Article

Combining Building Simulation and Sensitivity Analysis for the Evaluation of Passive Design Approaches for Residential Buildings in Nigeria

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ABSTRACT

This research investigates different passive design measures to improve residential buildings' energy efficiency and mitigate the effects of climate change. To identify the best passive design strategy for the climate under study, a four-Bedroom one-storey modern residential building for single-family was picked within the hot-dry climate zone of Nigeria as a case study. A questionnaire survey was adopted to ascertain the thermo-physical properties of the building envelope, energy consumption by taking meter readings, occupancy behaviour and electricity supply schedule. The base case model was then designed in IES VE software, and the construction materials and profiles were made to conform to the standard regulations and guidelines of Nigeria. The base model was subjected to two different scenarios (Traditional building envelope and thermal insulation of Modern building envelope) and the results of the simulation were analysed and compared to the actual energy consumption using ASHRAE 2014 standard guidelines. A sensitivity analysis was carried out using visual PROMETHEE II software to ascertain the robustness and stability of the results. The results of the study show that an average of 9–10 h of electricity is supplied to residential buildings per day. Additionally, the base case building's actual and simulated electricity consumption is 10.43 kWh/m^2 year and 45.1 kWh/m^2 year respectively and cooling load accounts for 35.6% (14.5 kWh/m^2 year) of the total annual energy consumption of the building. There was a reduction in annual electricity consumption and cooling load by 20.4% (35.9 kWh/m^2 year) and 36.6% (9.2 kWh/m^2 year) respectively when the use of a traditional building envelope (strategy 1) was adopted. Similarly, the adoption of thermal insulation of the modern building envelope (strategy 2) leads to a reduction in annual energy consumption and cooling load by 21.3% (35.5 kWh/m^2 year) and 47.6% (7.6 kWh/m^2 year) respectively. Strategy 2 performed better when compared to the base model and strategy 1 as 50% of the months achieved a PPD of less than 15%. Additionally, the sensitivity analysis result shows the use of thermal insulation in the modern building envelope (strategy 2) is the best compared to the traditional building envelope (strategy 1). The adoption of any of these approaches in the design of residential buildings in Nigeria can not only lead to comfortable indoor environments and energy savings associated with cooling but can also cause a reduction in

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carbon-dioxide emissions by 23.2% and 28.4% when strategy 1 or 2 is used respectively and cost of electricity savings by 20.4% and 25.7% when strategy 1 or 2 is adopted respectively.

KEYWORDS: passive design; energy efficiency; indoor thermal comfort; building simulation; cooling loads; climate responsive design; IES VE software; climate analysis; sensitivity analysis; Visual PROMETHEE II Software

ABBREVIATIONS

IES VE, Integrated Environmental Solutions-Virtual Environment; PROMETHEE, Preference Ranking Organisation Method for Enrichment Evaluation; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; KWh, kilowatt hour; KWh/m^2 year, kilowatt hour per meter square per year; GHG, Greenhouse gases; CO_2, Carbon dioxide; UHI, Urban Heat Island; ASHRAE, American Society of Heating, Refrigeration and Air-Conditioning Engineers; ISO, International Organisation for Standardisation; CIBSE, Chartered Institution of Building Service Engineers; BREEAM, Building Research Establishment Environmental Assessment Method; NZEBs, Nearly Zero Energy Buildings; CV RMSE, Coefficient of Variation of Root Mean Square Error; W/M^{2}K, Watts per meter square Kelvin; A.S.L, above sea level; FGoN, Federal Government of Nigeria; KM^2, kilometre square; N, Naira; Kg CO_2, Kilogram of carbon dioxide

INTRODUCTION

Climate change in the form of global warming is a major problem that is of great concern to the planet, which is caused by the emission of greenhouse gases (GHG) [1]. The building sector is the main cause of climate change which is responsible for global CO_2 emissions, energy, and electricity consumption by 19%, 32%, and 51% respectively [1]. In Nigeria, the building sector accounts for 65% of the yearly energy consumption [2] which is mainly due to the use of air conditioning systems [3].

The effect of climate change is already being experienced in countries situated in the tropical climate zone which are constantly being faced with extreme heat [4,5]; and it is believed that there will be an increase in the average global temperature by 2.6–4.8 °C between the year 2080–2100 if action is not taken [1]. This high temperature is more prevailing in urban areas where heat gains in buildings are high during the daytime [6], due to factors such as urban overpopulation, increase in the standard of living, and urban heat island (UHI) effects [7]. Thereby, resulting in the rapid increase in energy use due to cooling [8].

It is a well-known fact that high temperatures affect human health. As people spend 90% of their time indoors, and their continuous exposure to high indoor temperatures causes the body temperature to rise, and after long exposure to a body temperature of 40.5 ℃; it can result in health conditions such as heat stress, exhaustion, mental confusion, mottle, and loss of consciousness, convulsion or even death [9].

To mitigate the effect of climate change, the anthropogenic activities that increase global warming would have to be reduced. One of the ways to do this is by reducing the energy use of buildings by adopting the use of passive design measures to achieve the desired level of indoor thermal comfort [10]. This is important because completely relying on non-renewable energy sources for active cooling and heating contributes to the effect of climate change.

The Residential buildings in Nigeria are not designed to respond to the local climate, making the indoor thermal conditions for the residential buildings to be unconducive for the building occupants [6,11]. The lack of consideration of the features and approaches that leads to indoor thermal comfort makes the use of mechanical systems for cooling a common practice in Nigerian buildings [11,12]. However, the majority of building occupants in Nigerian residential buildings cannot acquire mechanical systems for cooling [6]. Those households with air conditioning systems barely use them even during hot weather conditions due to the epileptic power supply and very long periods of power outages [13] and more than 60% of the population in Nigeria are not connected to the national grid, making people resort to the use of diesel/petrol generators as a backup source of power, which adds up to the carbon dioxide concentration [14]. During the peak hot season in the summer months, the extreme heat increases the demand for people to use electricity for cooling their indoor space. This high increase in cooling demand and the inadequate supply of electricity to provide the needed amount of cooling to the indoor space leads to thermal discomfort of the building occupants thereby affecting their performance and health [6]. Therefore, this study evaluates passive design approaches with the aim of improving the thermal performance of residential buildings in Nigeria.

LITERATURE REVIEW

An Overview of the Climate Zones of Nigeria for Passive Design

Nigeria is in the Western part of Africa and has a total land area of 923,768 km² (13,000 km² water and 910,768 km² island) and lies between latitude 3°15'–13°30'N and longitude 2°59'–15°00'E; Nigeria shares boundary with Niger Republic in the north, Cameroun and Chad republic in the east, the Republic of Benin in the west, and to the southern part the Gulf of Guinea in the Atlantic Ocean [15]. Nigeria experiences different variations in climatic patterns throughout the year [16].

According to Tolulope & Parastoo [17], Nigeria is classified into five climatic zones such as Temperate-humid, hot-humid, temperate-dry with a cool climate, hot-dry, and temperate-dry. This climate classification is used in this study because previous classifications are not recent and was based mainly on vegetation which makes it difficult to be applied to the constantly changing climate [18–20]. Also, this classification depends on human thermal comfort and the condition of the local climate [17] which is the main concern of this study.

Demographics of Residential Buildings, Building Regulations and Energy-Efficient Guidelines in Nigeria

Residential buildings in Nigeria are divided into traditional and modern buildings. The former makes use of locally available building materials and the latter is constructed with beautiful, highly durable and stronger modern materials [21]. The modern building materials are however, not responsive to the local climate, not friendly to the environment, and they rely on mechanical cooling systems to provide the required amount of cooling during heat season [11,22,23]. Each climate zone of Nigeria should have its own recommended climate-responsive building design approaches. It is imperative for the building regulation of Nigeria to set minimum standards for the use of building materials and to emphasize energy-efficient building design and construction for contemporary and traditional residential buildings. However, energy efficiency measures are not found in the building code of Nigeria [24] although, the process of including passive design measures has already commenced [3,11]. Contrarily, some advanced countries in the world have developed building regulations, energy-efficient guidelines, and energy-efficiency rating tools as well as setting ambitious net-zero energy and carbon targets to respond to climate change [25–29]. The Nigerian Government have recently followed the train with the development of 'The National Renewable Energy and Energy Efficiency Policy' (NREEEP), the '2050 long-term vision for Nigeria', 'Climate Change Act', and 'Energy Transition Plan'. The objective of these policies is to mitigate the effects of climate change through the use of clean energy, increasing renewable energy generation, reduction of emissions by 50% across all sectors, and development of national climate action plans and net-zero emission targets [30–33]. Although this could have been a good head start, however, these policies did not address energy-efficient building design. It is important to design buildings that use the minimum amount of energy while providing optimum indoor thermal comfort to the building users. Hence, the need for Nigeria to begin to look at what the developed countries have done and start developing climate-responsive building design policies and guidelines that can improve the energy efficiency of Nigeria's built environments. The discussion should centre on the development of local green building rating tool, the adoption of best energy efficient measures in the design and construction of new buildings and retrofitting of existing buildings, the use of energy performance certificates, ensuring buildings are nearly energy and carbon zero by 2050, setting of minimum energy performance requirement for new and existing buildings, and to address energy poverty [26,34].

Given the above, the standard *U*-values recommended by Chinese and Nevada guides will be used for comparison in this study [17,27,28]. This is because they have a climate zone that is similar to the climate zone under study. The Table 1 below shows the recommended *U*-values for Chinese and Nevada Guides. These recommended *U*-values are essential towards improving the energy efficiency and indoor thermal comfort of the building occupants as they spend most of their time indoors.

Table 1. The standard *U*-values for walls, roofs, and windows in China and Nevada.

GUIDELINES		Fenestration	Skylight	Ceiling	Wooden wall	Mass wall	Floor	Slab
CHINESE GUIDE	U-Value (W/m^2K)	1.0–2.0	-	-	-	0.20–0.35	-	0.20–0.35
NEVADA GUIDE		0.35	0.60	0.15	0.28	0.44	0.19	0.57

Source: [27–29].

Thermal Comfort, Comfort Zone, and Cooling Set-Points in the Hot-Dry Climate Zone

Thermal comfort is 'that condition of the mind that expresses satisfaction with the thermal environment' [35]. Thermal comfort parameters such as temperature, relative humidity, and wind velocity in the hot-dry climate zone of Nigeria are above the comfort zone limits recommended by ISO and ASHRAE which are 23–26 ℃, 30%–70%, and <0.2 m/s for temperature, relative humidity, and air velocity, respectively [4,5,36,37]. To predict thermal comfort, different indices are used and all fall under the category of deterministic approach or adaptive model. Predicted mean vote (PMV) is a form of deterministic approach that creates heat balance between the Human body and its environment [37,38]. It is Fanger's 7-point scale that measures the thermal sensation of people in a static state and where people have no control of their thermal environment as seen in Figure 1 [39,40]. The acceptable comfort limits are PMV of –0.5 and +0.5 which corresponds to a PPD of 10% [37,38]. The adaptive model on the other hand is based on the belief that people are active and could have a level of control over their thermal environment and could adapt or adjust to the changing environment [41]. In other words, if a change in thermal condition that results in discomfort occurs, people tend to react to bring back their comfort [42]. Although Fanger's model is the most commonly used [43], it does not allow building occupants to have control over their thermal environment [41]. This explains why it is best used in HVAC-controlled rooms and not effective in naturally ventilated buildings [44]. The adaptive model, however, can be used to ascertain the thermal conditions that are acceptable and regulated by building users in naturally ventilated buildings (Figure 2); for instance, the opening of windows to admit fresh air or closing it to prevent heat gains [45]. PMV and PPD indices are calculated using Equations (1) and (2) and the Predicted percentage of dissatisfied (PPD) value can be found after the PMV value has been determined using either Equation (2) or Figure 1B below [37,38]. The analysis of thermal comfort in this study will be based on EN 15251 and ISO 7730 [37,38] comfort criteria as seen in Table 2.

$$\begin{aligned} PMV = {} & (0.303e^{-0.038M} \\ & + 0.028)\,\{(M - W) \\ & - 3.05.[5\,733 - 6.99\,(M - W) - Pa] \\ & - 0.42.[(M - W) - 58.15] - 1.7 * 10^{-5} M(5\,867 - Pa) \\ & - 0.0014\,M(34 - ta) - 3.96 * 10^{-8} fcl.[(tcl + 273)^4 \\ & - (\bar{tr} + 273)^4 - fclhc(tcl - ta)\} \end{aligned} \quad (1)$$

Where, PMV = predicted mean vote.

$$T_{cl}=35.7\text{-}0.028(\text{M-W})\text{-Icl}\{3.96.10^{-8} fcl.\left[(tcl + 273)^4 - (\bar{tr} + 273)^4 - fclhc(tcl - ta)\right\} \quad (1A)$$

$$h_c=\begin{cases} 2.38(tcl-ta)^{0.25} for\ 2.38(tcl-ta)^{0.25}>12.1\sqrt{var} \\ 12.1\sqrt{var}\ for\ 2.38(tcl-ta)^{0.25}<12.1\sqrt{var} \end{cases} \quad (1B)$$

$$f_{cl}=\begin{cases} 1.00+1.290Icl\ for\ Icl \le 0.078m^2.°C/w \\ 1.05+0.645Icl\ for\ Icl>0.078m^2.°C/w \end{cases} \quad (1C)$$

M = Metabolic rate (W/m^2).
W = external work (W/m^2).
I_{cl} = Thermal resistance (m^2 °C/w).
f_{cl} = ratio of the human surface area while nude to while clothed.
t_a = air temperature (°C).
$\bar{t}_r$ = mean radiant temperature (°C).
v_{ar} = relative air velocity to the human body (m/s).
pa = water vapour pressure (pa).
h_c = coefficient of convective heat transfer (W/m^2 °C).
t_{cl} = surface temperature of clothing (°C).

$$\text{PPD}=100 - 95.e^{-(0.033\,53\,.\,PMV^4+0.2179\,.\,PMV^2)} \quad (2)$$

(A)

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

(B)

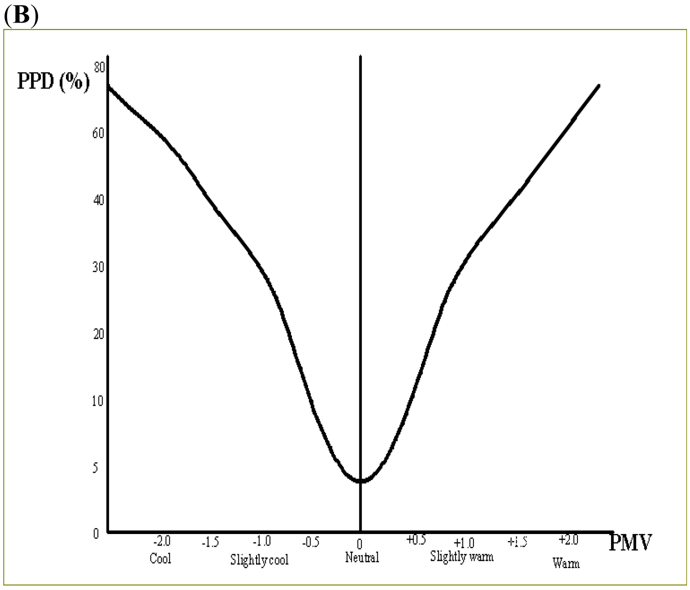

Figure 1. **(A)** 7-point thermal sensation scale. **(B)** PPD as determined using PMV [37,46].

