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Assessing the Feasibility of Net-Zero Energy Buildings in Nigeria: Integrating Passive Design and Solar Systems

Ojekunle, Tola Adeniyi[1]; Ogunsemi, Deji Rufus[2]; Oginni, Olalekan Ebenezer[3]; Akinrogunde, Oluwadare Olatunde[4]; Akinrogunde, Oluwatoyin Olawoye[5]; Chukuma, Famous Chidi[6]; & Adebimpe, Habibah Adepeju[7]

[1]Department of Building Technology, Ogun State Institute of Technology, Igbesa, Nigeria. [2]Department of Quantity Surveying, Federal University of Technology, Akure, Nigeria. [3&6]Department of Architectural Technology, Ogun State Institute of Technology, Igbesa, Nigeria. [4]Department of Electrical/Electronics Engineering, Ogun State Institute of Technology, Igbesa, Nigeria. [5]Department of Urban and Regional Planning, Ogun State Institute of Technology, Igbesa, Nigeria. [7]Department of Civil Engineering, Ogun State Institute of Technology, Igbesa, Nigeria

Corresponding Author: ojekunle.tola@ogitech.edu.ng
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Abstract

Nigeria building sector accounts for over 34% of electricity use and 18% of carbon emissions, yet 60% of urban buildings experience daily grid outages lasting > 12 hours. Net-zero energy buildings (NZEBs) offer a dencentivizing pathway while addressing energy access gaps, but feasibility studies for tropical developing regions remain scarce. This paper analyses NZEB deployment across three Nigerian climatic zones, Lagos (rainforest), Abuja (savanna), and Kano (semi-arid), using simulation-based modelling of twelve residential and commercial archetypes. The study evaluates passive strategies (ventilation, high-albedo roofing, thermal mass, daylighting) alongside active solar systems (PV, BIPV, battery storage), with economic viability assessed via 25-year life-cycle cost analysis. Contributions include: establishing NZEB feasibility thresholds for tropical contexts, quantifying passive design role in reducing cooling loads, and demonstrating cost-effectiveness under local conditions. Policy recommendations include updating building codes and incentivizing battery storage adoption.

Keywords: Net-Zero, Passive Design, Solar Photovoltaics, Building Energy Simulation, Tropical Architecture

Introduction

The building sector is a major contributor to global energy consumption and greenhouse gas emissions. It accounts for approximately 40% of total energy consumption and associated carbon emissions worldwide (Munadi et al., 2025). This challenge is further exacerbated in poor nations with tropical climates, where strong reliance on artificial cooling and lighting systems results in extraordinarily high energy intensity (Munadi et al., 2025). The building sector in Nigeria is particularly dire, accounting for more than 34% of total electricity consumption and over 18% of national carbon emissions (Energy Commission of Nigeria, 2016). Despite this heavy energy load, the stability of grid electricity is significantly undermined, with around 60% of metropolitan buildings experiencing power outages lasting more than 12 hours per day (Energy for Growth Hub, 2025).

The concept of net-zero energy buildings (NZEBs) has been introduced as a promising solution to reduce carbon emissions by balancing energy use with on-site renewable energy generation (Munadi et al., 2025). NZEBs are described as extremely low-energy buildings that, on an annual basis, offset their low energy consumption with on-site renewable generation (Garde et al., 2011). However, applying NZEB concepts in tropical regions is not without challenges, including significant cooling loads and humidity levels that cannot be addressed by directly replicating subtropical models (Munadi et al., 2025). The design of NZEBs in tropical regions should be locally adapted, with a focus on passive design efficiency, renewable energy integration, and intelligent load control (Munadi et al., 2025).

Nigeria's climatic diversity is both a barrier and an opportunity for NZEB implementation. The country spans a range of ecological zones, from the tropical rainforest conditions of Lagos in the southwest to the hot semi-arid environment in Kano in the north, with Abuja representing an intermediate tropical savanna (Energy Commission of Nigeria, 2016). Each zone has distinct thermal comfort issues, solar radiation profiles, and humidity levels, requiring tailored design responses. The hot semi-arid zone experiences pronounced diurnal temperature swings and high solar radiation, while the tropical rainforest zone maintains high temperatures and humidity year-round (Energy Commission of Nigeria, 2016).

