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EXPLORING SUSTAINABILITY PARAMETERS FOR NET-ZERO BUILDING IMPLEMENTATION USING AI DRIVEN GENERATIVE DESIGN AND ENERGY OPTIMIZATION FLATFORM: A QUALITATIVE CASE STUDY OF PAMPANGA STATE UNIVERSITY

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Abstract

Educational buildings are among the largest consumers of energy and contributors to carbon emissions in the Philippines, yet no state college or university in the country has fully adopted Net Zero Energy Building (NZEB) performance. This study aimed to develop sustainability parameters for transforming the existing buildings of Pampanga State University (PSU) into near-net-zero energy buildings through the integration of artificial intelligence (AI)-driven generative design and energy optimization platforms. Using a qualitative, simulation-driven, design-based research approach, building plans, material data, climate conditions, operational schedules, and estimated electricity consumption were evaluated using six digital platforms — Ecoify, One Click LCA Planetary, the Embodied Carbon in Construction Calculator (EC3), Build Carbon Neutral, EDGE, and OpenStudio, supplemented by the CBE Clima Tool for climate analysis. AI-assisted generative design and energy-optimization simulations were then applied to test passive and active interventions, including shading, natural ventilation, envelope improvement, efficient lighting and cooling, smart controls, landscape enhancement, and solar photovoltaic integration. Results showed that administrative air-conditioning accounted for 53.43% of the representative building's estimated monthly energy consumption, followed by classroom fans (28.50%), lighting (9.50%), and office equipment (8.56%). The campus's estimated embodied carbon footprint was approximately 14,639 metric tons of CO_2, driven primarily by reinforced-concrete construction. Comparative material and design-scenario simulations indicated that low-carbon and optimized interventions could reduce embodied carbon by 21–62% and operational Energy Use Intensity (EUI) by up to 56% (from 210 to 92 kWh/m²/year) relative to baseline conditions. On the strength of these findings, the study proposes a five-phase Sustainability Parameter — Assessment and Baseline Analysis, AI-Driven Generative Design Optimization, Energy Simulation and Validation, Sustainable Design Implementation, and Monitoring and Continuous Improvement — to guide PSU and comparable institutions toward NZEB performance. The study concludes that AI-driven design methodologies can support performance-based, evidence-driven decision-making for sustainable campus planning, while noting that its findings rest on simulation rather than post-occupancy measurement and should be read alongside the data-verification notes in Section 3.4 and the Editorial and Citation Integrity Notice preceding the reference list.

Keywords: *Net Zero Energy Building; AI-driven generative design; energy optimization platforms; sustainability parameters; educational infrastructure; Pampanga State University*

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Introduction

The growing urgency of climate change and environmental degradation has intensified the need for sustainable solutions across the built environment, which is recognized as one of the largest contributors to global energy consumption and greenhouse gas emissions, accounting for approximately 36% of total energy use and 39% of energy-related emissions worldwide (Cheng, 2021). This impact bears directly on United Nations Sustainable Development Goal (SDG) 13, Climate Action, and SDG 7, Affordable and Clean Energy (United Nations, 2015).

State colleges and universities occupy a distinctive position in this transition: as both knowledge producers and large-scale infrastructure operators, they are well placed to model sustainable practice in line with SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities) (United Nations, 2015). In the Philippine context, institutions such as Pampanga State University (PSU) face a dual challenge — accommodating expanding student populations while responding to intensifying environmental and energy constraints — and educational buildings are frequently designed under conventional, energy-intensive standards that respond poorly to climate or occupancy variability.

The Net Zero Energy Building (NZEB) concept, in which a building produces as much energy as it consumes annually through the combination of passive design, efficient systems, and renewable generation, represents an increasingly practical pathway for such institutions (Ragunath & Syal, 2022; Satola et al., 2022). Realizing this pathway, however, depends on performance data, iterative simulation, and optimization — conditions that existing PSU infrastructure, like much of the region's educational building stock, does not yet meet. Design decisions have historically relied on fragmented, experience-based evaluation rather than computational, performance-based methods, so energy considerations are frequently addressed late, producing inefficiencies that are costly to retrofit.

Artificial intelligence (AI), and generative design in particular, offers a transformative alternative to this deterministic, evaluation-only paradigm. Rather than assessing a small number of designer-selected options, AI-driven systems can process large datasets and iteratively generate, simulate, and rank many design alternatives against explicit performance criteria (Li et al., 2023; Wang et al., 2024). When paired with energy-optimization platforms, generative design supports a more holistic, adaptive process aligned with NZEB objectives and with SDG 9, SDG 11, SDG 12 (Responsible Consumption and Production), and SDG 17 (Partnerships for the Goals) (United Nations, 2015). Despite this potential, its application to educational infrastructure in the Philippines remains largely unexplored, and no Philippine state college or university has yet achieved full NZEB status.

This study addresses that gap by developing and testing a set of sustainability parameters for transitioning existing PSU buildings toward near-net-zero energy performance through integrated AI-driven generative design and energy-optimization platforms.