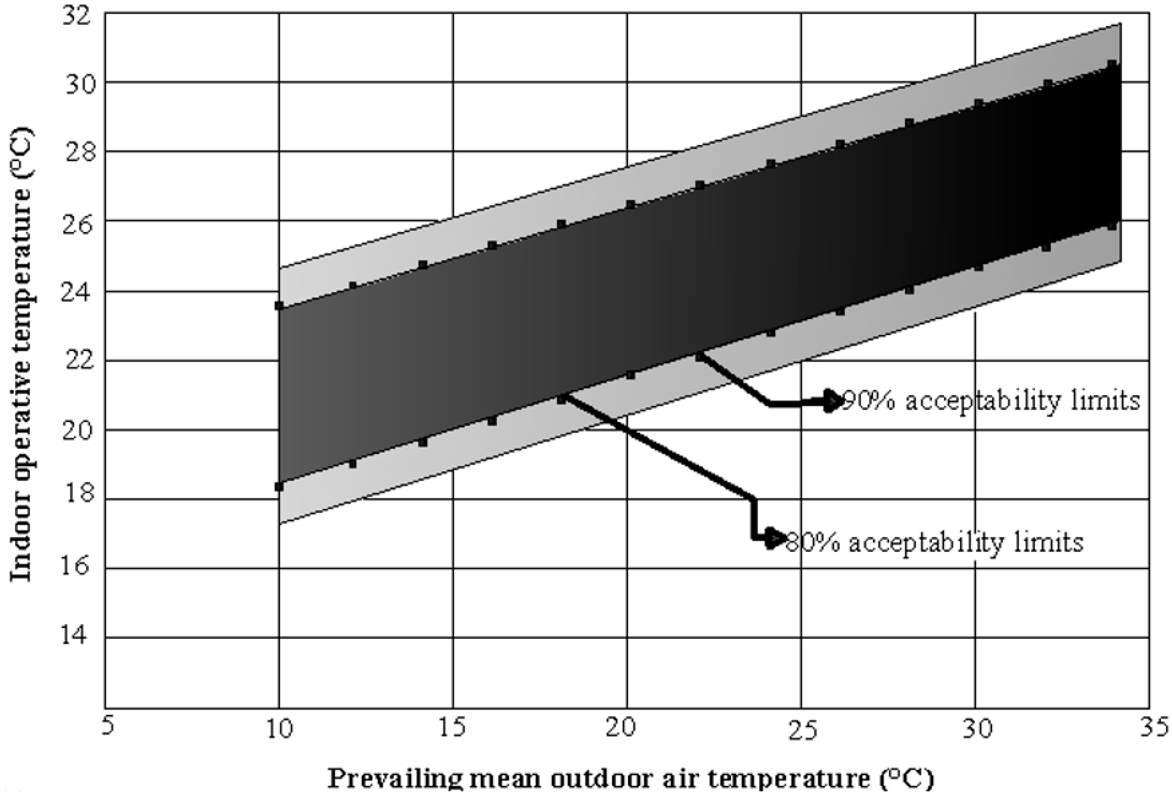

Figure 2. Acceptable operative temperature ranges for naturally ventilated spaces [46].

Table 2. Categories for the design of mechanically cooled and heated buildings.

Category	Thermal state of the body as a whole	
	PPD (%)	PMV
A	<6	−0.2 < PMV < + 0.2
B	<10	−0.5 < PMV < + 0.5
C	<15	−0.7 < PMV < + 0.7
D	>15	<−0.7; or PMV > + 0.7

Source: [37,38,47].

Due to the harsh indoor thermal conditions of residential buildings in the climate under study, air conditioning systems (which account for 29% of the total energy use in residential buildings) are mainly used to achieve the desired level of indoor thermal comfort during summer [3]. According to Amina et al. [13], the total yearly cooling load of a single-storey building in Nigeria is 26 kWh/m^2 year. Although, this consumption value would have been higher if the electricity supply is constant. According to Kayode et al. [48], 6–10 h of electricity is supplied daily to residential buildings in Nigeria. However, to ensure efficient use of energy for cooling, the Chinese energy efficiency guide recommended a yearly cooling demand of 15 kWh/m^2.year for the hot summer and cold winter climate zones [49], and the Nevada guide recommended a cooling set point of not more than 26 ℃ [27,28]. Other studies recommended a temperature set point of 26 ℃, 25 ℃, and 26 ℃ for use in China, Taiwan, and Thailand respectively [50–52].

Passive Design and Its Adoption in Nigeria

Passive design is the adoption of building design approaches, suitable materials, and environmental conditions by the designer at the early stage of the building design to design buildings that consider the local climate of the area and provide comfortable indoor conditions [53]. The building design approach does not make use of “active” (mechanical) systems but rather, provides the needed cooling by using shading techniques, natural ventilation, thermal mass and building orientation/layout; and the needed heating by utilizing the thermal mass, solar gain, and insulation [54,55]. A good passively designed building in a hot-dry climate is that which provides the needed amount of cooling naturally without relying on mechanical cooling systems [6]. Cooling a building passively is the cheapest and does not affect the environment negatively. The use of Passive design in buildings is important towards achieving indoor thermal comfort and the reduction in cooling loads [56]. In Nigeria however, there is a lack of consideration for passive design strategies during the design and construction of buildings [57] hence, the need to carry out this study. Additionally, some studies have highlighted some barriers that led to the adoption of passive design practices in the residential building sector in Nigeria to includes: lack of knowledge and awareness on the importance of passive design’s principles and practices by professionals, absence of local building rating tool, lack of technical expertise and inconsistencies in Government policies [11,57–59].

Impact of Passive Design Strategies on Indoor Thermal Comfort and Cooling Load

The impact of passive design strategies on indoor thermal comfort improvement and reduction of energy use associated with cooling load cannot be overstated. In a hot-dry climate zone, a good building orientation is one whose building length (longer side) is facing the North-South direction and the width (shorter side) is facing the East-West direction or when the building orientation is 0°, 135°, and 45° [54,56,60,61], which could lead to a reduction in cooling load by 8%–11% [62].

The use of overhang and double or triple glazing helps to prevent solar heat gains and the radiation from the sun from striking the window openings or building envelope. Double-glazed windows reduce heat loss through window openings by 50% [63], reduction in annual cooling load by 5.8% [64] and reduction in total annual energy consumption by 40.29% [65]. When overhangs of 760 mm at 400 mm above window openings are used, there is a reduction in cooling load by 4.41% [66].

Building materials of high thermal mass (bricks, concrete and stone) can absorb and store energy (heat) from the sun in the daytime when the ambient temperature is high then release it at night to warm the indoor space of the building when the ambient temperature is low [67,68], which improves the energy efficiency and indoor thermal comfort of a building.

Similarly, when the thickness of a building wall is increased, the *U*-value of the wall decreases, and the more its capacity to dampen the heat flowing from the outdoor to the indoor space through walls [54]. Therefore, the performance of thermal mass is determined by the thickness, thermal conductivity, and the area of the surface of the building material [56,67].

Thermal insulation prevents heat from coming in or going out of the building thereby keeping the building's indoor space cool in summer and warm in winter [69]. The type of insulation to be used, and the level, or position of the insulation depends on the climatic conditions of the building location [70]. To reduce heat gain in buildings, the recommended minimum U-value for insulation in hot-dry climates for roof and wall are 0.24 W/m^2K and 0.36 W/m^2K respectively, and roof insulation should be positioned below the roofing material, and wall insulation should be positioned either within cavities, inside or outside the solid wall [70,71]. Sayed [72] in his study made use of 150mm foam insulation in the roof. There is also a reduction in the annual cooling load by 38% and 28% when insulation material of 50 mm and 20 mm is used respectively [73,74]. A combination of insulation and night cooling recommended by Solgi [75] can reduce the cooling load by 47%, and in a situation where the heat could not be removed, extra cooling would be required using mechanical systems [76].

Natural ventilation allows fresh air into the building while removing stale air from the building, providing cooling to the interior space as well as the building occupants [77]. Natural ventilation can be single-sided, cross, and/or stack ventilation. The amount of fresh air (ventilation) flowing into the building depends to a large extent on the size and positioning of the window openings and the difference in wind pressure between the outdoor and indoor environment caused by differences in temperature, and humidity [78]. Natural ventilation results in 40% energy savings when compared with the use of an air-conditioned system and leads to improved indoor thermal comfort [79]. According to Bajwa [80] there is a reduction in indoor air temperature in the daytime when windows are opened between 3.00 p.m. to 8 a.m. to allow the cool outdoor air into the building to cool the indoor space, which satisfied 68% of the building occupants. Also, to prevent heat loss or gains, windows should remain closed during the winter and in the summer, windows should be closed during the daytime and open at night to take advantage of Night cooling [81].

Energy-Efficient Building Envelope Retrofitting

With the urgent need to address climate change by ensuring that new and existing buildings are nearly zero energy and carbon, Passive design strategies must be adopted from the design stage for new construction or during retrofitting of existing buildings to improve the building's thermal performance [34,82,83]. Renovation of existing buildings is important towards achieving a nearly zero energy and carbon building stock.

However, the materials to be used during building renovation must be environmentally friendly and the approaches to be adopted must be climate responsive, technically practicable and economically viable [11,34,57,58]. Previous studies have adopted different building retrofitting strategies in the design of energy-efficient buildings and the majority of which are simulation-based [11,54,56,60,61,69,72]. However, it is imperative to develop practical and workable building renovation strategies that can easily be implemented to bring about the improved thermal performance after the renovation work. Graziano, Marta & Giuliana [83] in their pilot study developed an approach to the 'deep renovation' of residential building stock in the Lombardy region, Italy. The work considered the replacement of windows and the installation of 'prefabricated composite panels', consisting of thermal insulation, external finishing and 'textile reinforced mortar'. After the 'deep renovation' work, measurements were carried out and the result shows a decrease in annual primary energy demand by 30.4% and 39% for the installation of prefabricated insulation panels and replacement of existing windows respectively. Additionally, a decrease in annual primary energy demand by 69% was observed when a combination of the two approaches was adopted. This study has further proven that building retrofitting has an impact towards improved energy efficiency of buildings as well as a reduction in carbon dioxide emissions. Additionally, buildings could be at risk of moisture attack during the wet season in Nigeria as seen in the climate analysis of Kano, Nigeria. Hence, the need to also consider moisture performance during the design or renovation of buildings in wet seasons. To help tackle moisture movement into the building fabric, the guideline for the control of moisture in buildings by United State environmental protection agency (EPA) [84], recommended the use of moisture-tolerant materials and the exterior wall assembly should consist of exterior cladding, air cavity, flashing, insulation material, water resistant barrier, gypsum sheathing, wall stud and interior finish in the construction and renovation of buildings.

Building Simulation and Multi-Criteria Analysis Methods

With the desire for more energy-efficient, healthier, and thermally comfortable indoor environments, many researchers have adopted different approaches to improve the thermal performance of buildings. These approaches range from the use of building simulation and field measurements [46,54,56,60,61,69,85], to the use of building simulation and multi-criteria analysis methods [82,86–91].

Building simulation at the design stage affords us the chance to know the thermal performance of the building before it is constructed or provides us with detailed information or strategies to take appropriate decisions for retrofitting [92]. Building simulation tools such as IES-VE, DOE-2, IDA ICE, ECOTECT, ESP-r, Design Builder, TRNSYS, HEED, EnergyPlus and eQUEST are currently being in use by architects or designers however, the majority of them prefer the use of IES VE simulation software because it is ranked as the best tool and is termed as the most "Architect friendly", simple and easy to learn and good graphics of simulation inputs and results [92]. Various calculations can be carried out in IES VE building simulation tools, such as SunCast, Lighting, Ventilation, Thermal comfort, energy consumption, thermal, cooling and heating loads [93].

