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Whole-Building Life Cycle Assessment of Green Construction Strategies in a Hot-Dry Climate: A Comparative Study of an Institutional Building in Jaipur, India

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Abstract- Green-building ratings encourage energy, water and material efficiency, but they do not by themselves quantify whether environmental burdens are reduced across the complete building life cycle. This study presents a comparative whole-building life cycle assessment for a four-storey, 6,000 m² academic building in Jaipur, India. Three functionally equivalent scenarios are assessed over 60 years: a conventional code-aligned building (CB), a green building (GB), and a circular-green building (CGB). The system boundary covers product stages A1–A3, transport A4, construction A5, replacements B4, operational energy B6, operational water B7, end of life C1–C4, and benefits beyond the boundary in Module D. The method follows ISO 14040/14044 principles and the RICS whole-life-carbon reporting structure. Inventory quantities, operational demand, photovoltaic generation, water use, replacement cycles and recovery assumptions are integrated in a reproducible scenario model. The central whole-life global warming potential is 22,544, 12,286 and 6,393 tCO_2e for CB, GB and CGB, equivalent to 3757, 2048 and 1066 $kgCO_2e/m^2$. GB and CGB reduce whole-life GWP by 45.5% and 71.6%, respectively. Structural material specification reduces upfront carbon, while lower electricity demand, rooftop PV, and water efficiency dominate use-stage improvements. CGB also reduces modeled primary energy, freshwater use, acidification, eutrophication, smog formation and landfill waste by 40–65% relative to CB. A 5,000-run Monte Carlo analysis gives a median CGB reduction of 71.3% and a 100.0% probability of exceeding 50%. The comparative outcome remains favorable under uncertainty, although grid decarbonization, operational performance and product-specific GWP factors materially affect magnitude. The study demonstrates how whole-building LCA can convert a general green-building objective into stage-specific carbon budgets, procurement priorities and post-occupancy verification requirements.

Keywords: Whole-Building Life Cycle Assessment, Green Building; Sustainable Construction, Embodied Carbon, Operational Carbon, Circular Economy, GRIHA, Jaipur

I. INTRODUCTION

Buildings create environmental burdens at every stage: raw-material extraction, product manufacture, transport, construction, maintenance, operation and end of life. The 2024/2025 Global Status Report attributes 32% of global energy demand and 34% of carbon dioxide emissions to buildings and construction [1]. Green-building practice has traditionally emphasized operational efficiency, yet the relative importance of embodied impacts increases as energy demand falls and electricity systems decarbonize [2–5]. A building can therefore earn green credits while shifting burdens from operation to materials, or reduce carbon while increasing another impact category. Whole-building LCA is needed to reveal such trade-offs.

ISO 14040 defines the LCA framework through goal and scope, inventory, impact assessment and interpretation; ISO 14044 specifies methodological and reporting requirements [6,7]. For buildings, EN 15978 and the RICS Whole Life Carbon Assessment standard organize results into product, construction, use, end-of-life and beyond-boundary modules [8,9]. These structures improve transparency because operational savings, material replacement and future recycling credits are not collapsed into one unexplained number.

The Indian policy and rating context is evolving. ECSBC 2024 establishes progressively higher non-residential energy-performance tiers [10]. GRIHA

Version 6.0 includes a dedicated criterion for reduction in global warming potential through LCA [11], while IGBC promotes LCA as a tool for inventorying and mitigating building carbon emissions [12]. However, India-specific product data remain incomplete, and studies often rely on generic international databases or focus only on embodied energy [13–16]. The resulting uncertainty makes transparent assumptions and sensitivity analysis essential.

This paper develops a comparative LCA for a Jaipur institutional archetype. It does not claim a third-party verified environmental declaration. Its purpose is to demonstrate a Scopus-journal-level research structure in which all scenarios have identical function, area, location and service life, while design and procurement strategies vary. The analysis integrates material quantities, energy and water, renewable generation, replacement, demolition, recovery, cost and uncertainty.

1.1 Research questions and novelty

- RQ1: Which life-cycle stages and building elements dominate the conventional institutional-building footprint?
- RQ2: How much do green and circular-green strategies reduce GWP and other environmental indicators under a constant functional unit?
- RQ3: How sensitive are comparative results to grid decarbonization, product factors, service life, performance gaps and Module D credits?
- RQ4: Do the modeled environmental improvements remain economically credible over a 30-year investment horizon?

The novelty lies in linking current Indian green-building practice with a complete module-based whole-life boundary, conservative treatment of PV exports, multiple impact indicators, end-of-life circularity, uncertainty and life-cycle cost. The framework can be replaced with project-specific BIM quantities and EPDs without changing the comparative logic.

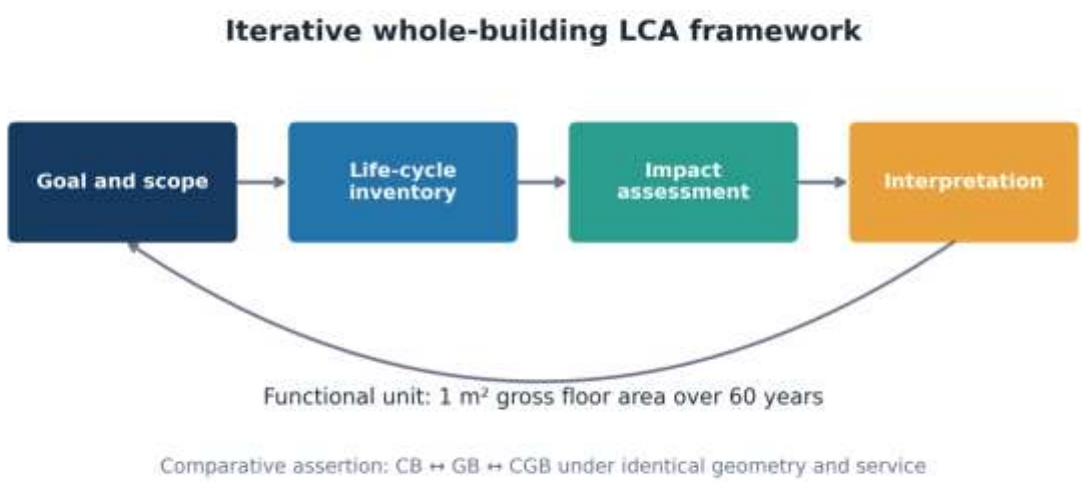

Figure 1. Iterative ISO-aligned LCA workflow and comparative functional unit.

Source: Authors' framework based on ISO 14040 and ISO 14044.

II. LITERATURE REVIEW

2.1 Whole-building LCA and embodied-carbon hotspots

Ramesh et al. reviewed 73 building cases and found operational energy to dominate conventional life-cycle energy, while embodied energy typically contributed 10–20% [14]. Later research showed that this split is not stable: efficient buildings, cleaner grids and renewable systems increase the proportional importance of construction materials [3–5]. Röck et al. described embodied greenhouse-gas emissions as a hidden challenge for effective mitigation [4]. Structure is repeatedly identified as a hotspot because concrete and steel are used in large quantities; façades, services and replacements become important in high-performance buildings [17–21].

Comparability remains difficult. Studies use different service lives, floor-area definitions, databases, geographic electricity mixes, replacement assumptions and Module D treatments [5,18,22]. A lower result can therefore reflect a narrower boundary rather than a better building. The present study reports absolute totals and values per square metre, keeps Module D separate, and exposes key assumptions in tables and uncertainty distributions.