Statement of the Problem

This study aimed to develop sustainability parameters for transforming educational buildings at Pampanga State University into near-net-zero energy buildings through the integration of AI-driven generative design and energy optimization platforms. Specifically, it sought to answer the following questions:

- What is the current condition of Pampanga State University's Main Campus in terms of (a) site and climate, (b) building performance, (c) energy consumption, (d) carbon emissions, and (e) sustainability?
- What current design and operational practices limit the achievement of net-zero energy performance in terms of (a) site planning, (b) building design, (c) operational and energy management, and (d) environmental and infrastructure conditions?

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- What are the perceived roles and applications of Ecoify, One Click LCA Planetary, the Embodied Carbon in Construction Calculator (EC3), and Build Carbon Neutral in optimizing building form, systems, and energy efficiency?
- What opportunities and considerations exist for integrating EDGE and OpenStudio to support data-driven decision-making in building transformation?
- What sustainability parameters can be developed to guide the transition of existing educational infrastructure toward net-zero building performance?

Theoretical and Conceptual Framework

This study is anchored on Sustainable Development Theory, which frames development as meeting present needs without compromising the ability of future generations to meet their own (Hajian & Kashani, 2021), and integrates environmental, economic, and social responsibility into architectural decision-making. It is further supported by four complementary theories. Performance-Based Building Design Theory holds that a building should be evaluated by measurable indicators — energy consumption, Energy Use Intensity (EUI), cooling load, daylight availability, thermal comfort, carbon emissions, and renewable generation — rather than by appearance or prescriptive compliance alone. The Net Zero Energy Building Theory establishes an energy hierarchy in which demand is first reduced through passive design, then met efficiently through active systems, and finally offset through renewable generation. Because existing PSU buildings are unlikely to achieve a complete annual energy balance immediately, this study adopts the term near-net-zero energy building (nZEB) throughout. Systems Theory frames the campus as an interconnected set of environmental, technological, and human subsystems whose interactions determine overall performance. Generative Design Theory explains how computational systems can produce and rank many design alternatives against explicit performance criteria rather than relying on a single designer-selected solution — the logic that underlies the AI-assisted design and optimization workflow used in this study.

These theories converge in an Input–Process–Output (IPO) conceptual framework (Figure 1). Inputs comprise PSU's architectural and structural data, environmental and climatic conditions, operational and occupancy data, NZEB benchmarks, and the AI-driven design and simulation tools themselves. The process stage covers data collection and analysis, AI-driven generative design, and energy simulation and optimization across the six platforms used in the study, culminating in an iterative refinement cycle that integrates passive strategies, active systems, and renewable technologies. The outputs are an optimized architectural design, a near-net-zero energy building model calibrated to PSU, and the proposed Sustainability Parameters that constitute this study's principal practical contribution (see Section 3.5).

Significance of the Study

The study offers educational institutions strategic guidance for improving energy efficiency and reducing operating costs; demonstrates to architects and engineers how AI can be embedded in sustainable design workflows; informs policymakers on the implementation of energy-efficient strategies within public institutions; and contributes to the literature on AI-driven sustainable design in state universities and colleges, a context in which Philippine-specific evidence remains scarce.

Scope and Limitations

The study evaluated selected PSU Main Campus buildings' current energy performance, architectural configuration, and environmental conditions, and used AI-based generative design and energy-optimization simulation — not physical retrofitting or construction — to test passive design, renewable-energy integration, and energy-efficient technologies appropriate to Philippine tropical conditions.

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Three limitations bear directly on the interpretation of the results. First, because the analysis is simulation-based, it may not fully capture real-world complexities such as occupant behavior, maintenance practice, and unmodeled environmental variables; the accuracy of the results depends on the input assumptions used. Second, EDGE and OpenStudio were adopted as the primary assessment tools because they are freely accessible, performance-based platforms with immediately downloadable results; consequently, the sustainability findings reported here reflect EDGE and OpenStudio outputs specifically and should not be interpreted as equivalent to compliance with or certification under BERDE, the Philippine Green Building Initiative (PGBI) rating system, the Philippine Green Building Code, or other national or international green-building rating systems.

Third, financial, regulatory, and implementation feasibility — cost–benefit analysis, funding, institutional policy, and stakeholder acceptance — fall outside the scope of this research and are recommended as directions for future study.

Review of Related Literature

This review synthesizes evidence on four themes central to the study: NZEB design in tropical and institutional settings; the operational and economic feasibility of NZEBs; the integration of generative design with energy optimization; and the determinants and barriers affecting NZEB adoption.

Net Zero Energy Building Design in Tropical and Institutional Settings

NZEB implementation in tropical regions faces climate-specific challenges — high temperatures, humidity, and solar radiation — that global frameworks, such as those of the International Energy Agency, often do not address at a regional scale (International Energy Agency, 2019). In the Philippine context, climate-responsive strategies such as natural ventilation, shading, and material optimization have been emphasized (Del Rosario et al., 2021), yet without examining how AI might enhance these strategies—a gap this study addresses directly.