Multi-criteria analysis method helps researchers to carry out analysis of a problem from different perspectives and different solutions to a problem can be compared to identify the best solution. Chen & Tsay [91] used a combination of building simulation and sensitivity analysis methods to assess the influence of input parameters on building energy and comfort performance in 24 coastal cities in China. The result of the research shows that the percentage influence of key parameters such as occupancy density, heating set point, roof *U*-value, equipment, cooling set-point, window SHGC, and infiltration rate are affected by geographical location and could affect comfort performance and energy use by 70% in the region. In a similar study, Chen et al. [87] used a questionnaire survey, building simulation (Design Builder) and sensitivity analysis method to evaluate the factors influencing the energy consumption of rural households in Zhejiang Province. The result of the research found that discomfort and energy consumption in the various household patterns had a significant influence while household patterns has little influence for cooling and heating on the ranking of the most significant factors. Pacheco-Torres, Anh & Luca [86] used the Simulation approach (Matlab) and sensitivity analysis method to assess thermal comfort and energy consumption of different heating scheduling. The result shows thermal insulation level is among the factors that affect the efficiency of a strategy and when the unheated period is reduced, the indoor space is kept within comfortable limits leading to improved energy efficiency. In a different study conducted by Maria et al. [88], a multi-domain methodology was adopted using a combination of energy simulation (Energy Plus) with a multi-criteria analysis method (PROMETHEE II) to rank solar shading devices of office buildings about different control strategies in North-West Italy. The result shows a combination of external shading with the most automated control strategy is the best alternative for reducing energy demand, occupants' comfort and environmental impact. Ying et al. [89] study is a multi-criteria optimisation approach using a combination of field measurement, building simulation (design-builder) and global sensitivity analysis to improve air conditioning and lighting energy efficiency by adopting three strategies—solar shading, cool roofs and natural ventilation in Guangzhou. The result shows roof insulation thickness, roof albedo, and window-to-wall ratio have an impact on energy use in lighting and air conditioning systems. Similarly, Marília & Leopoldo [90] is a multi-criteria methodology that used a combination of Simulation (Daysim 3.1), sensitivity analysis and ELECTRE III method to define windows for office buildings in Brazil. The result of the study shows that solutions without shading devices and solar control glazing performed poorly when compared to solutions with solar shading. A 4-phase energy retrofitting methodology was used in a study conducted by Ibrahim et al. [82] using a combination of field measurement, observations and building simulation (Design Builder) to assess the potential of transforming heritage building stock into nearly—zero-energy buildings in Egypt. The result shows that 66.4% of annual electricity consumption can be saved when a combination of active and passive non-energy generating scenarios are used.

The review of existing literature shows that what is common to these studies is the use of multi-criteria methodology to provide solutions to problems. Although the researchers adopted different building simulation software, they all made use of sensitivity analysis methods. Chen et al. [87] adopted a questionnaire survey in addition to the simulation and sensitivity analysis. This paper will adopt a multi-criteria methodology using a combination of a questionnaire survey, building simulation (IES VE software) and multi-criteria decision-making method to evaluate passive design approaches for residential buildings in Nigeria. The passive design strategies to be adopted in this study are the use of traditional building materials and thermal insulation of the Modern Building envelope.

METHODOLOGY

Research Design

This study investigates a residential building to adopt the best passive design strategy that resulted in indoor thermal comfort improvement and reduction in energy use. To achieve this, a questionnaire was first administered to the building occupants under study to determine the location of the building, building envelope properties, occupancy behaviour and actual energy use. The information obtained will be used in the development of the base model in IES VE software and for comparison with the simulation results. The building's current state is then subjected to dynamic energy simulation using IES VE software. Different passive design strategies were proposed as scenarios where the base model was optimized. The simulation results were then evaluated and compared to determine the best strategy in terms of reduction in energy use and indoor thermal comfort improvement using multi-criteria decision-making outranking method in visual PROMETHEE II software and then sensitivity analysis as shown in Figure 3. This study adopts a building simulation and multi-criteria methodology to evaluate the impact of passive design strategies in residential buildings in Nigeria and to ascertain which strategy has the highest thermal and comfort performance [88,90].

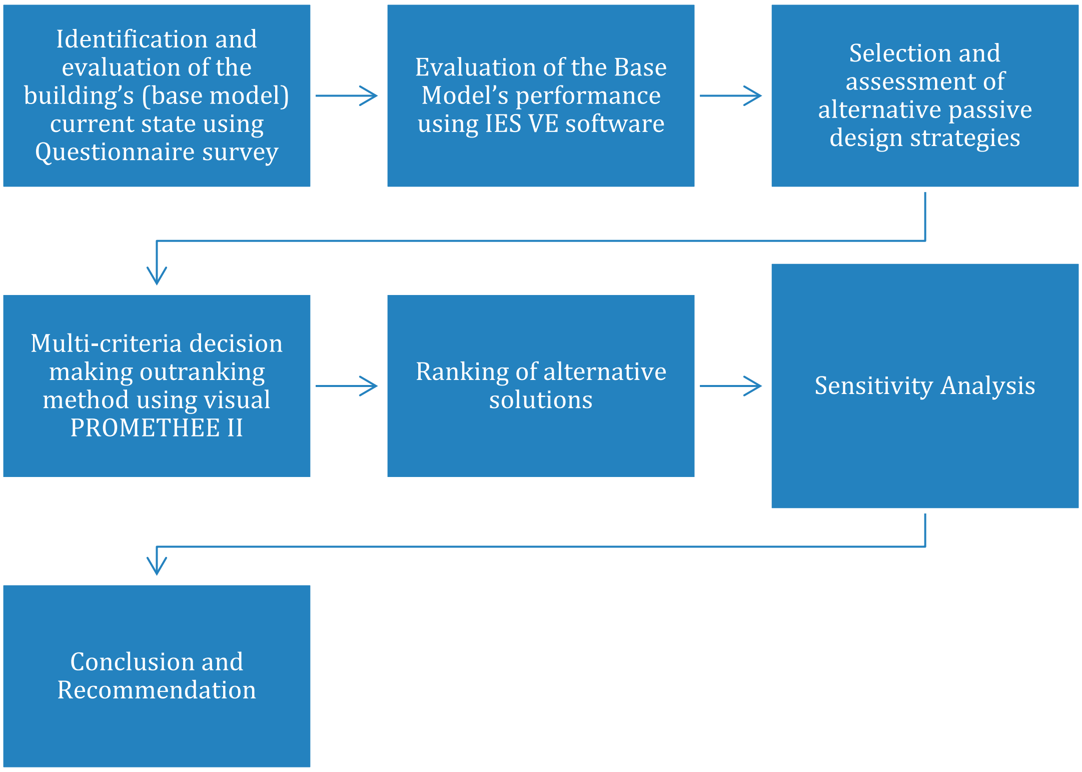

Figure 3. Workflow of a proposed multi-criteria methodology [88,90].

Location of the Study and Weather Data

The location of the study is Kano, Nigeria. Kano falls under the hot-dry climate zone, with coordinates (Latitude 12.0022°N, Longitude 8.5920°E), and elevation (488 m a.s.l) [17]. This location was chosen because it is the harshest in the climate zone, is a commercial city with many industries and is the most highly populated. For the simulation, the historical weather data of Kano was provided by climate.onebuilding.org weather files. The weather data is from 2007–2021 (January–December), containing the monthly maximum, minimum, and mean temperature, Relative humidity, precipitation, rainy days, average sunshine hours, and solar radiation.

Climate Analysis of Kano, Nigeria

Climate consultant software is used to analyse the climate of Kano, Nigeria using historical weather data of 2007–2021 derived from climate.onebuilding.org. As shown in Figure 4, the temperature is as low as 13.7 °C in January and as high as 38.7 °C in April and low humidity in the months of January–May and October to December. The figure also shows a high diurnal temperature variation of 15.7 °C in the dry season (January) and a low diurnal temperature variation of 5 °C in the rainy season (August). Although the average dry-bulb temperature in all the months has exceeded the comfort zone limits of 23–26 °C, the rainy season months are close to the comfort zone limits. Additionally, the outdoor relative humidity is high (exceeding the comfort limit of 30%–70%) during the rainy season in the months of June, July, August and September. This could lead to condensation or highly humid indoor space if the building envelope is not well insulated or does not have a moisture barrier and/or if there is moisture infiltration through building openings.

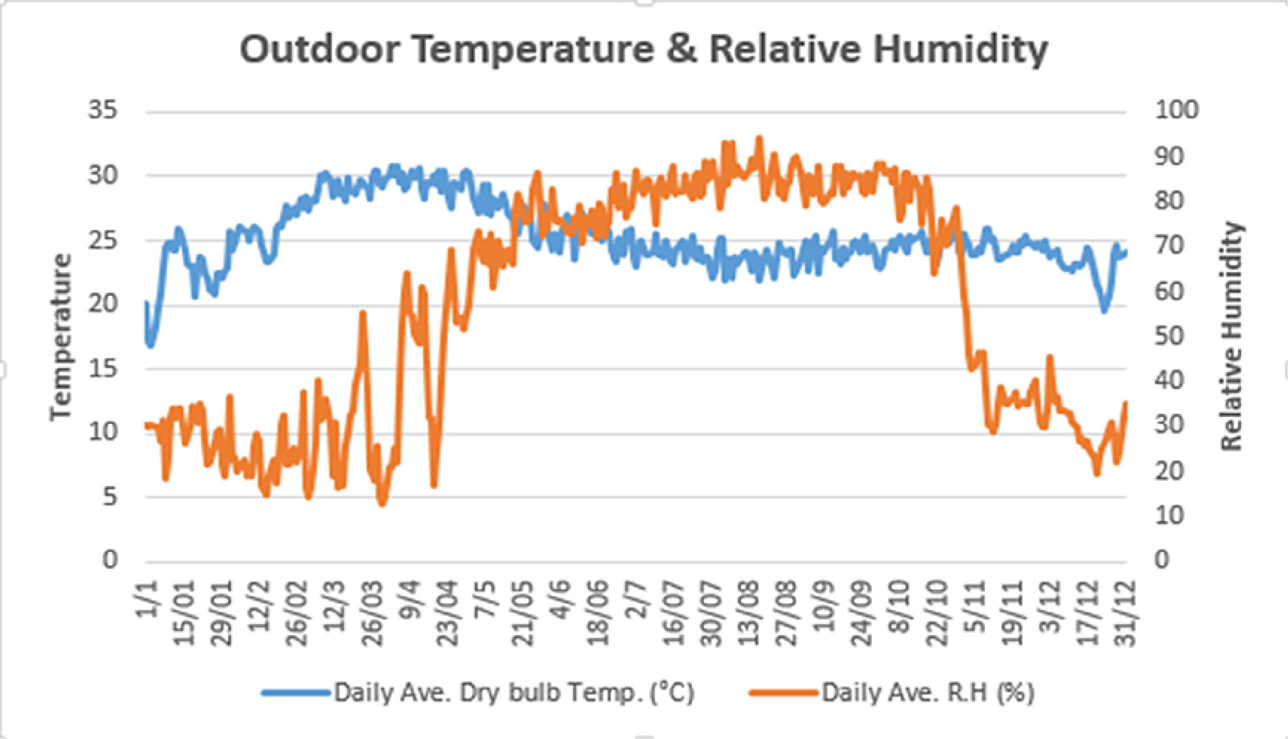

Figure 4. Daily average dry bulb temperature and outdoor relative humidity.

Questionnaire Surveyed

A questionnaire was designed to assess the current state of the building under study. The main content of the questionnaire is: Section A covers questions regarding the building location, type and occupants, section B covers the building envelope properties, section C contains questions relating to the occupancy behaviour and Section D has to do with energy consumption of the building. The questionnaire was administered to the building occupant and the responses were used in the development of the base model in IES VE software the energy use will be compared to the results obtained from the simulation.

Result of the questionnaire survey

The main content of the questionnaire and the results (responses) of the survey is shown in Table 3 while the actual monthly energy consumption of the building with the costs is shown in Figure 5.

Table 3. Data results of a questionnaire survey.

S/No.	Main Content of the questionnaire	Results
1	Building location	Kano, Nigeria
2	Type of apartment	Four Bedroom Duplex
3	Number of Building occupants	5
4	Wall Material	Sandcrete
5	Wall thickness	230 mm
6	Wall type	Solid wall
7	Wall Insulation	Nil
8	Roofing sheet material	Aluminium
9	Roofing sheets thickness	0.55 mm
10	Roof insulation	Nil
11	Lights	Switched off during the day
12	Lights	Switched off when building not occupied
13	Lights	Switched off during sleep
14	Air conditioning system	Switched off when the building is not occupied
15	24 h of electricity supply	No
16	Average hours of electricity supply per day	9–10 h
17	Annual energy consumption	5190.4 kWh (10.43 kWh/m^2 year)
18	Cost of electricity in Nigerian Naira	N62.4 per kWh

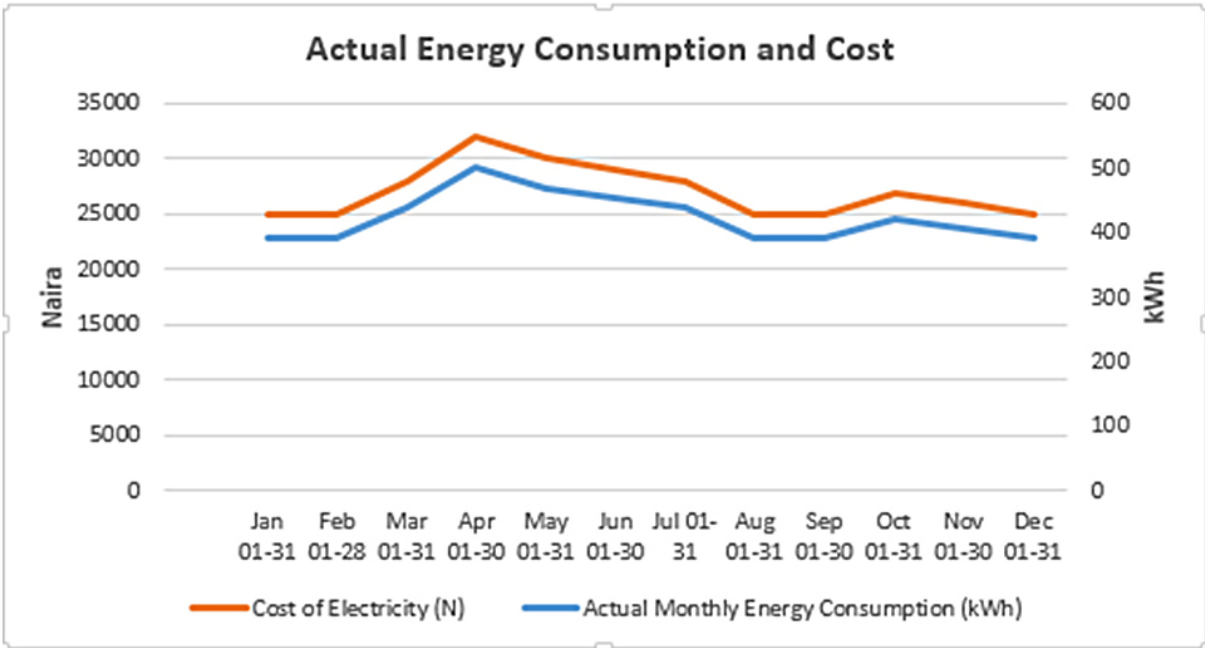

Figure 5. Actual monthly energy consumption of the case study building and cost of electricity.

