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Integrated Net-Zero Energy Design for Hot-Dry Institutional Buildings: A Scenario-Based Energy, Carbon and Cost Assessment for Jaipur, India

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Abstract

Net-zero-energy buildings in hot-dry regions must reconcile high cooling demand, limited roof area, grid interaction, embodied carbon and investment constraints. This study develops an integrated design-stage assessment for a four-storey, 6,000 m² institutional building in Jaipur, India. The baseline is aligned with the Energy Conservation and Sustainable Building Code 2024, while the proposed case combines east–west massing, solar control, improved opaque-envelope performance, high-performance glazing, daylight-linked LED lighting, efficient variable-refrigerant-flow cooling, demand-controlled ventilation, plug-load management and a 235 kWp rooftop photovoltaic system. A transparent monthly/end-use energy model is linked to annual and representative hourly energy-balance checks, an A1–A5 embodied-carbon inventory, a 60-year operational carbon model, a 25-year discounted cash-flow analysis and a 5,000-run Monte Carlo uncertainty assessment. The modeled annual site energy decreases from 748.8 to 375.0 MWh, equivalent to an EUI reduction from 124.8 to 62.5 kWh/m²·year. PV generation is 385.4 MWh/year, producing an annual surplus of 10.4 MWh; however, only 68.2% of PV electricity is used directly, so the building still imports 112.3 MWh and exports 122.7 MWh. Upfront embodied carbon falls from 4,030 to 3,050 tCO_2e despite the PV addition, primarily through lower-carbon concrete and recycled-content steel. Under a 2.5% annual grid-decarbonization trajectory, whole-life carbon falls by 73–86%, depending on whether exported electricity is credited. The ₹31.9 million incremental investment has a 5.8-year simple payback, an 8-year discounted payback, a 20.1% internal rate of return and a ₹46.4 million NPV. The study shows that annual net zero is technically and economically plausible for the selected archetype, but robust delivery requires explicit PV margin, commissioning, plug-load governance and post-occupancy verification.

Keywords: net-zero energy building; sustainable construction; hot-dry climate; ECSBC 2024; rooftop photovoltaics; embodied carbon; life-cycle cost; uncertainty analysis; Jaipur

1. Introduction

The buildings and construction sector remains central to global decarbonization because its demand is simultaneously shaped by urbanization, rising expectations for thermal comfort and the carbon intensity of construction materials. The 2024/2025 Global Status Report estimates that the sector consumes 32% of global energy and contributes 34% of global carbon dioxide emissions [1]. Although improvements in codes, equipment and renewable generation are slowing energy-intensity growth, total floor area and cooling demand continue to expand. In hot climates, the challenge is not simply to attach solar panels to a conventional building. The building must first suppress heat gains and internal loads, preserve indoor environmental quality, then match the residual demand to renewable generation within a physically constrained roof and a carbon-intensive grid [2,3].

The net-zero concept is deceptively simple but methodologically contested. Early work distinguished site energy, source energy, energy cost and emissions balances [4]. Later frameworks emphasized the need to declare the physical boundary, the balance metric, the period, the renewable-supply hierarchy and the treatment of exported energy [5,6]. The United States Department of Energy subsequently formalized zero energy as an annual source-energy balance for an energy-efficient grid-connected building [7], while ISO 52000-1 provides a modular basis for whole-building energy performance assessment [8]. For Indian practice, the IGBC Net Zero Energy system accepts projects that offset 100% of annual grid energy use through on-site or off-site renewable sources [15]. These definitions make annual balance a necessary compliance indicator, but they do not ensure load matching, peak-demand reduction, resilience or whole-life carbon neutrality.

India's Energy Conservation and Sustainable Building Code (ECSBC) 2024 provides a timely regulatory basis for higher-performance non-residential construction. It introduces ECSBC, ECSBC Plus and Super ECSBC tiers and retains performance-based comparison between proposed and baseline models [14]. Meanwhile, Indian NZEB benchmark research reports that design-stage EUI targets approximately 60% below minimum code performance are feasible across several building types and climate zones [13]. Yet a recurring gap remains between code-compliance studies and integrated net-zero studies. Many analyses stop at annual energy savings, omit temporal import/export behavior, ignore embodied carbon or use single-value financial assumptions without uncertainty. Such omissions are particularly important for institutional buildings, where daytime occupancy helps PV self-consumption but academic calendars, plug loads and cooling set points introduce substantial variability.

This paper addresses that gap through a transparent scenario-based case study for Jaipur. Rather than presenting invented field measurements, the study constructs a reproducible archetype and subjects it to linked energy, PV, grid-exchange, embodied-carbon, life-cycle carbon, economic and probabilistic checks. The approach is intentionally appropriate for early design, when geometry, envelope, system efficiency and roof allocation can still be changed. It produces a coherent dataset that can be replaced later by project-specific EnergyPlus or equivalent simulation outputs without changing the assessment framework.

1.1 Research questions and contribution

The study is organized around four research questions:

- RQ1: How far can an ECSBC-aligned institutional archetype in Jaipur reduce its site EUI through an efficiency-first package?
- RQ2: Can a roof-feasible PV system close the annual site-energy balance, and what level of grid exchange remains after annual net zero is reached?
- RQ3: How do the proposed energy measures affect upfront and 60-year whole-life carbon when grid decarbonization and export-credit conventions are varied?
- RQ4: Is the integrated package economically attractive and robust to uncertainty in occupancy, plug loads, set points, infiltration, PV yield and shading?

The principal contribution is a joined decision framework rather than a single optimized EUI. It connects the 2024 Indian code context to a declared annual site-energy boundary, checks direct PV utilization and imports/exports, introduces upfront-carbon trade-offs, and quantifies confidence in the net-zero claim. This matters because a design that balances in a deterministic annual spreadsheet can fail after occupancy changes, and a design that is operationally net zero can still carry high construction-phase emissions.

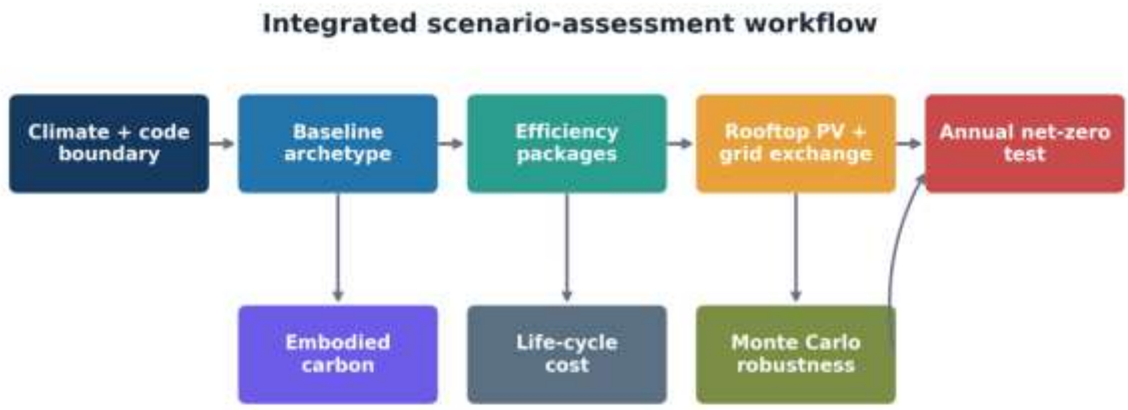

Figure 1. *Integrated workflow linking code boundary, efficiency packages, PV sizing, annual balance, embodied carbon, life-cycle cost and uncertainty.*

Source: Authors' framework developed for this study.

2. Literature review

2.1 Definitions, balance boundaries and performance indicators

Marszal et al. [5] and Sartori et al. [6] established that the meaning of "zero" depends on both the quantity being balanced and the weighting system applied to imported and exported energy. A site-energy balance is transparent for all-electric buildings because delivered electricity and PV generation use the same unit; a source-energy or emissions balance is more appropriate when fuels or time-varying grid factors are important. Deng et al. [9] further argued that NZEB evaluation should include efficiency, renewable supply, indoor environment, economic performance and life-cycle implications. Accordingly, this study uses annual site electricity as the primary net-zero test, while separately reporting self-consumption, import, export, peak demand, operational emissions and whole-life carbon.

Annual balance alone can conceal the timing mismatch between midday PV generation and late-afternoon or evening consumption. Load matching can be improved with daytime occupancy, thermal storage, batteries, pre-cooling or demand-response controls, but each option carries cost, embodied carbon and operational complexity. The present assessment therefore treats direct PV use as a secondary indicator and uses a representative summer weekday to visualize grid dependence. This does not replace a full 8,760-hour simulation, but it prevents the annual balance from being interpreted as electrical autonomy.

2.2 Efficiency-first design in hot climates

Evidence from zero-energy projects in warm climates consistently supports a hierarchy of load reduction, efficient systems and renewable supply. Reviews of hot-climate NZEBs identify orientation, solar control, high-performance envelopes, daylighting, efficient cooling and PV as recurring measures [12]. Measured evaluation of a hot-humid net-zero office also shows that the presence of efficient technologies does not by itself guarantee the predicted outcome; commissioning, controls and actual schedules remain decisive [11]. The hierarchy is particularly important where rooftop area is finite: every avoided kilowatt-hour reduces PV capacity, inverter size and embodied impact while increasing the probability that the annual balance survives operational variation.

Jaipur's hot-dry climate is characterized by intense solar radiation, large diurnal temperature swings, a long cooling season and a shorter monsoon period. These conditions favor external shading, low-solar-gain glazing, reflective insulated roofs, controlled ventilation and night-time or shoulder-season mixed-mode operation where outdoor conditions allow. High insulation must be coupled with solar control and operational strategies; otherwise internal gains can be trapped. For institutional buildings, daylight access and occupancy-responsive systems are valuable because lighting and ventilation loads coincide with daytime use.