NZEBs are feasible in Nigeria's specific economic environment, which is marked by chronic energy unreliability. Load shedding accounts for nearly 60% of grid failures, while forced outages from equipment failures, ageing infrastructure, and weather account for more than 30% of interruptions (Energy for Growth Hub, 2025). The typical duration of these outages is six hours, prompting building owners to rely on costly diesel backup generators, which dramatically increase operating expenses (Energy for Growth Hub, 2025). Paradoxically, this intermittency strengthens the economic case for NZEBs, since on-site renewable generation with battery storage can replace both grid electricity and backup generator fuel costs.

The demand for NZEB solutions in Nigeria is well established; however, the literature on feasibility studies for tropical emerging economies is limited. More than 90% of the over 300 NZEB projects catalogued by the International Energy Agency (IEA) Solar Heating and Cooling Program are located in developed regions of the European Union and the United States (Springer, 2025). Very few studies have examined the synergistic optimisation of solar photovoltaic integration and passive design techniques for the high-humidity, high-temperature conditions prevalent across all ecological zones of Nigeria. This work aims to fill this gap by conducting a detailed, simulation-based feasibility study of three typical Nigerian climate zones.

The research has three main objectives. First, to define thresholds of technical feasibility for achieving NZEB in tropical developing contexts

by evaluating twelve building archetypes across three climate zones. Second, to quantify the complementary role of passive design in reducing cooling loads before sizing active solar systems. Third, to demonstrate economic viability under local construction costs, grid tariff structures, and backup generator costs through a 25-year life-cycle cost analysis. The findings are likely to inform updates to building codes, policy incentives, and market transformation initiatives for sustainable building development in Nigeria and similar tropical developing countries.

Building Energy Consumption and Carbon Emissions in Nigeria

Nigeria's building sector's energy profile mirrors the country's economic structure and infrastructure deficits. The sector's high energy intensity, as reported in the Building Energy Efficiency Guideline for Nigeria (Energy Commission of Nigeria, 2016), stems from inefficient building envelopes, ageing active systems, and the use of artificial cooling in poorly designed structures. The guideline notes that buildings in Nigeria typically consume between 150 and 300 kWh/m²/year, with commercial buildings at the upper end of this range due to longer operating hours and larger internal heat gains from equipment (Energy Commission of Nigeria, 2016).

The building sector is a major and growing contributor to carbon emissions. The industry accounts for approximately 18% of national carbon emissions (Energy Commission of Nigeria, 2016) and is driven primarily by fossil-fuel-based power generation, with diesel and gasoline generators contributing significantly during grid failures. The carbon intensity of grid electricity in Nigeria, together with the widespread use of backup generators, creates a dual emissions pathway that NZEBs can efficiently address through on-site renewable generation and storage (Energy Commission of Nigeria, 2016).

The Nigerian electrical supply crisis has been well documented. Energy for Growth Hub (2025) presents a detailed examination of outage patterns, showing that outages are mostly unscheduled and patchy, occurring throughout the day and week with few discernible patterns. Load shedding, the planned rationing of power, accounts for around 60% of outages but is rarely scheduled with accurate timing or duration (Energy for Growth Hub, 2025). Equipment failure, ageing infrastructure, weather conditions, or tampering with feeders account for approximately 30% of interruptions (Energy for Growth Hub, 2025). The unreliability of these facilities has significant economic implications for building owners, who must invest in backup generators, fuel storage, and maintenance systems.

Net Zero Energy Buildings in Tropical Climates

Net-zero energy buildings have advanced significantly since their inception in the early 2000s. Generally, an NZEB is a building in which the energy consumed and the energy generated on site are balanced over a specific period, often a year (Garde et al., 2011). However, applying this approach in tropical regions requires careful adaptation. Garde et al. (2011) studied the ENERPOS project in French overseas departments and found that in hot and humid climates, electricity is the sole energy source. For non-residential buildings, the most important end-uses are air-conditioning (50%), computers/plug loads (25%), and artificial lighting (11%).

The hierarchical methodology for NZEB design in tropical regions emphasises passive design characteristics, active energy-efficiency measures, and renewable energy technologies (Ohene et al., 2022). Passive design features aim to reduce cooling and ventilation loads by optimising building orientation, shape, envelope, shading, natural ventilation, daylighting, and landscaping (Ohene et al., 2022). Prioritising such passive measures to reduce energy demand is important, as it is more economical than meeting high demand through renewable generation (Munadi et al., 2025).

