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Development of a Simulation-Based Technical Framework for Photovoltaic Retrofitting of University Buildings in Nigeria

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Abstract **Original Research Article**

The increasing energy demand of university buildings in tropical hot/dry climates, coupled with unreliable electricity supply and rising operational costs, necessitates effective energy retrofit strategies and renewable-energy integration. This study aims to develop a simulation-based framework for evaluating energy-efficient retrofit measures and supporting photovoltaic (PV) integration in existing university buildings in Nigeria. The research addresses the limited application of quantitative simulation tools, validated energy assessment methods, and climate-responsive retrofit frameworks for higher education facilities in developing regions. A case study approach was adopted using a lecture theatre at Federal University Birnin Kebbi, Nigeria. Empirical environmental measurements were combined with dynamic building simulation using the Integrated Environmental Solutions Virtual Environment (IESVE) to evaluate four fabric scenarios: as-built theatre (T1), retrofitted theatre (T2), ASHRAE 90.1, and Passivhaus benchmarks. The simulation assessed room cooling sensible load and annual energy performance under tropical hot/dry climatic conditions. Results showed that T1 recorded the highest annual cooling load of 1303.22 MWh, while T2 reduced the demand to 1235.73 MWh, achieving approximately 5.2% improvement and an annual energy saving of 67.49 MWh. Although Passivhaus (1161.35 MWh) and ASHRAE 90.1 (1194.70 MWh) demonstrated superior benchmark performance, the retrofit scenario provided a practical pathway for improving existing institutional buildings. The developed framework establishes a systematic approach linking building assessment, simulation-based fabric optimisation, and PV integration planning. Future studies should incorporate detailed PV system sizing, energy storage analysis, economic evaluation, and long-term operational validation to enhance implementation potential across Nigerian and Sub-Saharan African educational facilities.

Keywords: Building retrofit; Energy simulation; IESVE; Photovoltaic integration; University buildings; Tropical hot-dry climate; Building fabric optimisation.

1. Introduction

The global transition towards sustainability has increased the demand for renewable energy solutions within the built environment, which accounts for approximately 36% of global energy consumption and nearly 40% of CO_2 emissions (Arup, 2016). In developing countries such as Nigeria, this challenge is intensified by dependence on fossil-fuel-based energy generation, unreliable electricity supply, and increasing energy demand. These factors have contributed to rising operational costs and reduced productivity, particularly within public higher education institutions where continuous energy availability is essential.

University buildings represent critical infrastructure supporting teaching, research, and institutional development. Although initiatives such as the Tertiary Education Trust Fund (TETFund) have significantly contributed to infrastructure expansion, rapid growth in student enrolment and institutional development has placed pressure on existing facilities. Many university buildings continue to experience inefficient design, inadequate maintenance, and excessive energy consumption, highlighting the need for retrofit strategies that improve energy efficiency, occupant comfort, and sustainability performance (Sholanke et al., 2019; Bena & Adamu, 2024). Photovoltaic (PV) technology provides a viable pathway for addressing these challenges by enabling renewable electricity generation within building systems. According to Batista et al. (2025) Building-Integrated Photovoltaics (BIPV), through the incorporation of PV modules into roofs and façades, provide both energy generation and architectural functionality. The potential of PV integration has been internationally recognized, particularly following the 2016 Paris Climate Agreement, with numerous studies demonstrating its contribution to carbon reduction and sustainable building development (Kuhn et al., 2021; Noaman et al., 2022). For university facilities, PV integration combined with energy-efficient retrofitting provides an opportunity to reduce operational energy demand and improve campus resilience.

Lecture theatres are among the most energy-intensive university facilities due to their high occupancy density and dependence on artificial lighting, cooling systems, and digital equipment. Therefore, improving their building-envelope performance represents an important strategy for reducing cooling demand before renewable energy integration. This study investigates a 250-capacity university lecture theatre in the tropical hot-dry climate of Nigeria using a simulation-based approach to evaluate the passive energy performance of different building fabric configurations and their suitability for PV integration. The research combines in-situ environmental monitoring using a smart weather device with comparative building-energy simulations conducted using the Integrated Environmental Solutions Virtual Environment (IESVE) platform. The results provide technical guidance for future PV sizing, system placement, solar orientation, and electrical load evaluation. The main contribution of this research is the development of a replicable simulation-based framework for passive energy-efficient retrofitting and PV integration of university buildings. By focusing on building-fabric performance and climate-responsive retrofit assessment, the framework supports improved energy planning, renewable-resource utilisation, and sustainable transformation of existing higher education facilities in Nigeria and similar Sub-Saharan African contexts.

1.1 Problem Statement/ Justification

The increasing energy demand within Nigeria's higher education sector, coupled with unreliable grid electricity and rising operational costs, presents significant challenges for institutional buildings, particularly high-energy facilities such as lecture theatres. Despite infrastructure improvements through programmes such as TETFund, many university buildings continue to experience inefficient energy design, inadequate maintenance practices, and increasing environmental impacts. These challenges affect academic operations and limit progress towards national and global sustainability objectives.

Lecture theatres provide a strategic opportunity for intervention due to their intensive requirements for cooling, lighting, and electronic systems. Nadalipour-Kaldeh et al. (2025) lamented that although PV systems offer a promising renewable-energy solution, existing retrofit studies have largely focused on economic feasibility rather than developing technically validated frameworks for institutional building applications. Furthermore, energy-performance studies of educational buildings in Nigeria remain limited, with insufficient emphasis on simulation-based assessment and climate-specific retrofit strategies (Arup, 2016). Although international standards such as ASHRAE and CIBSE have been widely adopted due to limited local guidance, recent Nigerian initiatives, including the Nigerian Energy Support Programme (NESP) and the National Building Code, have introduced recommendations on passive design strategies and building-energy improvement. However, practical frameworks for assessing and implementing retrofit measures in existing educational buildings remain insufficient.

- **Research Aim**

The aim of this study is to develop a simulation-based retrofitting framework to assess and improve the energy performance of an existing university lecture theatre through comparative building-envelope analysis and potential photovoltaic integration in the tropical hot-dry climate of Birnin Kebbi, Nigeria.