2.3 Embodied carbon and economic feasibility

As operating demand decreases and grids decarbonize, embodied impacts become a larger fraction of whole-life emissions. Life-cycle zero-energy concepts explicitly extend the energy boundary to materials and replacement cycles [26]. Reviews of building life-cycle assessment identify structure, envelope and energy systems as dominant contributors [27–30]. Concrete and steel frequently dominate structural impacts, whereas PV modules, inverters, insulation and high-performance glazing introduce additional upfront burdens. A defensible net-zero design should therefore avoid assuming that operational balance automatically equals net-zero carbon.

Economic assessments similarly require more than a simple equipment payback. Kapsalaki et al. [10] emphasize joint optimization of efficiency and renewable supply, while NREL cost-control guidance shows that integrated design and explicit energy targets reduce the risk of expensive late-stage additions [37]. The cost model in this paper includes incremental capital, imported-electricity cost, export credit, operation and maintenance, degradation, tariff escalation and inverter replacement. Its purpose is not to predict a future tariff precisely, but to show whether the conclusion remains stable across reasonable assumptions.

Table *1. Positioning of the present study within representative net-zero-energy literature.*

Study	Method	Principal contribution	Gap relative to this study
Torcellini et al. [4]	Definition/case synthesis	Site, source, cost and emissions definitions	No India-specific design or uncertainty
Sartori et al. [6]	Definition framework	Boundary, weighting, balance and grid interaction	Does not size a specific building
Deng et al. [9]	Literature research	Multi-indicator NZEB evaluation	Limited project-level cost/carbon integration
Shin et al. [11]	Measured hot-climate office	Performance gap and operational evidence	Different climate and regulatory context
Vakil et al. [13]	India simulation benchmarks	EUI targets across climate/building types	No joined PV, embodied-carbon and cash-flow model
Present study	Scenario model + uncertainty	ECSBC 2024, PV/grid, carbon, cost and probability	Archetype; requires project-specific validation

Note: The table is selective and intended to establish the methodological gap, not to serve as a systematic review.

3. Materials and methods

3.1 Case-study archetype and system boundary

The case study is a hypothetical four-storey academic building located in Jaipur, Rajasthan. It represents classrooms, studios, faculty offices, circulation, support spaces and a small server/IT load. The gross floor area is 6,000 m² and the roof footprint is 1,500 m². The long axis is oriented east–west to reduce low-angle solar exposure on the east and west façades and to simplify south-façade shading. The primary energy boundary includes all regulated and unregulated site electricity: cooling, ventilation, pumps, lighting, plug equipment, lifts, domestic hot water and auxiliary uses. Cooking fuel, electric-vehicle charging and campus central-plant loads are outside the boundary.

The occupancy schedule assumes 600 persons at design capacity, weekday operation from 08:00 to 18:00, reduced Saturday use and academic vacation effects in December. The building is all-electric. Thermal-comfort control uses a 24–26°C occupied cooling band with zone-level control; mixed-mode ventilation is allowed in suitable shoulder hours but is not credited as a large annual energy reduction. This conservative treatment avoids overstating natural ventilation under dust, noise, security or air-quality constraints.

Table *2. Case-study building, operation and assessment boundaries.*

Parameter	Modeled value / boundary
Location and climate	Jaipur, Rajasthan; hot-dry
Building type	Institutional/academic, new construction
Gross floor area	6,000 m²
Storeys / footprint	4 / 1,500 m²
Conditioned floor area	5,400 m² (90% of gross)

Parameter	Modeled value / boundary
Design occupancy	600 persons
Typical occupied hours	08:00–18:00 weekdays; reduced Saturdays
Primary net-zero boundary	Annual site electricity; all regulated and plug loads
Analysis periods	1 year energy; 25 years cost; 60 years carbon
PV boundary	On-site rooftop array; no off-site renewable procurement

Source: Archetype assumptions developed for the present design-stage study.

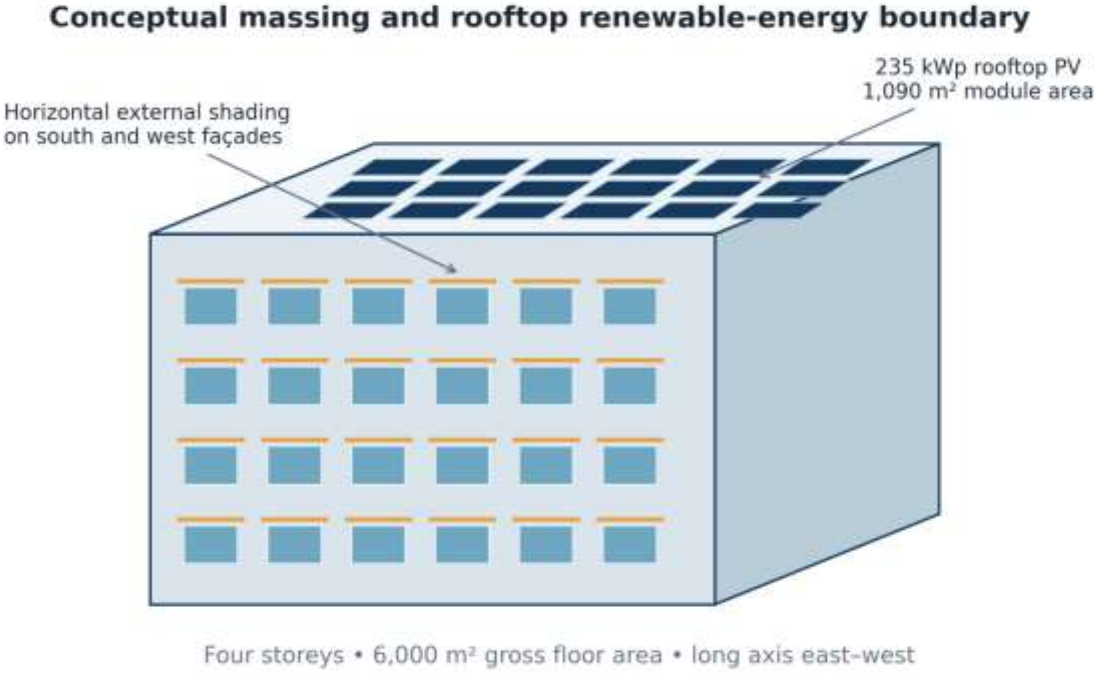

Figure 2. *Conceptual four-storey massing, external shading and rooftop PV allocation used to test roof feasibility.*

Source: Authors' conceptual illustration. It is not a construction drawing.

3.2 Baseline and efficiency scenarios

Scenario S0 represents a code-aligned baseline rather than poor practice. S1 changes orientation-sensitive envelope performance, shading, airtightness and roof reflectance. S2 adds high-efficacy LED lighting, occupancy sensing and daylight dimming. S3 introduces high-efficiency variable-refrigerant-flow cooling, dedicated outdoor-air control, variable-speed fans and demand-controlled ventilation. S4 adds plug-load schedules, advanced power strips, after-hours shutdown, submetering and supervisory controls. PV is added only after S4 so that renewable capacity is sized to the reduced demand.

Table 3. *Cumulative design scenarios used in the assessment.*

ID	Scenario	Cumulative measures
S0	Code baseline	ECSBC 2024-aligned envelope and systems; conventional controls
S1	Passive envelope	East–west massing, external shading, lower U-values/SHGC, cool roof, lower infiltration
S2	Lighting/daylight	LED LPD 5.5 W/m², daylight dimming and occupancy sensing
S3	Efficient HVAC	High-efficiency VRF, VSD fans, zone control and demand-controlled ventilation
S4	Controls/plug loads	Plug-load budgets, schedules, shutdown and energy submetering
S5	Net-zero package	S4 plus 235 kWp rooftop PV; lower-carbon concrete/steel procurement

Each scenario retains all measures from the preceding scenario.

Table 4. *Principal baseline and optimized design inputs.*

Design parameter	S0 baseline	S4 optimized
Wall U-value	0.44 W/m²·K	0.28 W/m²·K
Roof U-value	0.33 W/m²·K	0.20 W/m²·K
Roof solar reflectance	0.50	0.75 initial
Glazing U-value	3.3 W/m²·K	1.8 W/m²·K
Glazing SHGC	0.35	0.24
Window-to-wall ratio	35% uniform	30% overall; reduced east/west
External shading	Code-minimum	South projection factor 0.60; west fins
Infiltration	0.50 ACH occupied equivalent	0.30 ACH occupied equivalent
Lighting power density	8.0 W/m²	5.5 W/m² with controls
Cooling system	Conventional code-level VRF	High-efficiency VRF; seasonal COP 4.3

Values are design assumptions selected to be technically plausible under the ECSBC 2024 framework; manufacturer-specific compliance must be checked during design development.

3.3 Energy model and performance metrics

The energy dataset is constructed as an end-use scenario model at monthly resolution, with representative hourly profiles used only for grid-interaction illustration. The S0 EUI is anchored to a code-aligned institutional archetype. Savings from the cumulative packages are applied by end use and cross-checked against the magnitude of performance improvements reported in India's NZEB benchmark study [13], ECSBC performance tiers [14] and warm-climate NZEB literature [11,12]. Cooling responds to envelope, solar control, occupancy, set point, infiltration and seasonal HVAC efficiency; lighting responds to installed power, daylight availability and schedules; plug loads respond to diversity and shutdown assumptions. The model is deterministic in the central case and probabilistic in Section 3.7.

Energy-use intensity is annual site electricity divided by gross floor area. The primary net-zero indicator is the difference between on-site PV production and annual site electricity. Positive values indicate a modeled annual surplus. Renewable coverage is PV generation divided by annual site load. PV self-consumption is direct on-site PV use divided by generation. These metrics are calculated as follows:

$$EUI = E\_site / A\_gross \quad (1)$$

$$B\_NZ = E\_PV - E\_site \quad (2)$$

$$SC\_PV = E\_PV{,}direct / E\_PV \quad (3)$$

A full journal submission should replace the reduced-order dataset with an auditable 8,760-hour EnergyPlus model, preferably tested in accordance with ASHRAE Standard 140 [17–19], and should publish the input file, weather file and scripts. The present method is appropriate for comparing early design decisions and testing whether the integrated conclusion is internally consistent.