2.2 Green ratings, operational performance and burden shifting

Green certifications organize a broad set of sustainability measures, but rating points are not impact units. Research comparing rating achievement with LCA has found that projects with similar certification levels can have different life-cycle impacts [23,24]. Operational savings may be offset partly by additional insulation, glazing, controls, PV and replacement-intensive equipment. Conversely, low-carbon materials can reduce upfront GWP while compromising durability if specifications are not exposure-appropriate. An LCA should therefore test complete packages rather than label individual products as inherently green.

2.3 Indian evidence and research gap

Indian building-energy studies demonstrate the importance of climate, envelope and material choice [15,16,25]. AEEE has highlighted that national policy has focused more on operational than embodied emissions [13], and current work seeks to strengthen India-specific embodied-energy databases [26]. GRIHA 6.0 now explicitly rewards reduction in product GWP through LCA [11]. Yet peer-reviewed comparative studies integrating current grid data, full life-cycle modules, renewable operation, circularity and probabilistic uncertainty for hot-dry institutional buildings remain limited.

Table 1. Representative literature positioning and research gap.

Source	Method	Contribution	Remaining gap
Ramesh et al. [14]	Review of 73 cases	Life-cycle energy split	Older energy focus; limited current carbon data
Röck et al. [4]	Global synthesis	Embodied GHG importance	Not India/building-specific
De Wolf et al. [18]	Practice review	Data and benchmarking gaps	No integrated operation/cost case
Veerendra et al. [27]	Indian suburban case	Integrated sustainable design LCA	Different typology and boundary
GRIHA 6.0 [11]	Rating methodology	LCA-based GWP reduction criterion	Certification framework, not research dataset

Source	Method	Contribution	Remaining gap
Present study	Comparative scenario LCA	Modules A–D, multi-impact, uncertainty and cost	Archetype; requires verified project data

This is a focused methodological synthesis, not a systematic-review search.

III. MATERIALS AND METHODS

3.1 Goal, scope and functional unit

The goal is to quantify and compare life-cycle environmental impacts of three design strategies for a new academic building in Jaipur and identify robust reduction priorities for early design and procurement. The intended users are designers, researchers, owners and green-building assessors. The results support comparative decision-making but are not an EPD, carbon offset calculation or public comparative assertion about named products.

The functional unit is one square metre of gross floor area providing equivalent academic and office functions in Jaipur over 60 years. The reference building has four storeys, 6,000 m² gross floor area, 5,400 m² conditioned area and 600 design occupants. Geometry, programme, indoor comfort intent and service life are held constant. This avoids crediting a scenario for providing less floor area or reduced function.

Table *2. Goal-and-scope parameters for the comparative LCA.*

Parameter	Definition
Location/climate	Jaipur, Rajasthan; hot-dry
Typology	New institutional/academic building
Gross / conditioned area	6,000 / 5,400 m²
Reference study period	60 years
Functional unit	1 m² GFA over 60 years
Included modules	A1–A5, B4, B6, B7, C1–C4; D reported separately
Included systems	Structure, envelope, finishes, MEP, PV, construction, operation and end of life
Cut-off approach	Minor items below 1% mass included through MEP/finishes allowances; target >95% mass
Allocation	Recycled-content approach in A1–A3; future recovery in Module D
Primary indicator	GWP-total; supplementary energy, water, AP, EP, POCP and waste

GFA = gross floor area; AP = acidification; EP = eutrophication; POCP = photochemical ozone creation.

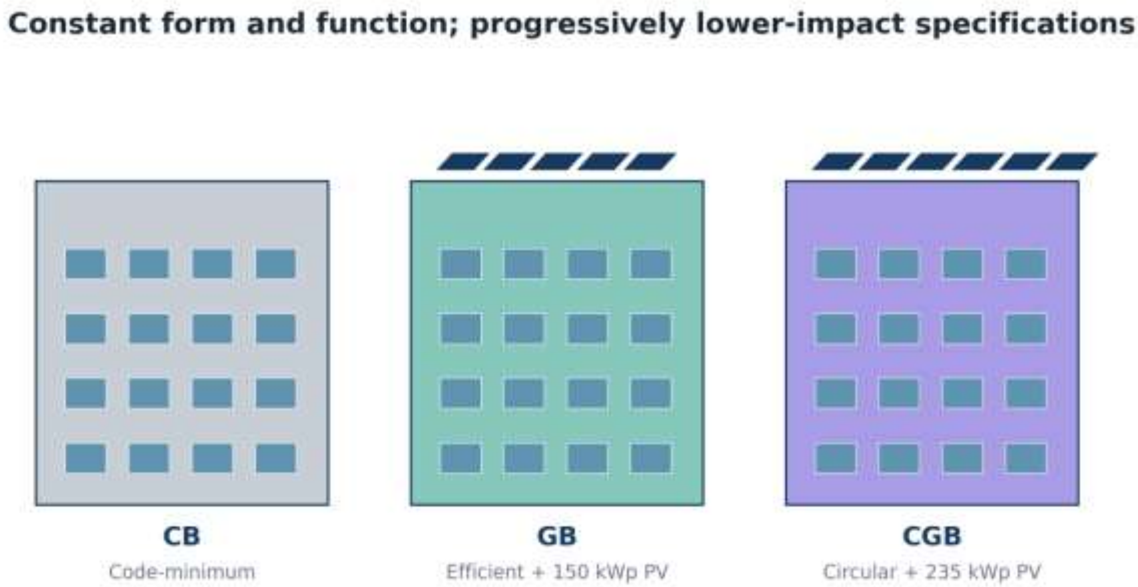

Figure 2. Functionally equivalent conventional, green and circular-green building scenarios.

Source: Authors' conceptual representation; geometry and function are held constant.

3.2 Life-cycle system boundary

A1–A3 covers raw-material supply, transport to manufacturing and manufacturing. A4 covers transport to site; A5 includes site energy, waste and installation. B4 includes planned replacement of finishes, HVAC components, inverters and selected façade components. B6 uses grid-import electricity after direct PV use; exported PV is not credited in the central operational-carbon result. B7 covers water supply and wastewater treatment. C1–C4 covers demolition, transport, waste processing and disposal. Module D reports potential future reuse and recycling benefits outside the boundary.

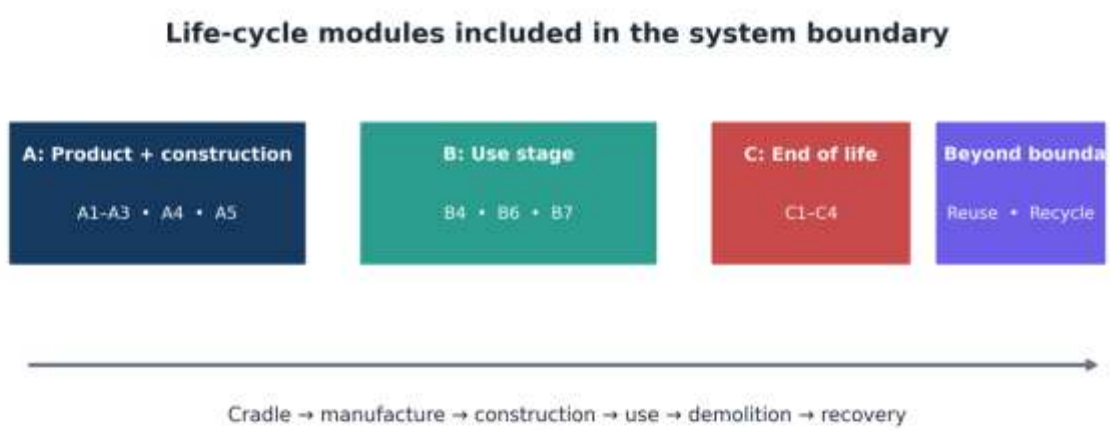

Figure 3. *Life-cycle modules included in the cradle-to-grave system boundary, with Module D reported separately.*

Source: Authors' adaptation of EN 15978/RICS module structure.