NZEB design strategies are typically organized around energy infrastructure, renewable energy integration, and efficiency measures, including grid connectivity, storage, renewable energy sources, high-performance envelopes, advanced HVAC systems, and phase-change materials (Wu & Skye, 2021). No universal configuration exists; optimal solutions must be tailored to local climate, regulation, and economics (Wu & Skye, 2021; Ragunath & Syal, 2022). In tropical climates specifically, evidence consistently supports a “passive-first” approach: passive measures such as shading, ventilation, daylighting, and airtightness can reduce energy-use intensity by roughly 48–50% before renewable systems are introduced (Ohene et al., 2022), and combined passive-and-active retrofits have achieved total energy savings of up to 90% in some regional case studies (Abdou et al., 2021; Kutty et al., 2023; Gupta & Deb, 2023). Systematic reviews confirm envelope design, glazing optimization, and shading as the most effective initial interventions in tropical climates (Chung-Camargo et al., 2024; Feng et al., 2019; Lakhiar et al., 2024), while active systems and renewables complete the pathway to full net-zero performance (Sun et al., 2018; Al-Saadi et al., 2023; Carpino et al., 2024; Es-Sakali et al., 2025).

Operational Effectiveness and Economic Feasibility of Net Zero Energy Buildings

Empirical evidence supports the economic viability of NZEBs. Optimized office buildings in Thailand achieved 79–82% energy savings with internal rates of return of 10.7–13.9% and payback periods of 7.2–8.5 years (Lohwanitchai & Jareemit, 2021); a residential retrofit in Türkiye reduced net primary energy consumption by 96% while remaining financially viable (Senturk & Ozcan, 2023); and iterative use of building information modeling (BIM) in the United States achieved near-net-zero performance with minimal added capital cost (Abaza & Shenawa, 2023). More broadly, passive strategies can reduce consumption by 20–50% and active systems an additional 20–30%, with integrated passive–active–renewable approaches yielding the greatest lifecycle savings (Ohene et al., 2022; Elaouzy & Fadar, 2022), though economic outcomes remain highly sensitive to local energy prices, interest rates, and incentive structures (Pernetti et al., 2021).

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Cost–benefit analyses generally show NZEBs achieving positive net present value and favorable payback despite higher upfront cost, particularly when renewables are integrated (Krarti & Karrech, 2024; Lohwanitchai & Jareemit, 2021), with photovoltaic systems in particular often paying back within five years (Wei et al., 2021) and delivering co-benefits in indoor air quality and occupant health (Beevers et al., 2024; Ürge-Vorsatz et al., 2020). Direct Philippine case studies remain absent from the literature, though regional evidence from comparable tropical settings indicates that passive strategies are particularly effective at reducing cooling and lighting demand (Feng et al., 2019) and that active systems and photovoltaic integration are essential for reaching net-zero status once passive gains are exhausted (Kong et al., 2023). Persistent barriers — high upfront cost, the absence of local policies and incentives, and limited technical expertise (Ahmed et al., 2021; Noh et al., 2024) — mean that the absence of a documented Philippine NZEB retrofit represents a genuine research gap that this study begins to address.

Generative Design and Energy Optimization Integration for NZEB Performance

AI integration in building design enhances net-zero performance by enabling real-time energy simulation and predictive analysis; three-dimensional, AI-enhanced modeling has achieved prediction accuracies above 90% with energy savings exceeding 10% (Yang, 2025). Embedding AI-driven results into parametric design cycles has reduced annual energy consumption by up to 30% while also improving structural (seismic) performance (Yusuf & Omefe, 2025), and AI-optimized distributed-generation design incorporating wind and photovoltaic sources has achieved net-zero-energy-cost buildings with payback periods near 6.8 years (Rocha et al., 2024). AI-driven HVAC redesign has achieved savings of up to 37% through precise, real-time optimization (Emam, 2025).

Despite this promise, the literature reveals a persistent gap: most studies treat design optimization and operational management as separate processes, producing fragmented rather than holistic sustainability outcomes. Simulation-based retrofit studies for educational buildings that do not incorporate AI-driven systems (Ascione et al., 2016) illustrate this gap directly — one that is especially relevant to PSU, where retrofitting existing buildings is likely to be more feasible than new construction, and where an integrated design–operation framework is still absent.

Determinants and Barriers to NZEB Adoption

Advanced simulation and optimization tools — including evolutionary algorithms for envelope, HVAC, and renewable-system design — face real constraints in computational complexity, modeling uncertainty, and steep learning curves (Attia et al., 2013). Beyond the purely technical, four categories of barrier recur across the literature. Economic and financial barriers — high initial investment, uncertain long-term returns, and the perception that net-zero projects cost more than conventional construction — are consistently ranked among the most significant (Attia et al., 2017; Ohene et al., 2022; Rauniyar et al., 2024; Salem & Elwakil, 2023). Legislative and policy barriers, including insufficient regulation, weak implementation, and inconsistent international definitions of net-zero system boundaries, further hinder comparability and uptake (Ohene et al., 2022; Rauniyar et al., 2024; Satola et al., 2022; Wilberforce et al., 2021; Zhang et al., 2021). Knowledge, skills, and organizational barriers — shortages of qualified professionals, fragmented stakeholder coordination, and low market awareness — constrain the supply side of NZEB delivery (Brown et al., 2024; Makvandia & Safiuddin, 2021; Satola et al., 2022). Finally, technical and performance barriers, including the well-documented gap between simulated and post-occupancy performance, mean that many buildings designed as nZEBs underperform in operation because simulations do not fully reflect actual equipment use or occupant behavior (Li & Wang, 2021; Belussi et al., 2019).

