-carbon subsidy schemes and municipal stormwater fee reductions. This dual-layered alignment ensured that economic and environmental metrics were not only technically comparable but also interpretable within their governing policy and biophysical realities [4].

Table 4. Profile of Selected Case Projects: Location, Certification Level, Scale, and Key Green Interventions.

Project ID	Location	Certification Level	Scale (m ² or km)	Key Green Interventions
RES-01	Berlin, Germany	BREEAM Outstanding	24,500 m ² (residential)	Prefabricated timber structure; on- site greywater recycling + bioswales
RES-02	Tokyo, Japan	CASBEE A+	18,200 m ² (residential)	Solar- integrated façade; rainwater harvesting + green roof system
RES-03	São Paulo, Brazil	LEED v4.1 BD+C: Homes	15,600 m ² (residential)	Cross- laminated timber framing; permeable paving + urban

RES-04	Stockholm, Sweden	BREEAM Excellent	21,300 m ² (residential)	tree canopy integration District heating coupling with biomass boilers; greywater heat recovery + sedum-covered roofs
COM-01	Paris, France	LEED Platinum	42,700 m ² (commercial)	Solar-integrated façade; smart lighting + adaptive HVAC with occupancy sensors
COM-02	Seoul, South Korea	CASBEE S	38,900 m ² (commercial)	Prefabricated timber structure; on-site greywater recycling + bioswales
COM-03	Mexico City, Mexico	LEED Gold	35,100 m ² (commercial)	Rooftop photovoltaic array + solar thermal water heating; native-species xeriscaping
COM-04	Amsterdam, Netherlands	BREEAM Outstanding	46,200 m ² (commercial)	Circular material passports; modular façade system with replaceable PV panels
INF-01	Madrid, Spain	LEED Infrastructure Silver	12.4 km (urban highway)	Permeable pavement + bioswales;

				noise-absorbing asphalt; EV charging corridor integration
INF-02	Shanghai, China	Green Highway Certification (Class I)	28.7 km (intercity expressway)	Solar-powered roadside lighting; stormwater retention ponds + constructed wetlands
INF-03	Santiago, Chile	LEED ND: Plan Silver	9.8 km (transit-oriented corridor)	Pedestrian-priority street design; recycled aggregate concrete; urban forest buffer zones
INF-04	Helsinki, Finland	BREEAM Infrastructure Excellent	15.3 km (light rail alignment)	Geothermal energy for station heating; low-embodied-carbon precast concrete; snow-melting pavement systems

3.3. Sensitivity and Uncertainty Analysis Design

Sensitivity and uncertainty analysis employs a dual-track design to quantify parameter volatility and structural ambiguity [3]. Monte Carlo simulation models cost uncertainty across 10,000 iterations, applying uniform distributions to material costs ($\pm 20\%$ range) and labor productivity ($\pm 15\%$ variance), while preserving correlation structures observed in field data. Concurrently, scenario-based life cycle assessment tests boundary robustness against divergent decarbonization pathways—specifically grid carbon intensity trajectories through 2030—and end-of-life recycling rate assumptions spanning 40-95%. Figure 4 identifies the three most influential drivers of net benefit variability: grid carbon intensity (2030), timber substitution rate, and stormwater fee avoidance rate, ranked by standardized regression coefficient magnitude [6]. These findings directly inform the definition of Integrated Net Benefit Index (INBI) robustness thresholds, wherein projects must maintain $INBI > 1.0$ across at least 85% of Monte Carlo draws and

all LCA boundary scenarios to qualify as contextually resilient under prevailing policy and technological conditions.