- **Objectives**

  1. To assess the existing physical, thermal, and operational characteristics of a selected university lecture theatre through building surveys and empirical measurement of indoor and outdoor environmental conditions.
  2. To develop, calibrate, and validate an IESVE simulation model of the selected lecture theatre using Typical Meteorological Year weather data and environmental measurements obtained from the study location.
  3. To compare the annual energy performance, fabric heat gains, and room sensible cooling loads of the as-built, retrofitted, ASHRAE 90.1-derived, and Passivhaus-derived building-envelope scenarios.
  4. To develop a simulation-based retrofit framework for identifying the optimal building-envelope configuration and establishing the reduced energy-demand basis for photovoltaic integration in university buildings located in tropical hot-dry climates.

2. Literature Review

Higher education buildings represent a critical sector for energy performance improvement due to their intensive operational schedules, high occupancy densities, and dependence on mechanical systems for maintaining acceptable indoor environmental conditions. Recent studies have demonstrated that improving university building performance requires an integrated understanding of building envelope characteristics, occupant behaviour, indoor environmental quality, and energy consumption patterns. Simulation-based approaches have increasingly become important tools for evaluating retrofit alternatives because they enable researchers to compare multiple intervention scenarios before implementation. Turhan and Ghazi (2023) demonstrated that calibrated building energy models provide a reliable method for assessing retrofit strategies in educational buildings by integrating measured environmental data with dynamic simulations. Similarly, Ahmed et al. (2025) proposed a structured sustainable retrofit framework emphasizing building assessment, energy evaluation, intervention selection, implementation, and performance verification. However, most existing frameworks remain focused on energy reduction measures without adequately integrating renewable energy technologies, particularly photovoltaic (PV) systems, within climate-responsive retrofit decision-making processes.

2.1 Passive Building Fabric Optimisation in Hot-Dry Climates

Building fabric performance significantly influences energy consumption in hot-dry climates, where high solar radiation and elevated temperatures increase heat transfer into indoor spaces and contribute to higher cooling demand. Improving envelope characteristics through passive strategies is therefore essential for reducing energy use while maintaining acceptable thermal conditions. Thermal comfort and indoor environmental quality have emerged as essential components of sustainable university building assessment because energy efficiency improvements must not compromise occupant wellbeing. Barbosa et al. (2024) showed that higher education buildings require simultaneous consideration of thermal conditions, ventilation, lighting, and operational factors because these variables collectively influence occupant satisfaction and energy demand. Similar findings were reported by Bena and Adamu (2024), who evaluated a university lecture theatre in Nigeria's hot-dry climate and demonstrated that indoor temperature, humidity, carbon dioxide concentration, and ventilation conditions significantly affect educational environments. Their study highlighted the importance of climate-specific assessment approaches, particularly in regions where intense solar radiation and elevated outdoor temperatures increase cooling demand.

The effectiveness of passive cooling strategies has been widely recognised as a pathway for reducing cooling energy consumption in warm climates. Studies have consistently identified building orientation, shading devices, natural ventilation, thermal mass, insulation, and material selection as major determinants of indoor thermal performance. Nevertheless, existing studies in tropical regions have frequently examined individual passive strategies rather than developing integrated optimisation frameworks that combine passive interventions with renewable energy systems.

Occupant behaviour has also been identified as a major source of uncertainty in university building energy simulation. Yu et al. (2026) developed a sensor behaviour model energy simulation framework to incorporate occupant presence and air-conditioning usage patterns into campus office energy modelling. Their findings showed that behavioural optimisation could achieve substantial energy savings compared with conventional operating strategies. This highlights the limitation of traditional simulation approaches that rely on standard occupancy assumptions and fixed operational schedules. Therefore, future simulation frameworks for university retrofitting should incorporate realistic operational patterns together with passive design optimization and renewable energy integration.

2.2 Simulation Software IESVE

The Integrated Environmental Solutions Virtual Environment (IESVE) is a comprehensive dynamic simulation platform employed in this study for assessing the thermal and energy performance of educational buildings. The software integrates multiple applications, allowing data exchange between modelling, energy analysis, cost evaluation, and environmental assessment modules (Corrado and Fabrizio, 2019). Its capability to combine HVAC, ventilation, daylighting, lighting, and computational fluid dynamics analyses enables holistic building performance evaluation (Mihara et al., 2019). IESVE provides reliable solutions for improving occupant comfort and energy efficiency (Vethanayagam and Abu-Hijleh, 2019), supported by tools such as ModelIT, SunCast, MacroFlo, ApacheSim, and VistaPro for integrated simulation analysis. The software validation, interoperability, and graphical outputs further support architectural and engineering applications (Alqadi et al. (2021). Recent research has further emphasised the importance of calibrated simulation models supported by empirical measurements. Chaer et al. (2026) developed an evidence-based methodological framework for overheating assessment in higher education buildings by combining environmental monitoring, occupant data, and dynamic building simulation. Their findings demonstrated that calibrated simulation models provide improved reliability for evaluating retrofit interventions, particularly when assessing overheating risks, ventilation performance, and future climate resilience. However, the study primarily focused on thermal risk mitigation rather than optimization of energy generation through renewable technologies. Zamwawosayi et al. (2025) demonstrated through field investigations and Ecotect simulations in Abuja, Nigeria, that passive design strategies such as orientation and cross ventilation could reduce indoor temperature by up to 4.5 °C, thereby reducing dependence on mechanical cooling.

2.3 Research Gap and Contribution

Existing studies have demonstrated the value of retrofit strategies, dynamic simulation, passive design optimisation, and photovoltaic integration for improving building energy performance. However, most studies examine these approaches separately rather than developing integrated frameworks that combine fabric optimisation, energy-demand reduction, and renewable-energy planning. Furthermore, simulation-based retrofit research remains limited in tropical hot-dry climates, particularly for university buildings in Nigeria, where existing studies are often focused on residential buildings or qualitative assessments. Although PV systems provide significant potential for improving institutional energy resilience, limited research has considered the integration of PV planning with simulation-based fabric optimisation and cooling-load reduction. Therefore, this study addresses the gap by developing an IESVE-based simulation framework that integrates empirical measurement, model validation, comparative evaluation of building-fabric scenarios, and PV integration potential for an existing university lecture theatre in Birnin Kebbi, Nigeria.

3. Methodology

This study adopted an integrated research design that combine empirical measurements with a simulation-based comparative retrofit framework to investigate the energy efficiency and building-envelope performance of a university lecture theatre in a tropical hot-dry climatic region. The assessment was conducted by evaluating four building fabric scenarios; the ASHRAE 90.1 benchmark, the Passivhaus standard, the proposed retrofitted condition, and the existing as-built (natural state) condition.