The results of Table 3 will be used together with the data obtained from the literature review to develop the building's model in IES VE software. The result in Figure 5 shows the actual monthly energy consumption and their corresponding electricity cost. The consumption values were derived through meter readings and energy cost per 1 unit of electricity.

Numerical Simulation

Layout and the description of the base model

The base case building was designed in AutoCAD software (Figure 6), the design was then exported in Dxf format and imported into IES VE software, thereby, producing the base model in IES VE (Figure 7). The model is a four (4) bedroom one-storey duplex modern residential building for a high-income group that has an entrance porch, a living area, an anteroom, dining, a visitor's bedroom, a toilet, a store, and kitchen on the ground floor and a general living room, chapel, 3-bedrooms, and toilets on the first floor. The living area on the ground floor is facing the south-east axis and the one on the first floor is facing the south-west direction, this could be beneficial in the winter when sunlight is desired. The kitchen is positioned to the northeast axis to receive sunlight in the morning. Two bedrooms on the first floor are facing the East, one bedroom in the west, and the general living room is facing the south. The building model measures 15,647 mm long and 14,650 mm wide, and height of 6800 mm (3000 mm each from floor level) from the outside ground level, and a roof height of 4951 mm. The total floor area of the building is 497.89 m² and a volume of 1140.94 m³. The rooms were grouped to enable easy assigning of profiles, circulation and lettable area, ventilation/infiltration rates, and internal heat gains.

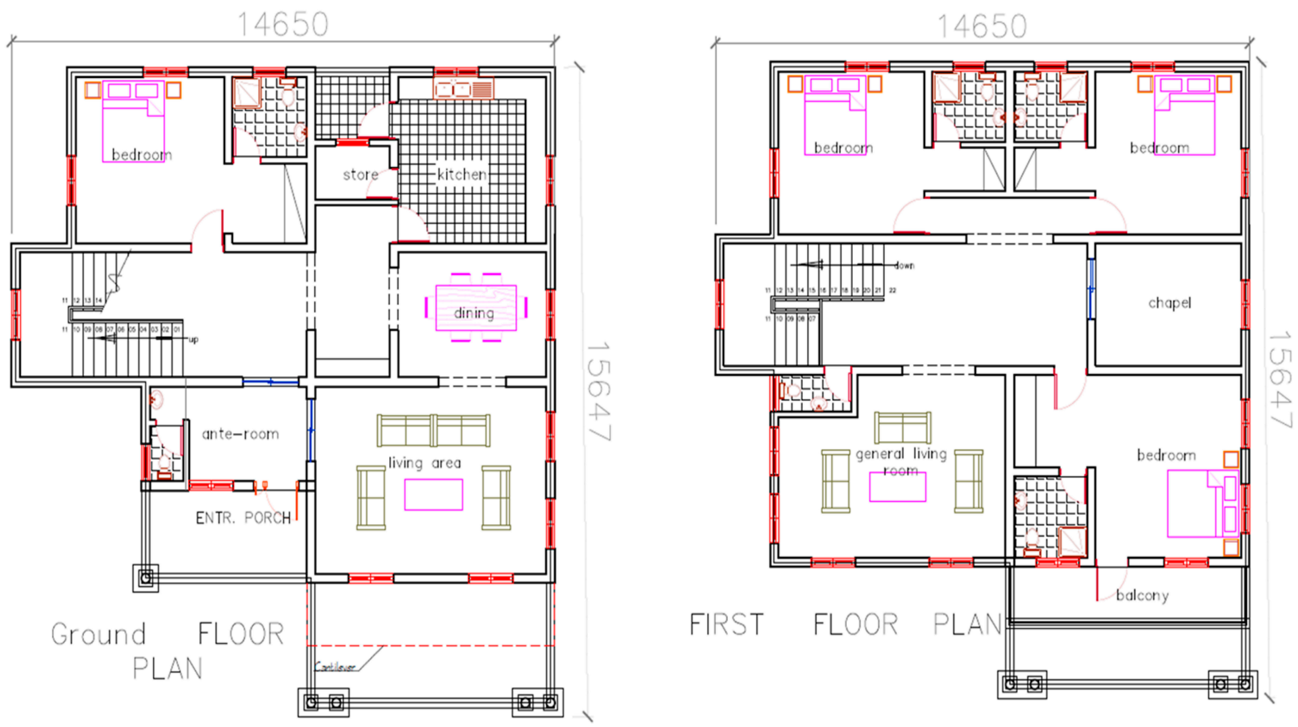

Figure 6. The base model in AutoCAD. Source: Iko Tambaya, Checked by: Architect Stephen Moses Maichibi & Architect James John Fainom (Member, Nigerian institute of Architects).

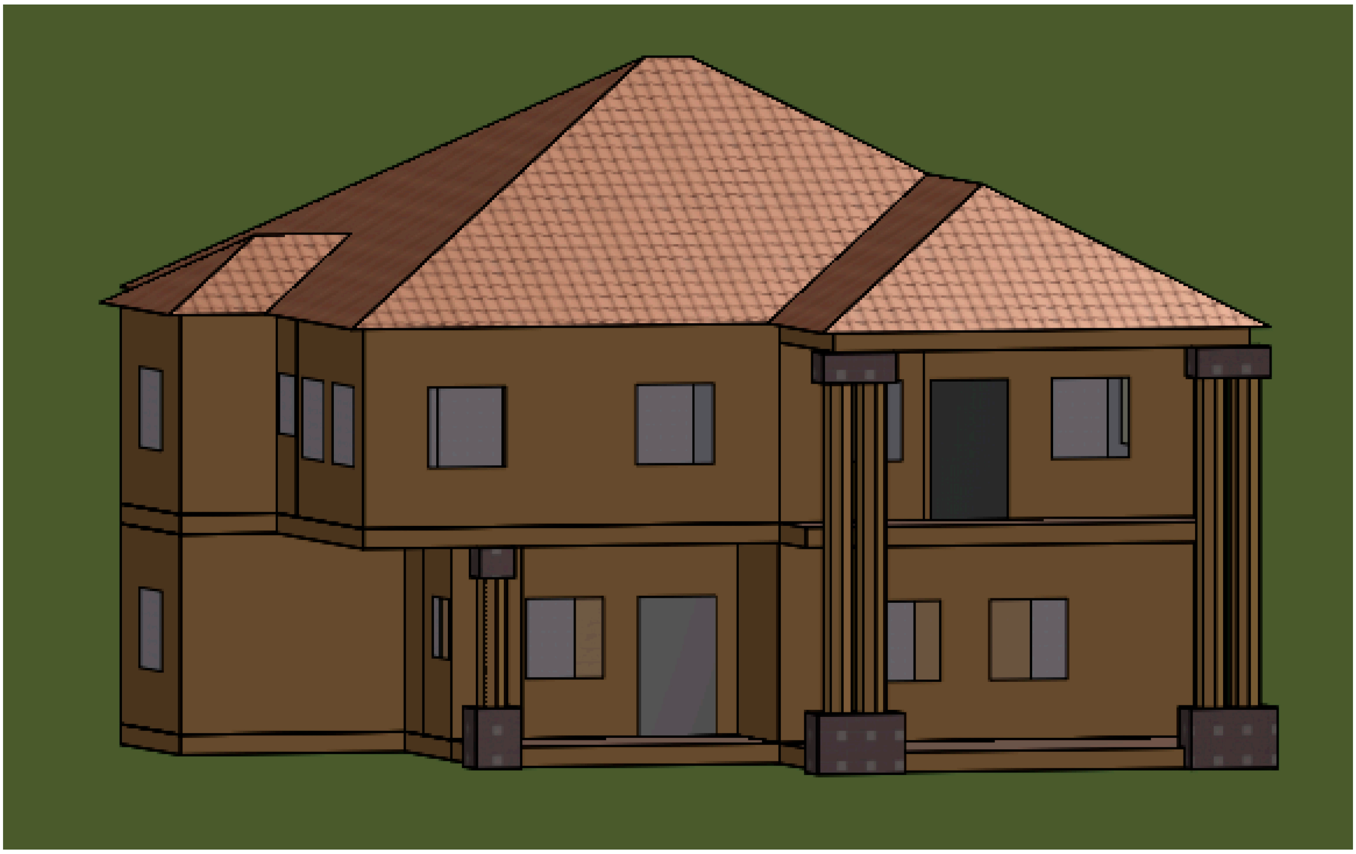

Figure 7. The base model in IES VE. Source: Iko Tambaya.

The door in the main entrance of the building is a black-coloured anti-rust steel bulletproof door of dimension 900 × 2100 mm, the internal doors are wooden flush doors on wooden frames with dimensions 900 × 2100 mm (rooms), and 750 × 2100 mm (toilet doors) [10,24]. The windows sill height is 900 mm and is made of aluminium framed casement windows with 6 mm thick tinted single glazing with dimensions 1200 × 1200 mm (rooms), and 900 × 900mm (toilets) [10,24].

Construction materials for the base model

The construction materials used in the base model are those in common practice in Nigeria as found in the literature and by the "National building code of Nigeria" [10,24,94]. The base model is a reinforced cement concrete (RCC) framed building with beams and columns of width sizes of 230 × 230 mm and 300 × 230 mm, respectively. The reinforced cement concrete first-floor slab thickness is 150 mm and cast in-situ concrete lintels span just above the opening of windows and doors. The description of the construction materials is shown in detail in Table 4.

Table 4. Construction material for the base model and their thermal properties, *U*-values, and standard *U*-values.

Construction		**External walls**			**Internal Partitions**			**Ground floor**		**Ceiling**		**Roof**	**Window**	**Doors**	
Construction layer	Cement plaster	Sandcrete Block wall	Cement plaster	Cement plaster	Sandcrete Block wall	Cement plaster	Ceramic tiles	Screed	Concrete Floor slab	Gypsum plaster (POP)	Reinforced concrete	Short-span aluminium roofing sheets	Aluminium framed single glazed	External metal doors	Internal wooden doors
Thickness (mm)	15	230	15	15	230	15	10	50	150	20	150	0.55	6	12	12
Thermal Conductivity W/(m*K)	0.72	1.63	0.72	0.72	1.63	0.72	0.84	1.40	1.13	0.42	2.3	160	1.06	50	0.15
Density kg/m^3	1800	2300	1800	1800	2300	1800	1900	2100	2000	1200	2300	2800	-	7500	560
U-value (W/m²K)		2.83			2.83			2.56		2.77		7.14	5.59	5.87	4.00
Standard *U*-value (W/m²K)		0.44			0.44			0.19		0.15		0.57	0.35	0.35	0.35

Source: [10,24,94]. Standard U-value (W/m²K) by Nevada guide [27,28].

Profiles and Assumptions

Occupancy profile

The model of the four-bedroom duplex is assumed to be occupied by five (5) people. On the first floor, the master bedroom is occupied by two people (husband and wife), and each of the two other bedrooms is occupied by one child. The visitor's room on the ground floor is assumed to be occupied by the housemaid only during weekdays. The living room on the first floor is where the building occupants spend most of their time in the evening and the living room on the ground floor is mostly used by the housemaid during weekdays, the children during weekends, and when there are visitors in the house. The kitchen is mainly used for cooking three meals a day. During weekdays, the parent leaves the house by 7:30 a.m. and returns by 4:30 p.m. while the two children leave the house by 7:30 a.m. and return by 2:00 p.m. On weekends, the full family is in the building except the housemaid who is allowed to spend her weekend with her family. The bedrooms on the first floor are only occupied during sleep from 10:30 p.m. to 6:30 a.m. and the dining area is only occupied when taking meals. It is assumed that the occupancy profile of toilets is the same as with bedrooms as they are all ensuite. The occupancy profile for the kitchen is the same as the store.

Natural ventilation, night cooling and AC system profile

The building makes use of a mixed mode of ventilation to achieve the desired level of indoor thermal comfort. It is assumed that during the cold season (December–February) the windows are permanently closed to prevent cold discomfort and dust infiltration, and during the hot season (March–July) the windows are closed during the daytime and open at night to prevent daytime heat infiltration and improve night-time cooling [75,76,79,80]. The air conditioning system set point is 26 ℃ and is only during occupied hours; also, windows will remain closed when the AC system is switched on [27,28,50–52]. Cooling by split air conditioning system is only provided in the four bedrooms, and the two living rooms during occupied hours. The airflow rate of 15 l/s, 30 l/s, and 13 l/s for bathrooms, kitchens, and bedrooms respectively was used as proposed by the building code of Nigeria [24]. For the rest of the months (August-November), the windows are configured to open by half from 11 am–6 pm and to open fully thereafter [80].