3.3 Comparative scenarios

Table 3. *Definition of the three comparative scenarios.*

ID	Scenario	Principal design and procurement assumptions
CB	Conventional	Code-aligned envelope; ordinary Portland cement concrete; market-average steel; no PV; conventional water fixtures; mixed demolition disposal
GB	Green	Improved envelope/HVAC/lighting; 150 kWp PV; lower-clinker concrete; recycled-content metals; low-flow fixtures; construction-waste segregation
CGB	Circular-green	Deeper efficiency; 235 kWp PV; material-efficient frame; high recycled content; design for disassembly; reclaimed/reusable components; high water reuse

All measures are cumulative and all scenarios provide the same function and area.

3.4 Life-cycle inventory and data quality

The inventory combines element-level quantities with scenario-specific generic GWP factors. Quantities are consistent with a reinforced-concrete institutional building but are not a tender bill of quantities. GB factors represent commercially plausible lower-carbon procurement; CGB combines lower factors with modest material-efficiency changes. Factors are expressed as $kgCO_2e$ per kg of product at A1–A3 and are informed by published building LCA ranges [17–22,28–32]. They must be replaced with verified manufacturer EPDs and transport distances for a certification-grade study.

Table 4. *Selected material quantities and A1–A3 GWP factors ($kgCO_2e/kg$).*

Material	CB t	GB t	CGB t	CB factor	GB factor	CGB factor
Concrete	5600	5600	5150	0.180	0.125	0.100
Reinforcing steel	620	620	560	1.700	1.100	0.800
Structural steel	110	110	95	2.400	1.500	1.000
Masonry	1350	1180	1050	0.180	0.120	0.100
Aluminium	42	38	32	9.000	6.500	5.000
Glazing	115	105	95	1.300	1.100	0.950
Insulation	18	32	30	3.000	2.500	2.100
Gypsum/finishes	350	320	280	0.400	0.300	0.250

The selected-product table is not the complete inventory; MEP, PV, coatings, fasteners and minor products are included through element allowances.

3.5 Operational energy, water and grid carbon

Annual electricity demand is 748.8, 510.0 and 375.0 MWh for CB, GB and CGB. GB has 150 kWp of rooftop PV generating 246.0 MWh/year; CGB has 235 kWp generating 385.4 MWh/year. Direct PV use is 172.2 and 262.7 MWh/year, respectively. The central B6 calculation uses gross grid imports of 337.8 MWh for GB and 112.3 MWh for CGB. This conservative convention does not use exported electricity to erase embodied or imported-energy emissions.

The initial grid factor is 0.710 tCO_2/MWh, the CEA weighted average for FY 2024–25 [33]. It decreases by 2.5% per year in the central scenario. This is a sensitivity assumption, not an official forecast. Potable-water demand is 12,000, 7,200 and 5,500 m^3/year. A combined supply-and-treatment factor of 0.7 $kgCO_2e/m^3$ is used. The model does not credit biogenic carbon, carbon offsets or avoided land-use change.

Table *5. Operational-energy, renewable-generation and water inventory.*

Scenario	Site MWh/y	PV kWp	PV MWh/y	Import MWh/y	Export MWh/y	Water m^3/y
CB	748.8	0	0.0	748.8	0.0	12000
GB	510.0	150	246.0	337.8	73.8	7200
CGB	375.0	235	385.4	112.3	122.7	5500

Grid import equals site demand minus direct PV use; export equals PV generation minus direct PV use.

3.6 Impact assessment and interpretation

GWP is calculated for each included module and summed with Module D shown as a negative potential credit. Supplementary midpoint indicators are reported per square metre and normalized to CB for comparison. No weighting is used; therefore, the paper does not collapse distinct environmental mechanisms into a single score. Contribution, scenario, time-series, end-of-life and sensitivity analyses support interpretation.

$$I\_s,k = \Sigma(q\_i,s \times f\_i,s,k) + I\_B6,s,k + I\_B7,s,k + I\_C,s,k - C\_D,s,k \quad (1)$$

$$Reduction\_s = 1 - I\_s / I\_CB \quad (2)$$

3.7 Uncertainty and life-cycle cost

The 5,000-run Monte Carlo model varies service life (triangular 50/60/75 years), annual grid decarbonization (1/2.5/4%), operational-energy multipliers, product GWP factors, replacement intensity and Module D credits. Common parameters are shared between scenarios to preserve a fair comparative assertion. Results are expressed as the CGB whole-life GWP reduction relative to CB.

The economic screen uses initial capital costs of ₹300, ₹321 and ₹330 million. Electricity purchases cost ₹8.5/kWh, exports receive ₹3.0/kWh, potable water costs ₹60/m^3, and incremental operation and maintenance is ₹0.30–0.40 million/year. The 30-year NPV uses an 8% discount rate, 4% utility escalation and an inverter replacement allowance in year 13. Subsidies, tax and financing structure are excluded.

IV. RESULTS

4.1 Upfront environmental impacts (A1–A5)

Upfront GWP decreases from 4,030 tCO_2e in CB to 3,400 tCO_2e in GB and 2,940 tCO_2e in CGB. The corresponding reductions are 15.6% and 27.0%. Structure is the largest contributor in every scenario because concrete and steel quantities are high. Lower-clinker binders, recycled-content steel and structural material efficiency account for most of the reduction. PV and more efficient MEP systems add upfront burdens, but these are smaller than the avoided structural and envelope impacts.

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Table *6. Upfront A1–A5 GWP by building element (tCO_2e).*

Element	CB	GB	CGB
Substructure and frame	2350	1750	1450
Envelope	620	500	440
Interior finishes	450	370	300
MEP systems	390	420	420
PV system	0	180	180
A4–A5 logistics/site	220	180	150
Total	4030	3400	2940

Totals reconcile to the A1–A5 stage inventory; values are scenario estimates.