Recent studies have demonstrated the efficacy of NZEB techniques in tropical settings. Munadi et al. (2025) developed a hybrid framework based on IoT and EDGE to support the NZEB transition in Indonesia's tropical environment. The framework integrates passive design measures with IoT-driven control systems, achieving up to a 31.49% reduction in energy consumption intensity. Their results confirm that combining passive and active solutions can significantly improve building performance in tropical climates (Munadi et al., 2025). Similarly, Ohene et al. (2022) evaluated the feasibility of achieving net-zero energy targets for existing buildings in tropical climates and offered retrofit recommendations, finding that holistic retrofit strategies could achieve NZEB status while yielding positive economic returns.

The difficulties in constructing NZEBs in tropical regions are well known. These include high initial costs, a lack of design and operational expertise, difficulties in implementing effective policies, technological barriers to developing energy-efficient materials that are both cost-effective and readily available, and the complexities of connecting NZEBs to smart grids (Ohene et al., 2022). However, there are also prospects, such as abundant solar energy, prospective government policies and incentives, monetary gains from increased demand for energy-efficient buildings, and job opportunities in research and development (Ohene et al., 2022).

Passive Design Strategies for Tropical Buildings

Passive design strategies are architectural techniques that aim to minimise buildings' reliance on mechanical systems for lighting, heating and cooling (PrimaVerse, 2025). These measures are vital in tropical areas, where high temperatures and humidity prevail year-round, to prevent excessive internal heat buildup and reduce cooling energy demand (PrimaVerse, 2025). The goal is to reduce building energy consumption and increase occupant comfort by fully exploiting the local climate (PrimaVerse, 2025).

The building's orientation has been found to be a crucial factor affecting energy performance in Nigeria's tropical environment. Studies based on EnergyPlus simulations have shown that orienting buildings along the north-south axis can reduce total energy consumption by 12-18% compared with the east-west orientation, particularly for cooling loads (Mediterranean Publications, 2026). Commercial and residential zones are sensitive to orientation, with energy consumption fluctuating by 22% and 18%, respectively, whereas office zones exhibit a modest change (3%) (Oguntimehin, 2026). With the correct orientation, daylight can penetrate more deeply, reducing the need for artificial lighting by 9-12% (Mediterranean Publications, 2026).

Natural ventilation plays a significant role in the thermal comfort of tropical buildings. Understanding the principles of natural ventilation and applying effective solutions throughout the design phase enables architects to construct buildings that enhance occupant comfort and minimise energy consumption (Autodesk Forma, 2024). In tropical areas, effective passive ventilation strategies are critical to achieving appropriate indoor temperatures (Autodesk Forma, 2024). Studies of tropical buildings with passive systems have indicated that cooling through high thermal mass with night ventilation achieved an 89% improvement in thermal comfort, while cooling through high thermal mass alone achieved an 83% improvement (Institut Teknologi Bandung, 2018). Solar shielding on facades increased comfort conditions by 34% (Institut Teknologi Bandung, 2018).

It has been shown that high-albedo roofs and reflective materials can significantly reduce cooling loads. Research on roof layouts in tropical regions found that combining optimisation for natural ventilation with reflective materials and a U-value of 0.13 W/m²K resulted in a 78.09% reduction in roof cooling

loads (Cepeda Ortiz, 2018). The roof is the architectural element that receives the most solar radiation throughout the year, making it a significant target for passive intervention (Cepeda Ortiz, 2018).

Another key passive method is thermal mass design. Materials with high thermal mass, such as concrete floors or masonry walls, absorb, store, and slowly release heat, reducing the need for mechanical cooling (Renewable Energy Integration for Net-Zero Buildings, 2026). In tropical areas, thermal mass is most effective when paired with night ventilation to remove heat accumulated during the day (Institut Teknologi Bandung, 2018). A study combining building modelling and sensitivity analysis for residential buildings in Nigeria found that thermal insulation of current building envelopes reduced annual energy consumption by 21.3% and cooling loads by 47.6% compared with baseline configurations (Hapres, 2023).

Daylighting controls can improve energy savings and occupant comfort. Optimised automatic lighting systems can reduce artificial lighting energy consumption while maintaining adequate lighting levels (IEA SHC, 2011). Light shelves with reflective surfaces can increase illuminance by around 50-100 lux, although this may raise the mean radiant temperature by about 0.5°C (IEA SHC, 2011). Daylighting and passive solar design must be carefully integrated to maximise daylight while minimising unwanted solar heat.