3.1 Research Design and Framework

i. Building Selection and Analysis: A university lecture theatre in Nigeria was selected as a case study for evaluating building-fabric energy performance and developing a retrofit assessment framework with potential application for photovoltaic (PV) integration guidelines. A quantitative comparative analysis was performed on the four fabric scenarios through a combination of field measurements and dynamic building-energy simulations.

ii. Data Input and Calibration: Typical Meteorological Year (TMY) weather data specific to Birnin Kebbi, Nigeria, was incorporated into the IESVE simulation environment to evaluate building performance under representative climatic conditions. In addition, environmental monitoring data were obtained using a NETATMO Smart Weather device to record indoor and outdoor thermal conditions. These measured data were applied for simulation model calibration and validation to improve the reliability and accuracy of the predicted building performance.

iii. Simulation and Parametric Analysis: The selected lecture theatre and three comparative building-fabric scenarios were modelled to examine the influence of different envelope configurations on annual energy consumption and room sensible cooling loads. The comparative simulation approach was employed to identify the most energy-efficient fabric configuration and establish a performance basis for potential renewable energy (PV) integration. The building models were developed using IESVE software, where the energy performance of the ASHRAE 90.1-based, Passivhaus-based, existing as-built, and proposed retrofitted fabric conditions were simulated and evaluated. The flow process is illustrated in Figure 1.

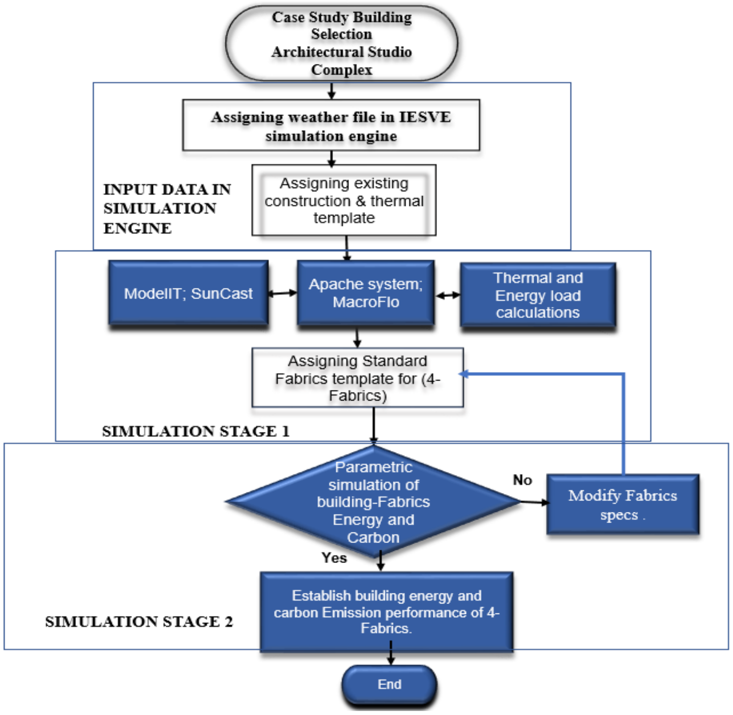

Figure 1. Research flow process

3.2 Climate of the Study Area

Birnin Kebbi, located in north-western Nigeria, falls within the tropical hot-dry climatic zone, characterised by high solar radiation, elevated temperatures, low humidity, and extended periods of sunshine. These climatic conditions create significant cooling challenges for buildings while providing favourable potential for solar energy applications, particularly photovoltaic (PV) integration. The region experiences two major seasons: a hot/wet season from March to mid-May and a cold/dry season from December to February. The hottest period occurs in April, with average maximum and minimum temperatures of approximately 40°C and 27°C, respectively, while winter temperatures range between 19°C and 33°C (Weathersparks, 2023). The climatic characteristics of Birnin Kebbi, including variations in relative humidity, wind speed, and solar radiation, directly influence building thermal performance and energy demand. The highest monthly relative humidity reaches approximately 77% in August, whereas the lowest value is recorded in February at about 24%. Average wind speeds vary seasonally, while global solar radiation reaches its peak value of approximately 6.8 kWh/m² in April and decreases to about 5.4 kWh/m² during December and January (Weathersparks, 2023; Mobolade and Pourvahidi, 2020).

The combination of intense solar exposure, high ambient temperature, and limited natural cooling potential contributes to increased heat gain through building envelopes and higher cooling requirements. Therefore, the climatic conditions of Birnin Kebbi provide an appropriate context for evaluating passive energy performance, building-fabric optimisation, and potential PV integration strategies for university buildings operating in tropical hot-dry environments.

3.3 The Lecture Theatre Building

The case study building selected for this research is a lecture theatre located at the permanent campus of the Federal University Birnin Kebbi (FUBK), situated along the Kalgo–Bunza Road in Kebbi State, north-western Nigeria. The university campus is positioned at approximately 12.3°N latitude and 4.2°E longitude and comprises various academic facilities, with the Faculty of Environmental Sciences (FES) lecture theatre selected as the focus of this investigation.

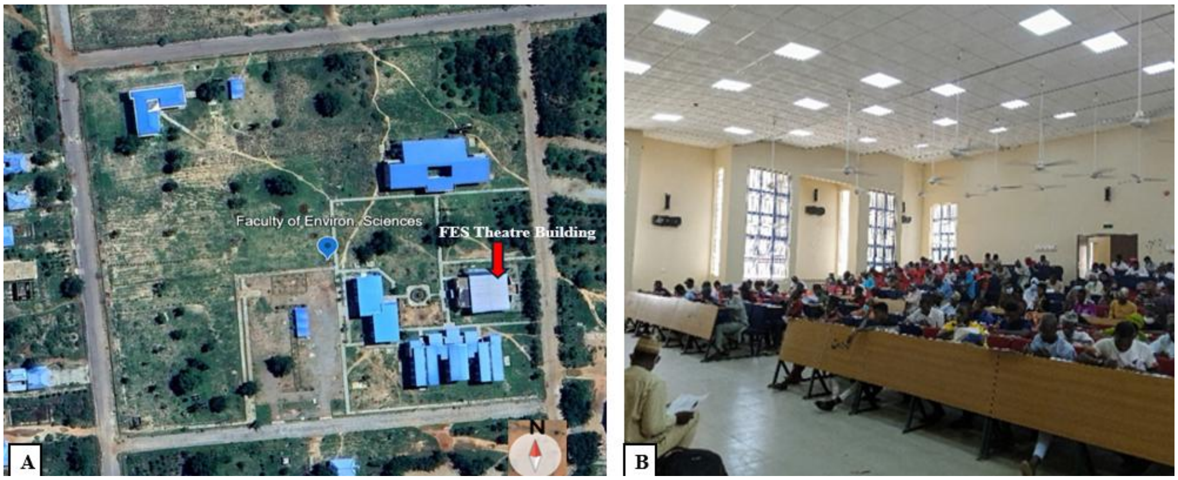

Figure 2. A; Google picture of the FES theatre building B; Interior view during teaching session