Taken together, the reviewed literature establishes that NZEBs are technically feasible and frequently economically viable across diverse climates and building types, and that integrating passive design, efficient active systems, and renewable technologies is essential to achieving that performance (Shi et al., 2020; Wei et al., 2018). It also exposes five specific gaps that this study addresses: (1) limited research on transforming educational institutions specifically into near-net-zero campuses; (2) weak integration between architectural design processes

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and digital tools such as AI, BIM, and simulation platforms; (3) minimal Philippine-context research on adapting NZEB strategies to tropical climates and institutional constraints; (4) the continued use of assessment platforms in isolation rather than as an integrated system; and (5) the absence of a scalable, transferable framework beyond single-case implementations (Ahmad et al., 2016; Wei et al., 2018).

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Methods

Research Design

This study used a qualitative, simulation-driven, design-based research approach grounded in building-performance modeling to examine how selected existing PSU buildings could transition toward near-net-zero energy performance. Rather than relying on observational or perception-based data, the research centered on measurable building performance, using simulation tools to evaluate how different design strategies influence energy use. The design process was iterative: initial building massing was developed from existing conditions and progressively refined through repeated simulation runs and performance evaluation. Although many of the resulting indicators — annual energy consumption, Energy Use Intensity, and system efficiency — are numerical, the qualitative descriptive-interpretive approach was appropriate because the analysis centered on comparing architectural design alternatives against performance standards rather than on statistical inference from a sampled population. The overall approach follows established practice in building energy modeling, which emphasizes calibration and validation to ensure simulation results reflect actual building behavior.

Research Locale

The study was conducted at the Pampanga State University (PSU) Main Campus in Bacolor, Pampanga, Philippines, a 78,963.54 sq m site comprising academic buildings (19.22%), student-services buildings (18.47%), paved surfaces (16.38%), asphalt/concrete roadway (16.19%), vegetation cover (10.92%), open space (10.89%), parking (5.38%), administration buildings (2.31%), and income-generating buildings (0.24%). The campus's mix of academic and administrative buildings, each with distinct physical and operational characteristics, made it possible to examine NZEB strategies across building types within one institutional setting. As a tropical, low-lying site, PSU experiences consistently high temperatures and solar exposure, which strongly influence cooling load and overall energy demand, and periodic flooding that affects infrastructure performance.

Subjects of the Study

The subjects of the study were selected existing PSU buildings, chosen for their suitability for simulation modeling and their relevance to campus energy use. Selection was guided by the availability of reliable architectural plans, operational schedules, and recorded energy consumption; buildings undergoing major renovation or lacking dependable records were excluded to avoid inaccuracies in calibration. The resulting set represented typical campus facilities, including both academic and administrative space.

Research Instruments

Architectural drawings and as-built plans formed the basis for digital models of each building, which were then simulated using six platforms recognized for reliability in building-performance analysis: Ecoify, One Click LCA Planetary, the Embodied Carbon in Construction Calculator (EC3), EDGE, OpenStudio, and the CBE Clima Tool.

Data Gathering Procedure

Baseline data collection covered total floor area, building materials, envelope fenestration, and historical energy consumption for each selected building, which were used to construct initial digital models. Each model was then calibrated by comparing simulated energy consumption against actual recorded data and adjusting key parameters to reduce discrepancies. Following calibration, design improvements — passive strategies such as shading and natural-ventilation enhancement, envelope upgrades, and renewable-energy integration — were introduced through generative design techniques that explored multiple configurations rather than a single proposed solution. Each design iteration was evaluated through simulation, with results guiding further refinement; this cycle

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continued until the models achieved near-net-zero energy performance under realistic operating conditions, and all assumptions and parameter changes were recorded to support transparency and replication.

Data Analysis Procedure

Descriptive analysis summarized key simulation outputs, including energy consumption and Energy Use Intensity. A sensitivity analysis further identified which input parameters most strongly influenced simulation results, confirming model robustness and ensuring that findings were not overly dependent on any single assumption.

Ethical Considerations

Approval for the study was obtained from the PSU Research Management Office Ethics Committee before data collection began. All data were drawn from PSU's Land Use Development and Infrastructure Plan, with formal permission secured for access and all information handled with due care for confidentiality and data management.

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Results

Results are organized around the study's five research questions: (3.1) the baseline condition of PSU's Main Campus; (3.2) limitations in current design and operational practice; (3.3) outputs of the AI-driven generative-design platforms; (3.4) outputs of the energy-simulation and optimization platforms; and (3.5) the resulting Sustainability Parameters framework.

Baseline Assessment: Site, Climate, Building Performance, Energy, Carbon, and Sustainability

PSU Main Campus sits in Bacolor, Pampanga, a low-lying area with a hot, humid tropical climate marked by distinct wet and dry seasons, high solar radiation, elevated humidity, and seasonal flooding exposure. Climate analysis using the CBE Clima Tool showed temperatures consistently high year-round, with humidity frequently exceeding the recommended comfort range and most months falling outside the thermal comfort zone, producing measurable occupant thermal stress and a strong dependence on mechanical cooling. Heat-map analysis further showed significant heat accumulation from extensive paved surfaces and limited vegetation cover, with concrete's thermal mass allowing surfaces to absorb and re-radiate heat, particularly in the afternoon. Favorable wind conditions exist for passive cooling, but narrow inter-building spacing constrains airflow and creates localized heat pockets, limiting natural ventilation's full potential; the campus's low elevation and flat topography also leave it vulnerable to stormwater accumulation during heavy rainfall.

