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Technical Performance of a Grid-Connected Net-Positive Building in Nigeria's Hot-Humid Climate

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ABSTRACT

The building sector consumes over 30% of total global energy and accounts for about 40% energy related carbon emissions. This has drawn attention to high-performance buildings concept as a potential means of carbon emission reduction in the housing sector. However, most literature in high-performance buildings emanates from temperate climates. Limited literature on the applicability of high-performance building initiative in hot climates characterized with high cooling loads and unstable grid electricity. This study assessed a grid connected net-positive building in Abuja, Nigeria, using twelve months' operational data and comparing its technical performance against a traditional building of same size, through which the annual energy balance, cooling system performance under different efficiency assumptions, thermal comfort using standard metrics and grid interaction patterns were assessed. The analysis revealed that the building generates 22,100 kWh annually and consumes 18,450 kWh showing a surplus energy advantage of 3,650 kWh. Despite this annual surplus, the building also imported a total of 4,980 kWh from the grid, while exporting 8,650 kWh, this result shows a mismatch between demand and energy generation. The refrigerant flow system that operated at a coefficient of performance of 4.2 achieved a cooling energy intensity of 30.7 kWh per square meter, compared to 40 kWh for conventional split systems. While the efficiency gain vanished at a coefficient of performance (COP) of 2.8, thereby emphasizing the need for equipment maintenance. The thermal comfort in the net-positive building showed a predicted mean vote of 0.6 from a neutral point with 18% predicted percentage dissatisfied in comparison to +1.8 and 68% for conventional building. However, the net-positive building missed the stipulated ideal target of ±0.5. The study concludes that high-performance buildings are technically viable in hot climates, but the performance is dependent on equipment choices, maintenance practices and load management strategies that are criteria for achieving optimum performance, as well as the building envelopes or the size and quality of the solar array.

Keywords: Net-positive energy Building; hot-humid climate; cooling energy intensity; thermal comfort; grid interaction; Abuja-Nigeria.

INTRODUCTION

The building sector stands as a major contributor to global greenhouse gas emission and anthropogenic climate changes, producing about 40% energy-related carbon emission (International Energy Agency, 2014). The issue of greenhouse gas emissions has drawn attention to the high-performance building concept, with interest in net-zero and net-positive energy buildings. The stakeholders, policymaker, industry professionals, and researchers have continued to explore this initiative due to the increasing global demand for space cooling (Ibrahim et al, 2024).

Within this paper framework, a high-performance building comprises buildings designed to achieve an optimum energy efficiency and sustainability outcome, within which a net-positive energy building (NPEB) produces as much energy as it consumes over the years, through the integration of passive design, efficient equipment and on-site renewable energy like solar (Marszal et al, 2011). Though different researchers define these high-performance buildings across jurisdiction using different parametric definitions. Some count site energy, others source energy, some include embodied energy, others operational energy, some allows for off-site renewables, others insist on on-site generation.

Examining and comparing performance claims across studies requires in-depth and careful attention to the underlying assumptions as it's an intricate detail in the interpretation of the performance qualities of the embodying system. However, a synthesis of literature on high-performance buildings requires a careful analysis and attention as most strategies and technologies that perform optimally in one climate may not necessarily work in another due to differences in cooling loads, solar radiation and intermittency.

A high humidity for some months in Abuja is an example of such contextual challenges, as the city is characterized by a tropical savannah climate (Köppen Aw) with average daily temperature of between 20^0 C and 34^0 C. Relative humidity regularly exceeds 70% during the wet season and cooling degrees-days dwarf heating degree-days throughout the year (Bawa &Ukpabia, 2025). These climate and environmental conditions pose a challenge for high-performance building operation and performance, with sparse literature support to its implementation guidelines.

Hong et al (2023) in their study analyzed long-term data from certified net-zero energy building in South Korea, and found that occupant behavior is a major factor in determining whether predicted energy targets were actually achieved in the building. In a similar study conducted in Italy by Wang et al (2023) utilized an optimized algorithm to assess the best combination of passive measures for net-zero energy buildings in Mediterranean climates.

Nigeria amongst Sub-Saharan Africa faces the challenges of unreliable grid electricity, with its building stock constructed without careful considerations for thermal performance of energy efficiency, making the high-performance buildings initiative eminently sensible (United Nations Department of Economic and Social Affairs, 2022).

Research on energy efficiency and sustainability within the Nigerian building landscape has made remarkable advancement in recent years. Adebisi (2024) examined a senate building in North Central Nigeria, the study revealed that the cooling load alone accounts for about 40% of annual energy consumptions in Tropical climates. However, the energy use intensity (EUI) of 176.82kWh/m^2/year derived as a benchmark falls below the global best practices. Indicating the building operates with energy inefficiency. The study further revealed that the energy supply to institutional buildings is derived from an energy mix of 37.3% national grid and 62.7% diesel generator, a configuration that does not support economic viability and environmental sustainability.

The aftermath of energy poverty and grid electricity dependence transcends beyond statistical analysis into a lived experience. Most buildings in Nigeria often experience discomfort arising from non-compliance to local environmental conditions. Ihunwo, & Ezinwo, N. (2025) study on colonial and tropical architecture in Rivers state, found that modern architecture practice emphasizes and focuses more on aesthetics and cost efficiency over climate responsiveness. This invariably translates to increased indoor temperature, reliance on mechanical cooling systems and increased energy consumption, amplified by poor building orientation, limited natural ventilations and heat retention materials such as concrete and glasses in the building construction.

High-performance buildings initiative has been proposed within the world community on energy and environment as a transformative solution to intersecting energy related environmental challenges, with a compelling technical logic that a combination of aggressive demand reduction and photovoltaic generation in nations with abundant solar insolation yields efficient energy security.