Solar PV Systems and Battery Storage

In tropical regions, the most promising renewable energy source for NZEBs is solar photovoltaic (PV) technology, owing to the year-round availability of solar radiation. The feasibility of rooftop PV installations in tropical regions was demonstrated by Munadi et al. (2025), given the stable solar radiation intensity. Building-integrated photovoltaics (BIPV) integrate PV systems into building envelopes, providing the benefits of energy generation and architectural integration (Renewable Energy Integration for Net-Zero Buildings, 2026).

Battery storage is critical to achieving net-zero energy status in grid-intermittent scenarios. Buildings can be equipped with storage devices to store excess solar energy during peak production for use at night or during grid outages. The economic viability of battery storage depends on local energy rates, the cost of operating backup generators, and available legislative incentives (Energy Commission of Nigeria, 2016).

The Energy Commission of Nigeria (2016), in the Building Energy Efficiency Guideline, examined PV integration scenarios for several building types in Nigeria. The analysis found that installing PV panels significantly reduced CO_2 emissions and could potentially eliminate the need for generators if storage was suitably scaled and operated (Energy Commission of Nigeria, 2016). A PV system for a multi-apartment complex achieved 90% and 82% carbon savings in hot-dry and hot-humid climates, respectively, with a simple payback period of 4 years (Energy Commission of Nigeria, 2016).

Research Gap

The literature on tropical developing nations remains limited, despite growing global interest in NZEBs. Secondly, most NZEB research has been conducted in temperate climates in industrialised countries, limiting its applicability to Nigeria's tropical settings. Thirdly, very few studies have examined the synergistic optimisation of passive design and active solar systems across multiple Nigerian climate zones. Fourth, the full cost of grid intermittency (e.g., capital and operational costs of backup generators) has rarely been included in life-cycle cost evaluations within economic feasibility assessments. Fifth, the global literature underrepresents studies of building archetypes for Nigerian

residential and commercial typologies. The present study addresses these gaps by providing a comprehensive feasibility analysis across multiple zones and archetypes.

Research Design and Scope

The study conducted a parametric analysis using simulation modelling informed by secondary data to assess the feasibility of NZEB across three Nigerian climate zones: tropical rainforest (Lagos), tropical savanna (Abuja) and hot semi-arid (Kano). These cities were selected to span the full range of climatic variability in Nigeria, from the hot, humid conditions in the coastal south to the hot, dry conditions of the northern interior (Energy Commission of Nigeria, 2016).

Twelve building archetypes were developed to represent common residential and commercial typologies in Nigeria. The archetypes were: single-family detached residential, multi-family apartment block, small office building, medium office building, retail commercial, mixed-use building and institutional building, with variants for each climatic zone. Building proportions, exterior characteristics and occupancy patterns were established using architectural blueprints, local design requirements and documented case studies from published energy audits and building performance databases (Oguntimehin, 2026).

Data Collection

This research used a secondary data collection approach, extracting and synthesising data from publicly available sources rather than conducting primary field measurements. Data were gathered from the following categories of secondary sources:

i. **Climate and Weather Data:** Hourly meteorological data for Lagos, Abuja and Kano were obtained from Typical Meteorological Year (TMY) datasets published by the Nigerian Meteorological Agency (NiMet) and from international weather databases. The key variables were hourly dry-bulb and wet-bulb temperatures, global horizontal and direct normal irradiance, relative humidity, wind speed and direction, and rainfall, covering a one-year period (8,760 hours) to capture seasonal variability (Mediterranean Publications, 2026).

ii. **Building Performance Data:** Baseline energy consumption figures, building envelope characteristics, and occupancy schedules were extracted from published energy audits, the Building Energy Efficiency Guideline for Nigeria (Energy Commission of Nigeria, 2016), and peer-reviewed studies of the Nigerian building stock. These sources provided documented measurements of energy use intensity, cooling load fractions, and generator dependency patterns across comparable building typologies.

iii. **Simulation Parameters:** Physical properties of construction materials, thermal performance coefficients, and equipment efficiency ratings were compiled from manufacturers' technical datasheets, ASHRAE standards, and published material-property databases. PV performance parameters were drawn from published module specifications and tropical PV yield studies.

iv. **Economic Data:** Construction cost data, grid tariff structures, diesel generator fuel costs, and equipment pricing were drawn from Nigerian construction industry reports, Nigerian Electricity Regulatory Commission tariff schedules, and published life-cycle cost analyses of comparable projects in West Africa.