Building-performance assessment found that most classroom buildings already incorporate passive features — large operable windows, open corridors, and cross-ventilation via open-sided corridors — that reduce dependence on mechanical cooling. However, building orientation across the campus is driven primarily by road alignment and available land rather than solar or wind considerations, exposing some façades to excessive heat gain, and the clustered site layout produces underused residual spaces with limited landscaping or shading.

Energy consumption was assessed using CBS Building 1 as the representative educational building. Estimated total monthly consumption was approximately 1,751.6 kWh, of which administrative air-conditioning accounted for 53.43%, classroom fans 28.50%, lighting 9.50%, and office equipment 8.56% (Table 1). Applying the Department of Energy's Philippine grid emission factor of 0.7 kg CO_2 per kWh, this consumption corresponds to approximately 1,226.12 kg of CO_2 emitted per month from CBS Building 1 alone, underscoring the direct link between cooling demand and operational carbon emissions.

Table 1. ***Estimated Monthly Energy Consumption of CBS Building 1 by End-Use Category***

End-Use Category	Share of Monthly Consumption	Estimated Monthly Consumption (kWh)
Administrative Air-Conditioning	53.43%	936.0
Classroom Fans	28.50%	499.2
Lighting	9.50%	166.4
Computers & Office Equipment	8.56%	150.0
Total (approx.)	100%	1,751.6

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Note. Percentages and category totals as reported by the author from equipment-rating and operational-schedule estimates (Figures 10–11 of the original manuscript); the category kWh figures sum to approximately 1,751.6 kWh, consistent with the reported total.

The sustainability assessment identified passive cooling (operable windows, open corridors, cross-ventilation), durable and locally available construction materials, and existing waste-segregation and composting practices as institutional strengths. It also identified persistent weaknesses: limited tree cover, no renewable-energy generation, outdated lighting technology, inefficient cooling practice, and recurring flood exposure during heavy rainfall. Overall, PSU Main Campus was found to possess a workable foundation for sustainability improvement but to fall well short of NZEB performance standards without further intervention.

Limitations of Current Design and Operational Practices

Site-planning limitations centered on the campus's flood-prone, low-lying topography; ongoing road-elevation and drainage improvements have inadvertently left several buildings sitting lower than adjacent roads, increasing stormwater accumulation around building perimeters. Site development has historically prioritized expansion over climate-responsive placement of buildings, circulation, and open space, and green infrastructure remains sparse and unevenly distributed, leaving large paved areas exposed to direct solar radiation.

Building-design limitations include orientation driven by road configuration rather than solar or wind exposure; heavy reliance on high-thermal-mass concrete without adequate shading or insulation; limited external shading devices on many façades; clustered massing that restricts airflow; and continued use of fluorescent lighting and older envelope systems despite the availability of more efficient alternatives.

Operational limitations include air-conditioning use that is largely schedule-driven rather than occupancy- or condition-responsive; the absence of a campus-wide energy-management system or real-time monitoring; minimal deployment of intelligent controls (occupancy sensors, programmable thermostats, daylight-responsive lighting); and standby energy losses from office equipment left powered on during inactive periods.

Environmental and infrastructure limitations include continued vulnerability to flooding despite drainage upgrades; limited integration of sustainable drainage measures such as rain gardens, bioswales, permeable pavement, or retention systems; aging electrical infrastructure with no renewable backup; negligible renewable-energy adoption campus-wide; and insufficient tree and vegetation cover to mitigate heat gain.

Application of AI-Driven Generative Design Platforms for Energy Efficiency Optimization

Four AI-assisted, sustainability-focused platforms — Ecoify, One Click LCA Planetary, EC3, and Build Carbon Neutral — were used to evaluate environmental performance, identify high-impact design variables, assess embodied carbon, and generate data-driven design interventions.

Ecoify

Ecoify estimated PSU's total embodied carbon footprint at approximately 14,639 metric tons of CO_2, driven primarily by the campus's extensive reinforced-concrete construction. The platform's outputs indicate that embodied carbon is shaped as much by material-selection decisions made during design and construction as by operational energy use, and it identified low-carbon materials, renewable-energy technologies, and climate-responsive systems as the principal levers for reduction.

One Click LCA Planetary

One Click LCA Planetary compared four structural alternatives: steel frame construction (approximately 600 $kgCO_2e/m^2$), reinforced concrete (approximately 450 $kgCO_2e/m^2$), hybrid structural systems (approximately 350

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kgCO_2e/m^2), and timber-based systems (approximately 220 kgCO_2e/m^2), indicating that replacing conventional concrete or steel with hybrid or timber-based alternatives could reduce embodied carbon by roughly 30–60%. A parallel design-scenario comparison (Table 2) showed total embodied carbon falling from 1,240 tCO_2e under the baseline design to 980 tCO_2e with an improved material mix (−21%), 780 tCO_2e with low-carbon materials (−37%), and 560 tCO_2e under a fully optimized low-carbon design (−55%). Concrete and steel accounted for approximately 40% and 30% of total embodied emissions respectively, confirming the centrality of material choice to embodied-carbon outcomes.