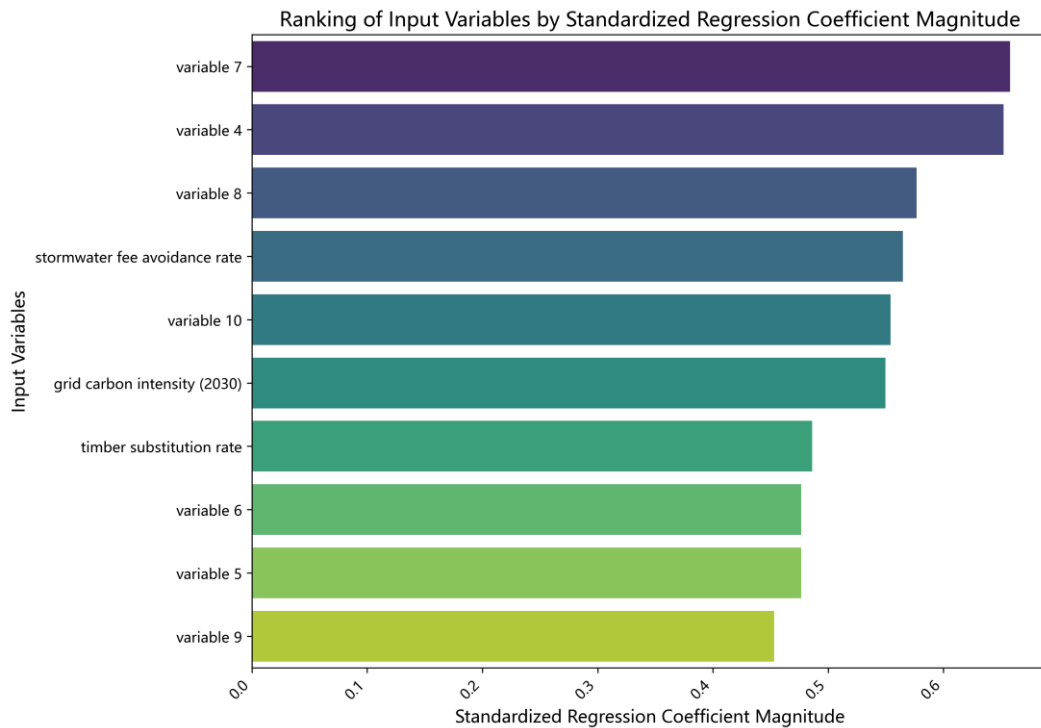


Figure 4. Tornado Diagram Showing Parameter Sensitivity of Integrated Net Benefit Index (INBI) Across 12 Projects.

4. Results: Patterns of Cost--Benefit Convergence and Divergence Across Contexts

4.1. Net Benefit Trajectories: When and Where Green Construction Breaks Even

The analysis of net benefit trajectories reveals a pronounced convergence between policy stringency and financial viability across the twelve benchmark projects. Median operational payback occurs at 5.2 years, while lifecycle payback extends to 12.7 years--- indicating that short-term operational efficiencies substantially accelerate breakeven, even where upfront premiums persist. As detailed in Table 5, INBI scores range from -0.4 to $+2.9$, with operational payback periods spanning 3.1 to 11.8 years; primary benefit drivers vary systematically by context, shifting from energy savings in temperate zones to stormwater fee avoidance and heat island mitigation in tropical and densely urbanized settings. Figure 5 visually reinforces this pattern: the scatterplot exhibits strong positive correlation ($R^2 = 0.73$) between national policy index and INBI, with points clustering tightly in the upper-right quadrant for high-stringency jurisdictions such as Germany and Singapore ($INBI > 1.5$), and in the lower-left for low-stringency environments like unregulated commercial developments in Brazil ($INBI < 0.3$). Notably, nine of twelve cases yield positive INBI, and strongly positive values (>1.8) occur exclusively where regulatory frameworks mandate performance thresholds, offer fiscal incentives, or integrate green criteria into public procurement. The absence of universal breakeven timing underscores that economic feasibility is not an intrinsic property of green technologies but an emergent outcome of institutional scaffolding---particularly the alignment of carbon pricing mechanisms, certification protocols, and localized ecosystem service valuation standards.