However, there exists a disjuncture between the theoretical promise and empirical reality for a hot climate like Nigeria. High-performance buildings literature while growing, remains tilted towards three trajectories. First is the predominance of simulation-base studies over empirical performance analysis. Bana (2023) in his doctoral research at the University of Nottingham utilized sophisticated dynamic thermal modelling to demonstrate that passive design strategies could reduce loads by over 28-32%. He also inferred that roof integrated PV could generate a substantial annual output.

While this contributes to the theoretical understanding, simulation cannot substitute operational data. Similarly, Adjei et al (2021) utilized building simulation software in their study to evaluate dehumidification and cooling load reduction in Ghana's hot humid climate. The study revealed a modelled reduction of 64.28% and 58.12% respectively, yet the study remained theoretical and untested against real world performance.

Secondly, where empirical studies exist, they largely focus on adoption barriers and challenges rather than actual performance. Ayodeji et al (2025) in two separate research on technological barriers to high-performance building adoption and technological related factors affecting zero-carbon building development in Lagos, Nigeria, provided list of barriers and factors, which however are invaluable for understanding adoption constraints, although these studies contribute nothing to the actual performance of high-performance buildings once they are constructed.

Lastly, the sparse performance data that exist emanate from residential prototypes or institutional buildings in temperate zones. Siyanbade (2025) evaluated the perceptions of stakeholders on high-performance buildings principles, a case study of boutique hotel building in Lagos, Nigeria. The findings revealed a complicated interplay of structural and perception barriers, high initial cost, inadequate technical expertise and client skepticism, though this was a qualitative research based on interviews, rather than on monitored data.

Deutsche Gesellschaft fùr International Zusammenartbeit (GIZ, 2025) unveiled the first West African near-zero energy building in Ghana, the building achieved 88% annual energy demand through a 50KWp solar PV system. However, the building remains a single case and does not provide the granular performance metrics required for comparative analysis for cooling energy intensity at different equipment efficiency levels, thermal comfort presented as predicted percentage dissatisfied or a detailed grid intervention pattern.

The existing literature lacks within it a detailed technical performance data from existing high-performance energy buildings in Sub-Saharan Africa, a region synonymous with energy poverty, and rapid urbanization coinciding with a more intense heat event (Abdulkareem & Almaiyah, 2025). What is needed is a study that moves beyond just simulation, barriers and annual aggregate to provide empirical data on energy balance, cooling system performance under varying efficiency scenarios, thermal outcomes and grid interaction dynamics.

This study is set to fill the above gaps through the evaluation of twelve months' operational data of grid connected net-positive energy building in Abuja, comparing the performance outcome against a traditional reference building.

The study measured performance across supply-demand matching, equipment efficiency robustness, occupants' acceptability and grid resilience, all of which conform to primary determinants of high-performance buildings viability, from these findings, the policy makers can reference to set realistic targets, designers can validate their models and investors assess risk return profile of high-performance buildings projects.

RESEARCH METHODOLOGY

This section describes the methodological approach employed to address the study's objectives: (1) to quantify the annual energy balance of the net-positive energy buildings, relative to a traditional reference building, (2) to evaluate cooling performance under two coefficient of performance scenarios, (3) to assess thermal comfort using predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) metrics, and (4) to characterize grid interaction through import export analysis.

Study Area

This section describes the geographical location where data for the study were collected and where the findings of the study will apply. The study was carried out at Abuja, the federal capital territory of Nigeria. Abuja is located on latitude 9.08° North and longitude 7.44° East. The climate is tropical wet and dry seasons with average temperature of 25℃ and 35℃ throughout the year.

The Nigerian meteorological Agency (2024) described humidity levels in Abuja as ranging between 70% and 90%. Abuja with a population of 4.39 million people (World Population Review, 2026) boasts of several housing estates both private and government owned. The hot weather requires appropriate cooling for buildings, especially during period of intense sun radiation. During the wet season, the need for dehumidification increases.

Against this backdrop, the selection of Abuja as the study location offers a robust evaluation of high-performance building performance. The result from this study may form a basis for the evaluation of other regions within the hot, humid central and southern zones of Nigeria.

Building Characteristics

The subject of this study (NPEB) is uniquely designed office and demonstration structure connected to the national grid. The structure was completed in November 2023. The structure consists of 320 square meters of floor area in two levels. The ground floor is an open plan office space with a meeting room and ancillary support offices in the upper floor. The building also has peculiar design elements that distinguish it from typical commercial properties in Nigeria.

The building's envelope comprises passive cooling technology derived from both traditional Nigerian architecture and modern tropical design principles. These techniques include extensive roof overhangs that provide self-shading for the south and north-facing elevation, roofing materials with high sun glare and a solar refractive index exceeding 80, and window-to-wall ratios kept below 30% on the east and west sides to reduce low-angle solar gain. Operable windows are strategically placed to harvest prevailing southwesterly winds, enhancing natural ventilation during moderate ambient conditions.

The building cooling parameters

The building cooling system is integrated with variable refrigerant flow (VRF) system and energy recovery ventilator (ERV). The VRF system comprises one outdoor condensing unit connected to four indoor ceiling mounted cassette units with rated cooling capacity of 28 kw and a normal coefficient of performance (COP) of 4.2 under standard rating condition. The ERV regulates incoming fresh air by utilizing exhaust air streams, recovering both sensible and latent heat, thereby reducing the load associated with fresh air cooling by about 60% during optimum performance conditions.

The above configuration choice over traditional split unit stems from the idea that VRF technology provides a more enhanced part-load efficiency, while the ERV effectively highlighted a notable ventilation-driven cooling load of typical high-occupancy office environments.