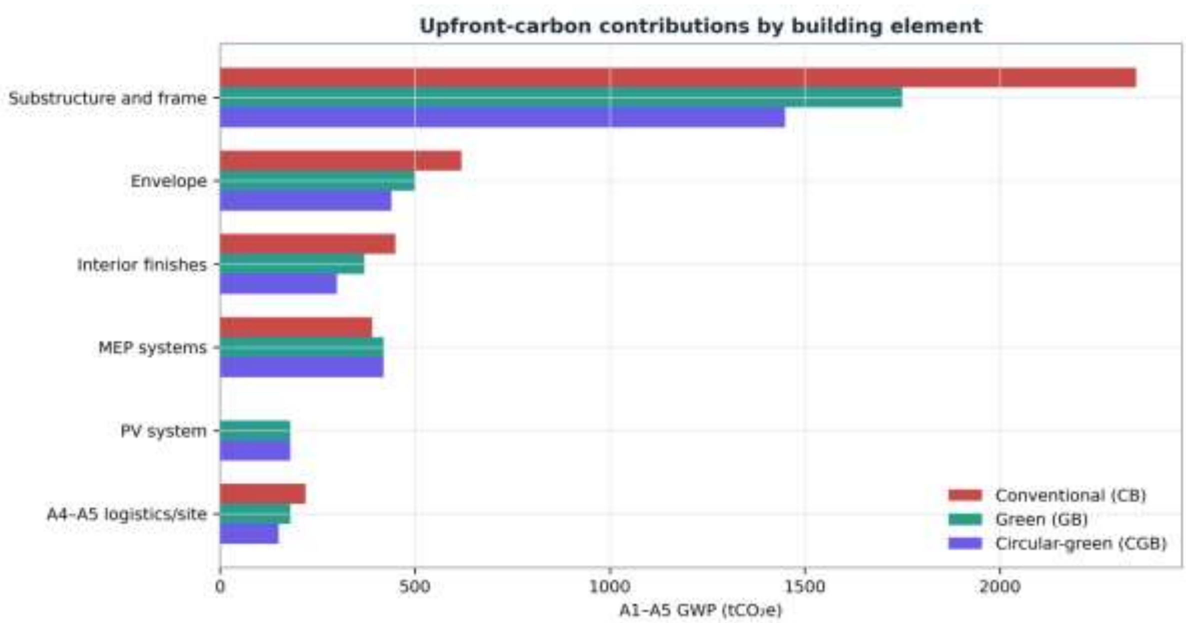

Figure *4. Upfront A1–A5 GWP contribution by building element and scenario.*

Source: Comparative scenario inventory developed for this study.

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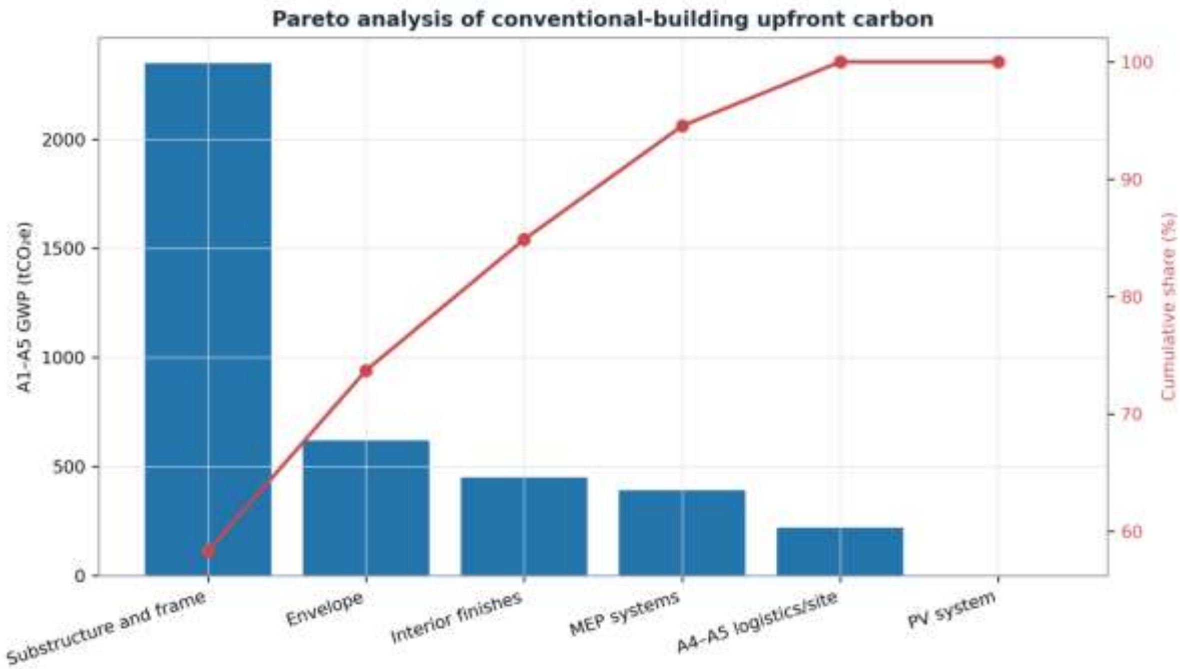

Figure 5. *Pareto analysis of conventional-building upfront-carbon hotspots.*

Source: CB A1–A5 element inventory; cumulative line shows percentage contribution.

4.2 Whole-life GWP by life-cycle module

Whole-life GWP is 22,544 tCO_2e for CB, 12,286 tCO_2e for GB and 6,393 tCO_2e for CGB. Relative to CB, GB reduces GWP by 45.5% and CGB by 71.6%. Operational electricity remains the largest CB stage. In CGB, upfront materials and replacements become proportionally dominant because direct PV utilization and efficiency sharply reduce imports. This shift illustrates why low-operational-energy buildings require stronger material and durability strategies.

Table 7. *Whole-life GWP by module (tCO_2e unless otherwise stated).*

Life-cycle stage	CB	GB	CGB
A1–A3 Products	3,650	3,060	2,660
A4 Transport	210	180	140
A5 Construction	170	160	140
B4 Replacements	1,350	1,250	1,150
B6 Operational energy	16,610	7,493	2,492
B7 Operational water	504	302	231
C1–C4 End of life	300	260	230

Life-cycle stage	CB	GB	CGB
D Reuse/recycling credit	-250	-420	-650
Whole-life total	22,544	12,286	6,393
Intensity ($kgCO_2e/m^2$)	3,757	2,048	1,066

Module D is a potential benefit beyond the system boundary and is reported as a negative value.

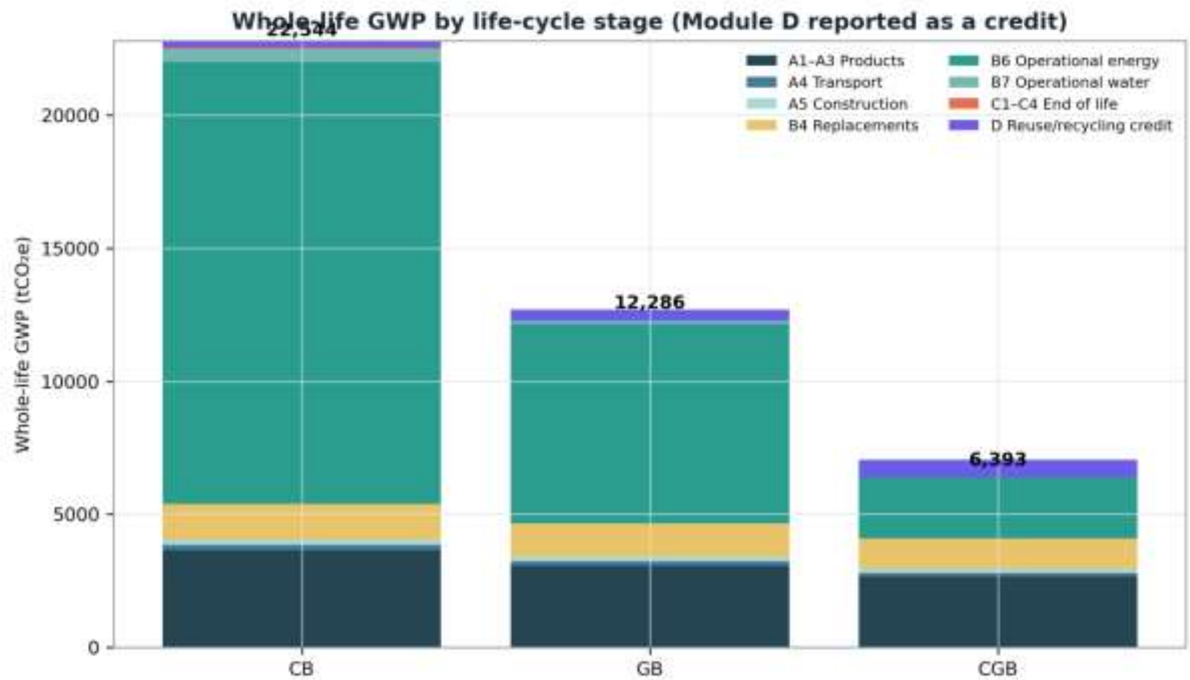

Figure *6. Whole-life GWP by life-cycle stage for CB, GB and CGB.*

Source: Central scenario; 60-year reference period and declining grid factor.