3.4 Photovoltaic sizing and grid exchange

The roof feasibility check reserves approximately 27% of the 1,500 m² roof for setbacks, access, drainage, equipment and fire-safety clearances. The remaining 1,090 m² supports approximately 235 kWp using high-efficiency modules at about 0.216 kWp/m² of module footprint. The central annual specific yield is 1,640 kWh/kWp, giving 385.4 MWh/year. This yield incorporates temperature, inverter, wiring, mismatch, soiling and availability losses at a design-stage level. The modeling logic follows the system-loss approach used by NREL PVWatts and the System Advisor Model references [21,22], but it is not a direct PVWatts run for the site.

Monthly direct PV utilization is estimated from the overlap between the academic load shape and the solar-production profile. Grid import is site load minus direct PV use; export is PV generation minus direct PV use. Exported electricity receives an economic credit in the central cash-flow case, but the paper reports carbon results both with and without an export credit because annual accounting conventions and marginal grid effects are not identical.

3.5 Embodied and operational carbon

The upfront embodied-carbon boundary covers product stages A1–A3, transport A4 and construction A5. Quantities are represented at element level rather than as a detailed bill of materials. The baseline total is 4,030 tCO_2e (672 $kgCO_2e/m^2$), while the proposed case uses lower-clinker concrete mixes where structurally and durably appropriate, reinforcement and structural steel with higher recycled content, material-efficiency measures and controlled construction waste. The proposed inventory includes the PV modules and balance of system. The calculation structure follows ISO 14040/14044 life-cycle principles [24,25] and established building LCA literature [27–34]. These values are benchmark-quality estimates, not product-specific environmental product declaration data.

Operational carbon uses the Central Electricity Authority FY 2024–25 weighted average grid factor of 0.710 tCO_2/MWh [23]. A 2.5% annual grid-decarbonization trajectory is applied over 60 years as a scenario, not as an official forecast. The annual export-credit case subtracts exported PV electricity at the same declining average factor; the conservative gross-import case assigns no avoided-emission credit to exports. The resulting range exposes the sensitivity of "net-zero carbon" claims to accounting convention.

$$C\_WLC = C\_A1\text{–}A5 + \Sigma[(E\_import,y - k\_export\ E\_export,y) \times EF\_grid,y] \quad (4)$$

In Equation (4), k_export is one in the annual export-credit case and zero in the gross-import case. Replacement-stage and end-of-life emissions are excluded because product-specific service lives and recovery routes were not available; this exclusion is carried into the limitations.

3.6 Life-cycle cost assessment

The financial boundary is incremental to the S0 building and spans 25 years. Central assumptions are an electricity purchase tariff of ₹8.5/kWh, an export credit of ₹3.0/kWh, 4% annual tariff escalation, 8% discount rate, 0.5% annual performance degradation and an inverter replacement allowance of ₹2.0 million in year 13. Fixed demand charges, taxes, financing structure, depreciation benefits and subsidies are excluded so that the result reflects project fundamentals. The net present value is the discounted sum of annual net cash flows less the initial incremental investment.

$$NPV = -I_0 + \Sigma[CF\_y / (1 + r)^\wedge y] \quad (5)$$

3.7 Uncertainty and sensitivity analysis

A 5,000-run Monte Carlo analysis propagates uncertainty in occupancy (triangular, 0.88–1.15), plug-load intensity (0.80–1.20), cooling set-point deviation (uniform, ±1°C), infiltration (0.75–1.25 of central), HVAC efficiency (normal, 5% standard deviation), PV specific yield (normal, 5.5% standard deviation) and shading loss (triangular, 0–8%). Parameter effects are applied only to relevant end uses rather than multiplying the whole building load by every uncertainty. The principal output is the probability that annual PV generation equals or exceeds site load. A one-at-a-time sensitivity chart supplements the probabilistic result and identifies the variables requiring the strongest design control.

4. Results

4.1 Energy-efficiency pathway

The central scenario reduces annual site electricity from 748.8 to 375.0 MWh, a 49.9% reduction. EUI falls from 124.8 to 62.5 kWh/m²·year. The optimized value is close to the order of magnitude expected for an efficiency-led Indian NZEB archetype, although it is not as aggressive as a 60% code reduction for every end use [13]. Cooling remains the largest end use after optimization, but its consumption falls from 330 to 135 MWh. Lighting decreases from 110 to 48 MWh, and equipment decreases from 180 to 115 MWh. These results show why the PV array is feasible: renewable sizing follows a 374 MWh efficiency reduction rather than attempting to offset the original 748.8 MWh demand.

Table 5. *Modeled cumulative energy performance across the efficiency pathway.*

Cumulative scenario	EUI (kWh/m²·yr)	Annual energy (MWh)	Savings vs S0 (%)
S0 Code baseline	124.8	748.8	0.0
S1 Passive envelope	106.0	636.0	15.1
S2 Lighting/daylight	92.7	556.2	25.7

Cumulative scenario	EUI (kWh/m²·yr)	Annual energy (MWh)	Savings vs S0 (%)
S3 High-efficiency HVAC	71.6	429.6	42.6
S4 Controls and plug loads	62.5	375.0	49.9

Values are rounded; annual energy equals EUI × 6,000 m².

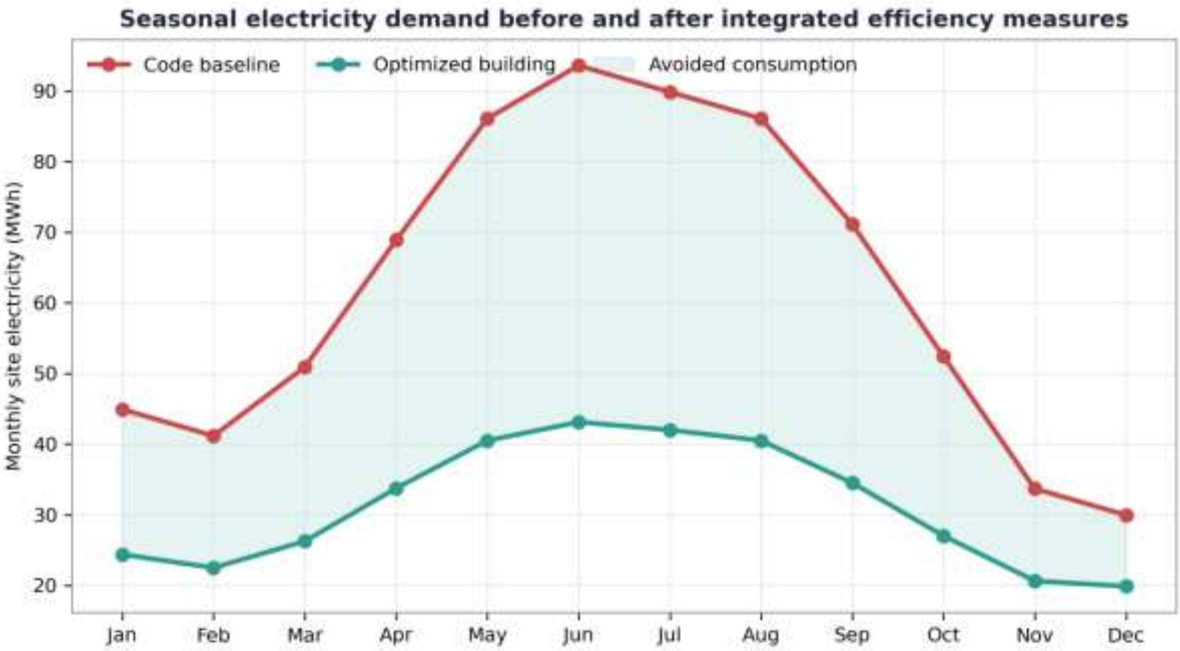

Figure 3. *Modeled monthly electricity demand for the code baseline and optimized building.*

Source: Scenario-model output. Monthly values sum to 748.8 MWh and 375.0 MWh, respectively.

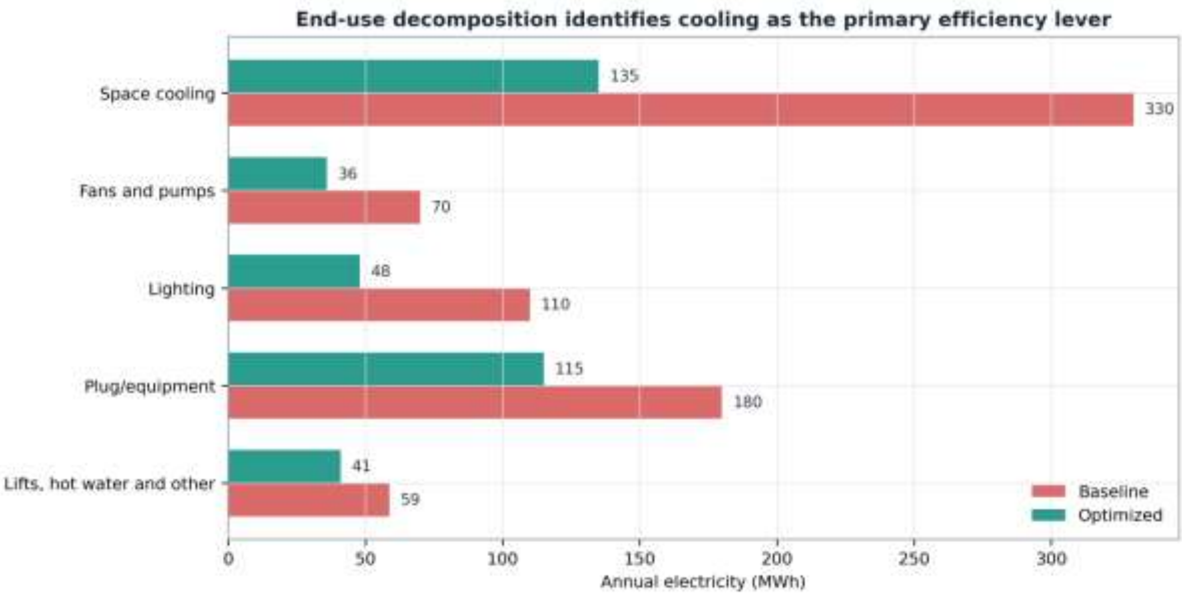

Figure 4. *Annual end-use electricity decomposition before and after integrated efficiency measures.*

Source: Scenario-model output; all end uses sum to the corresponding annual total.