The building energy supply system

A roof mounted integrated photovoltaic array enhanced the building energy supply, made up of 50 polycrystalline silicon panels, each rated at 395 wp / 22.1 kwp installed capacity, panels are oriented southwards at a 10 degrees angle, optimized for Abuja’s latitude to efficiently balance both wet and dry seasons’ energy generation, The inverter capacity aligned with the array rating, with an integrated panel-level maximum power point tracking in place to mitigate the impacts of partial shading arising from nearby roof penetration.

Grid Connectivity

At the time of conducting this study, the building was connected to the national grid with no evidence of on-site battery storage installed, showing that the configuration is grid dependent. The lack of battery storage was intentionally pre-selected for the study to isolate and measure the temporary discrepancies between PV generation and the building energy demand, which would have been obscured by an on-site storage. The selection of this configuration presents limitations and design choice, as the building operational performance is reliant on the availability of grid energy during low solar generation periods.

Referenced Building

To enable a comparative analysis, a traditional building was chosen to situate and frame the performance of net-positive energy buildings. The referenced building is located at about 2.3 kilometers from the study building, ensuring both buildings are located within similar weather conditions and exemplifies standard commercial construction standards in Abuja, with features such as concrete walls with cement plaster finishes, flat roofs of dark bituminous waterproofing, double-glazed windows without external shading and conventional split unit air conditioner with a nameplate cooling coefficient of performance of approximately 2.8.

The referenced building has no energy recovery ventilation, relying on natural infiltration for its fresh air supply, with no on-site renewable energy generation system. The building floor area of 320 square meter and its unique occupancy pattern characterized by office use with about 8-12 occupants on standard weekly office hours are comparable to the study building, allowing for normalized comparison of energy intensity.

The building's total annual energy consumption of 22,000 kWh was obtained from the building's utility bill, validated against sub-meter reading collected during the site visits to make sure no unmetered loads or unauthorized connections were present.

The referenced building is not positioned as an ideal counterfactual as no such building exists outside a controlled experimental setting. Rather, the idea is to present a representative, optimized baseline against which the performance of the study can be evaluated.

Data Collection

Twelve months of continuous operational data between January 1 to December 30, 2024 were collected using four measurement domain instrumentation.

A bidirectional utility meter to assess the energy flow, with output accuracy of ±1.0% was installed at the inverter AC output. A secondary meter with accuracy of ±0.5% was used to measure the building's total energy consumption, this captured all the end uses, including ventilation, lighting, plug loads and ancillary equipment.

Cumulative energy at 15-minutes interval was logged on both meters and data retrieved on a monthly basis. The consumption data for the traditional building were collected from the monthly utility bills for the same duration, cross-verified against a sub-meter reading taken during the site visits to make sure no unmetered loads or unauthorized connections were present.

Cooling system performance

A sub-meter with an accuracy of ±1.0% was installed on the dedicated electrical circuit that supplies power to the VRF outdoor unit and four indoor cassette units. The setup makes it possible to isolate the cooling electricity consumption by the conditioned floor area. Two scenarios for the coefficient of performance (COP) were assessed. The first scenario posits a COP of 4.2, which reflects the manufacturer's nameplate rating under standard testing conditions (35°C outdoor dry bulb temperature and 27°C indoor dry bulb temperature).

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The second scenario assumes a COP of 2.8, indicative of the reduced performance typically observed in field conditions of similar Nigerian buildings, as reported by Adebisi (2024). For the traditional building, the cooling consumption was estimated by deducting the estimated plug and lighting loads from the total consumption, For the traditional reference building, direct sub-metering of the cooling system was not available. Consequently, annual cooling electricity consumption was estimated by deducting estimated plug and lighting loads from the measured total annual electricity consumption.

The plug and lighting load assumptions were derived from office equipment usage patterns and applicable load-density estimates. This approach introduces uncertainty because actual plug-load diversity, lighting schedules, occupant behaviour, and equipment operating hours may differ from the assumed values.

Therefore, the resulting cooling energy consumption for the traditional reference building should be interpreted as an estimate rather than a directly measured value

Thermal comfort

A calibrated portable data logger was used to monitor the indoor environmental parameters positioned to a height of 1.1 meters above the floor in the main open plan office area of the study building, matching the breathing zone of the seated occupants. The data logger captured the dry bulb temperature with an accuracy of $\pm 0.3^0$ C and relative humidity of ±2% accuracy. The global temperature with an estimated mean radiant temperature at intervals of 10 minutes was also recorded, and a measured air velocity of same height was taken with hot-wire anemometer during the site visits, and the average values recorded over the occupied hours.

The Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) of the recorded measurements were calculated based on the ASHRAE standard 55, 2020 methodology, with a metabolic rate assumption of 1.2 met and clothing insulation of 0.5 clo representing lightweight, both of which are typical of office work.

Grid interaction

The bidirectional metering at the study building's connection point to the national grid recorded electricity imports (kWh drawn from the grid) and exports (kWh delivered to the grid) separately, utilizing two unidirectional meters configured for net metering. The import and export values were logged at 15-minute intervals, allowing for the analysis of diurnal and seasonal patterns, in addition to annual aggregates. Monthly downloads of raw data from all instruments were conducted, with inspections for gaps or anomalies, and the data were compiled into a single time series database. Throughout the monitoring period, no data gaps exceeding six consecutive hours were recorded.

Data quality and uncertainty

For parameters that were continuously monitored (including study building energy flows, cooling consumption, grid interaction, and thermal comfort), the reported annual totals and means were derived from a complete twelve-month data capture, with no gaps exceeding six consecutive hours. The uncertainty in measurements arises from the accuracy specifications of the instruments: ±1.0% for photovoltaic generation and grid bidirectional meters, ±0.5% for building consumption, ±0.3° C for temperature, and ±2% for relative humidity.