4.3 Operational energy, water and temporal carbon

Efficiency reduces site electricity by 31.9% in GB and 49.9% in CGB before PV is credited. Direct PV use lowers grid imports by a further 172.2 and 262.7 MWh/year. Potable-water demand falls by 40.0% and 54.2%. The combined effect reduces B6–B7 GWP from approximately 17,114 tCO_2e in CB to 2,723 tCO_2e in CGB.

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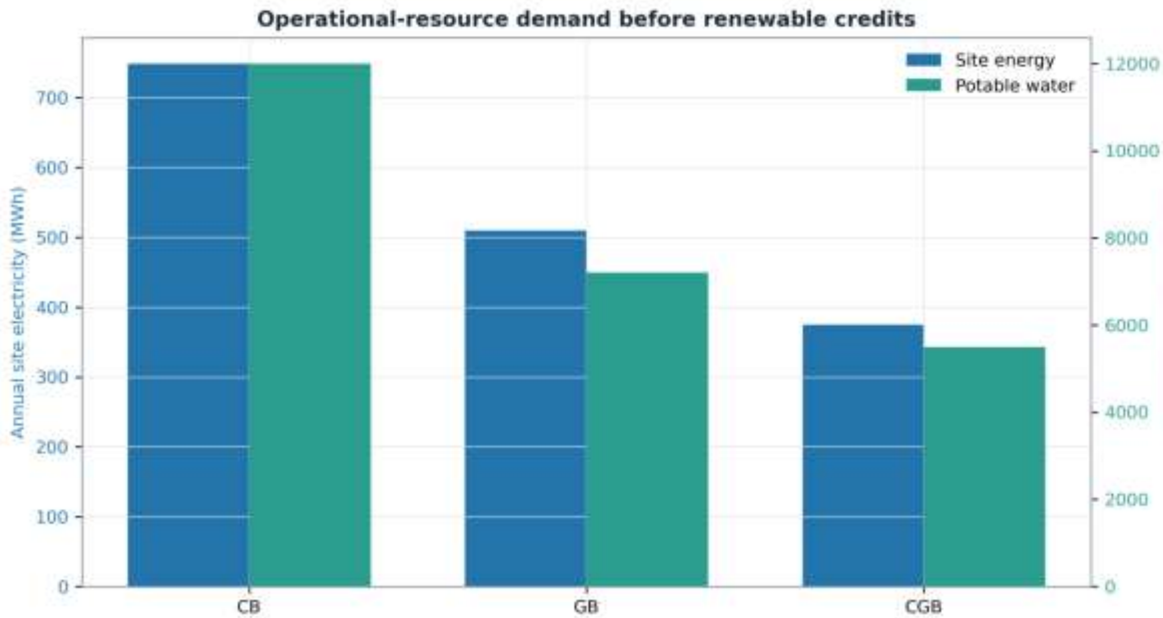

Figure 7. *Annual site electricity and potable-water demand before renewable export credits.*

Source: Scenario operational inventory. Site energy is shown before PV offset; B6 uses grid imports.

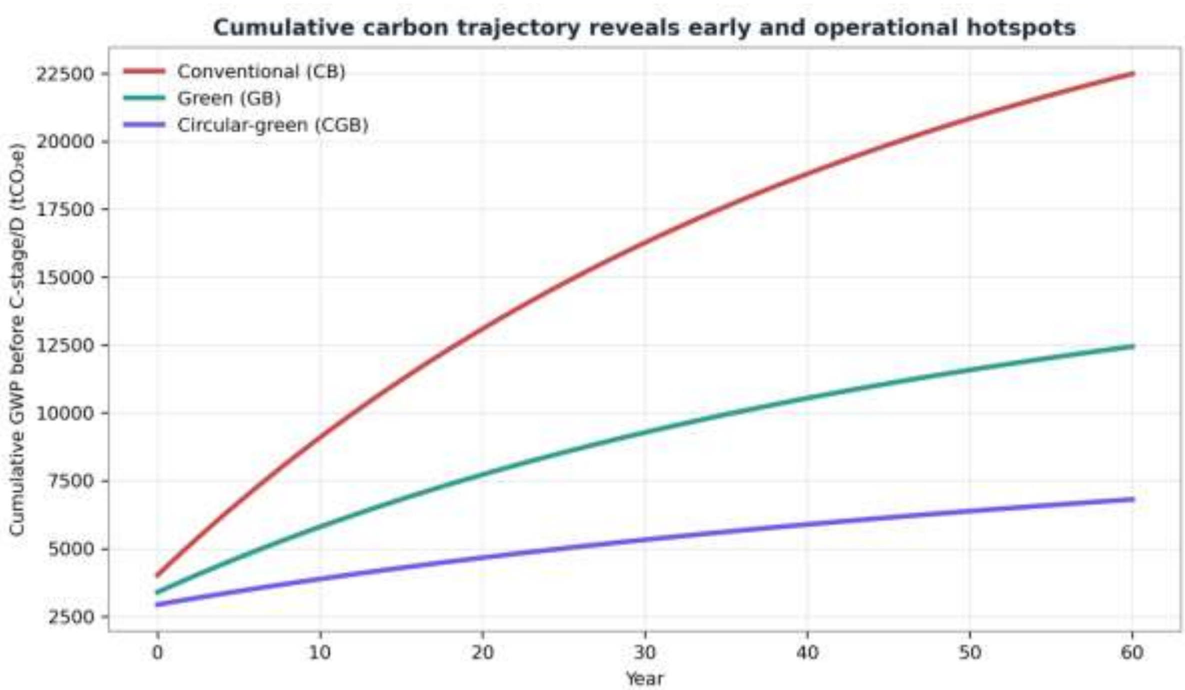

Figure 8. *Cumulative GWP trajectory over the 60-year reference study period before end-of-life stages.*

Source: Central scenario with 2.5% annual grid decarbonization and linearly annualized replacement allowance.

4.4 Multi-impact results and burden shifting

The green scenarios improve all reported indicators, so no modeled category-level burden shift reverses the ranking. CGB reductions relative to CB range from 40.3% for photochemical ozone creation to 65.4% for landfill waste. GWP decreases by 71.7% because the conservative central case still recognizes large reductions in gross grid imports. Freshwater demand decreases by 53.7%, while primary energy decreases by 43.0%. These indicators should not be weighted into one score without an explicit value choice.

Table *8. Life-cycle environmental indicators per square metre.*

Indicator	Unit	CB	GB	CGB	CGB reduction
Whole-life GWP	kgCO_2e/m²	3,757.41	2,047.62	1,065.52	71.6%
Non-renewable primary energy	GJ/m²	60.00	43.30	34.20	43.0%
Freshwater use	m³/m²	121.70	73.30	56.30	53.7%
Acidification potential	kg SO_2e/m²	15.00	10.83	8.33	44.5%
Eutrophication potential	kg PO_4e/m²	4.67	3.33	2.50	46.5%
Photochemical ozone creation	kg NMVOCe/m²	8.67	6.50	5.17	40.4%
Non-hazardous waste to disposal	kg/m²	867.00	550.00	300.00	65.4%

Indicators are midpoint scenario estimates and are not normalized or weighted in the table.