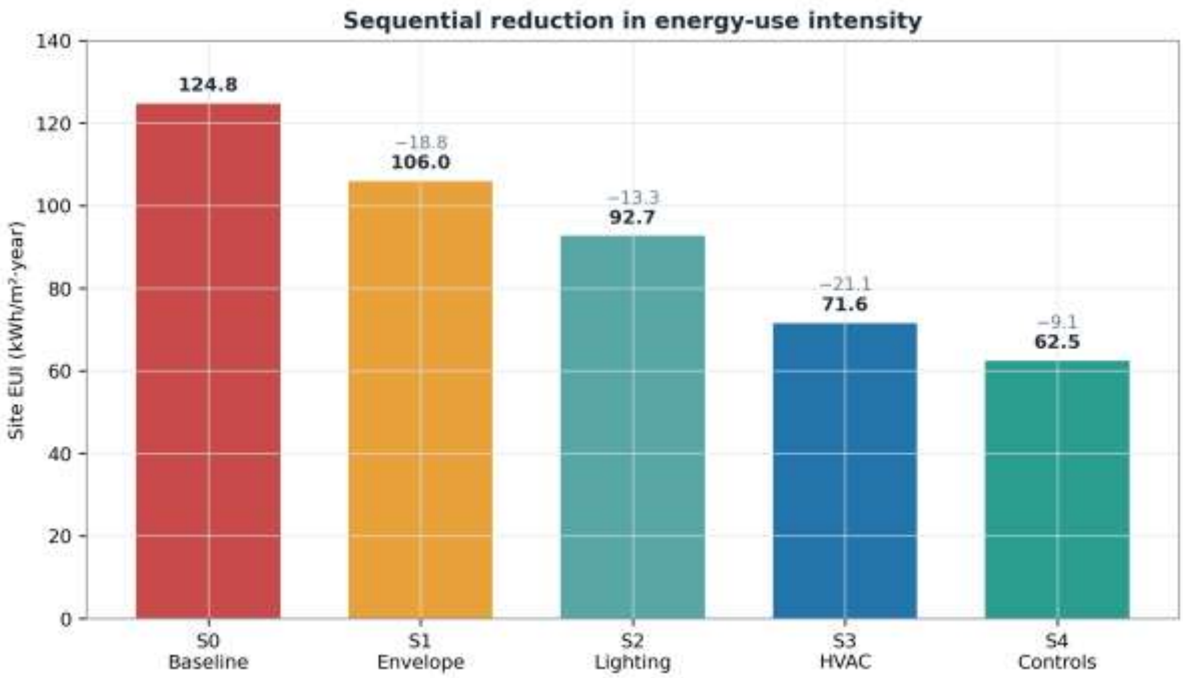

Figure 5. *Cumulative site-energy-use intensity reduction from the S0 code baseline to S4 controls and plug-load management.*

Source: Scenario-model output. Values represent cumulative, not isolated, packages.

4.2 PV production and annual net-zero balance

The 235 kWp array produces 385.4 MWh/year in the central case, equivalent to 1640 kWh/kWp·year. Because the optimized load is 375.0 MWh/year, the annual site-energy balance is +10.4 MWh and renewable coverage is 102.8%. Net zero is therefore achieved under the declared annual site-energy definition. Monthly generation exceeds load in eight months but falls below load during June–September cooling/monsoon conditions and in December under the selected academic and solar profiles.

Table 6. *Monthly electricity balance (MWh).*

Month	Load	PV	Import	Export	Net
Jan	24.4	27.0	7.6	10.2	+2.6
Feb	22.5	28.9	6.3	12.7	+6.4
Mar	26.3	34.7	6.3	14.7	+8.4
Apr	33.8	36.6	7.4	10.3	+2.9
May	40.5	40.5	8.1	8.1	-0.0
Jun	43.1	38.5	11.5	6.9	-4.6
Jul	42.0	30.8	17.6	6.5	-11.2
Aug	40.5	30.8	16.1	6.5	-9.7
Sep	34.5	32.8	9.6	7.9	-1.7
Oct	27.0	34.7	7.6	15.2	+7.7
Nov	20.6	27.0	7.0	13.4	+6.4
Dec	19.9	23.1	7.2	10.4	+3.2
Annual	375.0	385.4	112.3	122.7	+10.4

Import and export reflect estimated within-month load/PV overlap; net equals PV minus load.

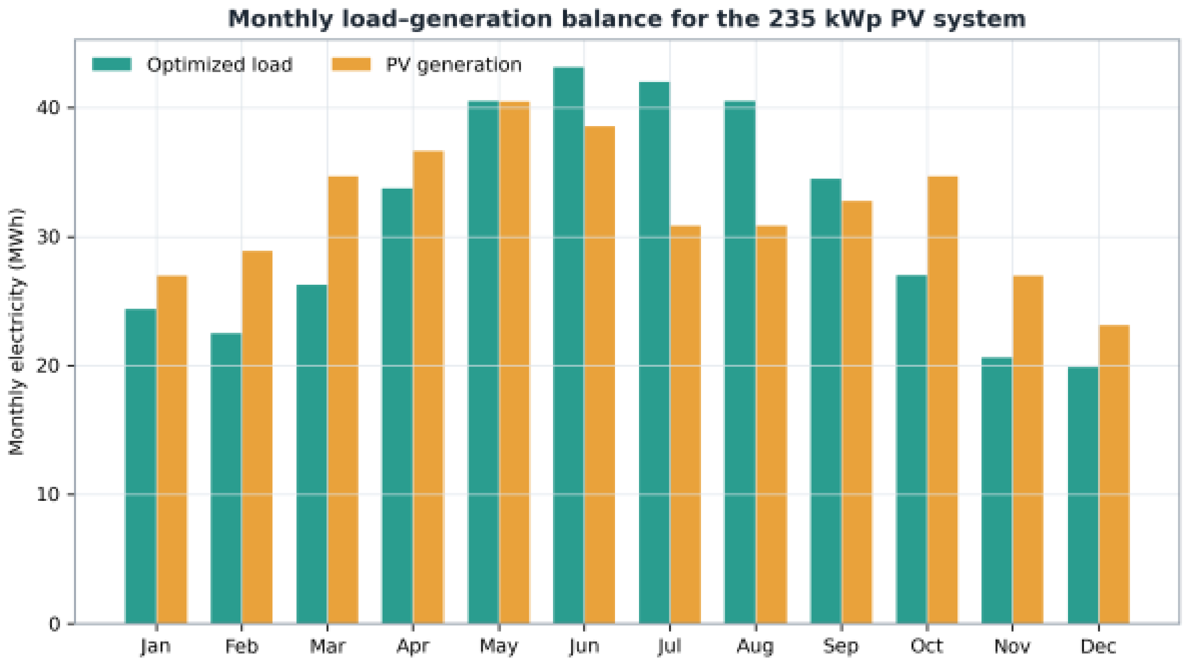

Figure 6. *Monthly optimized electricity demand and modeled rooftop-PV generation.*

Source: Scenario-model output. Annual totals are 375.0 MWh load and 385.4 MWh PV generation.

4.3 Load matching and grid interaction

Direct PV use is 262.7 MWh/year, or 68.2% of generation. The building imports 112.3 MWh and exports 122.7 MWh despite achieving an annual surplus. The representative May weekday shows morning import, a midday export interval and renewed late-afternoon/evening import. Therefore, the result should be described as grid-connected annual net zero, not autonomous or off-grid operation. A battery would increase self-consumption and reduce ramps, but it is not necessary for the annual balance and would add capital cost, replacement risk and embodied carbon.

Table 7. *Annual net-zero and grid-interaction indicators.*

Indicator	Central result
Annual optimized site load	375.0 MWh
Annual PV generation	385.4 MWh
Annual net balance	+10.4 MWh
Renewable coverage	102.8%
Direct PV use	262.7 MWh
PV self-consumption	68.2%
Grid import	112.3 MWh
Grid export	122.7 MWh
Baseline / optimized peak demand	221 kW / 132 kW

Peak demand is a representative design-day estimate; an interval-meter or 8,760-hour model is required for tariff-grade demand analysis.