The selected lecture theatre accommodates approximately 250 occupants and is primarily used by the Departments of Architecture, Building, and Quantity Surveying for teaching and learning activities. In addition to academic functions, the facility is also utilised for university events and other institutional activities, making it a representative example of an energy-intensive educational building. The theatre operates as an open-plan learning environment equipped with artificial lighting systems, ceiling-mounted fans for ventilation, and public address equipment, all of which contribute to its operational energy demand. Figures 2A and B illustrates. The selection of this building provides an appropriate case study for evaluating retrofit strategies because lecture theatres experience high occupancy levels, significant internal heat gains, and substantial dependence on environmental control systems. The building characteristics and operational conditions therefore provide a suitable basis for assessing building-fabric performance, passive energy behaviour, and potential photovoltaic integration within a tropical hot-dry climate.

3.4 Building Construction

The selected lecture theatre consists of a reinforced concrete structure with sandcrete block walls, a flat roof system covered with aluminium roofing sheets, and large glazed openings. The internal floor comprises concrete tile finishes, with stepped seating arrangements along both sides of the central circulation pathway. Although recessed windows and roof overhangs provide some protection from direct solar exposure, the building remains exposed to significant heat gain due to the hot-dry climate and limited surrounding vegetation.

The existing construction characteristics, including wall composition, roof materials, glazing type, and floor assembly, were incorporated into the IESVE model based on their thermal properties and corresponding U-values. Building geometry, furniture arrangement, occupancy conditions, and theatre configuration were also considered during model development and calibration to improve simulation accuracy.

Building form and envelope characteristics play an important role in thermal comfort and energy performance, as appropriate material selection and geometric design can reduce cooling requirements (Trepci et al., 2021; Jones et al., 2021).

Table 1: Building fabric and construction material specifications

Fabric Element	Composition	U-value (W/m^2K)
External Walls	18mm external wall plaster; 230mm hollow Sandcrete Conc. Blocks: 12mm internal wall plaster	1.36
Doors	37mm hollow in steel framed	2.1
Roof	0.045mm Aluminium roofing sheet on steel hollow pipe steel-struts roof members	7.28
Internal walls (Partition)	18mm external wall plaster; 230mm hollow Sandcrete Conc. Blocks: 12mm internal wall plaster	1.36
Windows	Single glazed pane (6mm)	6.9
Ground Floor	10mm tiles finish, 20mm cement screed, 150mm dense concrete 300mm hardcore fill.	3.72
Upper Floor/ Ceiling	190mm Cast in-situ concrete	1.8

However, the existing theatre experiences considerable solar heat gain due to its large glazed areas and exposure to intense solar radiation, demonstrating the need to evaluate improved fabric configurations suitable for hot-dry climates (Arup, 2016). The existing building construction properties used as baseline simulation inputs are presented in Table 1.

3.5 Building Measurement and Instrumentation Set-up

Empirical environmental monitoring was conducted to support the calibration and validation of the IESVE simulation model. Indoor and outdoor thermal conditions were measured using a NETATMO Smart Weather device equipped with internal and external sensing modules. The system recorded key environmental parameters, including air temperature, relative humidity, and CO_2 concentration. Although the device was configured for long-term monitoring, this study analysed data obtained during the hottest week of the academic period (8–14 April), representing a period of high occupancy and thermal stress conditions. Measurements were recorded at 30-minute intervals to capture variations in indoor and outdoor environmental conditions. The monitoring sensors were installed at representative locations within and outside the lecture theatre. The indoor sensor was positioned at approximately 1.0–1.1 m above floor level, corresponding to the occupant breathing zone and following recommended measurement practices based on ASHRAE-55 (2013) and CIBSE Guide A (2021) Similar monitoring approaches have been applied in previous educational building thermal studies (Guevara et al., 2021; Kooi et al., 2018). The collected environmental data were subsequently used as reference inputs for simulation calibration and validation, improving the reliability of the predicted building performance results.

3.6 Fabric Simulation Process and Assumptions

The fabric simulation process was developed using the IESVE ModelIT environment to evaluate the energy performance of the lecture theatre under different envelope configurations. The building model was generated using the original architectural characteristics, material properties, and corresponding thermal parameters, while the Birnin Kebbi Typical Meteorological Year (TMY) weather file was incorporated to represent local climatic conditions. The simulation inputs included construction properties, thermal templates, ventilation, infiltration rates, occupancy profiles, and internal heat gains.

Several assumptions were established to ensure consistency among the simulated fabric scenarios. Since the study focused on passive energy performance assessment, the cooling set-point was excluded during the initial simulations to evaluate the influence of envelope characteristics and passive strategies on heat gain and cooling demand. However, a reference indoor comfort condition of 26°C was considered based on the ASHRAE thermal comfort guideline for educational buildings. Internal heat gains associated with occupants, lighting, equipment, ventilation, and infiltration were defined according to standard building operation profiles following (CIBSE Guide A, 2021). The simulation assessment considered the influence of passive retrofit measures, including improved fabric properties, shading strategies, glazing performance, ventilation conditions, and solar heat reduction approaches. The modelling process involved developing the baseline building, modifying envelope parameters, and comparing the resulting energy performance of the as-built, retrofitted, ASHRAE 90.1, and Passivhaus fabric scenarios.

Simulation assumptions include:

- Climate data: Typical Meteorological Year (TMY) file for Birnin Kebbi hot-dry climate.
- Occupancy schedule: 8:00 AM–6:00 PM during weekdays based on academic operation periods.
- Internal gains: Consideration of occupants, lighting, and equipment loads.
- Ventilation and infiltration: Defined according to standard building-performance assumptions.
- Simulation resolution: Hourly time-step analysis for annual performance evaluation.