Lighting profile/Internal heat gains

The sunshine hours in Kano range between 8–11.3 h. For this reason, lighting was set to go off by 7:00 a.m. and come back on by 5:00 p.m. Also, the lights are off during sleep (22:30–6:00) [17,95]. The internal heat gains considered in this study are those from people, lighting, and equipment/appliances as presented in Table 5.

Table 5. Internal heat gains and their profiles.

Room Name	Source of Heat gain	Variable Profile
GF Bedroom	People (1)	Occupancy profile
	Fluorescent lamp	Lighting profile
FF Master Bedroom	People (2)	Occupancy profile
	Computer	From 18:00–23:00
	Fluorescent lamp	Lighting profile
FF Bedroom 1	People (1)	Occupancy profile
	Fluorescent lamp	Lighting profile
FF Bedroom 2	People (1)	Occupancy profile
	Fluorescent lamp	Lighting profile
Dining room	People	Dining Occupancy profile
	Fluorescent lamp	Lighting profile
Kitchen	Gas cooker	Kitchen Occupancy profile
	Refrigerator	On continuously
	Fluorescent lamp	Lighting profile
	People	Kitchen Occupancy profile
GF Sitting room	Fluorescent lamp	Lighting profile
	Television	Occupancy profile
	People	Occupancy profile
FF Sitting room	Fluorescent lamp	Lighting profile
	Television	Occupancy Profile
	People	Occupancy profile
Toilets	Fluorescent lamp	Lighting profile
	People	Occupancy profile
Chapel	Fluorescent lamp	Lighting profile
	People	Occupancy profile
Stairs/Circulation Area	Fluorescent lamp	Lighting profile
	People	Occupancy profile

Source: [96].

Comfort parameters

A default clothing level (insulation) of 1 Clo from IES VE was picked for all the building occupants and the activity levels were based on the major activity of a room. Bedrooms were set to sleeping, living rooms were set to seated at rest, Kitchen was set to sedentary work, standing, toilets were set to seated at rest, the dining room was set to seated at rest, and corridors were set to very light work, walking about.

Case Study

The simulation cases are set out to enable the objectives of the study to be achieved. They are passive design strategies adopted after the numerical simulation of the base model to determine which strategy is appropriate to the climate under study. The base model was optimized using these approaches however, the profiles of the base model remained the same. The strategies adopted are shown below:

Strategy 1: Traditional building envelope

This strategy seeks to compare the modern building materials used in the base model to the locally available (traditional) building materials in common use in the climate under study [97]. In the Northern part of Nigeria which is predominantly hot-dry climate [17], the traditional buildings are constructed of non-durable materials such as elephant grasses, reeds, and leafages. Houses and boundary walls are built with mud (adobe), or sun-dried bricks (tubali) made from clay [97]; The common roof types found in the North are dome-shaped or flat roofs usually made of clay, matting or thatched [98]. Table 6 shows the traditional building envelope and its *U*-values.

Table 6. Traditional Building Envelopes, their *U*-values, and standard *U*-values.

Case ID	Description (outside to inside)	*U*-Value	Standard *U*-Values
Wall	15 mm cement plaster, 230 mm sun-dried clay bricks, 15 mm cement plaster	0.87	0.44
Ground/Exposed floor	150 mm concrete floor slab, 150 mm laterite filling, 150 mm hard-core bed	1.22	0.19
Ceiling/upper floor	300 mm concrete floor slab, 20 mm gypsum plaster	2.02	0.15
Roof	350 mm thatch roof (straw)	0.19	0.57

Source: [17,97,98].

Strategy 2: Thermal insulation of modern building envelope

This strategy introduced insulation to the wall, floor and roof of the building. Foam insulation is used in this study ([72]. Table 7 shows the positioning and description of the insulation materials, their *U*-values and the standard U-values recommended by the Nevada guide for hot summer and cold winter climates [27,28].

Table 7. Insulation materials, their *U*-values, and standard *U*-values.

Case ID	Description (outside to inside)	*U*-Value	Standard *U*-Values
Wall Insulation T2 (i)	15 mm cement plaster, 100 mm foam insulation, 230 mm Blockwork, 15 mm cement plaster	0.23	0.44
Insulated ground floor T2 (ii)	10 mm ceramics tiles, 50 mm tile bedding, 100 mm foam insulation, 150 mm concrete floor slab	0.23	0.19
Insulated ceiling/upper floor T2 (iii)	10 mm clay tiles, 50 mm tile bedding, 100 mm foam insulation, 150 mm concrete floor slab, 20 mm gypsum plaster	0.23	0.15
Insulated roof T2 (iv)	0.6 mm aluminium roofing sheets, 150 mm foam insulation	0.16	0.57

Source: [70,72–74,96,99].

PROMETHEE II Multi-Criteria Analysis

Preference ranking organisation method for enrichment of evaluation (PROMETHEE) II is a multi-criteria decision-making method that is used to evaluate and compare (rank) different alternatives based on a set of criteria. There are eight (8) steps involved in the PROMETHEE II method as seen in the equations below:

(1) Start by creating an evaluation matrix that consists of alternatives and criteria.

$$(a_{ij})MxN \quad (3)$$

Where M is the alternative and N, is the criteria.

(2) Calculate the normalised decision matrix.

$$R_{ij} = \frac{\lfloor x_{ij} - Min\ (x_{ij}) \rfloor}{\lfloor Max\ (x_{ij}) - Min\ (x_{ij}) \rfloor} \text{ Benefit criteria} \quad (4)$$

$$R_{ij} = \frac{\lfloor Max\ (x_{ij}) - x_{ij} \rfloor}{\lfloor Max\ (x_{ij}) - Min\ (x_{ij}) \rfloor} \text{ Cost Criteria} \quad (5)$$

Where x_{ij} is evaluation values provided by decision-makers, i=1,.......,n, and numbers of criteria j=1,.......,m.

(3) Calculate the weighted wj of the criteria.

$$\sum_{j=1}^{k} wj = 1 \quad (6)$$

Each criterion must have its weight and the sum of all the weights should be 1. In this study, the weights were derived based on experts' knowledge.

(4) Determination of deviation by pairwise comparison.

$$d_j(a,b) = g_j(a) - g_j(b) \quad (7)$$

Where *dj (a,b)* is the difference between the evaluations of *a* and *b* on each criterion.

(5) Define the preference function.

$$P_j(a,b) = F_j\left[d_j(a,b)\right] \quad (8)$$

Where *Pj (a,b)* is the function of the difference between the evaluations of alternatives *a* regarding alternative *b* on each criterion into a degree ranging from 0 to 1.

(6) Calculate the multi-criteria preference index.

$$\pi(a,b) = \sum_{j=1}^{k} p(a,b)w_j \quad (9)$$

(7) Determine the positive and negative outranking flows.

$$\emptyset^{+}(a) = \frac{1}{n-1}\sum_{x \epsilon A} \pi(a,x) \quad \text{Positive outranking flows} \quad (10)$$

$$\emptyset^{-}(a) = \frac{1}{n-1}\sum_{x \epsilon A} \pi(x,a) \quad \text{Negative outranking flows} \quad (11)$$

(8) Calculate the net flow values and rank accordingly.

$$\emptyset(a) = \emptyset^{+}(a) - \emptyset^{-}(a) = \frac{1}{n-1}\sum_{j=1}^{k}\sum_{x \epsilon A}\left[p_j(a,x) - p_j(x,a)\right]w_j \quad (12)$$

The alternatives to be assessed in the visual PROMETHEE II software is the two strategies adopted in this study as shown in Tables 6 and 7 and the criteria to be used for the assessment are, the total annual energy consumption and cooling load, total annual CO_2 emissions, percentage of satisfied people in each month and cost of electricity as shown in Table 8.

Table 8. Selection of the Criteria for the Assessment.

S/N	Domain	Symbol	Criterion	Unit of Measurement
1	Energy	ENER1	Annual energy consumption	kWh/m^2 year
		ENER2	Annual cooling load	kWh/m^2 year
2	Environment	ENV1	Total annual CO_2 emissions	Kg CO_2 year
3	Thermal Comfort	COM1	% of satisfied people in all the months	%
4	Economy	ECON1	Cost of electricity per year in Nigerian Naira (N)	N/kWh/m^2 year

Source: [88,90,100].

Table 9 shows the parameters to be inputted into the Visual PROMETHEE II software after defining the alternatives and criteria. The performance of each alternative relative to each criterion is also shown. The weighting of the criteria is based on three experts' opinions. After completing the decision matrix (which is based on Equations 3 to 8), the data is inputted into the software for analysis.

Table 9. Input parameters of the decision matrix.

Preferences and Alternatives	Beneficial criteria				Non-beneficial
	ENER1	ENER2	ENV1	COM1	ECON1
	kWh/m^2 year	kWh/m^2 year	Kg CO_2.year	%	N/ kWh/m^2 year
Weightings	0.20	0.20	0.20	0.20	0.20
Direction of preference	Min	Min	Min	Max	Min
Preference function	*V*-shape	*V*-shape	*V*-shape	*V*-shape	*V*-shape
Indifference threshold (q)	n/a	n/a	n/a	n/a	n/a
Preference threshold (p)	2.4	2.0	616.6	1	N149.76
Strategy 1	35.9	9.2	9,150.6	0	2240.16
Strategy 2	33.5	7.6	8,534.0	50	2090.4

Source: [88,90,100].

RESULT AND ANALYSIS

Base Model Results Validation

The calibration of the base model was based on ASHRAE 2014 guidelines using the equation of coefficient of variance of the root mean square error (CV RMSE) and linear regression analysis [82,101]. This was done to ascertain the correlation and accuracy between the actual energy consumption (derived from the energy meter) of the case study building and simulated results. The CV RMSE calculation method is shown in Equation (13) below [87,101]. CV RMSE index helps to evaluate how well the model data fit and the lower the CV RMSE value, the better and more valid the simulation model. According to ASHRAE [101] guidelines, for the model to be acceptable the difference in value between the data measured and simulation data should be within ±30% of the CV RMSE (when using hourly data) and 15% when using monthly data.

Figure 8 shows the actual and simulated monthly energy consumption of the case study building and their coefficient of variation of root mean square error (CV RMSE). Although there is a wide difference in energy consumption, the consumption trend is almost the same. For instance, the highest actual and simulated energy consumption is in the month of April and the least consumption is in the months of August, December and January. Additionally, the CV RMSE values shown in Figure 8 are higher above the acceptable limit. However, the reason for the large difference is because of the epileptic power supply being experienced in Nigeria [6,48]. Based on the results obtained from a questionnaire survey of the case study building and result from a study conducted by Kayode et al. [48], residential buildings in Nigeria are usually supplied with electricity for only 9–10 h and 6–10 h per day respectively; as opposed to the simulation model that is controlled by 24 h/day electricity supply profile. If the actual annual electricity consumption of 10.43 kWh/m^2 year was to be based on an electricity supply of 24 h per day, the annual energy consumption would be 31.29 kWh/m^2 year as seen in Equation (14). Additionally, when the CV (RMSE) of the simulated annual energy consumption is recalibrated with the new actual annual electricity consumption of 31.29 kWh/m^2 year (based on 24 h per day electricity supply), the result (CV RMSE value of 10.4%) is within the acceptable limit recommended by ASHRAE 14 guidelines and is hereby accepted as seen in Table 10. Figure 9 shows a large difference between the actual annual energy consumption (based on an average of 8 h electricity supplies) and the simulated result of the building under study. However, the same figure shows an acceptable difference is observed when the actual energy consumption was recalibrated based on 24 h electricity supply. Linear regression is also carried out in SPSS to ascertain the accuracy of the calibration and the correlation between the actual and simulated energy consumption. A correlation coefficient (R^2) of 0.515 was obtained based on the results of Figure 8, showing a partially strong correlation between the actual and simulated energy consumption.

$$\text{CV RMSE} = \sqrt{\frac{\frac{\sum(Qi-\hat{Q}i)^2}{(n-p)}}{Q}} \quad (13)$$

Where, Qi = measured energy consumption and $\hat{Q}i$ = simulated energy consumption, n = 12, p = 1.

$$Ac = \frac{As}{Fs * Mc} \quad (14)$$

Where Ac, is annual electricity consumption in kWh/m^2 year, As, is actual electricity supply per day in hours (8 h), Fs, is full electricity supply per day in hours (24 h per day assumption) and Mc, is measured (actual) annual electricity consumption (10.43 kWh/m^2 year).

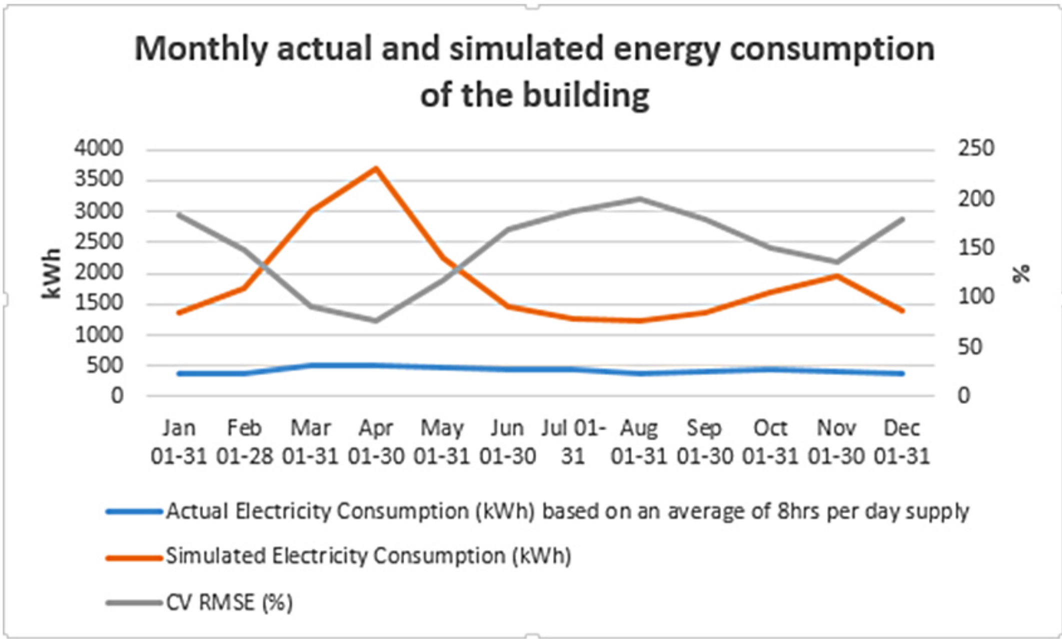

Figure 8. Monthly actual and simulated energy consumption of the building.