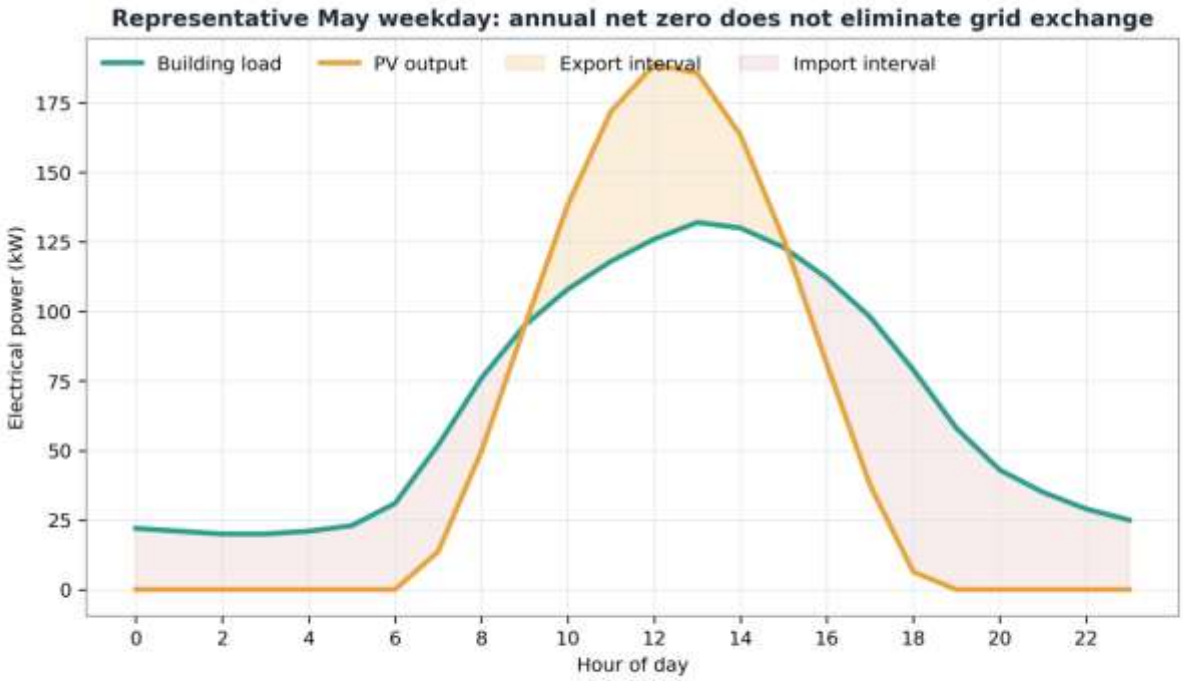

Figure 7. *Representative May weekday load and PV output showing import and export intervals.*

Source: Authors' representative hourly profile; used for interpretation, not annual energy calculation.

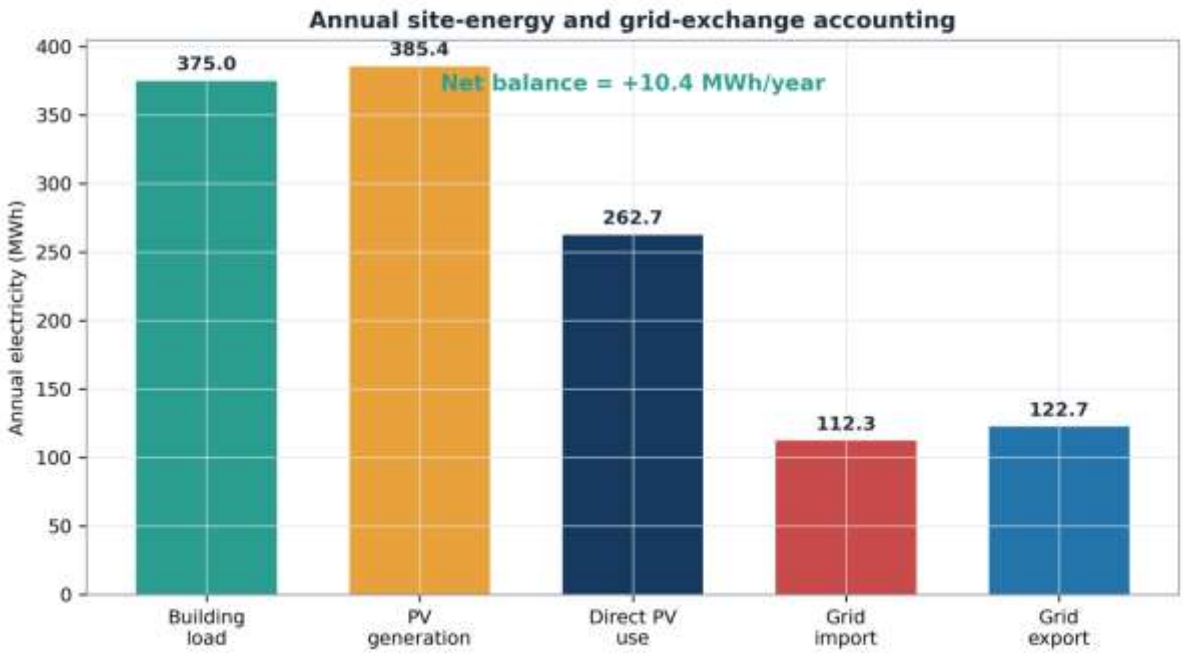

Figure 8. *Annual load, PV generation, direct PV utilization, grid import and grid export.*

Source: Scenario-model output. Annual balance equals PV generation minus site load.

4.4 Embodied and whole-life carbon

Upfront embodied carbon decreases by 980 tCO_2e, from 4,030 to 3,050 tCO_2e, a 24.3% reduction. Structural measures provide the largest reduction: the structure falls from 2,350 to 1,450 tCO_2e through material efficiency and lower-carbon procurement assumptions. The PV system adds 180 tCO_2e and the more efficient MEP system slightly increases upfront MEP impact, but these additions are smaller than the structural and envelope reductions. This result demonstrates that energy and material strategies can be coordinated rather than treated as competing agendas.

Table 8. *Upfront embodied-carbon inventory, A1–A5 (tCO_2e).*

Element	Baseline	Proposed	Change
Structure	2350	1450	-900
Envelope	620	480	-140
Finishes	450	340	-110
MEP systems	390	430	+40
Construction (A4–A5)	220	170	-50
PV system	0	180	+180
Total	4030	3050	-980

Values are element-level benchmark estimates. Product-specific EPDs and a detailed bill of quantities are required for verified reporting.

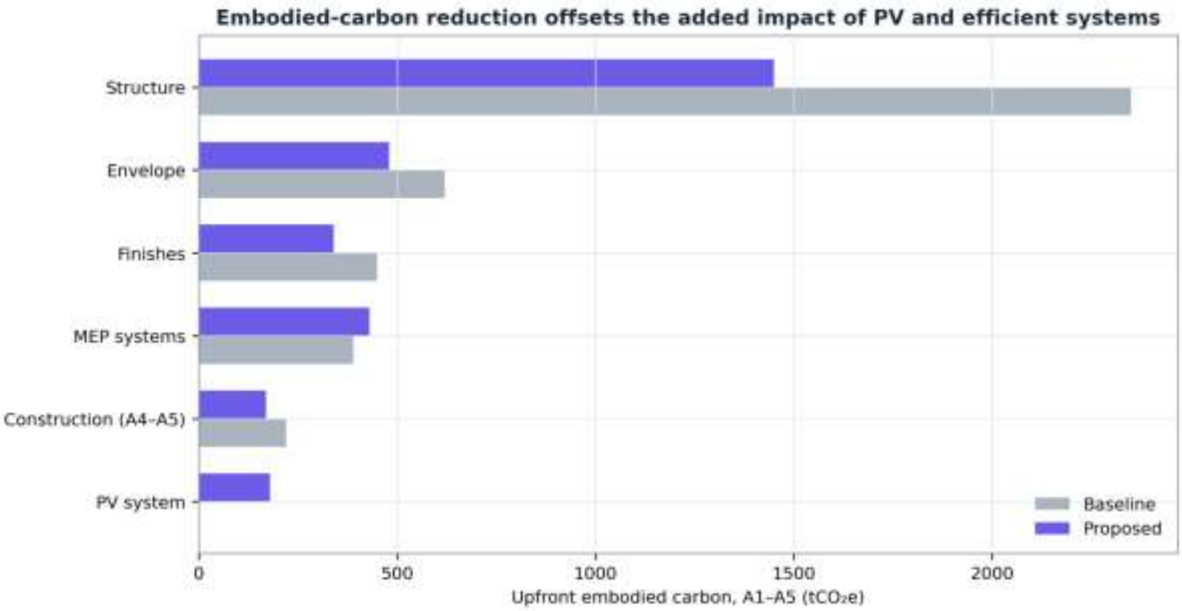

Figure 9. *Upfront embodied-carbon contribution by building element for baseline and proposed cases.*

Source: Scenario LCA inventory developed for this study; system boundary A1–A5.

Over 60 years with a 2.5% annual decline in the grid factor, baseline operational emissions are 16,610 tCO_2, producing whole-life emissions of 20,640 tCO_2e. If annual exports receive the same average-factor credit as imports, the proposed operational balance is -231 tCO_2 and whole-life emissions are 2,819 tCO_2e, an 86.3% reduction. If exports receive no credit, whole-life emissions are 5,542 tCO_2e, still 73.1% below baseline. This range is more informative than a single claim of zero operational carbon.

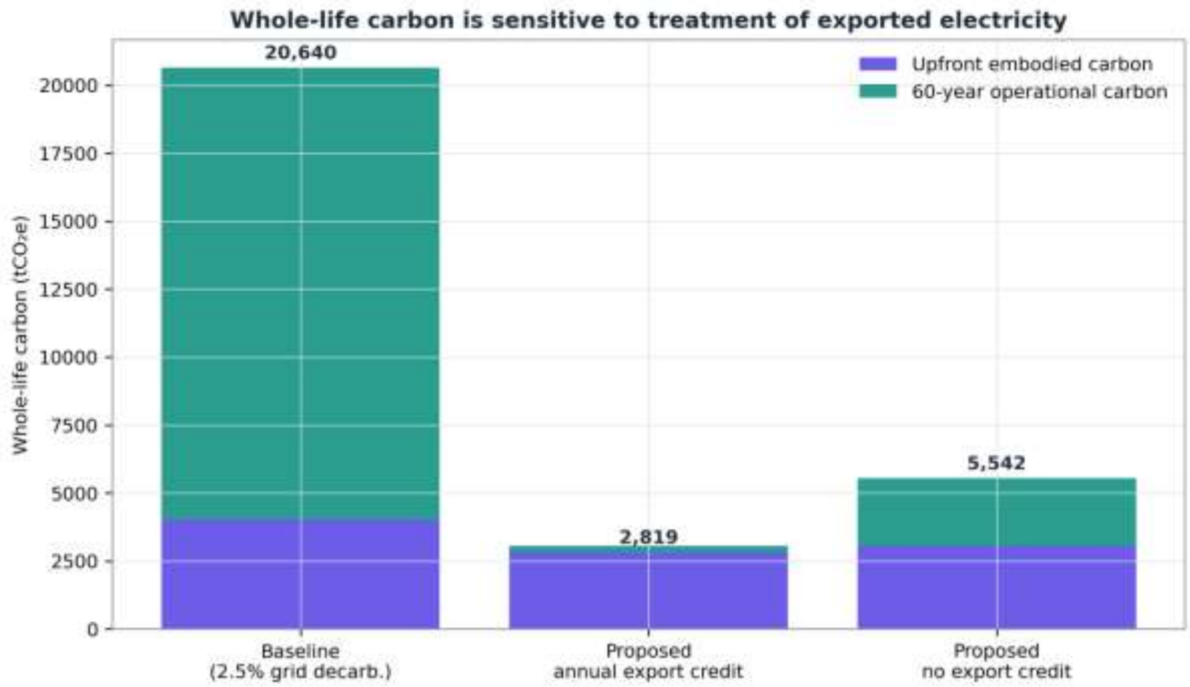

Figure 10. *Sixty-year whole-life carbon under export-credit and no-export-credit conventions.*

Source: Authors' scenario calculation using CEA FY 2024–25 factor of 0.710 tCO_2/MWh and 2.5% annual grid decarbonization.