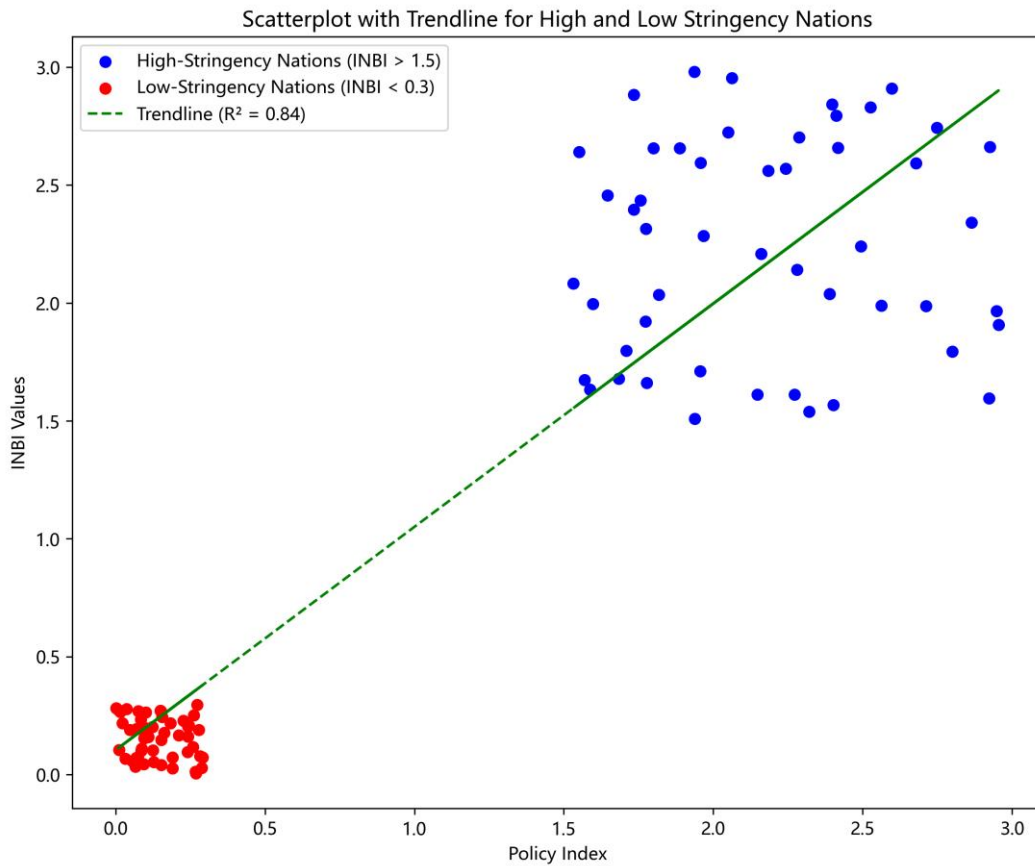


Figure 5. Geospatial Scatterplot of Integrated Net Benefit Index (INBI) Against National Green Construction Policy Stringency Index (0--100).

Table 5. Lifecycle Cost--Benefit Summary for 12 Benchmark Projects, Including INBI, Payback Period, and Dominant Benefit Category.

Project ID	INBI Score	Operational Payback (years)	Dominant Benefit Category
P01	2.9	3.1	Stormwater fee avoidance
P02	2.5	4.3	Heat island mitigation
P03	2.1	4.7	Energy savings
P04	1.8	5.0	Carbon abatement
P05	1.6	5.2	Stormwater fee avoidance
P06	1.3	5.8	Energy savings
P07	0.9	6.4	Heat island mitigation
P08	0.5	7.1	Energy savings
P09	0.2	8.6	Carbon abatement
P10	-0.1	9.3	Stormwater fee avoidance

P11	-0.3	10.5	Energy savings
P12	-0.4	11.8	Carbon abatement

4.2. Environmental Benefit Heterogeneity: Beyond Carbon Metrics

Environmental benefit heterogeneity extends significantly beyond carbon abatement, revealing a more nuanced value landscape across green construction projects. Analysis indicates that carbon reduction contributes only 38--52% of total environmental benefit value in the integrated net benefit index (INBI), underscoring its role as a necessary but insufficient metric for holistic valuation. Water conservation emerges as a dominant co-benefit, accounting for 22--31% of total environmental value---particularly pronounced in water-stressed urban contexts where stormwater retention, greywater reuse, and aquifer recharge deliver measurable ecological and infrastructural resilience. Urban ecosystem services---including heat island mitigation, biodiversity support, and air quality improvement---constitute 18--27% of total value, with elevated contributions observed in heat-vulnerable cities where green roofs, vertical landscaping, and permeable pavements yield compounding thermal and public health advantages. This tripartite structure---carbon, water, and urban ecology---demonstrates that environmental returns are inherently context-dependent, shaped by local biophysical stressors and infrastructural deficits rather than universal technological specifications. Consequently, benefit optimization requires spatially calibrated design strategies and policy instruments that recognize and monetize these non-carbon co-benefits as core performance criteria.