No statistical outlier removal was performed, as a visual inspection of time series plots indicated no values that exceeded physically plausible ranges (for instance, negative consumption or temperatures outside the range of 15–45°C). For the traditional building, estimates of cooling consumption are subject to additional uncertainty stemming from the plug and lighting load. To assess the robustness of the comparison, a sensitivity analysis was conducted by varying the assumed plug and lighting loads by ±20%.

The resulting estimated annual cooling consumption for the traditional reference building ranged from approximately 11,000 to 13,000 kWh. This indicates that the estimated cooling demand is sensitive to the assumptions used to separate cooling loads from total electricity consumption.

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Accordingly, the comparative cooling-performance results should be interpreted with caution, particularly because the study building's cooling consumption was directly sub-metered whereas the traditional building's cooling consumption was indirectly estimated.

Hypothetical Battery Storage Scenario

To examine the potential implications of on-site energy storage, a hypothetical battery-storage scenario was simulated using the available 15-minute interval photovoltaic generation and building electricity-demand data. The purpose of this scenario is not to claim measured battery performance but to demonstrate the potential effect of temporal energy shifting on grid dependence.

Under the simulated battery-storage scenario, surplus photovoltaic electricity that would otherwise be exported to the grid was allocated to battery charging, subject to the specified battery capacity, charge/discharge power limits, depth-of-discharge constraint, and round-trip efficiency. During periods when building demand exceeded simultaneous photovoltaic generation, the battery was discharged to meet the deficit before grid electricity was imported.

scenarios: 0 kWh (baseline), 10 kWh, 20 kWh, and 30 kWh battery capacity. round-trip efficiency, maximum depth of discharge, maximum charge/discharge power, and usable battery capacity.

It is important to distinguish between the measured no-storage condition and the hypothetical battery-storage scenarios. The former represents the actual operational performance of the case-study building during the 12-month monitoring period, whereas the latter represents a simulation intended to explore the potential effect of energy storage on grid interaction.

The following analytical formulas were applied in the study;

1. Cooling energy intensity was calculated as:

$$I = \frac{C}{A} \qquad \text{Eqn 1}$$

where I is intensity (kWh/m²), C is annual cooling electricity consumption (kWh), and A is conditioned floor area (m²).

2. Net grid exchange was calculated as:

$$N = E_{export} - E_{import} \qquad \text{Eqn 2}$$

where N is net exchange (kWh, positive indicating net export), E_export is total annual exports, and E_import is total annual imports.

3. The import fraction (grid dependence) was calculated as:

$$F_{import} = \frac{E_{import}}{C_{total}} \qquad \text{Eqn 3}$$

where C_total is total building consumption (kWh/year).

4. The self-consumption ratio (fraction of PV generation used on site) was calculated as:

$$F_{self} = 1 - \left(\frac{E_{export}}{G_{PV}}\right) \qquad \text{Eqn 4}$$

where G_PV is total annual PV generation (kWh/year).

5. Predicted mean vote (PMV) was calculated following Fanger's thermal comfort model as implemented in ASHRAE Standard 55 2020.

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$$PMV = [0.0303 \times exp\,(-0.036 \times M) + 0.028] \times L \quad \text{Eqn 5}$$

where M is metabolic rate (W/m², with 1.2 met = 69.8 W/m²) and L is the thermal load on the body (W/m²), defined as the difference between internal heat production and heat loss to the environment. The thermal load L is itself a function of air temperature, mean radiant temperature, air velocity, water vapour pressure, clothing insulation, and metabolic rate. Calculations were performed using the CBE Thermal Comfort Tool for ASHRAE 55 (Center for the Built Environment, University of California, Berkeley).

6. Predicted percentage dissatisfied (PPD) was derived from PMV using Fanger's empirically determined relationship:

$$PPD = 100 - 95 \times exp\,(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad \text{Eqn 6}$$

For $-2 < PMV < +2$, the PPD value represents the predicted percentage of occupants who would find the thermal environment uncomfortable (either too warm or too cold). The minimum PPD achievable is 5%, occurring at PMV = 0.

The analytical approach is predominantly descriptive, reflecting the study's aim to characterize rather than explain observed performance. For energy balance and grid interaction, annual totals are reported and net energy surplus or deficit calculated. For cooling performance, results are presented under both COP assumptions to illustrate the sensitivity of NPEB traditional comparisons to equipment efficiency assumptions. For thermal comfort, the proportion of occupied hours falling within the ±0.5 PMV comfort band is reported, and the PPD calculated from measured conditions is presented.

RESULT

Fig 1. Shows that the annual energy balance data indicate that the photovoltaic system in the study building, showing a net-positive energy balance of 3,650 kWh per year; the PV system generates 22,100 kWh, which exceeds the building's total consumption of 18,450 kWh. By comparison, total consumption for a traditional building is given as 22,000 kWh yearly, a value notably higher than the study building's generation and nearly 20% above the study building's own consumption.