Table 2: Simulation input parameters and assumptions across fabric configurations

S/N	Parameter Category	Input/Assumption
i	Climate Data	Typical Meteorological Year (TMY) for hot-dry zone
ii	Occupancy Schedule	8:00 AM – 6:00 PM, weekdays only (studio hours)
iii	Internal Gains	100 W/person (lighting, plug loads, and occupants)
iv	HVAC System	Split-type AC; set point 26°C; performance (COP) 3.5
v	Ventilation Rate	10 L/s per person (ASHRAE Standard 62.1-2019)
vi	Simulation Resolution	Hourly time step
vii	Energy Model	Sun cast, Construction and thermal templates

3.7 Building Geometry and Modelling

The lecture theatre geometry was developed in the ModelIT module of IESVE using architectural drawings, field measurements, and existing building conditions. The model incorporated key geometric parameters, including building dimensions, orientation, roof configuration, wall elements, glazing areas, floor levels, and internal spatial arrangements, which influence solar exposure and thermal behaviour.

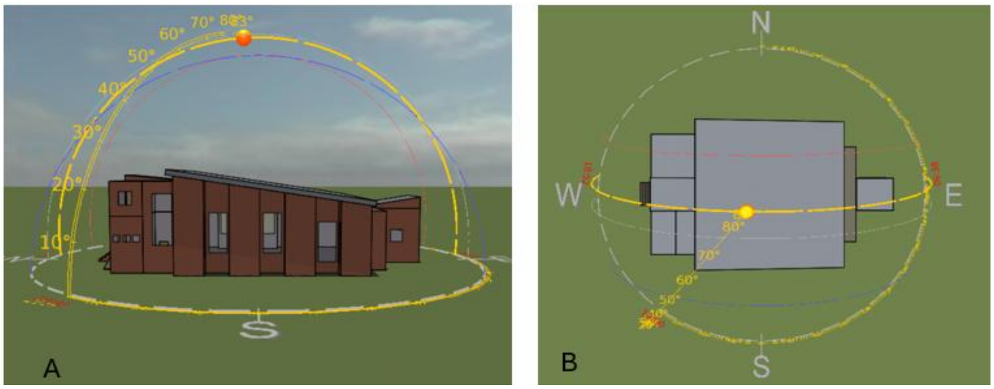

Figure 3. IESVE 3D model of lecture theatre geometry. A-South view and B-Roof plan view

The developed model was assigned the corresponding construction properties, thermal parameters, occupancy profiles, lighting loads, equipment gains, and ventilation conditions. The baseline as-built model was subsequently modified to generate the retrofitted, ASHRAE 90.1, and Passivhaus fabric scenarios for comparative energy-performance assessment. Shown in Figure 3. The developed model provided the foundation for evaluating fabric performance and establishing the simulation-based retrofit framework by integrating building form, climatic response, and energy-performance indicators.

- **Sun-cast**

Solar analysis was performed using the Sun Cast module to evaluate the influence of solar radiation and shading conditions on building thermal behaviour.

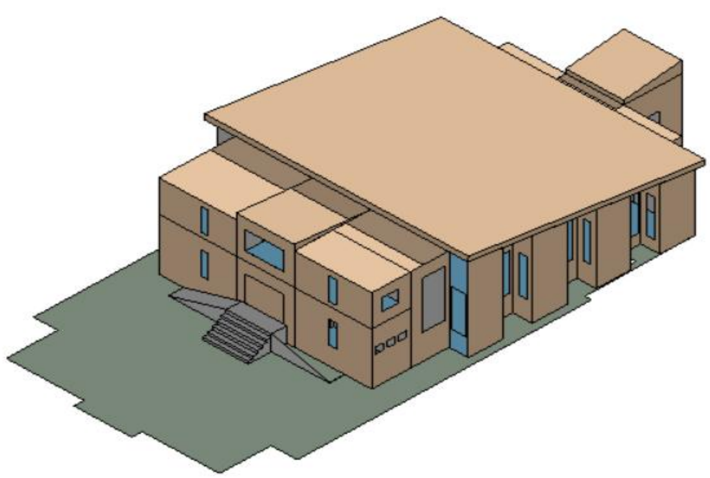

Figure 4. Sun cast, (shade and shadow) model of the theatre building

- **Model Calibration**

The IESVE model was calibrated by defining appropriate thermal templates while maintaining consistent design conditions throughout the simulation process. Key parameters, including ventilation and infiltration rates, occupancy levels, and cooling set-point conditions for natural and auxiliary ventilation modes, were incorporated to represent the actual building operation.

Operational schedules were configured through the Building Template Manager, incorporating occupancy profiles based on the typical usage pattern of educational facilities. The lecture theatre was assumed to operate mainly between **8:00 a.m. and 5:00 p.m.,** with full occupancy during weekdays and reduced occupancy during weekends. The defined occupancy profile used for simulation calibration is presented in Figure 5. Observational surveys and institutional timetables were used to assess typical occupancy schedules and operational hours, allowing the identification of peak energy demand periods.

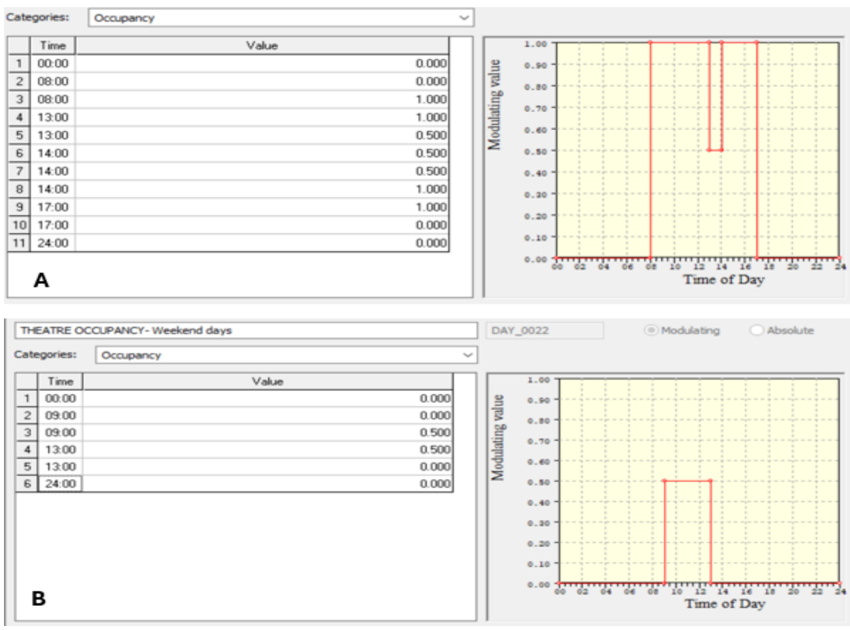

Figure 5. Weekday occupancy (A), and weekend occupancy (B)