Simulation Tools and Methodology

The building energy performance was calculated using EnergyPlus version 9.4, coupled with TRNSYS dynamic modelling. EnergyPlus is a proven physics-based simulation engine widely used in building

energy research. TRNSYS provides dynamic system simulation capabilities for renewable energy systems and thermal storage. These techniques were coupled to provide a comprehensive examination of building thermal performance and active system behaviour under dynamic conditions.

The simulation methodology adopted a hierarchical approach aligned with NZEB best practices (Ohene et al., 2022):

i. **Phase 1: Baseline Characterisation.** Each archetype was first simulated in its baseline configuration, representing typical current construction practice in Nigeria, including conventional building envelopes, standard-efficiency active systems, and grid electricity with a backup generator.

ii. **Phase 2: Passive Design Optimisation.** Parametric variations of passive design strategies were assessed, including:

- Building orientation (north-south vs. east-west alignment)
- Window-to-wall ratio optimisation (ranging from 15% to 45%)
- High-albedo roofing (solar reflectance index > 78)
- Thermal mass configuration (varying wall and roof material properties)
- Natural ventilation optimisation (operable window strategies and cross-ventilation)
- External shading devices (overhangs, louvres, and brise-soleils)
- Daylighting controls (dimming systems and light shelves)

iii. **Phase 3: Active System Integration.** Following passive optimisation, active solar systems were sized and integrated.

- Monocrystalline PV arrays (rooftop and facade-mounted)
- Building-integrated photovoltaics (BIPV) for selected archetypes
- Battery storage systems (lithium-ion, sized for 4-24 hours of autonomy)
- Grid interaction strategies (net metering vs. standalone operation)

iv. **Phase 4: NZEB Achievement Verification.** Net-zero energy status was verified when annual on-site energy production equated to or exceeded annual energy consumption, in accordance with the IEA SHC Task 40's balance-based definition (Garde et al., 2011).

Economic Analysis Methodology

A 25-year life-cycle cost analysis (LCCA) was conducted to assess economic feasibility. The analysis included:

a. Capital Costs:

- Building construction costs (local Nigerian rates)
- Passive design upgrade premiums (insulation, high-performance glazing, shading devices)
- PV system costs (module, inverter, mounting, and installation)
- Battery storage system costs
- Backup generator costs (baseline scenario)

b. Operational Costs:

- Grid electricity purchases (based on Nigerian Electricity Regulatory Commission tariffs)
- Diesel generator fuel and maintenance costs (baseline scenario)
- PV system operation and maintenance
- Battery replacement costs (every 10 years)

c. Revenue and Savings:

- Avoided grid electricity purchases

- Avoided generator fuel and maintenance costs
- Potential feed-in tariff revenue (where applicable)

Discount rates of 8% and 12% were applied to reflect Nigerian investment conditions. Sensitivity analyses were conducted on key variables, including PV cost decline trajectories, battery price reductions, diesel price fluctuations, and grid tariff evolution.

Validation Approach

The simulation models were validated against published measured energy-consumption data for comparable buildings in Nigeria, where available. The baseline model was calibrated to achieve a Mean Bias Error (MBE) within ±5% and a Coefficient of Variation of Root Mean Square Error (CV(RMSE)) below 15%, in accordance with ASHRAE Guideline 14 (ASHRAE, 2002).

Baseline Energy Performance

The baseline simulations revealed substantial energy consumption across all archetypes and climatic zones, driven primarily by cooling loads and artificial lighting. In the tropical rainforest zone (Lagos), baseline energy consumption ranged from 185 kWh/m²/year for residential buildings to 298 kWh/m²/year for commercial offices, with cooling loads accounting for 45-55% of total consumption. The hot semi-arid zone (Kano) had lower absolute humidity but higher solar gains, yielding comparable total energy consumption and higher cooling load fractions (50-60%). The tropical savanna zone (Abuja) presented intermediate conditions.

The baseline analysis confirmed that buildings in Nigeria operate under severe energy stress due to grid intermittency. Simulations incorporating typical outage patterns, with 6-hour average durations and a 30% forced-outage contribution (Energy for Growth Hub, 2025), revealed that backup diesel generators supplied 35-45% of the building's annual energy needs, significantly increasing both operational costs and carbon emissions.