Table 2. ***Total Embodied Carbon by Design Scenario (One Click LCA Planetary)***

Design Scenario	Total Embodied Carbon (tCO_2e)	Reduction vs. Baseline	Reduction (%)
Baseline Design	1,240	—	—
Improved Material Mix	980	−260	−21%
Low-Carbon Materials	780	−460	−37%
Optimized Low-Carbon Design	560	−680	−55%

Note. Reproduced from the original manuscript's Appendix Table 2 (p. 89 of the source document).

Embodied Carbon in Construction Calculator (EC3)

EC3 provided a material-specific breakdown of embodied carbon for the proposed redevelopment scenario, estimating a total of approximately 1,240 tCO_2e, of which structural systems accounted for 35%. Concrete was the single largest contributor (approximately 520 tCO_2e), followed by reinforcing steel (approximately 280 tCO_2e), with aluminum, glazing, and gypsum board contributing smaller shares. By life-cycle stage, material extraction accounted for approximately 45% of emissions, manufacturing 35%, and transportation the remaining 20%. EC3 estimated that replacing conventional materials with low-carbon concrete, recycled steel, and recycled aluminum could reduce total embodied carbon from 1,240 tCO_2e to approximately 560 tCO_2e — a reduction of roughly 55%, consistent with the One Click LCA Planetary scenario analysis above. Material-level comparisons (Table 3) showed reductions of approximately 29–31% across concrete, reinforcing steel, aluminum, and glass when low-carbon or recycled options replaced conventional baselines.

Table 3. ***Comparative Analysis of Building Material Baseline and Low-Carbon/Recycled Alternatives***

Material	Option	Embodied Carbon (kgCO_2e/unit)	Reduction vs. Baseline
Concrete	Conventional (Baseline)	320	—
Concrete	Low-Carbon Concrete	220	−31%
Reinforcing Steel	Conventional (Baseline)	1,800	—
Reinforcing Steel	Recycled Steel	1,250	−31%

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Material	Option	Embodied Carbon ($kgCO_2e$/unit)	Reduction vs. Baseline
Aluminum	Conventional (Baseline)	8,500	—
Aluminum	Recycled Aluminum	5,900	−31%
Glass	Standard Glass (Baseline)	120	—
Glass	Low-E Glass	85	−29%

Note. Reproduced from the original manuscript's Appendix Table 3 (p. 89 of the source document).

Build Carbon Neutral

Build Carbon Neutral was used to validate the reductions identified above and confirmed the campus baseline embodied-carbon estimate of approximately 14,639 metric tons of CO_2. It identified three priority interventions — optimization of building form and structural systems, integration of renewable-energy technologies, and adoption of low-carbon construction materials — while cautioning that the adoption of low-carbon materials must also weigh local availability, cost, and constructability, and recommended locally available sustainable materials, renewable technologies, and passive systems as the most practical near-term combination for PSU.

Collectively, the four platforms informed five design-optimization strategies: permeable pavement and sustainable drainage; residual-space redevelopment into rain gardens, green buffers, and shaded outdoor areas; solar photovoltaic integration on roofs and shading structures; stack ventilation and other passive cooling measures; and complementary interventions in landscaping, low-carbon material substitution, energy-efficient glazing, and climate-responsive shading.

Integration of Energy Simulation and Optimization Tools for Data-Driven Decision-Making

Two performance-simulation platforms, EDGE and OpenStudio, were used to evaluate energy performance, resource efficiency, daylighting, thermal comfort, and carbon-reduction potential for the proposed campus redevelopment.

EDGE (Excellence in Design for Greater Efficiencies)

The author's narrative results report an overall EDGE score of 72%, described as meeting the requirements for “EDGE Advanced Certification,” with energy consumption reduced by approximately 41%, water consumption by approximately 33%, and embodied energy in materials by approximately 28% relative to baseline.

Contribution analysis in the narrative attributed energy savings to efficient HVAC systems (approximately 35% of total savings), lighting improvements (approximately 25%), and envelope enhancement and renewable-energy integration (approximately 20% each), and attributed water savings chiefly to low-flow fixtures (approximately 40% of water savings) and rainwater harvesting (approximately 30%). These proportional breakdowns describe the relative contribution of each intervention category and are independent of which absolute EDGE savings figure (28% vs. 41% energy savings) is ultimately confirmed.

OpenStudio

OpenStudio simulations indicated that the optimized design would reduce annual Energy Use Intensity (EUI) from a baseline of approximately 210 kWh/m²/year to approximately 92 kWh/m²/year (−56%), and annual

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operational carbon emissions from approximately 185,000 kgCO_2e/year to approximately 78,000 kgCO_2e/year (−58%). Cooling remained the dominant energy end-use at approximately 35% of total consumption, followed by lighting (25%), equipment (20%), and ventilation (10%). Peak cooling load fell from approximately 1,250 kW at baseline to approximately 620 kW under the optimized design. Daylighting performance reached a Daylight Autonomy of approximately 78% (exceeding the commonly applied 75% benchmark for educational facilities) and a Useful Daylight Illuminance of approximately 74% of occupied hours within the 100–2,000 lux range. Thermal comfort, assessed via the Predicted Mean Vote (PMV) index, averaged approximately −0.2 — within the recommended −0.5 to +0.5 comfort band — with operative temperatures ranging from approximately 21.1°C to 30.4°C. A comparative scenario analysis (Table 4) confirmed that the fully optimized design outperformed the baseline, an improved-envelope-only option, and a high-performance-HVAC-only option across every indicator evaluated, supporting the conclusion that integrated, rather than isolated, interventions yield the greatest sustainability gains.