4.5 Economic performance

The integrated package adds ₹31.9 million to the baseline project. The first-year baseline energy bill is ₹6.36 million. The proposed building purchases approximately ₹0.95 million of electricity and earns ₹0.37 million in export credit; after ₹0.308 million of incremental operation and maintenance, first-year net savings are ₹5.47 million. Simple payback is 5.8 years. At the central assumptions, discounted payback occurs in year 8, NPV is ₹46.4 million and IRR is 20.1%.

Table 9. *Incremental cost and life-cycle financial results.*

Cost or financial indicator	Central value
High-performance envelope	6.2
LED/daylight controls	2.1
Efficient HVAC and controls	7.4
Plug-load controls	1.4
235 kWp rooftop PV	10.8
Lower-carbon materials	2.8
Commissioning and submetering	1.2
Total incremental investment	31.9
First-year net operating saving	5.47
Simple / discounted payback	5.8 years / 8 years
25-year NPV at 8%	₹46.4 million
Internal rate of return	20.1%

Central assumptions: purchase tariff ₹8.5/kWh; export credit ₹3.0/kWh; 4% tariff escalation; 8% discount rate; 25-year horizon.

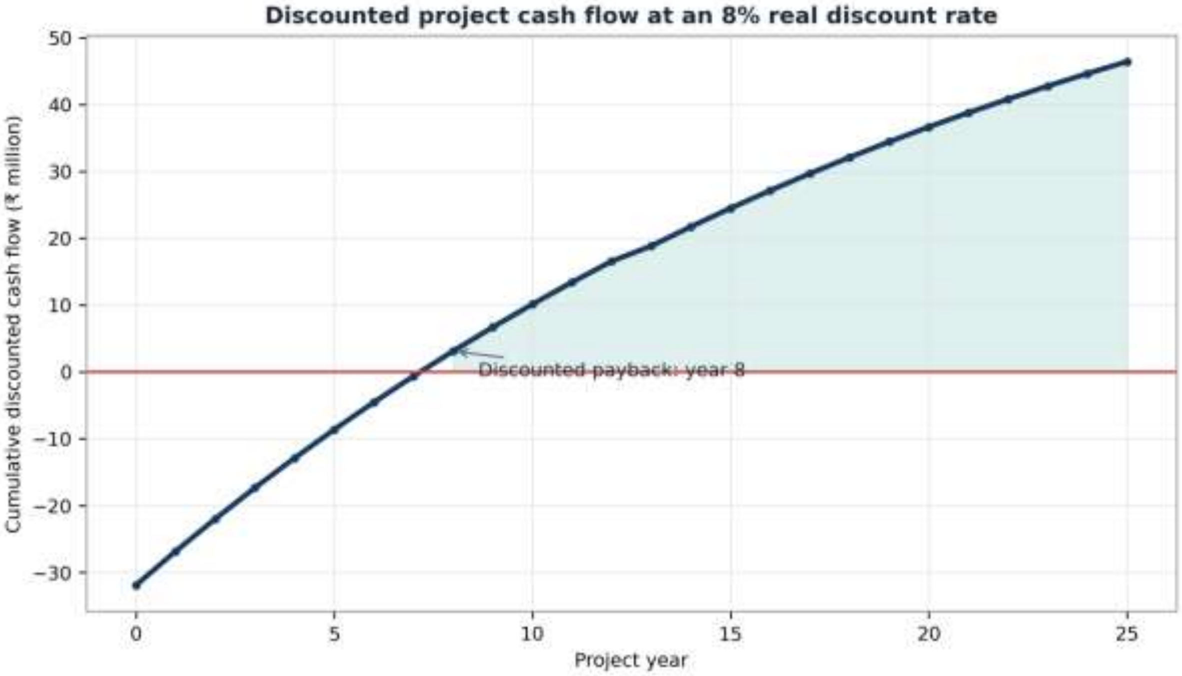

Figure *11. Cumulative discounted cash flow of the integrated net-zero package over 25 years.*

Source: Authors' discounted cash-flow model. Year 13 includes a ₹2.0 million inverter replacement allowance.

4.6 Uncertainty and sensitivity

The deterministic surplus of 10.4 MWh is small relative to plausible variation in occupancy, plug loads and solar yield. Across 5,000 runs, the median annual balance is -5.7 MWh, the 10th percentile is -44.0 MWh and the 90th percentile is 31.9 MWh. The probability of meeting or exceeding annual net zero is 42.5%. A PV capacity of approximately 264 kWp is required for 90% confidence under the same uncertainty distributions. That capacity would require either denser/high-efficiency modules, canopy PV, building-integrated PV or additional load reduction because the roof is already substantially allocated.

Table *10. Uncertainty variables used in the 5,000-run Monte Carlo assessment.*

Variable	Distribution	Parameters	Applied to
Occupancy multiplier	Triangular	0.88 / 1.00 / 1.15	Cooling, fans, lighting, plugs, other
Plug-load multiplier	Triangular	0.80 / 1.00 / 1.20	Plug/equipment
Cooling set-point deviation	Uniform	−1°C to +1°C	Cooling
Infiltration multiplier	Triangular	0.75 / 1.00 / 1.25	Cooling and fans
HVAC efficiency multiplier	Normal	μ=1.00; σ=0.05	Cooling
PV yield multiplier	Normal	μ=1.00; σ=0.055	PV production
Additional shading loss	Triangular	0.00 / 0.02 / 0.08	PV production

μ = mean; σ = standard deviation. Distributions are transparent design-stage assumptions, not fitted to monitored data.

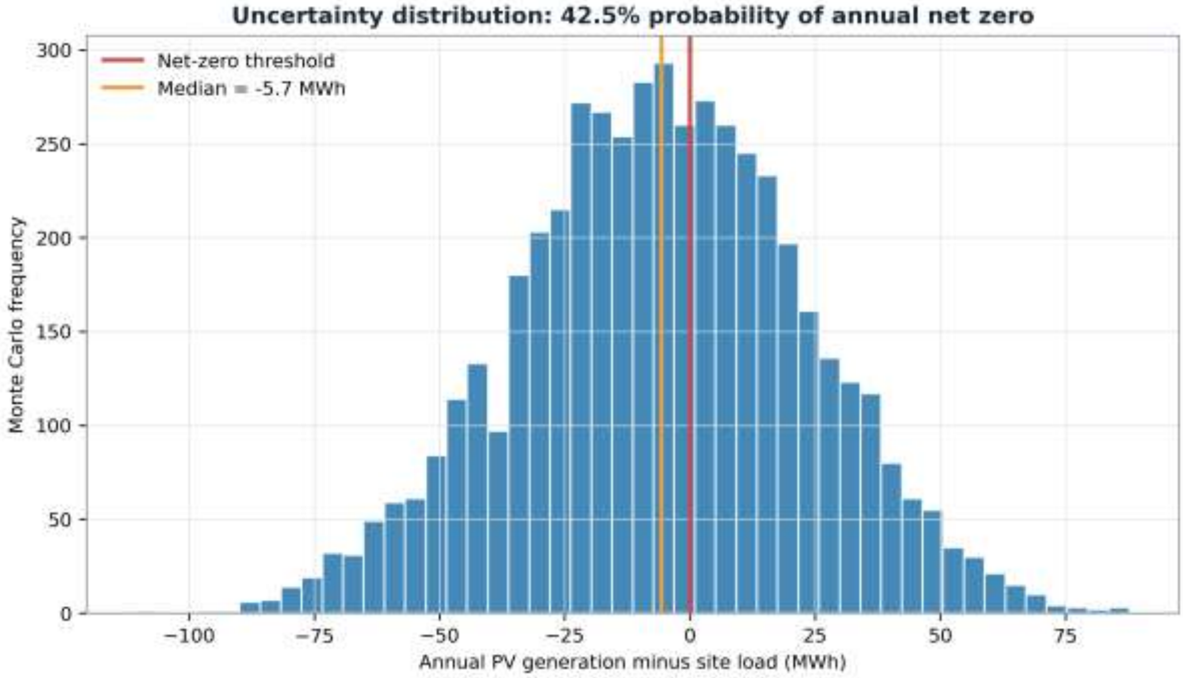

Figure 12. *Monte Carlo distribution of annual PV generation minus site load for the 235 kWp design.*

Source: 5,000-run reproducible simulation with random seed 20260718.