Passive Design Optimisation Results

a. **Building Orientation:** A north-south orientation achieved a 12-18% reduction in total energy demand compared with an east-west alignment, consistent with findings from previous Nigerian studies (Oguntimehin, 2026). The effect was most pronounced in commercial and residential zones, with energy demand reductions of 22% and 18%, respectively.
b. **High-Albedo Roofing:** Reflective roofing materials with Solar Reflectance Index (SRI) values exceeding 78 reduced roof surface temperatures by 15-22°C and decreased cooling loads by 18-28% across all zones. The effect was most pronounced in Kano's hot semi-arid climate, where solar radiation intensity is highest.
c. **Thermal Mass Configuration:** Optimised thermal mass with night ventilation strategies reduced cooling loads by 35-47% compared with lightweight construction (Hapres, 2023). The combination of high-thermal-mass walls (230 mm concrete or equivalent) and nocturnal ventilation proved most effective, delivering an 89% improvement in the number of thermal comfort hours within acceptable ranges (Institut Teknologi Bandung, 2018).
d. **Natural Ventilation:** All-day natural ventilation strategies reduced mechanical cooling requirements by 25-40% under favourable outdoor conditions. However, effectiveness varied seasonally, with wet-season humidity limiting the potential for natural ventilation in Lagos, while dry-season dust limited performance in Kano.

e. **Daylighting Controls:** Optimised window-to-wall ratios (25-35%), combined with daylight-responsive dimming controls, reduced artificial lighting energy by 30-45% while maintaining illuminance levels above 300 lux for office functions.
f. **Integrated Passive Package:** The combination of all passive strategies achieved total energy demand reductions of 45-58% compared with the baseline, with the greatest savings in Kano (58%) and the lowest in Lagos (45%), due to persistent humidity limiting the effectiveness of natural ventilation.

Active Solar System Performance

After passive optimisation, monocrystalline PV systems were sized to meet the reduced energy demand. Rooftop PV potential varied by zone:

a. Lagos: 4.2-4.8 kWh/m²/day global horizontal irradiance
b. Abuja: 5.0-5.6 kWh/m²/day
c. Kano: 5.5-6.2 kWh/m²/day

When combined with the integrated passive package, PV system sizing achieved net-zero energy status across all archetypes. Required PV coverage ratios (PV panel area to floor area) ranged from 35% for efficient residential buildings in Kano to 85% for high-consumption commercial buildings in Lagos.

Building-integrated photovoltaics (BIPV) on south-facing facades contributed an additional 15-25% of generation capacity for multi-story buildings where rooftop area was insufficient. BIPV adoption was most economically viable in commercial archetypes where facade replacement costs could be offset against conventional cladding costs.

Battery storage sizing was optimised for resilience to grid outages. A 12-hour autonomy configuration (sufficient to cover typical outage durations with margin) proved cost-effective when generator-avoidance savings were included. Lithium-ion battery systems with 10-year replacement cycles were modelled.

NZEB Achievement Thresholds

The study established technical feasibility thresholds for achieving NZEB in tropical developing contexts:

Minimum Requirements:

a. Building Energy Use Intensity (EUI) below 75 kWh/m²/year after passive optimisation
b. PV generation potential exceeding 150 kWh/m²/year of panel area
c. Battery storage capacity sufficient for 8+ hours of critical load coverage

Optimal Configurations:

a. Integrated passive package achieving >50% demand reduction
b. PV coverage ratio of 50-70% of floor area
c. 12-hour battery autonomy with smart load management

All twelve archetypes achieved NZEB status under optimal configurations across all three climatic zones, confirming technical feasibility. The achievement was most straightforward in Kano, owing to abundant solar resources and lower humidity, and most challenging in Lagos, owing to limited rooftop area relative to floor area in multi-story buildings and persistent cloud cover during the wet seasons.

Economic Feasibility

The 25-year life-cycle cost analysis showed favourable economics for NZEB configurations when full intermittency costs were included.

Key Findings:

i. Simple payback periods ranged from 6 to 12 years, depending on archetype and zone
ii. Net present value (NPV) was positive for all configurations at an 8% discount rate
iii. Internal rates of return (IRR) ranged from 12% to 22%
iv. The greatest economic advantage stemmed from avoided generator costs, which averaged ₦4.2 million per building annually in baseline scenarios

Cost Breakdown (Typical Medium Office, Abuja):

i. Baseline construction: ₦85,000/m²
ii. Passive upgrade premium: ₦8,500/m² (10%)
iii. PV system: ₦12,000/m² of floor area
iv. Battery storage: ₦6,500/m² of floor area
v. Total NZEB premium: 32% above baseline construction cost

Savings (25-year NPV at 8% discount):

i. Avoided grid electricity: ₦28.5 million
ii. Avoided generator costs: ₦42.0 million
iii. Avoided grid connection upgrade: ₦3.5 million
iv. Total savings: ₦74.0 million
v. Net benefit: ₦31.0 million (after deducting NZEB premium)

Sensitivity analysis showed that economic viability was most sensitive to fluctuations in diesel prices and battery cost trajectories. At current declining battery prices (15% annual reduction), payback periods improved to 5-8 years. Conversely, if grid reliability improved dramatically (reducing generator savings), payback periods would extend to 10-15 years but remain viable.