Table 4. ***Comparative Design-Scenario Performance (OpenStudio)***

Design Alternative	EUI (kWh/m²/yr)	Peak Cooling Load (kW)	Daylight Autonomy (%)	Annual CO_2e (kg/yr)
Baseline (Existing)	210	1,250	48%	185,000
Option 1: Improved Envelope	158	980	62%	136,000
Option 2: High-Performance HVAC	126	760	70%	104,000
Option 3: Optimized Design (Recommended)	92	620	78%	78,000

Note. Reproduced from the original manuscript's Appendix Table 4 (p. 91 of the source document).

Proposed Sustainability Parameters for Transitioning Educational Infrastructure Toward NZEB Performance

Synthesizing the assessment, generative-design, and simulation findings above, the study proposes a five-phase Sustainability Parameter intended to guide PSU — and, by extension, comparable educational institutions — toward near-net-zero energy performance. The framework is iterative rather than linear: information generated during monitoring feeds back into subsequent assessment and design cycles.

- Phase 1 — Assessment and Baseline Analysis: climate, site, energy, carbon, and sustainability assessment establishes the baseline data required for all subsequent phases.
- Phase 2 — AI-Driven Generative Design Optimization: Ecoify, One Click LCA Planetary, EC3, and Build Carbon Neutral generate and evaluate design alternatives addressing building form, material selection, carbon reduction, renewable-energy integration, passive cooling, sustainable site development, and resource efficiency.
- Phase 3 — Energy Simulation and Validation: EDGE and OpenStudio provide quantitative validation of the effectiveness of proposed interventions before implementation.

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- Phase 4 — Sustainable Design Implementation: validated interventions — renewable energy, passive cooling, green infrastructure, and low-carbon materials — are translated into practical design and construction strategies.
- Phase 5 — Monitoring and Continuous Improvement: ongoing tracking of electricity consumption, operational and embodied carbon, occupant satisfaction and comfort, and performance against sustainability targets, feeding back into future assessment cycles.

This sequence — Assessment → AI-Driven Generative Design Optimization → Energy Simulation and Validation → Sustainable Design Implementation → Monitoring and Continuous Improvement → Net Zero Energy Educational Campus — constitutes the study's principal practical contribution and is intended as a transferable roadmap rather than a PSU-specific prescription.

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Discussion

The findings indicate that transforming PSU into a near-net-zero energy campus is both technically feasible and strategically relevant within the Philippine educational context, and they extend the tropical-NZEB literature in several specific ways.

First, passive environmental strategies proved central to the results: the OpenStudio-simulated 56% EUI reduction (210 to 92 kWh/m²/year) is consistent with the passive-first pattern reported for tropical climates elsewhere (Feng et al., 2019; Ohene et al., 2022; Chung-Camargo et al., 2024). At the same time, PSU's narrow inter-building spacing, extensive paved surface, and limited tree cover were found to constrain the effectiveness of natural ventilation alone — a finding that qualifies, rather than simply confirms, tropical-design literature that treats natural ventilation as broadly sufficient for institutional thermal comfort. This is consistent with Attia et al.'s (2017) argument that climate-responsive strategies must be spatially adaptive and site-specific rather than applied as generic prescriptions; at PSU, passive strategies appear to require deliberate integration with site-level landscape and microclimate planning to realize their full potential.

Second, the embodied-carbon findings — approximately 14,639 metric tons of CO_2, concentrated in reinforced-concrete construction — reinforce the growing emphasis on embodied, and not only operational, carbon in NZEB evaluation (Wu & Skye, 2021; Satola et al., 2022). The comparative material and design-scenario results (Tables 2 and 3) show that AI-driven carbon-assessment platforms can meaningfully inform material selection and scenario comparison at the early design stage, when the majority of embodied-carbon decisions are effectively locked in. The consistent 30–62% range of reductions across the Ecoify, One Click LCA Planetary, and EC3 outputs — despite each platform using a different assessment method — lends some convergent support to the magnitude of achievable savings, though the underlying assumptions of each platform were not independently reconciled in this study and should be treated as an area for future verification.

Third, the study's AI-driven generative-design workflow supports the broader claim that AI functions as a transformative, rather than incremental, tool for building design (Yang, 2025; Yusuf & Omefe, 2025; Emam, 2025), by enabling iterative comparison of multiple alternatives against energy, carbon, and comfort criteria simultaneously rather than sequential, single-solution evaluation. At the same time, the analysis surfaced practical limitations already documented in the wider literature: the extensive data collection, calibration, and technical expertise the workflow required may not be readily available across the broader Philippine SUC (state universities and colleges) system, and the reliance on simulated rather than post-occupancy performance data leaves open the possibility — well documented by Li and Wang (2021) — that operational results will diverge from simulated projections once occupant behavior and maintenance practice are taken into account.

Fourth, the CBS Building 1 energy breakdown, in which administrative air-conditioning accounted for more than half of monthly consumption while naturally ventilated classrooms consumed comparatively little, points to an internal inconsistency within PSU's own operations: academic spaces already reflect passive-first principles while administrative functions remain heavily dependent on mechanical cooling. This suggests that sustainability practice at PSU, as at many institutions, is currently fragmented across building types rather than institutionally coordinated — a pattern that the proposed five-phase Sustainability Parameter is explicitly designed to correct by embedding assessment and monitoring at the institutional, rather than building, level.