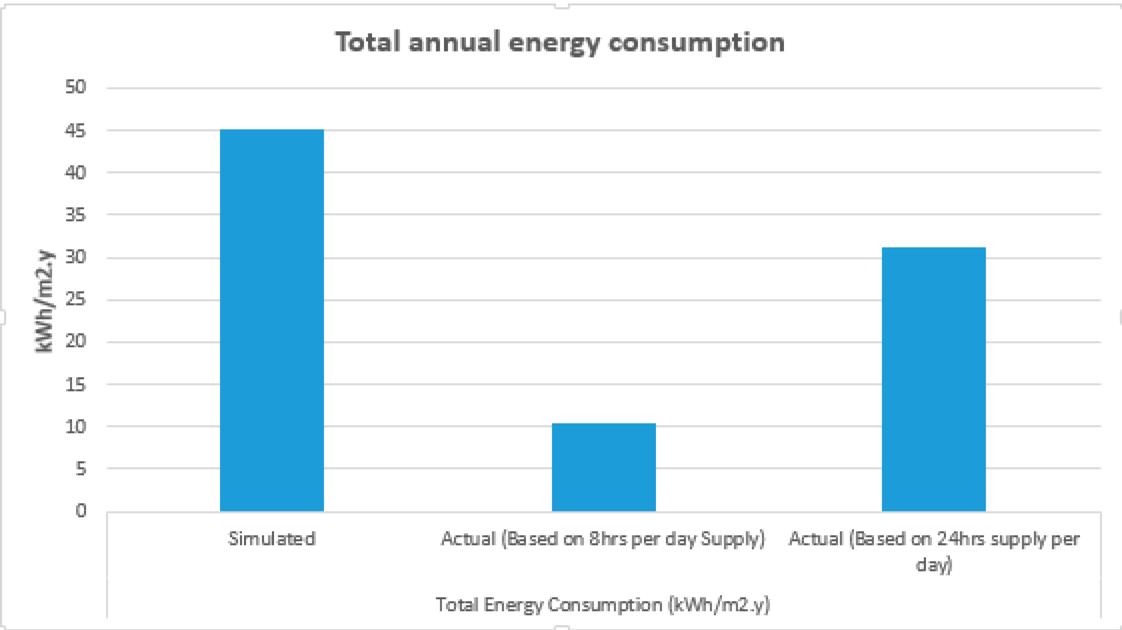

Figure 9. Actual and simulated energy consumption of the case study building.

Table 10. Annual actual and simulated energy consumption of the building (based on 24 h of electricity supply).

Actual Electricity Consumption (kWh/m^2 year)	Simulated Electricity Consumption (kWh/m^2 year)	CVRMSE (%)
31.29	45.1	10.4

Base Model Simulation Results

The result of the simulation show that the total annual energy consumption of the whole building is 45.1 kWh/m^2 year, which generated 11,919.6 kg CO_2 of carbon dioxide emissions. The total annual cooling load of the building is 14.5 kWh/m^2 year, representing 35.6% of the total annual energy use. The impact of cooling load predicted mean vote (PMV) and indoor air temperature on energy consumption can also be assessed. Additionally, the annual cooling load of the base model is lower when compared to the result of a study conducted by Amina et al. [13] and the recommendation by Chinese energy efficiency guideline [49] of total annual cooling loads of 26 kWh/m^2 year and 15 kWh/m^2 year respectively as seen in Figure 10.

In Figure 11, the peak energy consumption and cooling load are in the summer month of April, and the lowest energy consumption is in the months of August. Also, energy use is very high during the summer months due to the high demand for cooling the indoor space and low during the rainy season and winter months. The cooling demand reduces as soon as the rainy season commences in mid-May. The chart in Figure 11 also shows a strong relationship between the energy use of the building and the cooling load where a high cooling load leads to high energy consumption and vice versa. Similarly, the chart in Figure 12 shows a positive relationship between the cooling load and indoor air temperature. That is, an increase or decrease in indoor air temperature resulted in an increase or decrease in cooling load. Higher cooling load is observed in the summer months of March, April and May because the indoor air temperature in those months is higher, above the comfort conditions of 23–26 °C recommended Akande & Michael [4], ASHRAE [36], Hayatu et al [5] and ISO 7730 [37].

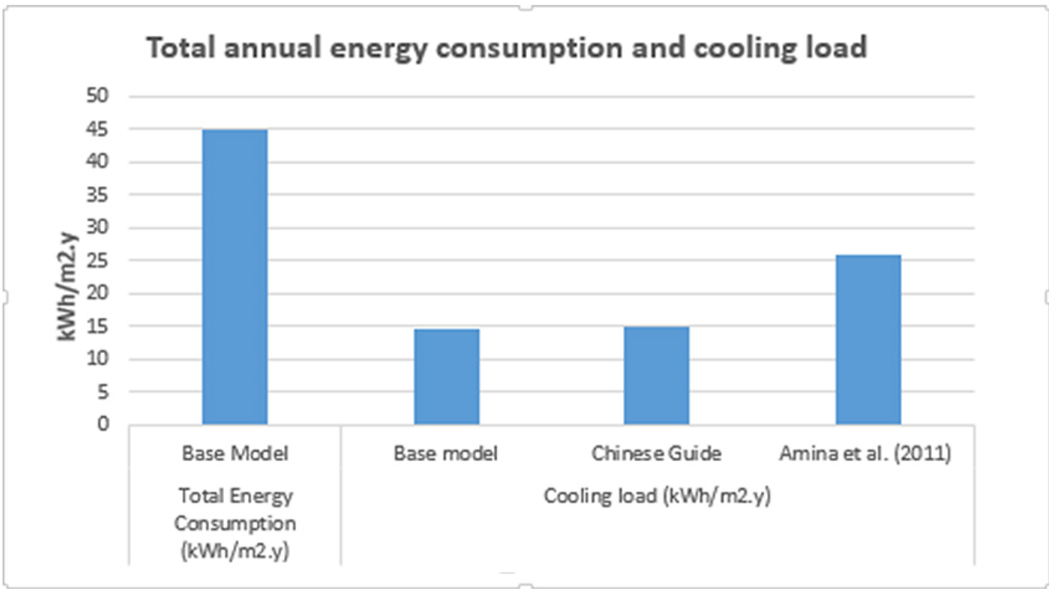

Figure 10. Comparing total annual energy consumption and cooling load.

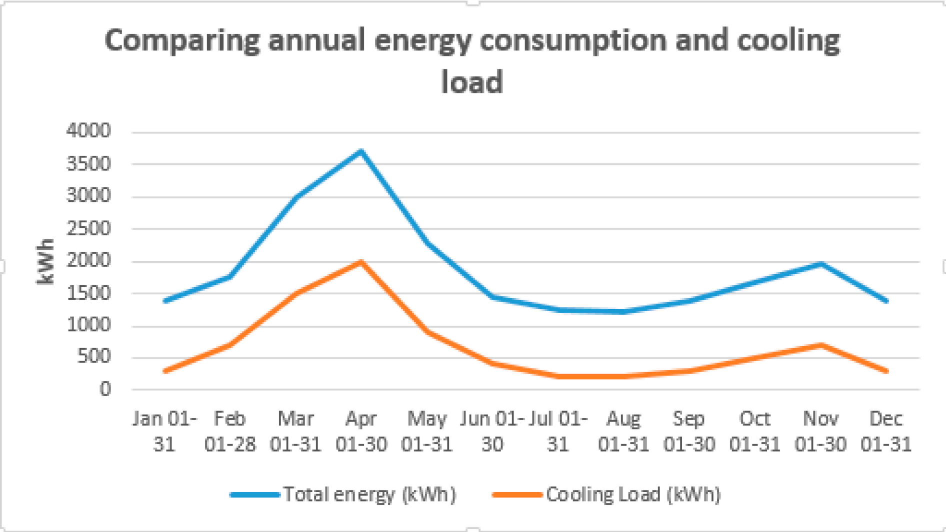

Figure 11. Comparing annual energy consumption and cooling load.

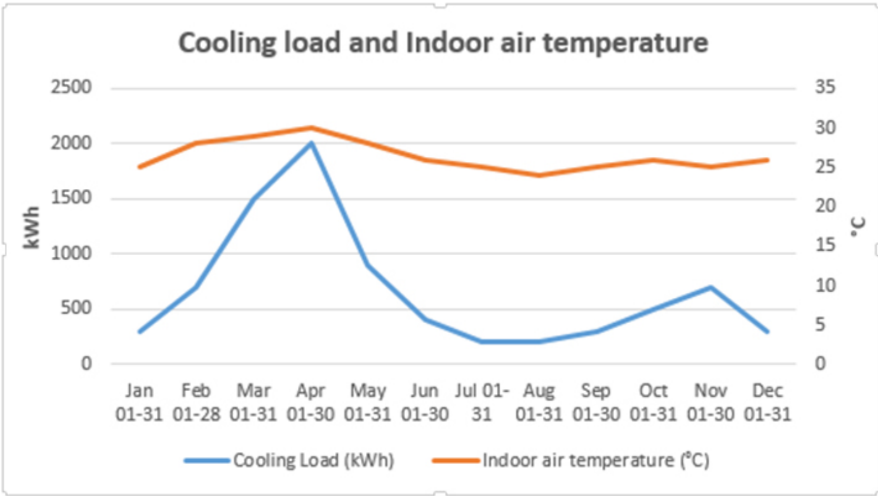

Figure 12. Comparing cooling load and indoor air temperature.

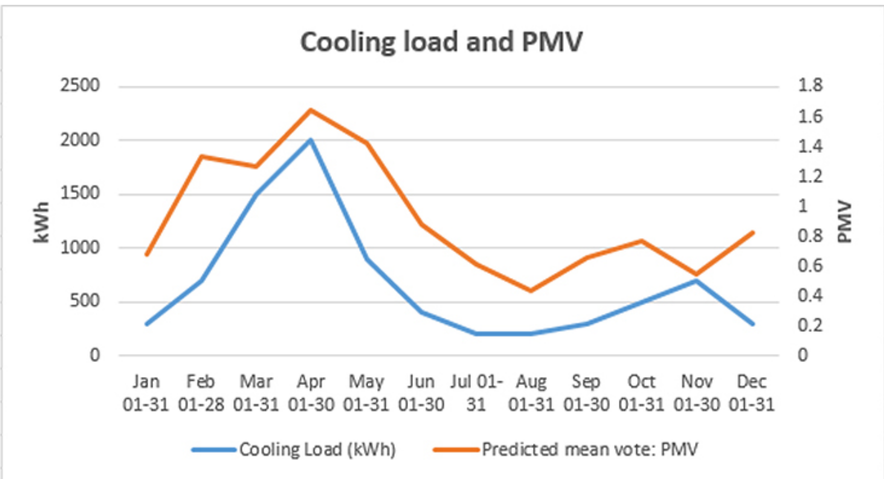

Figure 13. comparing cooling load and predicted mean vote.

Figure 13 shows the average monthly PMV values of the base model. The chart shows only the months of August and November are within the acceptable PMV range of –0.5 to +0.5 in the Fanger's thermal sensation [40]. Additionally, the months of January to July, September, October and December are within the PMV range of dissatisfaction in the thermal sensation scale ranging from PMV of +0.61 to +1.64. The heat discomfort associated with these values means that cooling is required to restore the building to acceptable comfort conditions [37,39,40]. The chart in Figure 13 also shows the relationship between predicted mean vote (PMV) and cooling loads; a high cooling load is observed especially in the summer months because the air conditioning systems are switched on to keep the temperature within an acceptable comfort range (PMV of –0.5 to +0.5) [37,39,40].

Scenarios and Cases

Strategy 1: Traditional building envelope

The building envelope is optimized using traditional building materials as shown in Table 6. The simulation result shows the total yearly energy consumption of the whole building to be 35.9 kWh/m^2 year which generated 9150.6 kg CO_2 of carbon dioxide emissions. The total annual cooling load of the whole building is 9.2 kWh/m^2 year, representing 25.7% of the total annual energy use of the building.

The charts in Figures 14 and 15 show the average monthly energy use, cooling load, air temperature and PMV. In Figure 14, the relationship between indoor air temperature and cooling load can be analysed. Higher temperatures that are outside of the comfort zone, leading to high energy consumption and cooling load are experienced in the months of March, April and May. The rest of the months are within the temperature range of 23–26 °C [4,5,36,37], keeping energy consumption and cooling load low in those months. In Figure 15, the PMV is acceptable when the temperature is kept within acceptable comfort conditions by the use of air conditioning (AC) systems [37,39,40].

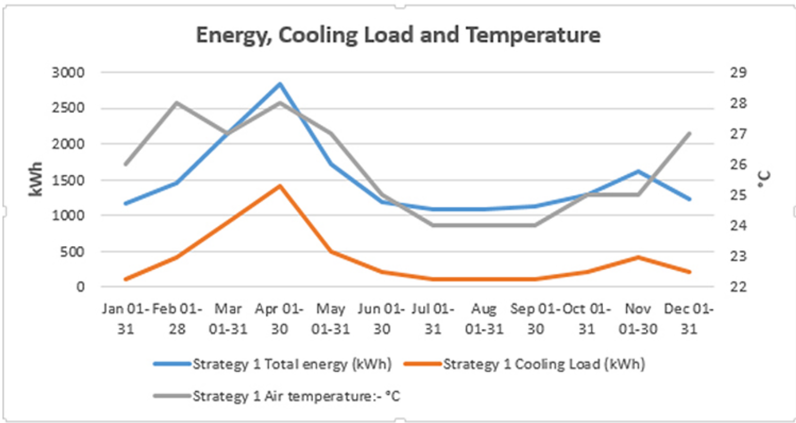

Figure 14. Average monthly energy consumption, cooling load and indoor air temperature.