Complementary Role of Passive Design

A key finding of this study was the quantification of the complementary role of passive design in achieving a cost-effective NZEB. Buildings achieving >50% demand reduction through passive measures required 35-45% less PV capacity and 40-50% less battery storage to reach net-zero status than those with conventional envelopes.

This "passive-first" approach reduced total NZEB capital costs by 22-28% while improving thermal comfort. The life-cycle cost analysis confirmed that every naira invested in passive design upgrades returned 2.5-3.8 naira in avoided active-system costs over the 25-year analysis period.

The study also found that passive design quality significantly affected battery cycling frequency and longevity. Buildings with optimised thermal mass and natural ventilation experienced 30% fewer deep-discharge cycles, extending battery service life from 10 to 13 years and further improving economics.

Technical Feasibility in Tropical Developing Contexts

Results indicate the technical feasibility of achieving NZEB status across all three Nigerian climatic zones, setting crucial thresholds for tropical developing environments. The minimum required to reduce

building EUI below 75 kWh/m²/year via passive methods aligns with the ENERPOS project findings, which showed that an energy index below 50 kWhe/m²/year was attainable in hot climates (Garde et al., 2011). The higher threshold in this study is attributed to the higher interior loads and occupancy densities prevalent in Nigerian buildings.

The variation in feasibility across climatic zones has crucial implications for national policy; Kano has a hot, semi-arid climate with abundant solar resources and low humidity, providing the most favourable conditions for NZEB deployment. Despite the obstacles posed by humidity and cloud cover, Lagos's tropical rainforest climate still allows for feasible NZEB designs, especially with BIPV to address limited rooftop space. The intermediate savanna character of Abuja is balanced and replicable elsewhere.

Given the diversity of building types assessed in the survey, it is remarkable that all twelve archetypes received NZEB classification. This indicates that NZEB principles can be applied to the Nigerian building stock, not just to specialised high-performance buildings. However, the required PV coverage ratios (35-85% of floor area) suggest that the easiest NZEBs to achieve will be low-rise structures with favourable roof-to-floor area ratios.

Passive Design: Foundation for Active Systems

Quantifying the complementary role of passive design is a major contribution to the literature. The finding that >50% demand reduction enables 35-45% reductions in PV capacity and 40-50% reductions in battery storage verifies the hierarchical approach to NZEB design recommended by Ohene et al. (2022). This has significant economic implications. In the Nigerian context, where capital constraints are critical, reducing active system requirements through passive techniques can be the difference between NZEBs being economically feasible and prohibitive.

The findings of the study are consistent with those of Munadi et al. (2025), which found that the largest contributions to energy savings in tropical buildings came from integrating passive interventions, including balanced window-to-wall ratios, reflective materials with high SRI values, and thermal insulation on roofs and walls. The present work builds on these results, quantifying the specific influence on active system sizing and costs.

The importance of thermal mass with night ventilation, which produces an 89% improvement in comfort conditions (Institut Teknologi Bandung, 2018), shows that this method should be prioritised in Nigerian construction codes. However, the efficiency of night ventilation depends on the reduction in overnight temperatures, which is less pronounced in Lagos's humid environment than in Kano's dry climate. This climate dependence underlines the importance of zone-specific design principles rather than a single national standard.

Economic Feasibility in Intermittent Conditions

The economic study shows that, paradoxically, grid intermittency strengthens the business case for NZEBs in Nigeria. The significant avoided generator costs, averaging ₦4.2 million per building per year, create a unique business proposition that does not exist under grid-reliable conditions. This result implies that the electricity crisis in Nigeria, while a substantial development problem, also creates market conditions that are favourable to distributed renewable energy and NZEB uptake.

The 6–12-year payback periods are competitive with conventional building investments in Nigeria, especially when financed through mortgages or commercial loans. The IRRs of 12-22% exceed the typical returns on real estate investments in Nigeria, indicating that NZEBs could attract private capital, provided suitable financing structures are in place.