3.8 Fabric Parametric Simulation Set-up

The IESVE parametric simulation was conducted to assess the thermal performance of the selected fabric configurations under existing and retrofit conditions. The model incorporated climatic conditions, internal heat gains, and passive interventions, including shading, glazing improvement, roof modification, infiltration, and natural ventilation assessment. The as-built (T1) and retrofitted (T2) theatre conditions were compared with the selected fabric standards. The study adopted a passive energy simulation approach; therefore, electrical load analysis was excluded. The assessment focused on solar heat gain, indoor temperature variation, ventilation performance, and fabric heat transfer characteristics. The sensible cooling loads obtained from the iterative simulations were compared to determine the optimal fabric performance for future PV integration and retrofit planning. The thermal properties and U-values assigned to each fabric scenario are presented in Table 3

Table 3: Fabric standards configuration and U-values of simulated building elements

S/N	Fabric Elem: U-valu	ASHRAE90	Passivhaus	ORIG. Building	Full Retrofitted
i	Walls: **W/m²K**	**≤ 0.50**	≤ 0.15	**> 0.50**	≤ 0.35
ii	Windows: **W/m²K**	**≤ 1.90**	≤ 0.80	**> 1.90**	**≤ 1.50**
iii	Infiltration; ACH	≤ 0.6 ACH	≤ 0.6 ACH	>10 ACH	≤ 0.6 ACH
iv	Glazing Type	**Double glazing**	Triple glazing	Single glazing	Double glazing

4. Results and Discussions

The four fabric configurations were evaluated using the IESVE ApacheSim simulation engine, while performance outputs were analysed through VistaPro. The assessment focused on annual cooling sensible load and total fabric energy consumption (MWh) to determine the effectiveness of passive retrofit interventions.

4.1 Fabric Yearly Room Cooling Sensible Load

The room cooling sensible load represents the cooling energy requirement influenced by building-fabric characteristics. Figure 6 presents the monthly and annual cooling load variations for the four simulated scenarios. The as-built theatre (T1) recorded the highest annual cooling load of 1303.22 MWh, indicating greater cooling demand due to its existing envelope performance. After passive retrofit intervention, T2 reduced the annual cooling load to 1235.73 MWh, achieving approximately 5.2% energy reduction compared with T1. The monthly analysis showed that the highest cooling demand occurred during the hotter months, with T1 reaching 169.32 MWh in March, while T2 reduced the corresponding load to 161.80 MWh. Although ASHRAE 90.1 (1194.70 MWh) and Passivhaus (1161.35 MWh) demonstrated lower benchmark values, the improved performance of T2 confirms that fabric optimisation can effectively reduce cooling requirements in existing university buildings. The reduction in sensible cooling load indicates potential for lower HVAC capacity requirements and improved suitability for future PV integration.

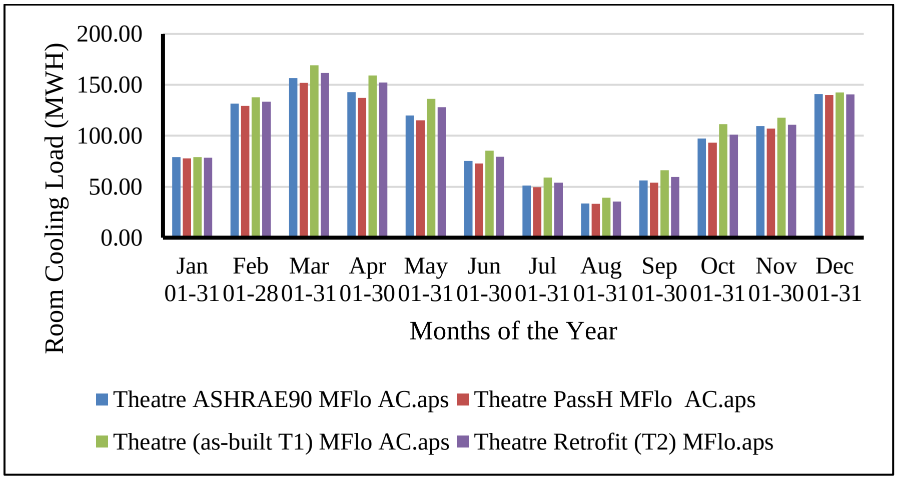

Figure 6: Monthly room cooling sensible load comparison of four fabric scenarios

The results confirm that passive fabric optimisation is an important first step before photovoltaic integration, as reducing the building energy baseline allows future PV systems to be designed with lower generation requirements. Therefore, the T2 retrofit configuration provides a more energy-efficient foundation for developing a low-energy university building framework.

4.2 Annual Total Energy Performance of Fabric Configurations

The annual energy assessment confirms the improvement achieved through passive retrofit measures. The as-built theatre (T1) recorded the highest energy requirement of 1303.22 MWh, while the retrofitted theatre (T2) reduced consumption to 1235.73 MWh, representing an annual saving of approximately 67.49 MWh. Although ASHRAE 90.1 (1194.70 MWh) and Passivhaus (1161.35 MWh) achieved lower benchmark values, the improved performance of T2 demonstrates that fabric optimisation can enhance energy efficiency in existing university buildings without complete reconstruction. The reduced energy demand of T2 provides a lower baseline for PV system sizing, improving the feasibility of renewable-energy integration within the proposed retrofit framework.