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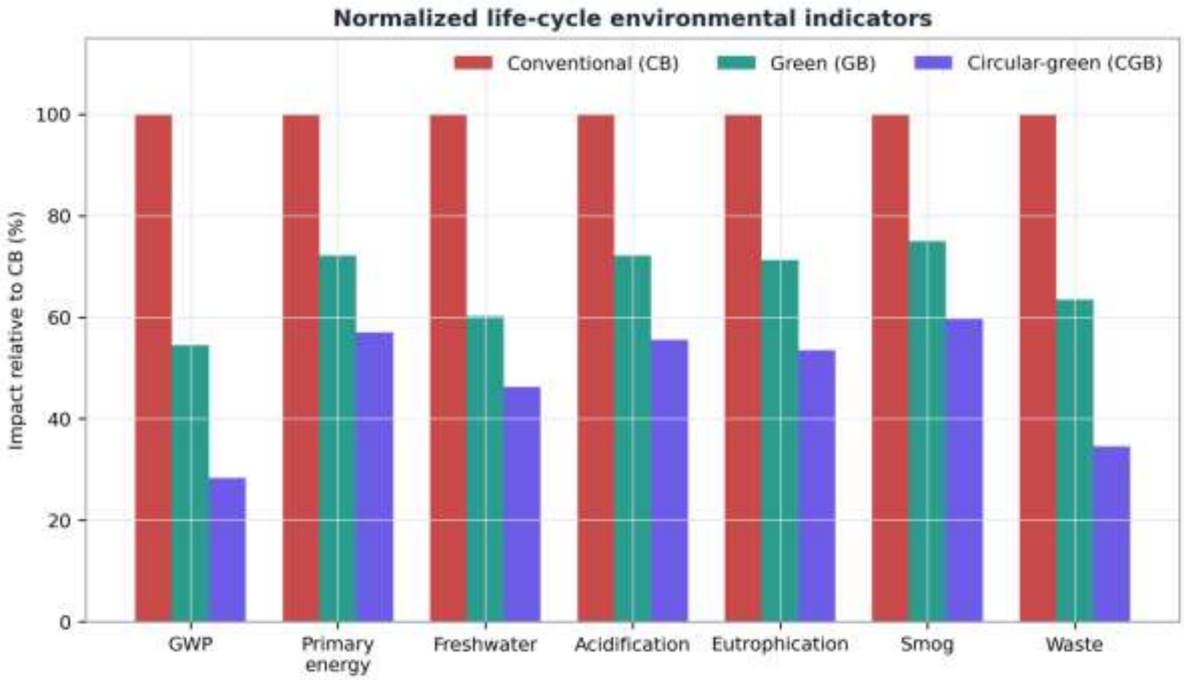

Figure *9. Environmental indicators normalized to the conventional-building result.*

Source: Comparative impact-assessment dataset; CB equals 100% in every category.

4.5 Circularity and end-of-life implications

CGB increases assumed direct reuse and closed-loop recycling from 30% in CB to 70%, while landfill falls from 40% to 8%. Design for disassembly, reversible connections, material passports and separation of service layers support this change. Module D credits increase accordingly, but they do not compensate for high A1–A3 emissions one-for-one because future recovery is uncertain and occurs decades later. The central result therefore prioritizes present material reduction and low-carbon procurement before future credits.

Table *9. Assumed end-of-life mass pathways.*

End-of-life pathway	CB	GB	CGB
Direct reuse	2%	8%	22%
Closed-loop recycling	28%	38%	48%
Downcycling	25%	27%	18%
Energy recovery	5%	5%	4%
Landfill	40%	22%	8%

Pathway shares sum to 100% for each scenario. Module D credit is varied separately in sensitivity analysis.

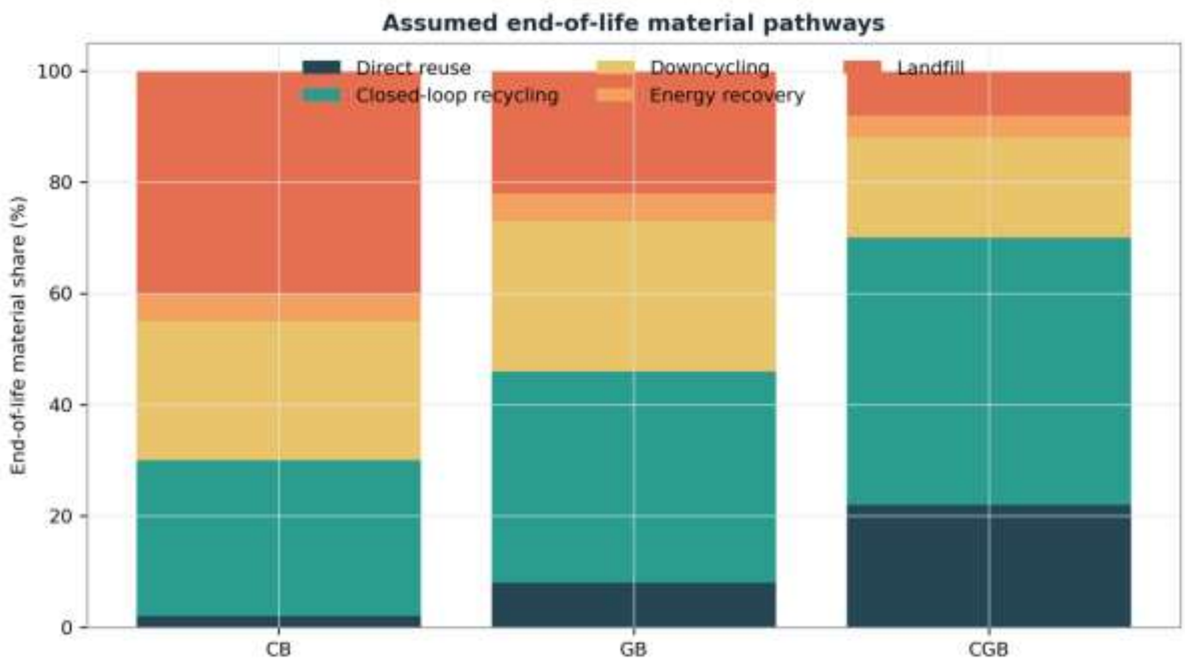

Figure *10. End-of-life material pathways assumed for CB, GB and CGB.*

Source: Scenario assumptions reflecting progressively stronger recovery planning.

4.6 Uncertainty and sensitivity

The Monte Carlo median CGB reduction is 71.3%. The 10th and 90th percentiles are 67.6% and 74.5%, and the probability of exceeding a 50% reduction is 100.0%. The scenario ranking does not reverse in the simulations. Operational performance and product GWP factors exert the strongest one-at-a-time effects, followed by grid decarbonization, service life and Module D. The result supports a robust direction of change but not false precision in the central total.