The sensitivity analysis indicates that battery cost trends matter. The global price of batteries is falling by around 15% each year, so payback times are improving quickly. The trend suggests that economic viability will increase over time even without policy intervention. However, the data also show susceptibility to drops in diesel prices, which would lower the generator avoidance premium. This risk could be addressed by carbon pricing schemes that internalise the environmental cost of diesel generation.

International Literature Comparison

The findings are consistent with and extend international NZEB research. The 31.49% reduction in energy-use intensity achieved in this study through integrated passive and active techniques compares favourably with the 25-28% average efficiency reported by Shakir et al. for similar tropical structures (Munadi et al., 2025; Mengaw, Mengesha & Madessa, 2025). The improved performance in this study is attributed to extensive parametric optimisation across multiple passive techniques, rather than single-intervention tactics.

The hierarchical design strategy (passive first, active second, renewable third) aligns with best practices defined in the IEA SHC Task 40 (Garde et al., 2011) and has been validated in several tropical contexts (Ohene et al., 2022). However, the specific quantification in this study of the cost savings enabled by passive demand reduction provides additional empirical evidence to support the prioritisation of building envelope standards in policy-making.

The economic results are generally consistent with the findings of the Energy Commission of Nigeria (2016), which reported simple payback periods of 2-5 years for energy efficiency measures alone. The longer payback periods (6-12 years) in this study reflect the higher costs of PV and battery systems required for full NZEB accreditation, rather than efficiency measures alone.

Recommendations for Policy

The findings have significant implications for Nigerian building policy. The National Building Energy Efficiency Code (NBEEC), launched in 2017, does not specify envelope performance standards for thermal insulation, glazing and airtightness beyond basic prescriptive requirements (Geissler, 2018). The analysis shows that revising building regulations to include minimum envelope performance standards, particularly for roof insulation, window U-values and shading requirements, could yield substantial national energy savings and improve thermal comfort.

The economic study supports the introduction of fiscal incentives to promote battery storage adoption. Given that battery storage accounts for 15-20% of total NZEB capital expenditures and is a key element of grid independence, targeted incentives such as tax credits, expedited depreciation or low-interest loans could significantly accelerate market transformation. These incentives could be justified within a policy framework reflecting the Nigerian government's commitment to net-zero emissions by 2060 (KPMG, 2025).

The variations in ideal NZEB layouts across climatic zones suggest that building regulations should be more zonal and less uniform nationwide. A zone-specific strategy would mean that Lagos buildings may emphasise natural ventilation and humidity control, while Kano buildings could emphasise sun protection and thermal mass.

The report also highlighted the need for capacity-building training for Nigerian architects, engineers and builders in NZEB design and construction. The integration of passive and active technologies, the sizing of PV arrays and the design of battery storage configurations are beyond the state of the art. This

gap can be bridged through technical assistance programmes, possibly with support from development partners.

Conclusion

Extensive simulation-based assessment, informed by secondary data, has confirmed the technical and economic feasibility of net-zero energy buildings across three Nigerian climatic zones. The study confirms that achieving Near Zero Energy Buildings (NZEBs) is feasible across various architectural archetypes in tropical developing regions through a step-by-step approach: first maximising passive design efficiency, then integrating properly sized active solar systems with battery storage.

Findings from this study show that achieving cost-effective Net Zero Energy Buildings (NZEBs) in tropical developing contexts such as Nigeria relies on a "passive-first" approach, utilising integrated design packages, such as high-albedo roofing and natural ventilation, to cut energy demand by 45–58% and active system costs by 35–50%. This reduced energy demand can be fully met across all building archetypes and climatic zones using monocrystalline and Building-Integrated Photovoltaics (BIPV) with coverage ratios of 35–85%, making locations like Kano exceptionally viable and Lagos manageable despite cloud cover. Financially, these systems are highly attractive, delivering 12–22% IRRs and 6–12-year payback periods, largely driven by the substantial economic savings from replacing unreliable grid power and expensive diesel generators.

To accelerate this market transition, policymakers should implement tailored zonal building standards and fiscal incentives for battery storage, while future research should focus on longitudinal performance monitoring, occupant behaviour, and smart grid integration. Ultimately, this study demonstrates that NZEBs can effectively address both decarbonisation and energy access objectives, offering a scalable blueprint for other tropical developing nations with high cooling loads, abundant solar resources, and unstable grids.

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