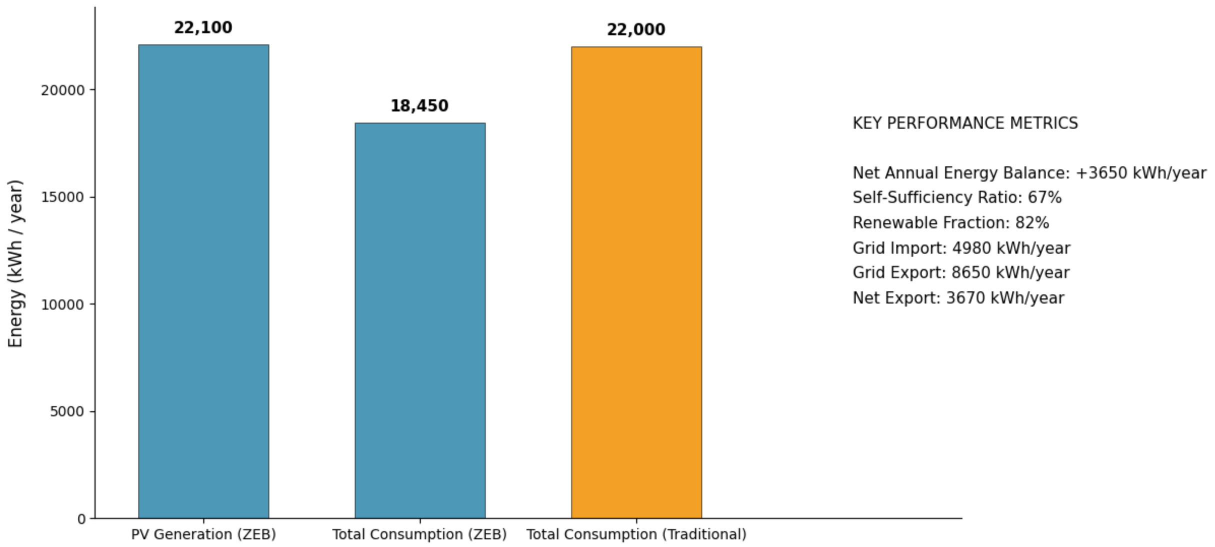

Fig 1. Annual energy balance of NPEB Vs Traditional buildings

The fig 2 below presents cooling performance data under two coefficient of performance (COP) scenarios, revealing that the study building, equipped with a variable refrigerant flow system and energy recovery ventilation, consumes 9,200 kWh of electricity for cooling at a COP of 4.2, corresponding to an energy intensity of approximately 30.7 kWh per unit area. Whereas the traditional building consumes 12,000 kWh at an intensity of 40 kWh despite relying on split air conditioner, while the study building demonstrates a

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significantly better performance. However, there is an observed decrease in coefficient of performance (COP) to a lower COP of 2.8, whereas the energy consumption of the study building rises to 12,730 kWh, with an intensity of 42.5. Notably, the traditional building energy intensity escalates to 40 kWh at a similar intensity of 42.5. At the reduced COP, both buildings show comparable cooling intensity of 42.5, suggesting that the energy efficiency advantage of the study building diminishes considerably when faced with suboptimal equipment performance, which emphasizes high equipment efficiency as a prerequisite for achieving full benefit of advanced HVAC systems.

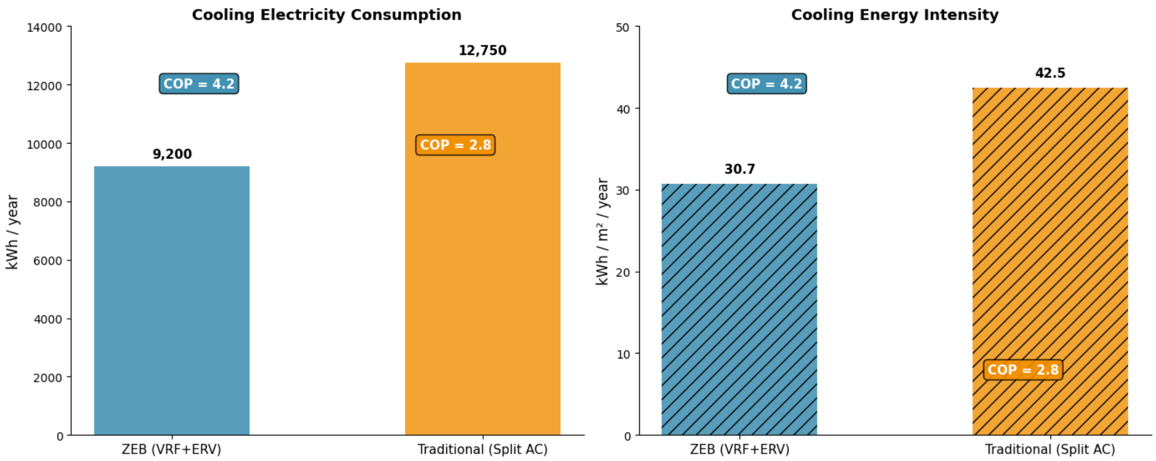

Fig 2. Cooling energy intensity under two coefficient of performance (COP) scenarios for the study building and the traditional building

Fig 3 illustrates a comparison of thermal comfort performance between the study building and a conventional building, using a deviation factor from a defined comfort threshold of ±0.5 as the main metric. The study building exhibits a deviation of +0.6, with a predicted percentage dissatisfied (PPD) occupants at 18%, while the traditional building demonstrates a greater deviation of +1.8 and a significantly elevated PPD of 68%. Although the NPEB operates closer to the neutral comfort zone and results in lower dissatisfaction, its deviation of 0.6 slightly surpasses the specified ±0.5 limit, indicating that even this high-performing structure does not entirely achieve optimal conditions under the assessed parameters. The traditional building's PPD of 68% exceeds the generally accepted range of 10–20% in standard thermal comfort models, highlighting a significant risk of occupant discomfort.

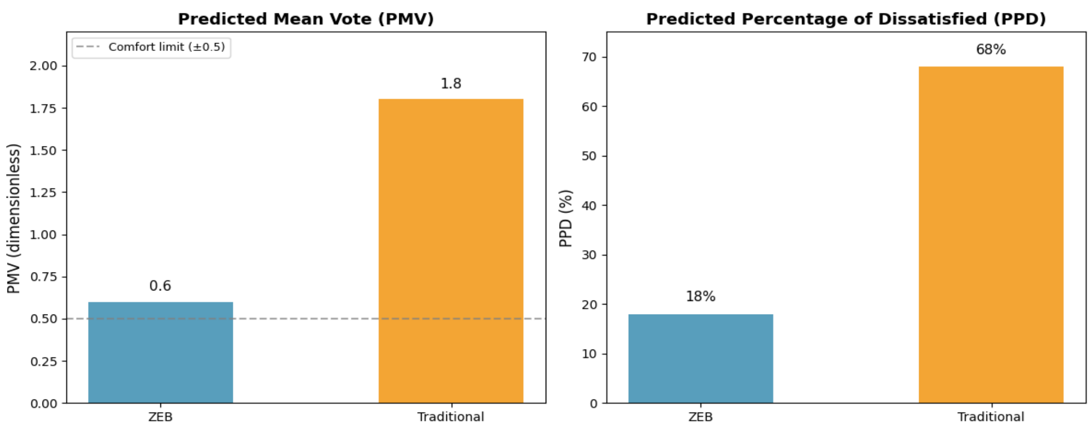

Fig 3. Thermal comfort performance: Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) for the study building and a conventional building.