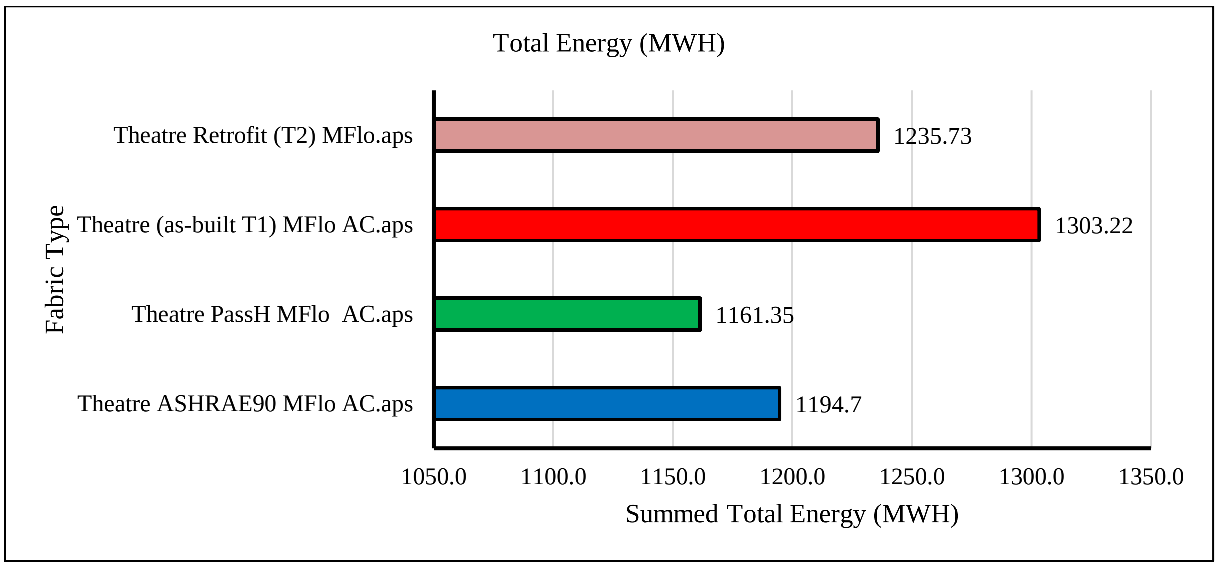

Figure 7. Annual total energy comparison among fabric configurations

4.3 Simulation-Based Conceptual Framework Development

The simulation outcomes provided the basis for developing a conceptual framework for energy-efficient retrofit and future photovoltaic (PV) integration in university buildings. The framework follows a three-phase process, beginning with building performance assessment, followed by IESVE-based simulation evaluation, and concluding with retrofit optimisation and PV integration planning.

Phase 1: Building Assessment and Data Preparation

The framework begins with case study selection, field measurement, and climatic assessment. Real-time environmental data, including temperature, humidity, CO_2 concentration, and wind conditions, were collected to support simulation inputs and model validation.

Phase 2: IESVE Simulation and Performance Evaluation

The building model was developed using IESVE by integrating geometric characteristics, thermal properties, weather data, and operational parameters. The simulation evaluated cooling sensible load and annual energy performance of the different fabric configurations, providing a quantitative basis for retrofit assessment.

Phase 3: Retrofit Framework and PV Integration Planning

The simulation results guided the development of a decision-support framework for fabric optimisation and PV integration. The reduced energy demand achieved through T2 retrofit provides a suitable baseline for PV sizing, considering system capacity, rooftop suitability, orientation, shading effects, and potential annual energy generation, as illustrated in Figure 8.

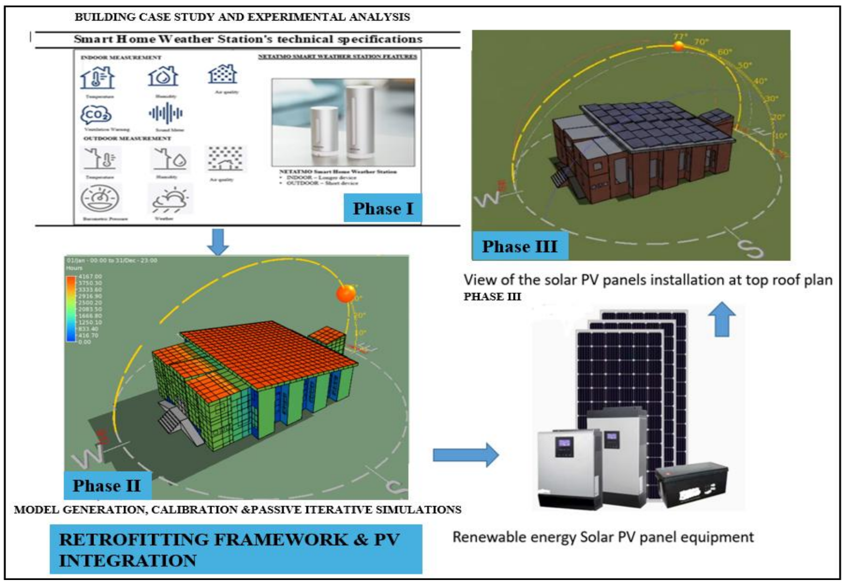

Figure 8: Simulation-based framework for energy-efficient retrofit and PV integration.

The proposed framework provides a systematic approach for evaluating retrofit strategies before physical implementation. By integrating empirical measurements, validated simulation, fabric performance assessment, and renewable-energy planning, it offers a practical pathway for improving energy efficiency and supporting PV deployment in higher education buildings within tropical hot-dry climates.

5. Conclusion and Recommendation

This study demonstrates the effectiveness of a simulation-based approach for assessing energy-efficient retrofit strategies and supporting photovoltaic (PV) integration in university buildings. Using the lecture theatre at Federal University Birnin Kebbi as a case study, the research combined environmental monitoring with IESVE-based simulation to evaluate fabric performance, cooling demand, and energy reduction potential under different retrofit scenarios.

The developed framework provides a structured approach for evaluating existing building performance, identifying suitable fabric improvements, and establishing a basis for future PV system sizing and integration. The improved performance of the retrofitted fabric scenario highlights the importance of reducing building energy demand before renewable-energy deployment. This approach offers a practical decision-support pathway for facility managers, designers, and policymakers seeking to improve energy resilience and sustainability within higher education buildings in tropical hot-dry climates.

Future applications of the framework should incorporate detailed PV system design, storage assessment, economic evaluation, and long-term operational monitoring to further enhance its applicability. The proposed methodology contributes to sustainable campus development by demonstrating how validated simulation tools can support climate-responsive retrofit decisions and renewable-energy integration in Nigerian and similar Sub-Saharan African educational environments.

References

Ahmed, E. K. A., Dewidar, K. M., El-Hakeem, Y. A., & Guirguis, M. N. (2025). An integrated framework for sustainable retrofitting of existing university buildings. *Discover Sustainability*, *6*(1). https://doi.org/10.1007/s43621-024-00703-7

Alqadi, S., Elnokaly, A., & Sodagar, B. (2021). Calibrating Building Thermal Simulation Model Using Indoor Environmental Measurements. *ZEMCH International Conference*, 516–528.