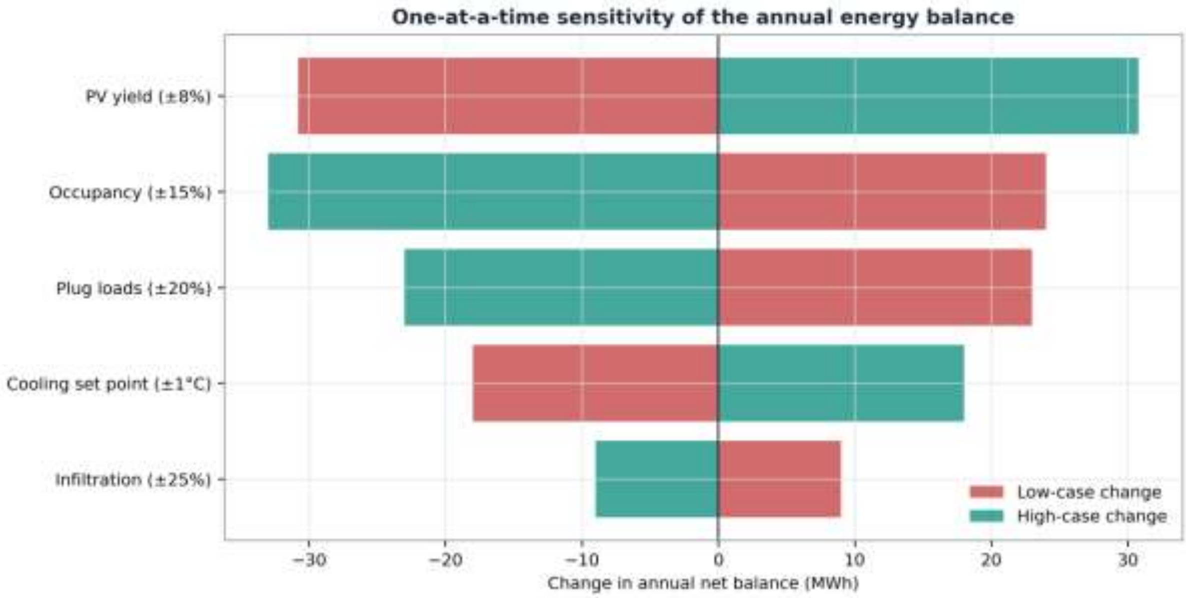

Figure 13. *One-at-a-time sensitivity of the annual net-energy balance to key design and operation variables.*

Source: Authors' sensitivity calculation. Positive change increases the annual surplus.

5. Discussion

5.1 Why the efficiency hierarchy matters

The most important design result is not the 235 kWp array; it is the reduction of 373.8 MWh before PV is applied. If the baseline building attempted to reach annual net zero at the same specific yield, it would require about 457 kWp—nearly twice the selected capacity and beyond the roof allocation. The envelope, lighting, HVAC and control packages therefore convert net zero from a nominal procurement target into a physically plausible building target. This finding is consistent with the efficiency-first hierarchy in international definitions [4–7], hot-climate case studies [11,12] and the logic of higher ECSBC performance tiers [14].

The staged results also show diminishing and interacting returns. Better glazing reduces solar cooling loads but can reduce daylight if visible transmittance is not protected. Lower lighting power reduces both electricity and internal heat, which in turn reduces cooling. High HVAC efficiency has the largest single incremental effect after the envelope and lighting loads are reduced. Plug-load management then becomes important because unregulated loads constitute almost one-third of the optimized demand. This interaction supports integrated design workshops and a shared energy model rather than separate discipline compliance checks.

5.2 Annual net zero versus grid-friendly operation

The building satisfies the annual site-energy balance but uses the grid as both sink and source. The 68.2% PV self-consumption ratio is relatively favorable because institutional occupancy coincides with solar production; nevertheless, 235 MWh of annual bidirectional exchange remains when import and export are added. Distribution constraints, export limits, demand charges and time-of-use tariffs can therefore change project value even when the annual energy balance is unchanged. The next design stage should use hourly simulation and the applicable Jaipur distribution-company tariff and interconnection rules.

Storage should be evaluated against a defined problem. If the objective is annual net zero, the current PV system is sufficient in the central case. If the objective is demand management, resilience or export limitation, storage, pre-cooling and flexible loads may be justified. A battery-only solution can increase self-consumption but will not correct excessive annual demand; controls and passive design should remain first.

5.3 Whole-life carbon interpretation

The carbon results reinforce two cautions. First, the baseline grid factor should not be held constant for six decades without sensitivity analysis. Using a declining factor reduces the apparent lifetime operational benefit of PV compared with a static-grid calculation, which makes upfront material choices more consequential. Second, exported electricity cannot automatically be treated as a one-for-one carbon offset. The 73–86% whole-life reduction range is therefore more credible than declaring the building whole-life net zero.

The proposed upfront intensity of 508 $kgCO_2e/m^2$ remains material. A project seeking net-zero carbon would need a verified quantity take-off, product-specific EPDs, structural optimization, cement-replacement and steel-procurement specifications, construction-stage energy data, replacement cycles and end-of-life scenarios. It may also require additional renewable generation or high-quality removals after deep reduction. This distinction between net-zero energy and net-zero carbon should be explicit in claims and certification documents.

5.4 Robustness and performance risk

The 42.5% modeled probability of annual net zero demonstrates that a small deterministic surplus is not equivalent to a robust guarantee. PV yield and occupancy produce the largest swings, followed by plug-load control and cooling set point. The finding is operationally useful: module quality, shading control and commissioning must be paired with lease/occupancy rules, equipment procurement budgets and visible energy feedback. A modest formal performance margin—either additional PV or a lower EUI target—should be included before construction.

The most cost-effective risk response is unlikely to be a single larger technology. A portfolio can combine a 3–5% design EUI reserve, rooftop layout protection, high-efficiency module procurement, seasonal set-point governance, plug-load allowances, functional testing and a one-year post-occupancy tuning period. Such measures increase confidence without the embodied and financial burden of oversizing every system.

6. Practical design and construction implications

For architects, the roof must be treated as an energy asset from concept design. Stairheads, tanks, HVAC equipment, parapets and future services should be consolidated to protect the 1,090 m² solar zone. East and west glazing should be limited, while visible transmittance and glare are assessed alongside SHGC. External shading geometry should be coordinated with façade access, fire egress and maintenance.

For structural and material teams, carbon targets should be written as procurement requirements before tender. Concrete performance specifications can permit optimized cement replacement where exposure, early strength and curing constraints are satisfied. Steel suppliers should disclose route and recycled content where possible. Design efficiency, grid rationalization, repeated spans and accurate reinforcement scheduling reduce both cost and carbon. The target should be verified against actual quantities, not only square-metre benchmarks.

For MEP teams, the energy target should be decomposed into end-use budgets and connected to submetering. Cooling, lighting, plug loads, PV production, imports and exports should be separately measured. Controls sequences must be included in tender documents and functionally tested. The first operational year should include seasonal commissioning, operator training, fault detection and comparison of normalized measured EUI against the design target.

Table *11. Stage-gated implementation pathway for converting the modeled target into verified performance.*

Project stage	Priority actions	Evidence required
Concept design	Protect roof solar zone; orient long axis east–west; set EUI and carbon caps	Energy model v1; roof allocation plan
Design development	Optimize shading, envelope, HVAC and daylighting together	Updated model; thermal bridges; glare/daylight checks
Tender	Performance specifications, EPD requirements, controls sequences, metering	Employer requirements; measurement plan
Construction	Envelope QA, airtightness, material submittals, PV shading verification	Inspection records; product data; quantity log
Commissioning	Functional tests, trend logs, set-point and scheduling verification	Commissioning report; issue register
Operation	Monthly energy balance and annual normalized verification	Metered EUI, PV yield, import/export and comfort report

The table translates the research findings into project controls; certification-specific documentation should be added as applicable.

7. Limitations and future research

The study has five principal limitations. First, the building is an archetype and has no measured baseline, detailed geometry or calibrated operation. Second, monthly energy data and one representative day cannot reproduce 8,760-hour coincidence, extreme weather or demand-charge behavior. Third, PV production is a transparent specific-yield estimate, not a bankable yield study with horizon, soiling and degradation measurements. Fourth, the embodied-carbon inventory is elemental and excludes B-stage replacements, C-stage end of life and benefits beyond the system boundary. Fifth, the cost model excludes project financing, taxation, subsidies, demand charges and uncertainty in future interconnection rules.

Future work should develop and publish a full EnergyPlus model using a traceable Jaipur weather file, conduct daylight and glare simulation, test thermal comfort under future climate files, model hourly tariffs and grid carbon, and optimize PV, storage and flexible loads jointly. A BIM-linked bill of quantities should be connected to India-relevant EPDs or verified product data. After construction, at least 12 months of submetered data should be normalized for weather, occupancy and schedule, enabling calibration and a formal assessment of the performance gap.

8. Conclusions

This study demonstrates an integrated, transparent pathway for a net-zero-energy institutional building in Jaipur's hot-dry climate. The selected efficiency package reduces modeled annual site electricity from 748.8 to 375.0 MWh and EUI from 124.8 to 62.5 kWh/m²·year. A roof-feasible 235 kWp PV system generates 385.4 MWh/year, yielding a 10.4 MWh annual surplus and 102.8% renewable coverage under the declared site-energy boundary.

Annual balance does not eliminate grid dependence. Direct PV utilization is 262.7 MWh, while imports and exports are 112.3 and 122.7 MWh, respectively. This distinction should be retained in design reporting and grid studies. The materials strategy reduces upfront embodied carbon from 4,030 to 3,050 tCO_2e despite adding PV and efficient MEP systems. Across the two export-credit conventions, 60-year whole-life carbon is 73–86% below the baseline, but it is not demonstrated to be whole-life net zero.

The ₹31.9 million incremental package is economically attractive in the central case, with a 5.8-year simple payback, 8-year discounted payback, 20.1% IRR and ₹46.4 million 25-year NPV. However, the Monte Carlo probability of meeting annual net zero is only 42.5% at 235 kWp. A robust project should therefore target a lower design EUI or provide additional renewable capacity, together with commissioning and operational governance. The broader conclusion is that net-zero energy is best treated as a verified performance process—beginning with load avoidance and ending with measured annual balance—rather than as a PV quantity added late in design.

Declarations

Funding: No external funding was used for preparation of this modeled case-study manuscript.