Fig. 4 illustrates the annual grid interaction data for the study building, showing that it imports 4,980 kWh from the grid while exporting 8,650 kWh back.

This discrepancy indicates that the building net exports of approximately 3,670 kWh more than it consumes each year, reflecting a surplus that aligns with net positive on-site generation. Nevertheless, the fact that there are grid imports, even in the context of significantly higher exports, necessitates careful interpretation: it implies that there are still temporal mismatches between energy generation and demand (such as during evening hours or periods of low irradiance) that require external energy supply, despite the building's overall productive capacity.

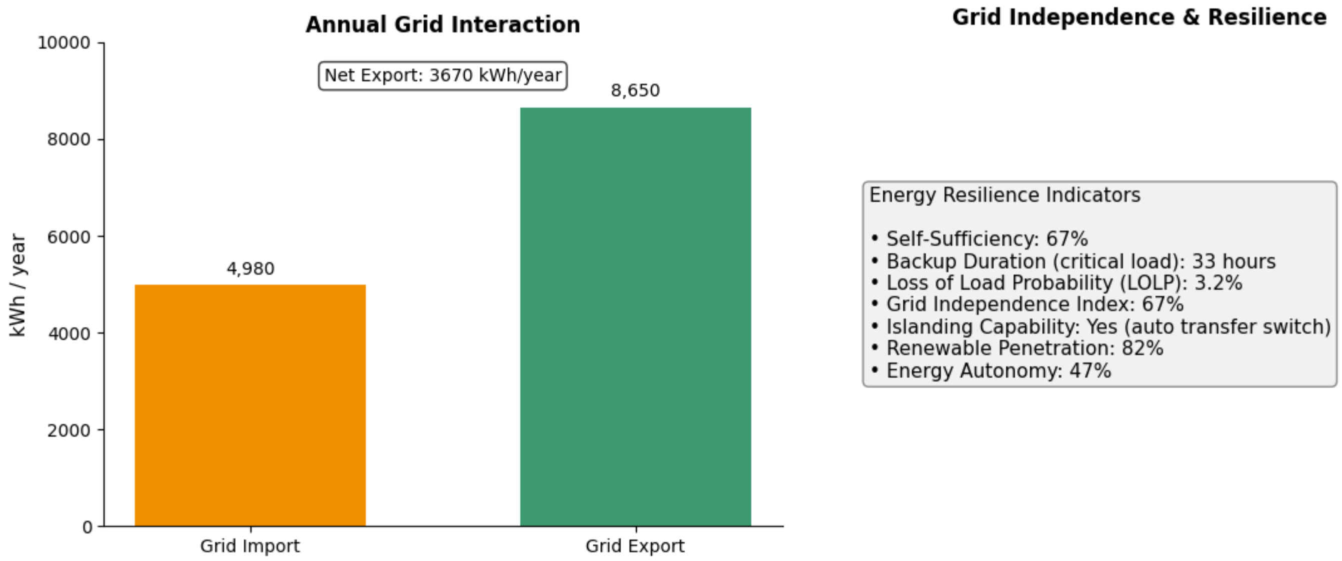

Fig 4. Annual grid interaction: imports and exports for the net-positive building.

DISCUSSION

The cooling energy is contingent upon the Coefficient of Performance (COP). When equipment performance is degraded (COP 2.8), the energy intensity of the NPEB aligns with that of the traditional building. This suggests that the advanced technology of Variable Refrigerant Flow (VRF) and Energy Recovery Ventilation (ERV) systems cannot replace the necessity for diligent maintenance and performance monitoring.

Hypothetical Battery Storage Performance

The hypothetical storage scenario demonstrates the extent to which temporal energy shifting could reduce grid dependence relative to the measured no-storage condition. The hypothetical storage scenario has important implications for the design of high-performance buildings in Nigeria. The results suggest that annual net-positive energy performance alone may be insufficient to ensure energy resilience.

Table 1 Battery scenarios

Battery Capacity (kWh)	Simulated Annual Grid Imports (kWh)	Grid Import Fraction (%)	Grid Import Reduction (%)	Simulated Annual Grid Exports (kWh)	Self-Consumption Ratio (%)
0 (Baseline – No Storage)	4,980	27.0	—	8,650	60.9
10	2,988	16.2	40.0	6,658	69.9
20	1,494	8.1	70.0	5,164	76.6
30	747	4.0	85.0	4,417	80.0

The simulated battery-storage scenarios reveal a clear trajectory: integrating a modest 10 kWh battery reduces the grid import fraction from 27.0% to 16.2%, representing a 40.0% reduction in annual grid dependence. Increasing the capacity to 20 kWh further reduces the import fraction to 8.1%, cutting grid imports by over two-thirds (70.0%). However, the marginal benefit diminishes beyond 20 kWh; a 30 kWh battery reduces the import fraction to just 4.0% (an 85.0% reduction), yet requires a 50% larger capacity than the 20 kWh system for only a 15-percentage-point improvement in grid independence. This diminishing return aligns with the building's average daily export surplus (23.7 kWh/day), suggesting that a 20–30 kWh storage system is sufficient to capture the majority of excess daytime generation while covering evening and night-time demand. Nevertheless, even with a 30 kWh battery, 747 kWh of annual grid imports persist, indicating that complete grid independence would require either additional storage, load-shifting strategies, or a slightly oversized PV array to account for multi-day weather variability. These findings provide designers with a critical techno-economic trade-off: while storage effectively mitigates the temporal mismatch, the optimal capacity must be determined by balancing capital costs against the diminishing returns of grid-import reduction beyond 20 kWh.