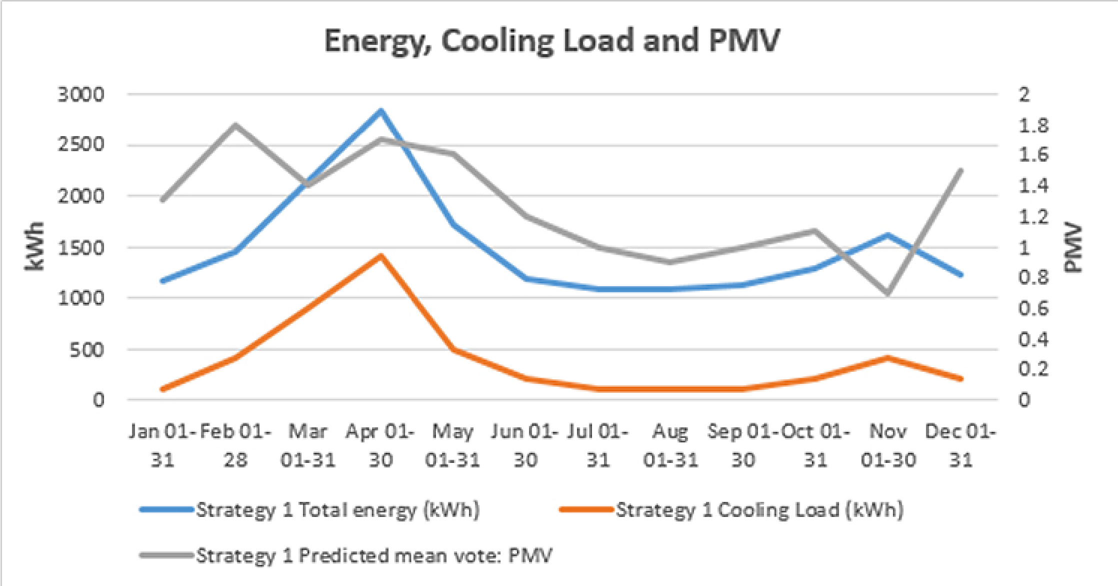

Figure 15. Average monthly energy consumption, cooling load and predicted mean vote.

Strategy 2: Thermal insulation of modern building envelope

Thermal insulation is added to the Modern building envelope as detailed in Table 7. The result shows the total yearly energy consumption to be 33.5 kWh/m^2 year, accounting for 8534.0 kg CO_2 of the carbon dioxide emissions. The total annual cooling load is 7.6 kWh/m^2 year, which represents 22.8% of the total annual energy use of the building.

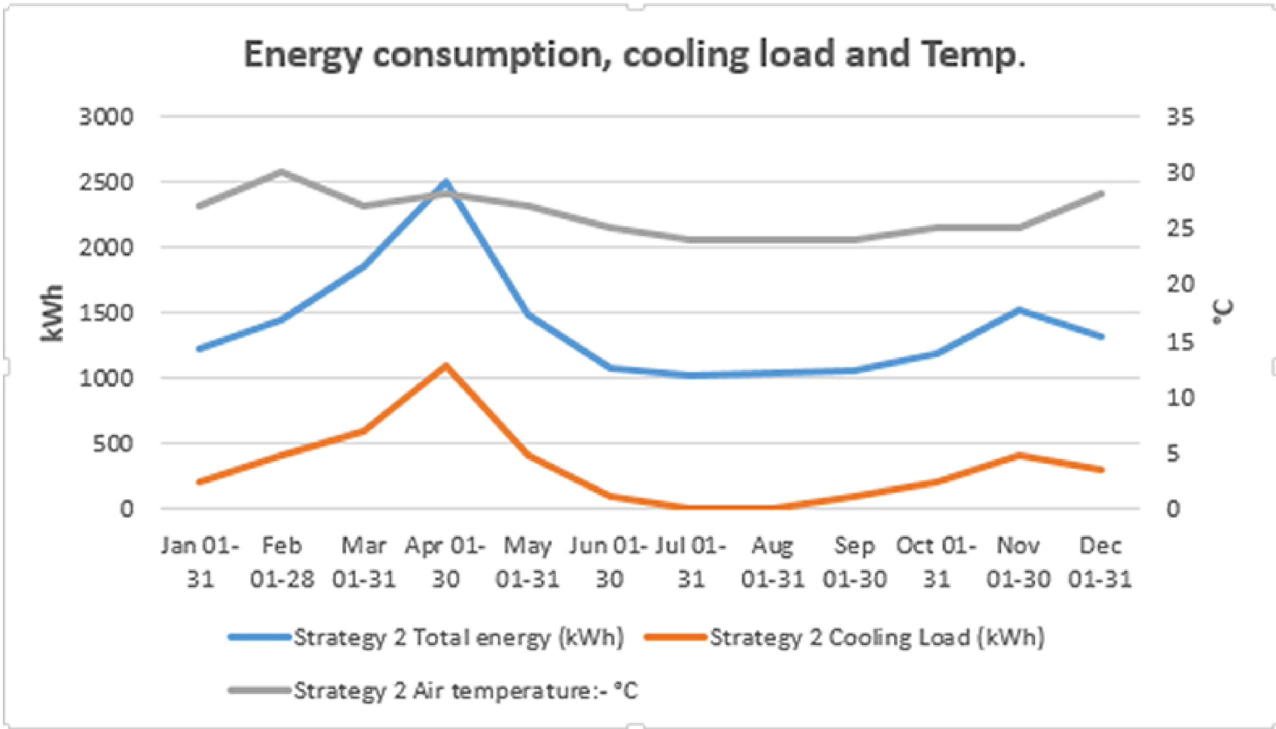

Figure 16. Average monthly Energy consumption, cooling load and indoor air temperature.

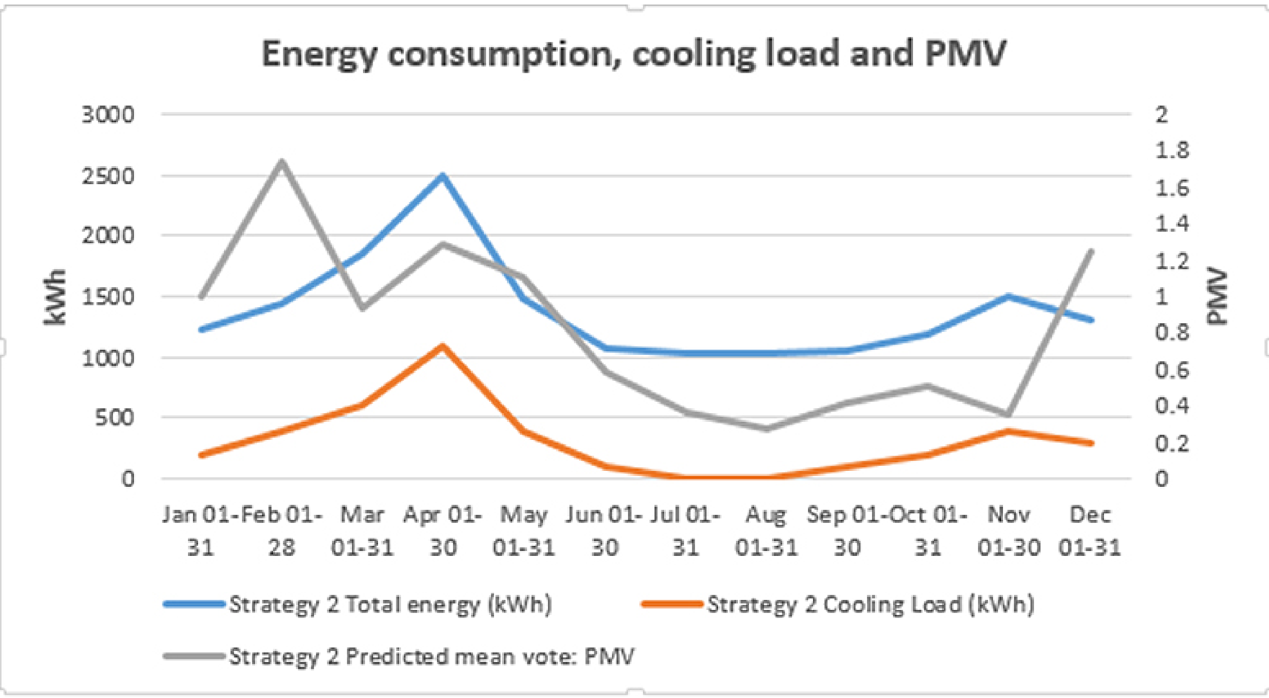

Figure 17. Average monthly energy consumption, cooling load and predicted mean vote.

The charts in Figures 16 and 17 show the average monthly energy use, cooling load, air temperature and predicted mean vote (PMV). In Figure 16, higher temperatures that are outside of the comfort zone, leading to high energy consumption and cooling load are observed in the summer months of March, April and May. The rest of the months are within the temperature range of 23–26 °C [5,36,37,40], keeping energy consumption and cooling load low in those months. The months of June to November are within the acceptable PMV limit of –0.5 to +0.5, making the building's indoor space comfortable for occupants as seen in Figure 17.

Comfort analysis for base model and strategy 1 and 2

This section analyses the comfort performance of the base model, strategies 1 and 2. The analysis is based on EN 15251 [38], ISO 7730 [37] and a study conducted by Graziano, Jens & Marta [25] and the result can be seen in Table 11. From the table, thermal comfort analysis for the base model shows only the months of August and November are within the comfort limit of −0.5 < PMV < +0.5 (PPD < 10%), representing 16.7% and 83.3% months of satisfaction and dissatisfaction respectively. Similarly, the comfort analysis of strategy 1 shows all the months are within the range of dissatisfaction (PPD > 15%), representing 0% months of satisfaction and 100% dissatisfaction. The analysis of strategy 2 shows the months of June to July to be within the comfort limit of –0.5 < PMV < + 0.5 (PPD < 10%), representing 50% and 50% months of satisfaction and dissatisfaction respectively.

Table 11. Criteria for thermal comfort analysis of base model and strategies 1 and 2.

Category	Thermal state of the body as a whole		Months under this category		
	PPD (%)	PMV	Base model	Strategy 1	Strategy 2
A	<6	−0.2 < PMV < + 0.2	Nil	Nil	Nil
B	<10	−0.5 < PMV < + 0.5	August, November	Nil	June to November
C	<15	−0.7 < PMV < + 0.7	January, July, September, October	November	Nil
D	>15	PMV<−0.7; or PMV > + 0.7	February, March, April, May, June, December	January to October and December	January to May and December
Percentage of Satisfied months			16.7%	0%	50%

Comparing base model to strategies 1 and 2

In Figure 18, thermal insulation of the modern building envelope (strategy 2) performed better in terms of energy use and cooling load, followed by the traditional building envelope (strategy 1) and lastly the base model. The Base model can also be compared to strategy 1 (Traditional Building Envelope) and strategy 2 (Thermal Insulation of Modern Building Envelope). There is a reduction in energy use by 20.4% and 25.7% and in cooling load by 36.6% and 47.6% when strategy 1 or 2 is used respectively. The high performance of strategy 2 (Thermal insulation of Modern building envelope) is due to the presence of thermal insulation in the building envelope compared to the absence of thermal insulation in the building envelope of the base model and strategy 1 (traditional building envelope). Thermal insulation of the building envelope doesn't only prevent heat from coming in or going out of the building leading to a reduction in cooling load by 38% [72], but can also serve as a moisture barrier which can reduce energy use due to dehumidification in the wet-humid season as seen in the climate analysis in Figure 4 [69,73,74,76,84].

The adoption of any of these strategies can also lead to a reduction in carbon-dioxide emissions as seen in Figure 19. When compared to the base model, there is a reduction in carbon-dioxide emissions by 23.2% and 28.4% when strategy 1 or 2 is used respectively. Figure 20 shows that the cost of electricity can also be reduced by 20.4% and 25.7% when strategy 1 or 2 is adopted respectively. Similarly, strategy 2 performed better when compared to the base model and strategy 1 as 50% of the months achieved a PPD of less than 15% as seen in Figure 21.

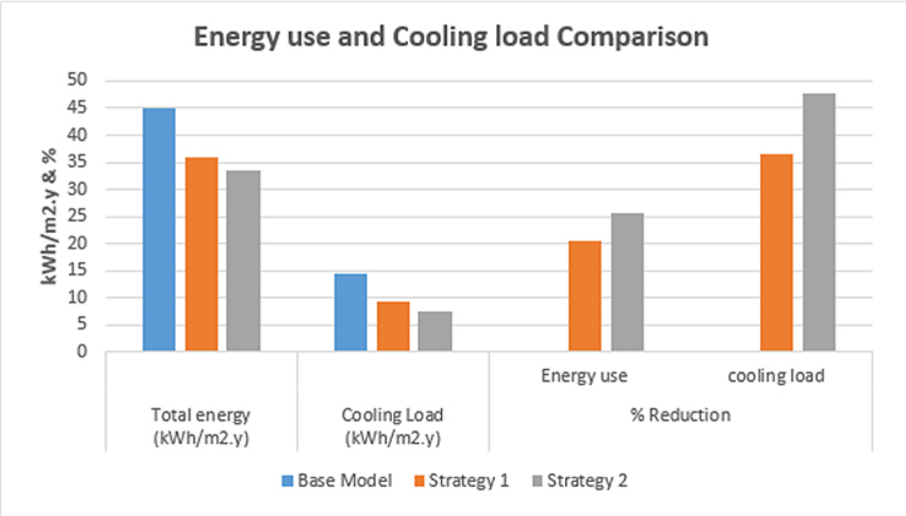

Figure 18. Energy use and cooling load comparison.