Conflict of interest: The author declares no known conflict of interest.

Data availability: The monthly scenario dataset is generated reproducibly within this study. Values needed to reconstruct the central results are reported in the tables and Appendix A.

Ethics statement: The study uses no human participants, personal data or animal subjects.

Use of modeled data: Results are scenario outputs for research and design exploration; they must not be represented as monitored performance.

References

[1] United Nations Environment Programme, Global Status Report for Buildings and Construction 2024/2025: Not Just Another Brick in the Wall, UNEP, Nairobi, 2025. https://www.unep.org/resources/report/global-status-report-buildings-and-construction-20242025

[2] International Energy Agency, Buildings—Energy System, findings updated June 2026, IEA, Paris. https://www.iea.org/energy-system/buildings

[3] IPCC, Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report, Cambridge University Press, 2022. https://doi.org/10.1017/9781009157926

[4] P. Torcellini, S. Pless, M. Deru, D. Crawley, Zero Energy Buildings: A Critical Look at the Definition, NREL/CP-550-39833, National Renewable Energy Laboratory, 2006. https://www.osti.gov/biblio/883663

[5] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building—A review of definitions and calculation methodologies, Energy and Buildings 43 (2011) 971–979. https://doi.org/10.1016/j.enbuild.2010.12.022

[6] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: A consistent definition framework, Energy and Buildings 48 (2012) 220–232. https://doi.org/10.1016/j.enbuild.2012.01.032

[7] U.S. Department of Energy and National Institute of Building Sciences, A Common Definition for Zero Energy Buildings, U.S. DOE, 2015. https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf

[8] ISO, ISO 52000-1:2017, Energy performance of buildings—Overarching EPB assessment—Part 1: General framework and procedures, International Organization for Standardization, Geneva, 2017.

[9] S. Deng, R.Z. Wang, Y.J. Dai, How to evaluate performance of net zero energy building—A literature research, Energy 71 (2014) 1–16. https://doi.org/10.1016/j.energy.2014.05.007

[10] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of Net Zero Energy Buildings, Energy and Buildings 55 (2012) 765–778. https://doi.org/10.1016/j.enbuild.2012.10.022

[11] M. Shin, J.-C. Baltazar, J.S. Haberl, E. Frazier, B. Lynn, Evaluation of the energy performance of a net zero energy building in a hot and humid climate, Energy and Buildings 204 (2019) 109531. https://doi.org/10.1016/j.enbuild.2019.109531

[12] W. Feng, Q. Zhang, H. Ji, R. Wang, N. Zhou, Q. Ye, B. Hao, Y. Li, D. Luo, S.S.Y. Lau, A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings, Renewable and Sustainable Energy Reviews 114 (2019) 109303. https://doi.org/10.1016/j.rser.2019.109303

[13] G. Vakil, S. Jayaram, J. Bhadra, Y. Jain, P. Vaidya, V. Paralkar, M. Dahlhausen, EUI benchmarks for net-zero energy buildings in India, Building Simulation 2023. https://doi.org/10.26868/25222708.2023.1318

[14] Bureau of Energy Efficiency, Energy Conservation and Sustainable Building Code 2024, Ministry of Power, Government of India, New Delhi, 2024. https://www.beeindia.gov.in/WriteReadData/L45218/7534511430467336.pdf

[15] Indian Green Building Council, IGBC Net Zero Energy Rating System, CII–IGBC, Hyderabad. https://igbc.in/igbc-net-zero-energy-rating/

[16] GRIHA Council, GRIHA Version 2019, Volume 1, New Delhi, 2019. https://www.grihaindia.org/sites/default/files/pdf/Manuals/griha-manual-vol1.pdf

[17] U.S. Department of Energy, EnergyPlus—Open-source whole-building energy simulation engine. https://www.energy.gov/cmei/buildings/articles/energyplus

[18] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, J. Glazer, EnergyPlus: creating a new-generation building energy simulation program, Energy and Buildings 33 (2001) 319–331. https://doi.org/10.1016/S0378-7788(00)00114-6

[19] ASHRAE, ANSI/ASHRAE Standard 140-2023: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, Atlanta, 2023.

[20] ASHRAE, ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy, Atlanta, 2023.

[21] A.P. Dobos, PVWatts Version 5 Manual, NREL/TP-6A20-62641, National Renewable Energy Laboratory, Golden, CO, 2014. https://www.nrel.gov/docs/fy14osti/62641.pdf

[22] P. Gilman, A. Dobos, N. DiOrio, J. Freeman, S. Janzou, D. Ryberg, SAM Photovoltaic Model Technical Reference Update, NREL/TP-6A20-67399, 2018. https://www.nrel.gov/docs/fy18osti/67399.pdf

[23] Central Electricity Authority, CO_2 Baseline Database for the Indian Power Sector: User Guide Version 21.0, Ministry of Power, Government of India, 2025. https://cea.nic.in/wp-content/uploads/baseline/2025/12/User_Guide_V_21.0.pdf

[24] ISO, ISO 14040:2006, Environmental management—Life cycle assessment—Principles and framework, Geneva, 2006.

[25] ISO, ISO 14044:2006, Environmental management—Life cycle assessment—Requirements and guidelines, Geneva, 2006.

[26] P. Hernandez, P. Kenny, From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB), Energy and Buildings 42 (2010) 815–821. https://doi.org/10.1016/j.enbuild.2009.12.001

[27] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: An overview, Energy and Buildings 42 (2010) 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

[28] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, Renewable and Sustainable Energy Reviews 29 (2014) 394–416. https://doi.org/10.1016/j.rser.2013.08.037

[29] C. De Wolf, F. Pomponi, A. Moncaster, Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice, Energy and Buildings 140 (2017) 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

[30] M. Röck, M.R.M. Saade, M. Balouktsi, F.N. Rasmussen, H. Birgisdottir, R. Frischknecht, G. Habert, T. Lützkendorf, A. Passer, Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation, Applied Energy 258 (2020) 114107. https://doi.org/10.1016/j.apenergy.2019.114107

[31] T. Lützkendorf, Embodied carbon emissions in buildings: explanations, interpretations, recommendations, Buildings & Cities 3 (2022). https://doi.org/10.5334/bc.257

[32] R. Minunno, T. O'Grady, G.M. Morrison, R.L. Gruner, Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis, Renewable and Sustainable Energy Reviews 143 (2021) 110935. https://doi.org/10.1016/j.rser.2021.110935

[33] L. Ma, R. Azari, M. Elnimeiri, A building information modeling-based life cycle assessment of the embodied carbon and environmental impacts of high-rise building structures: A case study, Sustainability 16 (2024) 569. https://doi.org/10.3390/su16020569

[34] National Institute of Standards and Technology, Systematic Review of Embodied Carbon Assessment and Reduction in Buildings, NIST, 2024. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=958514

[35] E. Rodriguez-Ubinas, C. Montero, M. Porteros, S. Vega, I. Navarro, M. Castillo-Cagigal, E. Matallanas, A. Gutiérrez, Passive design strategies and performance of Net Energy Plus Houses, Energy and Buildings 83 (2014) 10–22. https://doi.org/10.1016/j.enbuild.2014.03.074

[36] M. Ferrara, V. Monetti, E. Fabrizio, Cost-optimal analysis for nearly zero energy buildings design and optimization: A critical review, Energies 11 (2018) 1478. https://doi.org/10.3390/en11061478

[37] M. Leach, E. Bonnema, S. Pless, Cost Control Best Practices for Net Zero Energy Building Projects, NREL/TP-5500-61365, National Renewable Energy Laboratory, 2014. https://www.nrel.gov/docs/fy14osti/61365.pdf

[38] National Renewable Energy Laboratory, Designing for the Future: Zero Energy Ready K–12 Schools, NREL/FS-5500-68883, 2017. https://www.nrel.gov/docs/fy17osti/68883.pdf

Appendix A. Reproducible central monthly dataset

Table 12. *Unrounded monthly dataset used to generate the energy and PV figures (MWh).*

Month	Baseline	Optimized	PV	Direct PV	Import	Export
Jan	44.928	24.375	26.978	16.819	7.556	10.159
Feb	41.184	22.500	28.905	16.200	6.300	12.705
Mar	50.918	26.250	34.686	19.950	6.300	14.736
Apr	68.890	33.750	36.613	26.325	7.425	10.288
May	86.112	40.500	40.467	32.374	8.126	8.093
Jun	93.600	43.125	38.540	31.603	11.522	6.937
Jul	89.856	42.000	30.832	24.357	17.643	6.475
Aug	86.112	40.500	30.832	24.357	16.143	6.475
Sep	71.136	34.500	32.759	24.897	9.603	7.862
Oct	52.416	27.000	34.686	19.440	7.560	15.246
Nov	33.696	20.625	26.978	13.613	7.012	13.366
Dec	29.952	19.875	23.124	12.720	7.155	10.404

Totals may differ by 0.001 MWh because values are displayed to three decimals.

Appendix B. Reproducibility and journal-submission checklist

Table 13. *Recommended evidence upgrades for converting this design-stage manuscript into an empirical submission.*

Workstream	Required upgrade before empirical journal submission
Energy model	Replace archetype with project geometry and 8,760-hour model; archive model and weather file
Calibration	Use at least 12 months of utility/submeter data; report CV(RMSE) and NMBE where applicable

Workstream	**Required upgrade before empirical journal submission**
PV	Complete bankable yield, shade study, interconnection and export-limit assessment
Embodied carbon	Link BIM quantity take-off to verified EPD/product data; add B4, C and D scenarios
Cost	Update tariff, demand charges, taxes, financing, subsidies and tendered capital costs
Comfort and IAQ	Report operative temperature, humidity, ventilation and occupant-acceptability metrics
Statistics	Publish scripts, random seed, distributions and sensitivity assumptions
Claims	Distinguish net-zero energy, net-zero operational carbon and whole-life net-zero carbon

This checklist is intentionally explicit so modeled scenario results are not misrepresented as field observations.