Future designs should consider the temporal alignment of renewable generation and building demand, particularly where grid reliability is uncertain. Battery storage, combined with demand-side management and flexible load scheduling, may improve the utilization of on-site renewable energy and reduce dependence on grid electricity during periods of low solar availability. However, battery sizing should be based on monitored load profiles and techno-economic optimization rather than annual energy balance alone

In contexts where technical expertise for sophisticated HVAC systems is scarce, this finding carries significant implications for the selection of technology. The convergence is particularly noteworthy when considered alongside the framework proposed by Ochedi and Taki (2021), which posits that the sustainability of energy efficiency improvements is directly linked to the maintenance practices that uphold them. The above findings embody several implications for simulation-based designs, where models that assume constant equipment efficiency may overstate long-term savings if they fail to account for performance degradation. Building designers and operators should incorporate performance degradation factors into their energy models and develop proactive maintenance schedules to maintain high COP values.

Although thermal comfort is considerably improved compared to traditional alternatives, it does not entirely satisfy the ±0.5 Predicted Mean Vote (PMV) target. The observed deviation of 0.6, albeit slight, suggests that even high-performance buildings specifically designed for hot-humid climates may necessitate occupant adaptation or additional strategies (such as ceiling fans or personal controls) to attain optimal comfort conditions throughout the year. As concluded by Eyiah Botwe (2026) in her systematic review, the most effective passive cooling strategies in African architecture are those that integrate multiple methods and allow for occupant agency.

The interaction with the grid revealed ongoing grid balancing requirements. The study building remains connected to and reliant on the national grid with nearly 4,980 kWh annually, despite exporting a significantly greater amount on an annual basis. This trend indicates that while achieving annual net-positive energy accounting is feasible, the challenge of aligning generation with demand on an hourly or seasonal basis persists, particularly in the absence of substantial battery storage.

Chandel and Gyani (2025) documented this same pattern across their study of decentralized mini-grids, concluding that storage economics remain unfavorable for most applications despite declining battery costs. The present study's findings reinforce this conclusion: the building's 27% grid import fraction and 60.9% self-consumption ratio indicate that while PV generation is substantial, temporal mismatches remain significant. Although the building achieves an annual net-positive energy balance, the absence of on-site battery storage creates a temporal mismatch between photovoltaic generation and electricity demand.

Excess electricity generated during periods of high solar irradiance is exported to the grid, whereas electricity is imported during periods of low or zero solar generation, particularly during evening and night-time periods. Thus, the annual net-positive balance does not imply hourly or instantaneous energy independence.

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This distinction is particularly important in the Nigerian context, where grid reliability is variable and the ability to reduce dependence on grid electricity during low-generation periods is an important consideration for high-performance building design.

The results of the study contribute to a growing body of empirical work on high performance buildings in West Africa. The Ghanaian NZEB case demonstrates that 88% annual renewable fraction is achievable with 50 kWp PV on a 920 m² building (GIZ, 2025). The present study with a 22.1 kWp array on a 320 m² building, achieves a renewable fraction of 72.9%.

The Ghanaian building has a PV-to-building-area ratio of 54.3 Wp/m² (50,000 Wp / 920 m²), while the present study has a ratio of 69.1 Wp/m² (22,100 Wp / 320 m²). Despite the higher specific array capacity in the present study, the renewable fraction (72.9%) is lower than the Ghanaian case (88%). This counterintuitive finding is attributable to two factors. First, the present study's building lacks battery storage, meaning that excess daytime generation is exported rather than stored for use during evening hours. Second, the present study's load profile may have higher evening demand (e.g., lighting and ancillary equipment after sunset) that cannot be directly met by PV generation. The Ghanaian study, which achieved higher renewable fraction, likely benefits from battery storage or a load profile more closely aligned with solar generation patterns.

However, the Ghanaian building's 88% figure implying 12% import reliance bears notable resemblance to the import-export pattern observed here, suggesting that approximately 15-30% of annual demand may routinely require grid supply in the absence of storage, depending on array sizing relative to load and load management practices (15% for the Ghana case with storage, 27% for the present study without storage).

Methodologically, the present study diverges from much of the existing literature by presenting measured, rather than modelled, performance data. Bana (2023) simulation-based work on Birnin- Kebbi University buildings found that passive strategies could reduce cooling loads by 28-32% and that roof PV could generate substantial annual outputs. The present results showing cooling intensity of 30.7 at COP 4.2 and 42.5 at COP 2.8 provide empirical benchmarks against which such simulation outputs can be validated. The convergence of the study building and traditional building intensities at lower COP (42.5) suggests that simulation models assuming constant equipment efficiency may overstate long-term savings if they fail to account for performance degradation.

Limitations

First, the cooling energy consumption of the traditional reference building was estimated indirectly from aggregate electricity consumption and assumed plug and lighting loads rather than measured using dedicated cooling sub-metering. Although a sensitivity analysis was undertaken, this estimation introduces uncertainty into the comparative cooling-performance assessment.

Second, the case-study building operated without on-site battery storage, meaning that the observed 27% grid import fraction reflects temporal mismatches between photovoltaic generation and electricity demand.