Arup. (2016). Building Energy Efficiency Guideline for Nigeria. In *Building Energy Efficiency Guideline for Nigeria*. https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf

ASHRAE-55. (2013). ASHRAE-55-2013. In ANSI ASHRAE (Ed.), *Thermal Environment Conditions for Human Occupancy: Vol. Addenda o.* (Q, Issue Q, p. 16). ASHRAE USA. www.ashrae.org

Barbosa, E. F. T., Labaki, L. C., Castro, A. P. A. S., & Lopes, F. S. D. (2024). Energy Efficiency and Thermal Comfort Analysis in a Higher Education Building in Brazil. *Sustainability (Switzerland)*, *16*(1). https://doi.org/10.3390/su16010462

Batista, F., Guimarães, A. S., & Palmero-Marrero, A. I. (2025). Building Integrated Photovoltaics: a multi-level design review for optimized implementation. *Renewable and Sustainable Energy Reviews*, *220*(December 2024). https://doi.org/10.1016/j.rser.2025.115837

Bena, A. A., & Adamu, M. B. (2024). Assessment of Thermal Comfort and Indoor Environmental Quality in University Buildings. *Nijerian Journal of Environmental Sciences and Technology (NIJEST)*, *8*(2), 145–154. https://doi.org/https://doi.org/10.36263/nijest.2024.02.24

Chaer, I., Ozarisoy, B., & Ismail, M. A. E. (2026). Development of an evidence-based methodological framework for overheating risk assessment of higher education buildings: occupant-centric retrofitting design strategies. *Energy and Buildings*, *351*, 116723. https://doi.org/10.1016/j.enbuild.2025.116723

CIBSE GUIDE A. (2021). CIBSE Guide A: Environmental Design. In K. B. C. Butcher (Ed.), *Incorporating corrections as of Jan 2021* (No. 8; Eighth edi). CIBSE Publications. https://doi.org/10.5040/9781472596178-bed-e035

Corrado, V., & Fabrizio, E. (2019). Steady-State and Dynamic Codes, Critical Review, Advantages and Disadvantages, Accuracy, and ReliabilityNo Title. In *Handbook of Energy Efficiency in Buildings* (1st ed., pp. 263–294). Elsevier Inc. https://doi.org/https://doi.org/10.1016/B978-0-12-812817-6.00011-5

Guevara, G., Soriano, G., & Mino-Rodriguez, I. (2021). Thermal comfort in university classrooms: An experimental study in the tropics. *Building and Environment*, *187*(August 2020), 107430. https://doi.org/10.1016/j.buildenv.2020.107430

Jones, R. V, Korsavi, S. S., Bilverstone, P. A., &

Fuertes, A. (2021). A longitudinal assessment of the energy and carbon performance of a Passivhaus university building in the UK A longitudinal assessment of the energy and carbon performance of a Passivhaus university building in the UK. *Journal of Building Engineering*, *103353*(September). https://doi.org/10.1016/j.jobe.2021.103353

Kooi, L., Mishra, A. K., Loomans, M. G. L. C., Pennings, L., & Hensen, J. L. M. (2018). Long-term monitoring of the thermal environment in office buildings. *The REHVA European HVAC Journal*, *55*(1), 23–30.

Kuhn, T. E., Erban, C., Heinrich, M., Eisenlohr, J., Ensslen, F., & Neuhaus, D. H. (2021). Review of technological design options for building integrated photovoltaics (BIPV). *Energy and Buildings*, *231*, 110381. https://doi.org/10.1016/j.enbuild.2020.110381

Mihara, K., Sekhar, C., Takemasa, Y., Lasternas, B., & Tham, K. W. (2019). Thermal comfort and energy performance of a dedicated outdoor air system with ceiling fans in hot and humid climate. *Energy and Buildings*, *203*, 5–10. https://doi.org/10.1016/j.enbuild.2019.109448

Mobolade, T. D., & Pourvahidi, P. (2020). Bioclimatic approach for climate classification of Nigeria. *Sustainability (Switzerland)*, *12*(10). https://doi.org/10.3390/su12104192

Nadalipour Kaldeh, S., Yousefi, H., Noorollahi, Y., & Abdoos, M. (2025). Integration of renewable sources in buildings: A review of energy savings, feasibility, and challenges. *Energy Reports*, *14*(October), 3905–3934. https://doi.org/10.1016/j.egyr.2025.10.046

Noaman, D. S., Moneer, S. A., Megahed, N. A., & El-Ghafour, S. A. (2022). Integration of active solar cooling technology into passively designed facade in hot climates. *Journal of Building Engineering*, *56*(May), 104658. https://doi.org/10.1016/j.jobe.2022.104658

Sholanke, A. B., Adeboye, A. B., & Alagbe, O. A. (2019). Design solutions creating barriers to achieving universal design compliance of academic buildings in universities in Nigeria. *International Journal of Civil Engineering and Technology*, *10*(1), 671–690.

Trepci, E., Maghelal, P., & Azar, E. (2021). Urban built context as a passive cooling strategy for buildings in hot climate. *Energy and Buildings*, *231*, 110606. https://doi.org/10.1016/j.enbuild.2020.110606

Turhan, C., & Ghazi, S. (2023). Energy Consumption and Thermal Comfort Investigation and Retrofitting Strategies for an Educational Building : Case Study in a Temperate Climate Zone. *Journal of Building Design and Environment Vol 2 Issue 2 2023*, *2*(August), 1–12. https://doi.org/10.37155/2811-0730-0201-7

Vethanayagam, V., & Abu-Hijleh, B. (2019). Increasing efficiency of atriums in hot, arid zones. *Frontiers of Architectural Research*, *8*(3), 284–302. https://doi.org/10.1016/j.foar.2019.05.001

Weathersparks. (2023). *Climate and Average Weather Year Round in Birnin Kebbi*. https://weatherspark.com/y/50099/Average-Weather-in-Birnin-Kebbi-Nigeria-Year-Round

Yu, Y., Chen, M., Wei, M., Wang, X., & Li, T. (2026). Optimizing energy performance of campus office buildings by modeling and simulation of occupant and air-conditioning behaviors. *Energy and Buildings*, *359*(March), 117355. https://doi.org/10.1016/j.enbuild.2026.117355

Zamwawosayi, B. Z., Emusa, H., & Owoicho, B. C. (2025). Assessment of the Application of Design Strategies for Thermal Comfort Optimization in Residential Buildings in Abuja, Nigeria. *IIARD International Journal of Geography & Environmental Management*, *11*(8), 56–69. https://doi.org/10.56201/ijgem.vol.11.no8.2025.pg56.69