Table *10. Monte Carlo uncertainty inputs.*

Variable	Distribution	Parameters
Service life	Triangular	50 / 60 / 75 years
Grid decarbonization	Triangular	1 / 2.5 / 4% per year
CB operational multiplier	Normal	μ=1.00; σ=0.06
CGB performance gap	Triangular	0.92 / 1.00 / 1.18
CB product factors	Normal	μ=1.00; σ=0.10
CGB product factors	Normal	μ=1.00; σ=0.13

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Variable	Distribution	Parameters
Replacement intensity	Triangular	0.80 / 1.00 / 1.25
Module D credit	Triangular	0.60 / 1.00 / 1.35

μ = mean and σ = standard deviation. The model uses 5,000 runs and seed 20260719.

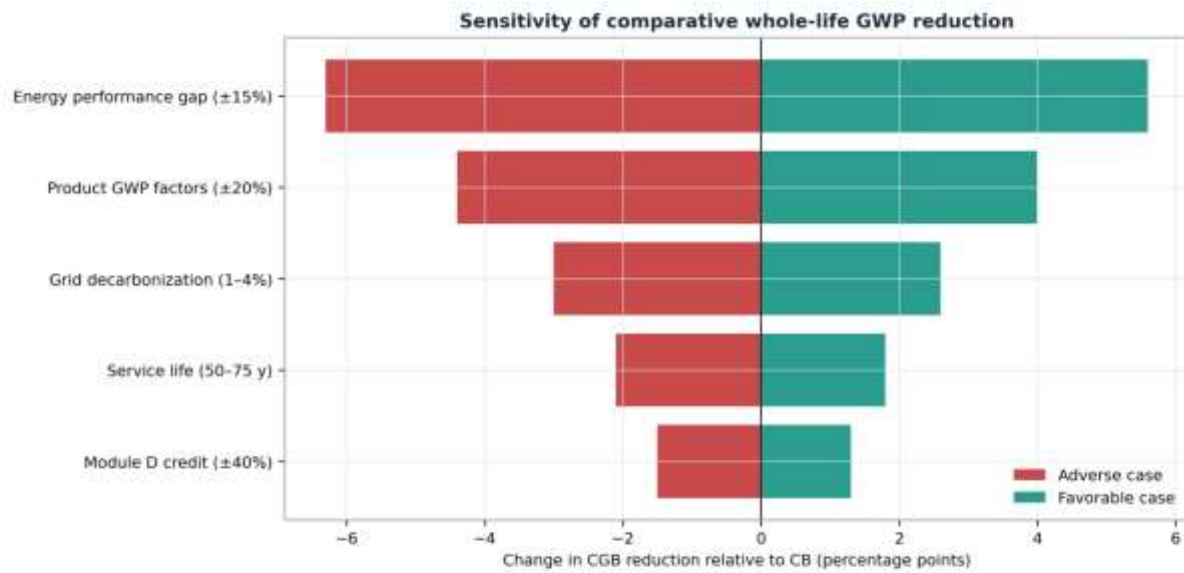

Figure *11. One-at-a-time sensitivity of the CGB whole-life GWP reduction relative to CB.*

Source: Authors' sensitivity calculation; adverse cases reduce the comparative benefit.

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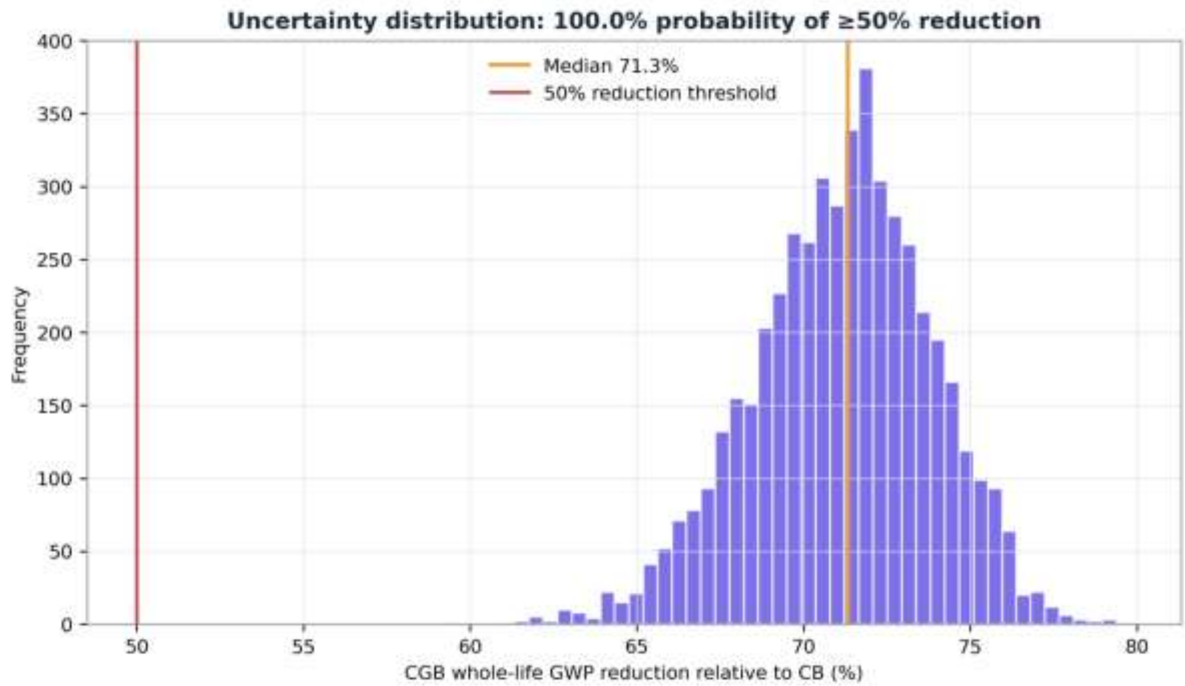

Figure *12. Monte Carlo distribution of the CGB whole-life GWP reduction relative to CB.*

Source: 5,000-run uncertainty model with shared grid and service-life parameters.

4.7 Life-cycle economic screen

GB and CGB require incremental capital of ₹21 and ₹30 million. Central annual net utility-and-maintenance savings are ₹3.70 and ₹5.77 million, giving simple paybacks of 5.7 and 5.2 years. The 30-year NPVs are ₹41.2 and ₹67.0 million. Thus, the environmental ranking is not achieved through a modeled life-cycle financial penalty in the central case. Tariff structure, demand charges and tender prices should nevertheless be updated for a real project.

Table *11. Central life-cycle economic indicators.*

Scenario	Capital cost	Annual utility	Net saving	Simple payback	30-y NPV
CB	₹300.0m	₹7.08m	—	—	—
GB	₹321.0m	₹3.08m	₹3.70m	5.7 y	₹41.2m
CGB	₹330.0m	₹0.92m	₹5.77m	5.2 y	₹67.0m

Net saving includes incremental O&M. NPV uses an 8% discount rate and 4% annual utility escalation.