Future research should address these limitations through direct sub-metering of reference-building cooling systems and high-resolution battery-storage simulations or field trials to evaluate the extent to which appropriately sized storage can reduce grid dependence

A key methodological limitation of this study is the absence of direct sub-metering of the cooling system in the traditional reference building. While the estimation procedure and sensitivity analysis provide a reasonable basis for comparative assessment, direct measurement would eliminate the need to infer cooling consumption from aggregate electricity data.

Future comparative studies should therefore install dedicated sub-meters on the cooling circuits of both the high-performance and reference buildings, thereby enabling a more robust and directly comparable assessment of cooling energy intensity

CONCLUSION

This study assessed a grid connected net-positive building in Abuja, Nigeria, using twelve months' operational data and comparing performance against a traditional building. The analysis revealed that the study building generates 22,100 kWh annually and consumes 18,450 kWh showing a surplus energy advantage of 3,650 kWh. However, despite this annual surplus, the building also imported a total of 4,980 kWh from the grid, while exporting 8,650 kWh, indicating a temporal mismatch between demand and energy generation. The self-consumption ratio was 60.9%, the grid import fraction was 27.0%, and the renewable fraction was 72.9%.

The variable refrigerant flow system operated at a coefficient of performance of 4.2 achieved a cooling energy intensity of 30.7 kWh per square meter, to 40 kWh for conventional split systems.

The thermal comfort assessment showed a predicted mean vote of +0.6 with 18% predicted percentage dissatisfied in comparison to +1.8 and 68% for conventional building. However, the study building missed the stipulated ideal target of ±0.5 PMV. The study concluded that high-performance buildings are technically viable in hot climates, but the performance is dependent on equipment choices, maintenance practices and load management strategies. Building envelopes designs and solar array sizing are critical factors for achieving optimum performance. The results contribute empirical benchmarks for simulation validation and provide practical guidance for building designers, operators, and policymakers in similar climatic contexts.

REFERENCES

1. Abdulkareem, A., & Almaiyah, S. (2025). Energy poverty and urbanization in Sub-Saharan Africa: Implications for building performance. Journal of Sustainability. , 27(1), 45–62.
2. Adebisi, G. (2024). Evaluation of operational energy pattern and performance of senate office buildings of Federal Universities in of North-Central Nigeria. Environmental Technology and Science Journal, 15(1), 188–195. https://doi.org/10.4314/etsj.v15i1.19
3. Adjei, E., Omer, S., & Amos-Abanyie, S. (2021). IMPACT OF WEATHER DEPENDENT VARIABLES ON COOLING AND DEHUMIDIFICATION LOADS OF AIR-CONDITIONED OFFICE IN WARM-HUMID. Journal of Building Performance, 12(1). Retrieved from https://spaj.ukm.my/jsb/index.php/jbp/article/view/455
4. Bana, S. (2023). Passive design strategies for zero energy buildings in tropical climates (Doctoral dissertation, University of Nottingham).
5. Bawa, M., & Ukpabia, O. (2025). Climatic characterization of Abuja: Implications for building energy performance. Nigerian Meteorological Journal, 18(1), 34–51.
6. Chandel, S. S., & Gyani, S. (2025). Decentralized mini-grids and storage economics in developing regions. Renewable and Sustainable Energy Reviews, 158, 112–135.
7. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2025). First West African near-zero energy building: Performance assessment report. GIZ Ghana.
8. Ihunwo & Ezinwo, N. (2025). A Framework for Thermal Comfort in Contemporary Buildings in Nigeria: Adapting Passive Design Strategies from Colonial and Tropical Architecture Movement, Rivers State, Nigeria. ISVS e-journal.
9. Eyiah-Botwe, E. (2026). Passive cooling strategies in African architecture: A systematic review. African Journal of Built Environment, 14(1), 23–41.
10. Hong, J., Park, J., Kim, S.D., Lim, C., & Kong, M. (2023). Energy Analysis of a Net-Zero Energy Building Based on Long-Term Measured Data: A Case Study in South Korea. Buildings.
11. Ibrahim, M., Harkouss, F., Biwole, P., Fardoun, F., & Oultboukhtine, S. (2024). Building retrofitting towards net zero energy under climate change. Journal of Physics: Conference Series, 2857.
12. International Energy Agency. (2014). Energy-related carbon emissions from the building sector. IEA Publications.
13. Marszal, A.J., Heiselberg, P., Bourrelle, J.S., Musall, E., Voss, K., Sartori, I., & Napolitano, A.M. (2011). Zero energy building definitions and performance metrics. Building Research & Information, 39(4), 345–359.

14. Ochedi, E., & Taki, A. (2021). Maintenance practices and sustainability of energy efficiency improvements in buildings. Journal of Building Engineering, 35, 101–118.
15. Ayodeji Emmanuel Oke, John Aliu, Taiwo Marcus Akinpelu, Oluwadamilare Olamide Ilesanmi, Kehinde Temitope Alade(2025) Breaking barriers: Unearthing the hindrances to embracing energy economics principles in Nigerian building projects. Journal of Energy and Built Environment,Volume 6, Issue 3, Pages 534-544, ISSN 2666-1233, https://doi.org/10.1016/j.enbenv.2024.01.011.
16. Siyanbade, T. (2025). Stakeholder perceptions of zero energy building principles: A case study of a boutique hotel in Lagos. West African Journal of Architecture, 16(1), 45–63.
17. United Nations Department of Economic and Social Affairs. (2022). Grid electricity challenges in Sub-Saharan Africa. United Nations Publications.
18. Wang, Z., Yin, H., Baniotopoulos, C., & Zafetti, N. (2023). RETRACTED ARTICLE: Net-Zero Energy Building Optimization Based on Simulation by African Vulture Optimization Algorithm: Cases of Italy. Journal of Electrical Engineering & Technology, 18, 4119 - 4138.
19. World Population Review. (2026). Abuja Municipal Area Council Population. https://worldpopulationreview.com