Finally, the EDGE discrepancy documented in Section 3.4 warrants direct discussion rather than omission. Because the source appendix contains the primary evidentiary certificate, and because the certificate's 28%/32%/22% figures are internally consistent with an EDGE Certified (not Advanced) rating, this discrepancy does not by itself invalidate the study's broader OpenStudio-based EUI and carbon findings, which rest on a separate simulation platform and are internally consistent with the appendix's Table 4. It does, however, mean that any claim of “EDGE Advanced Certification” for the proposed design should be treated as unverified pending

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confirmation from the author's original EDGE project documentation, and it illustrates the broader methodological point — also raised in the barriers literature (Satola et al., 2022; Rauniyar et al., 2024) — that inconsistent reporting across NZEB assessment platforms and certification tiers remains a live obstacle to comparability, even within a single study.

From a theoretical standpoint, the results support Sustainable Development Theory as the study's guiding framework: the environmental, economic, and social dimensions of the proposed interventions are shown to be interdependent rather than separable, and the study extends this theory by demonstrating that AI functions not merely as a technical calculation tool but as a mediator between environmental performance data and architectural decision-making. For policy and practice, the findings support calls for updated Philippine building codes, localized NZEB standards, and incentives for energy-efficient educational infrastructure, and suggest that sustainability should be treated as a core institutional strategy linked to climate resilience and operational efficiency rather than an optional design enhancement.

Limitations

The study's principal limitation is its reliance on simulation rather than post-occupancy monitored performance; actual energy consumption may diverge from projections due to occupant behavior, operational inconsistency, and maintenance conditions. The analysis was further limited to selected PSU buildings, constraining generalizability to other institutional contexts, and did not include financial feasibility, construction logistics, or long-term implementation analysis, so technically effective strategies identified here may still face budgetary, political, or regulatory constraints in practice. The rapid evolution of AI-assisted design tools also means that platforms more capable or more tightly integrated than those used here may become available in the near term. Finally, as documented in Sections 3.4 and the Editorial and Citation Integrity Notice, one platform's headline results (EDGE) could not be fully reconciled against its own supporting appendix, and a substantial share of the in-text citations in the source manuscript lack corresponding reference-list entries; both issues limit the extent to which specific numeric and attributional claims in this article can be treated as independently verified pending the author's review.

Conclusion and Recommendations

This study aimed to develop sustainability parameters for transforming existing Pampanga State University buildings into near-net-zero energy buildings through AI-driven generative design and energy-optimization platforms. The evidence indicates that PSU possesses substantial potential to become a more sustainable, energy-efficient campus: passive design strategies — natural ventilation, building orientation, shading, and landscaping — meaningfully reduce energy demand and improve thermal comfort; AI-driven platforms (OpenStudio, EDGE, EC3, Ecoify, and One Click LCA Planetary) support better design decision-making by enabling comparison of multiple alternatives; most embodied carbon originates from reinforced-concrete construction, underscoring the importance of low-carbon and locally available materials in future development; and administrative air-conditioning is the single largest contributor to operational energy use, pointing to cooling-system efficiency as the campus's most immediate improvement opportunity.

The study contributes to Sustainable Development Theory by showing, empirically, how environmental responsibility, energy efficiency, and occupant comfort can be integrated through data-driven, climate-responsive design, and it demonstrates a workable role for AI in helping architects and planners design more efficient, sustainable educational buildings. For universities and policymakers, the findings point to a need for stronger sustainability policy, renewable-energy integration, and long-term campus planning grounded in measurable performance data rather than prescriptive compliance alone.

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Although the study focuses on PSU, the proposed five-phase Sustainability Parameter (Section 3.5) is intended as a transferable guide for other educational institutions pursuing similar transitions. Based on the findings, the study recommends that PSU and comparable institutions (1) implement a campus-wide energy-management system with real-time monitoring; (2) prioritize solar photovoltaic integration, beginning with administrative buildings identified as the largest cooling-related energy consumers; (3) upgrade cooling and lighting equipment, particularly replacing fluorescent fixtures with LED technology and introducing occupancy- and daylight-responsive controls; (4) improve shading and vegetation coverage to reduce heat accumulation and support passive cooling; and (5) adopt the proposed Sustainability Parameters as a standing institutional framework rather than a one-time project, given that NZEB performance is achieved and maintained through continuous assessment and monitoring rather than a single design intervention.

Future research should prioritize post-occupancy validation that compares simulated projections with actual operational performance, ideally through longitudinal monitoring before and after retrofit interventions. Further work should also explore digital twins, real-time sensor networks, and machine-learning-based adaptive controls; investigate low-carbon materials, including indigenous and rapidly renewable options, suited to tropical institutional construction in the Philippines; and undertake economic feasibility analysis, stakeholder acceptance studies, and policy-implementation research to strengthen the practical applicability of NZEB transformation strategies across the Philippine state-university system. In parallel, and as detailed in the Editorial and Citation Integrity Notice below, the author is encouraged to reconcile the EDGE Design Stage certificate against the narrative EDGE results reported in Section 3.4, and to complete the reference list against the full set of in-text citations, before this manuscript is submitted for peer review.

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