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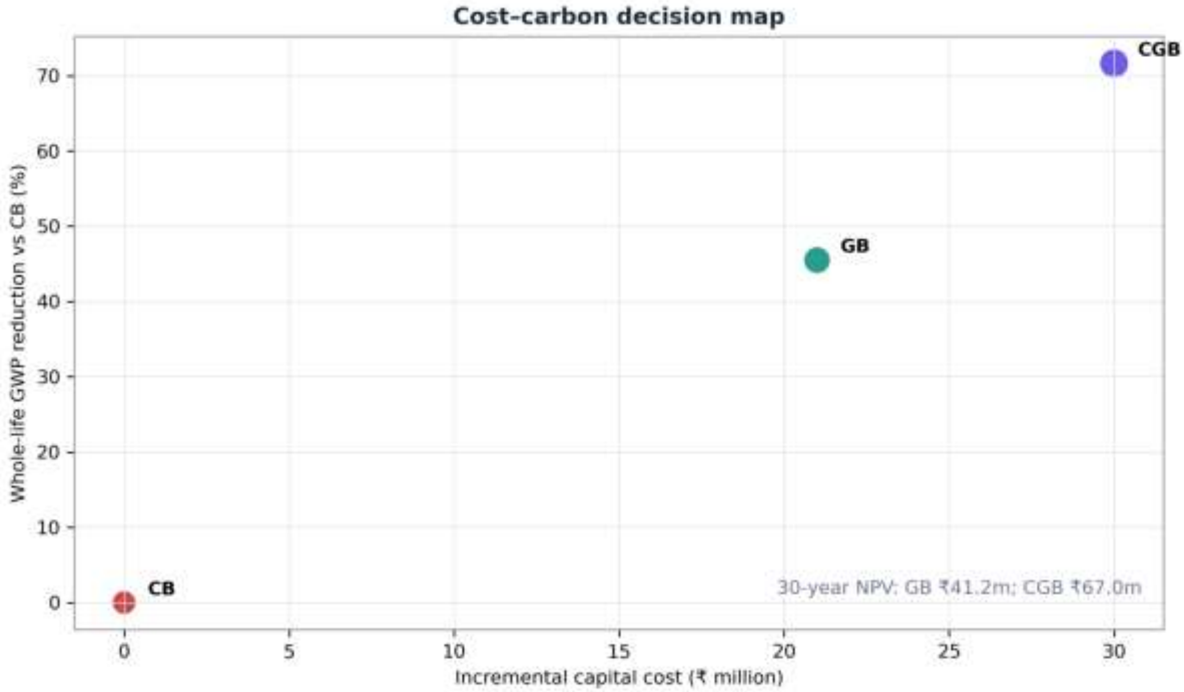

Figure *13. Incremental capital cost versus whole-life GWP reduction.*

Source: Central comparative carbon and discounted cash-flow models.

V. DISCUSSION

5.1 Environmental interpretation

The results show that green design is most effective when operational and embodied strategies are coordinated. Efficiency and PV produce the largest lifetime reduction, but structure remains the dominant upfront hotspot. Specifying low-carbon concrete without reducing material volume leaves a large residual burden; structural optimization without supplier data may select a theoretically efficient but carbon-intensive product. The CGB package succeeds because it combines quantity reduction, lower factors, efficient operation, renewable generation, water efficiency and recovery planning.

The conservative no-export-credit convention is important. An annual net-energy balance can make B6 appear near zero, while the building still imports electricity at non-solar hours. Gross-import accounting avoids using an annual export to erase temporally distinct imports and embodied emissions. Hourly marginal-carbon modeling would be a stronger next step and could be reported alongside annual accounting.

5.2 Implications for Indian green-building practice

GRIHA 6.0's LCA criterion creates a direct route from rating intent to quantified product GWP [11]. The present results suggest three implementation priorities: establish an upfront-carbon budget before structural design is fixed; require product-specific EPDs or verified supplier data at tender; and preserve operational energy, PV and water targets through commissioning and metering. Rating documentation should retain quantities, data sources, replacements and Module D assumptions so the calculation remains auditable.

Local data quality is a key constraint. Generic factors are useful for concept comparison but cannot distinguish plants, fuel mixes, recycled content or transport routes. India's emerging material databases should report representativeness, uncertainty and production route. Until then, studies should avoid excessive decimal precision and publish ranges.

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5.3 Circularity, durability and future uncertainty

Circular design is not synonymous with a large Module D credit. Reuse potential depends on documentation, connection type, contamination, market demand and selective deconstruction. A component that is theoretically recyclable may be downcycled or landfilled. The CGB assumptions are therefore targets requiring design for disassembly, material passports, accessible connections, adaptable service zones and contractual recovery plans. Durability must remain primary; premature replacement can erase upfront savings.

5.4 Comparison with published evidence

The dominance of conventional operational energy is consistent with the earlier life-cycle energy literature [14–16]. The growing share of embodied emissions in CGB agrees with recent whole-life-carbon studies [3–5,17–21]. The magnitude of reduction is project- and boundary-specific and should not be transferred directly to another building. The more general finding is the hotspot transition: as B6 decreases, structure, replacements and product data quality control the next increment of improvement.

VI. DESIGN, PROCUREMENT AND VERIFICATION FRAMEWORK

Table *12. Stage-gated LCA implementation and verification framework.*

Stage	Priority action	Evidence
Concept design	Set GWP budgets for A1–A5 and whole life; compare structural systems	Element quantities; generic ranges; uncertainty
Design development	Optimize spans, envelope, services, PV and water together	BIM take-off; energy/PV model; replacement plan
Tender	Require EPDs, recycled content, plant/route data and carbon reporting	Supplier declarations; transport distances; alternatives
Construction	Track actual quantities, waste, site energy and substitutions	Delivery records; waste tickets; site meters
Commissioning	Test controls, PV, water systems and metering	Functional tests; trend data; issue closure
Operation	Verify annual energy/water and update B4 schedules	Utility/submeter data; maintenance records
End-of-life planning	Maintain material passports and recovery partners	Asset register; connection details; take-back agreements

Project-specific rating and statutory documentation should be added to this research-oriented evidence map.

A practical project should maintain a live LCA linked to BIM quantities. Changes above a defined carbon threshold should trigger recalculation. The same model should be updated at tender, as-built and post-occupancy stages. This converts LCA from a retrospective rating exercise into a design-control process.

VII. LIMITATIONS AND FUTURE RESEARCH

The paper is limited by its archetype status, generic factors and reduced-order operational model. It does not use a complete BIM bill of quantities, project EPDs, hourly energy simulation, local water utility LCA, site-specific transport routes or measured construction and operation data. Replacement intervals are aggregated, and Modules B1–B3 and B5 are not modeled separately. Biogenic carbon, refrigerant leakage, occupant transport, biodiversity and social LCA are outside the boundary. Supplementary impact categories are scenario indicators rather than third-party database results.

Future research should develop India-region product datasets with uncertainty scores, couple BIM to an ISO-compliant LCA engine, model hourly energy and marginal grid carbon, include refrigerants, compare alternative structural systems and validate operational assumptions after occupancy. Dynamic LCA should test timing of emissions and recycling credits. A formal critical review is required before making a public comparative assertion about real products or projects.

VIII. CONCLUSION

A module-based whole-building LCA was developed for conventional, green and circular-green versions of a 6,000 m² academic building in Jaipur. Under the declared 60-year boundary, whole-life GWP decreases from 22,544 tCO_2e for CB to 12,286 tCO_2e for GB and 6,393 tCO_2e for CGB. The reductions are 45.5% and 71.6%, respectively. Upfront GWP falls by 15.6–27.0%, while use-stage reductions are larger because efficiency, direct PV utilization and water conservation reduce recurring demand.

CGB improves every reported impact category, reduces landfill from 40% to 8% of end-of-life mass, and remains environmentally preferable throughout the uncertainty analysis. The Monte Carlo result demonstrates robust direction but a wide enough range to reject false precision. Operational performance gaps and product GWP factors are the most important controllable uncertainties.

The core practical conclusion is that a green-building label should be supported by stage-specific budgets and evidence: efficient form and systems, verified low-carbon products, actual quantities, construction records, commissioning, submetered operation and a realistic recovery plan. LCA adds value when it changes design and procurement before impacts are locked in and remains active through post-occupancy verification.

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