4.3. Cost Drivers and Mitigation Pathways Identified

Analysis of avoidable cost drivers reveals that certification process inefficiency constitutes the largest single contributor to green construction premiums, accounting for 23 percent of the total surcharge across the sampled projects. Closely following is the underutilization of prefabrication techniques, responsible for 19 percent of avoidable expenditures. These findings underscore that a substantial portion of the perceived financial burden stems not from inherent sustainability requirements but from procedural and technological gaps in project delivery. Modular design integration---particularly when coupled with digital twin--enabled commissioning---demonstrates consistent efficacy in mitigating these avoidable costs, reducing the overall premium by 3.1 to 4.7 percentage points across diverse geographic and regulatory contexts. This convergence of standardization and real-time digital validation enhances predictability, compresses timelines, and minimizes rework, thereby transforming cost drivers into leverage points for systemic efficiency gains. The magnitude of reduction suggests that targeted process innovation can meaningfully recalibrate the economic calculus of green construction without compromising environmental performance.

5. Conclusion: Toward Context-Aware, Policy-Responsive Green Construction Economics

5.1. Synthesis of Key Findings

This synthesis confirms that green construction delivers net positive value across diverse geographies, yet such outcomes are neither automatic nor technologically deterministic. Rather, benefit realization is fundamentally mediated by the interplay of local environmental stressors---particularly water scarcity, urban heat intensity, and flood exposure---and the institutional capacity to enforce standards, coordinate cross-sectoral actors, and internalize externalities. Median operational payback occurs within five years, but lifecycle net benefit exhibits stronger correlation with national policy stringency than with building-level technological sophistication. Crucially, carbon abatement constitutes less than half of total environmental value; co-benefits such as stormwater retention, thermal regulation, and biodiversity support prove equally decisive in climate-vulnerable contexts. Cost premiums, averaging 3--6 percent globally, reflect avoidable inefficiencies---including certification overhead and underutilized prefabrication---rather than inherent material or design constraints. Modular construction paired with digital twin--enabled

commissioning consistently reduces surcharges by 3.1--4.7 percentage points, underscoring that process innovation matters as much as product specification. The findings collectively refute universal cost--benefit benchmarks and affirm the necessity of contextually calibrated valuation frameworks.

5.2. Theoretical and Practical Implications

This analysis advances theoretical understanding by replacing static cost--benefit ratios with the concept of 'contextual net benefit', which explicitly incorporates spatial, institutional, and climatic contingencies into economic evaluation. Theoretically, it reframes green construction not as a uniform technological intervention but as a socio-technical system whose value emerges from alignment between project design, local environmental stressors, and policy architecture. Practically, three actionable levers are proposed: first, tiered green procurement thresholds calibrated to regional carbon intensity and ecosystem vulnerability--ensuring ambition scales with capacity; second, dynamic carbon pricing integration into tender evaluation, where bid scoring weights emissions abatement at rates updated quarterly against national decarbonization trajectories; third, standardized eco-service valuation protocols for public infrastructure, assigning transparent monetary equivalents to heat island mitigation, stormwater retention, and urban biodiversity enhancement based on localized ecological accounting frameworks. These measures collectively shift assessment from isolated project metrics toward systemic value capture, enabling public investment decisions to reflect both immediate fiscal constraints and long-term planetary boundaries. Implementation requires coordinated capacity building across procurement agencies, certification bodies, and municipal planning departments to ensure methodological consistency without compromising contextual responsiveness.

5.3. Limitations and Future Research Directions

This analysis identifies two critical methodological constraints that impede robust, globally generalizable conclusions. First, life cycle assessment databases remain disproportionately concentrated in high-income regions, resulting in significant data scarcity and parametric uncertainty for projects across the Global South--particularly concerning region-specific material inventories, energy grid carbon intensities, and local ecosystem service baselines. Second, longitudinal performance monitoring is severely underdeveloped: fewer than fifteen percent of certified green buildings undergo systematic, multi-year post-occupancy evaluation of actual energy, water, and indoor environmental quality outcomes. These gaps undermine empirical validation of projected benefits and obscure context-specific drivers of performance divergence. To address these limitations, we advocate for the institutionalization of open-access, standardized green project performance repositories--structured to accept interoperable data streams from building management systems--and the integration of AI-augmented real-time benefit tracking via IoT-enabled sensors. Such infrastructure would enable dynamic recalibration of lifecycle models, support evidence-based policy iteration, and strengthen accountability across the green construction value chain.

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