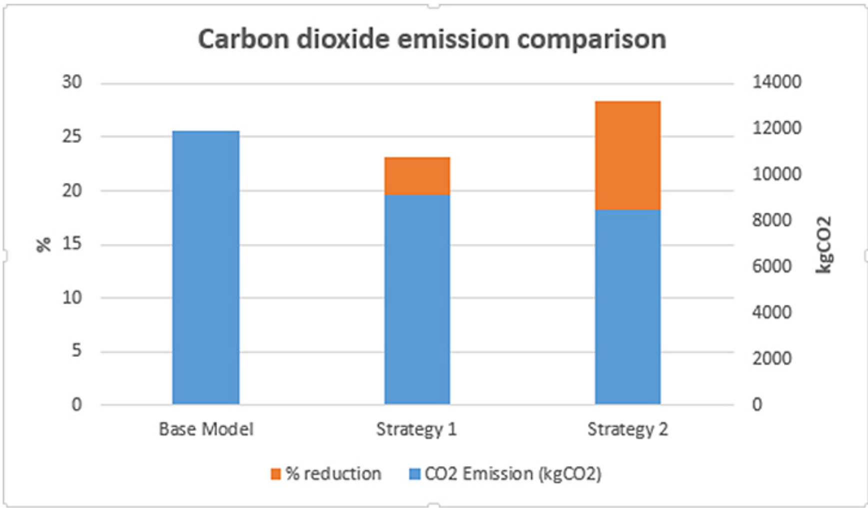

Figure 19. Carbon dioxide emission comparison.

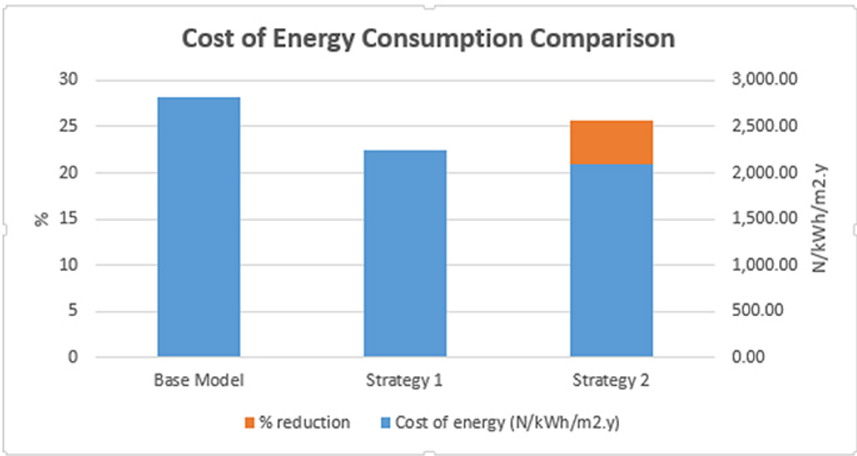

Figure 20. Cost of energy consumption comparison.

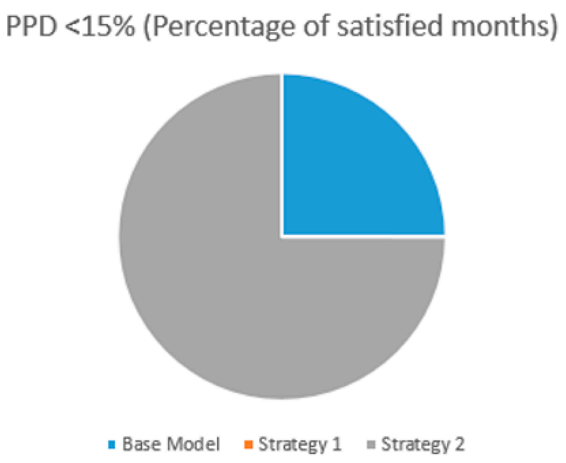

Figure 21. Percentage of months with PPD < 15%.

Sensitivity Analysis Approach

This sensitivity analysis was carried out using a combination of PROMETHEE I, PROMETHEE II and GAIA analysis to ensure robust and stable results. While PROMETHEEI is a partial outranking method that is based on positive and negative flows, PROMETHEE II is a complete outranking method that provides inter-criterion analysis that shows the performance of different alternatives, and GAIA plane shows the performance of the alternatives (strategies 1 and 2) in each criterion and their impacts. The positive, negative and net outranking flows of all the alternatives are presented in Table 12. Positive outranking flow shows how an alternative is outranking other alternatives. The higher the value the better and more powerful the alternative is over other alternatives. Conversely, a negative outranking flow shows how an alternative is outranked by other alternatives. The higher the negative outranking flow the weaker the alternative over others. Additionally, the net outranking flows are derived by finding the difference between the positive and negative flows. The higher the net flow value the better the alternative. The result in Table 12 and Figure 22 shows strategy 2 with the highest positive outranking flow and lower negative outranking flow, making it the best alternative when compared to strategy 1. Figure 22 also shows consistency in the information provided by both flows and the two alternatives are hereby considered comparable. Table 12 and Figure 23 show the net outranking flow (complete preference analysis) where the final ranking of the alternatives is derived, and strategy 2 remains the highest when compared to strategy 1, hence, becomes the best alternative.

The output from the GAIA plane in Figure 24 shows the graphical display of the alternatives and criteria. The two alternatives are represented by neon blue-coloured squares, the criteria are represented by blue axes and the decision stick is represented by red axis. The result in Figure 24 shows that the Percentage of satisfied people is not expressing similar preference with other criteria because the criterion axis is longer and is not oriented in approximately the same direction as other criteria and red decision stick. The total annual energy consumption, cooling load, CO_2 emissions and cost of electricity are expressing similar preferences as they are aligned in the same axes and towards the direction of the red decision stick. Furthermore, the figure also shows a moderate conflict among all the criteria because the red decision stick is pointed towards the right as other criteria. However, the two alternatives (strategies 1 and 2) show a wide conflict as the points are located directly opposite one another. Strategy 2 performed better in all the criteria as they are located on the same axis, pointing towards the decision stick.

The above results have further shown that the use of thermal insulation in the building envelope can effectively lead to energy savings associated with cooling load and improved thermal comfort, than the use of traditional building envelope without insulation (although, thatched roof provided good insulation to the roof). Although the thatch roof and clay bricks (tubali) adopted in the traditional building envelope (strategy 1) are locally available and are environmentally friendly building materials, the lack of durability, moisture and fire resistance of these materials [17,97,98] will likely make it unattractive to homeowners and building developers. Contrarily, the best-performing approach (strategy 2) can easily be adopted by homeowners because the building materials are made of modern, highly durable and aesthetically appealing [21–23].

Table 12. Values and rankings of strategy 1 and 2 using PROMETHEE II method.

STRATEGIES	Positive outranking flow	Negative outranking flow	Net outranking flow	PROMETHEE II RANKING
Strategy 1	0.0000	0.9600	−0.9600	2
Strategy 2	0.9600	0.0000	0.9600	1

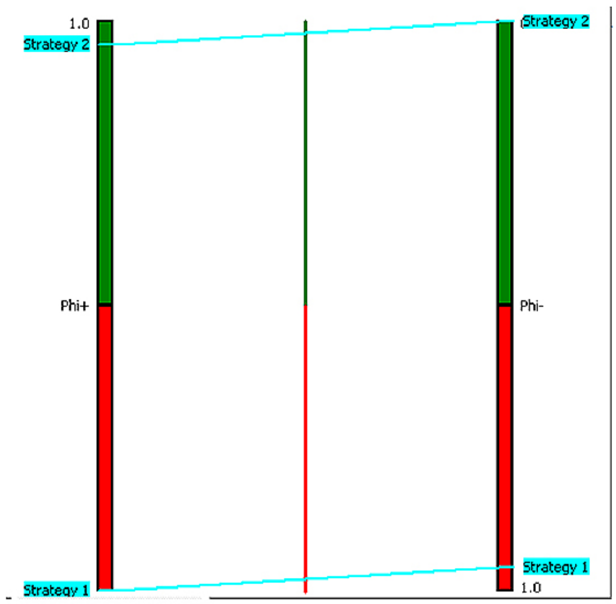

Figure 22. Partial preference analysis (PROMETHEE I) of the two alternatives (strategies 1 and 2).

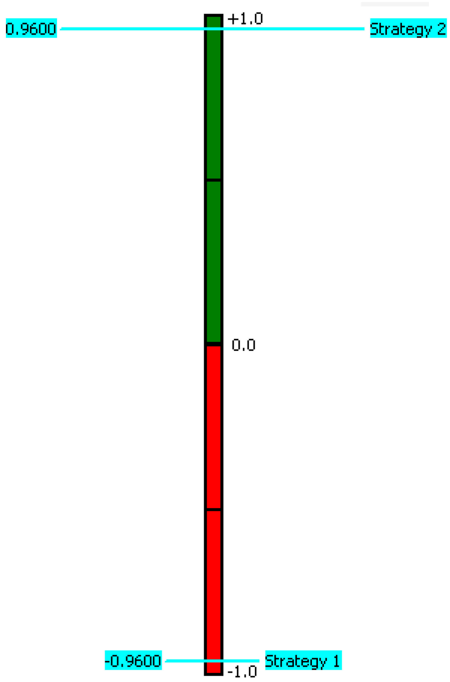

Figure 23. Complete Preference analysis (PROMETHEE II) of the two alternatives (strategies 1 and 2).

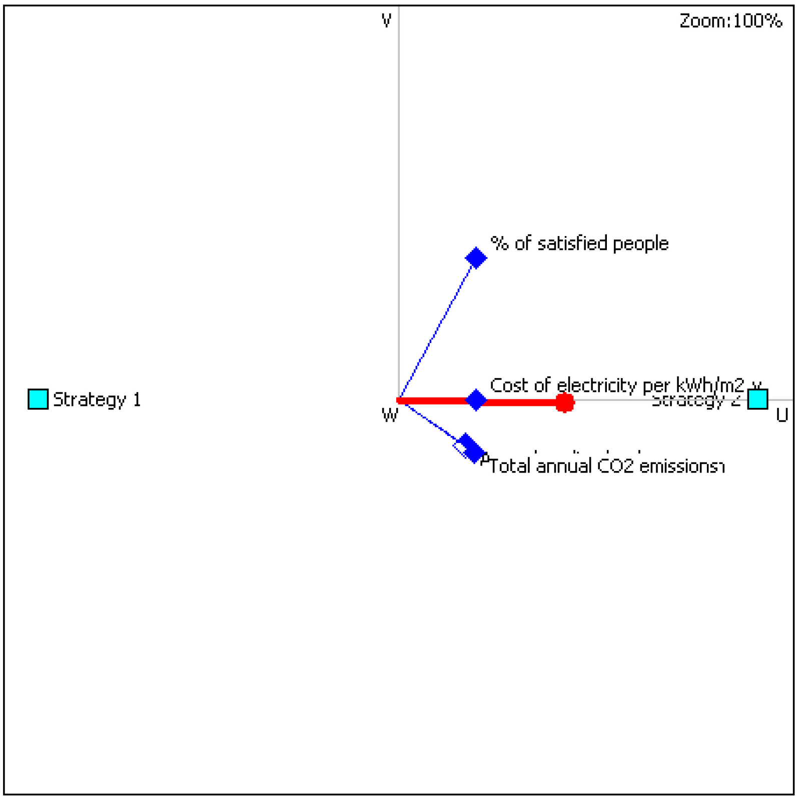

Figure 24. Analysis based on output from GAIA plan.

Although these strategies have shown a high impact on the thermal performance of buildings, several factors are preventing the adoption of passive design practices in the residential building sector in Nigeria, these include the lack of knowledge and awareness of passive design's importance, principles and practices by professionals, lack of absence of local building rating tool, lack of technical expertise, inconsistencies in Government policies [57–59]. When compared to other advanced countries of the world like the UK, they have adopted different energy efficient guidelines, policies and regulations to help mitigate climate change such as green building rating tools (BREEAM), BSI standards (approved documents F, L1, L1A, L2A, L2B), CIBSE guides, Net Zero targets et cetera. The Nigeria Government should declare a climate change emergency by engaging in the formulation of new policies and enforcing existing ones, setting nearly zero energy buildings (NZEBs) targets and energy efficiency guidelines. Our building code should not only centre on the durability and aesthetics of buildings [3,24] but should also address comfort and climate-responsive design. There should be a local green building rating tool and professionals and homeowners should be encouraged to use local building materials in construction. Lastly, the only way to decarbonize the residential building sector is by discouraging house owners from using diesel-powered generators and encouraging the use of renewable energy. In addition to the passive design strategies explored in this study, the proposed guideline and policy should also consider other passive design measures such as building orientation, cool roofs/walls, green roofs, overhangs, shading devices, double/triple glazing, and thermal mass as it has proven by previous studies to be effective in improving thermal comfort and energy efficiency in buildings [54,56,60–66,69,72–76].

CONCLUSION

As Residential buildings in Nigeria are not designed to respond to the local climate and the lack of consideration for the features and approaches that lead to indoor thermal comfort, building users have no choice than resort to the use of mechanical systems for cooling. These mechanical systems need energy to operate, and the epileptic nature of the electricity supply in Nigeria forces building occupants to rely on non-renewable energy sources which are carbon-intensive and could lead to climate change. To identify the best passive design strategies for the climate under study, a four-Bedroom one-storey modern residential building for single-family was picked within the hot-dry climate zone of Nigeria as a case study. The building is made up of a 230 mm hollow Sandcrete block wall and an aluminium roof. The design and construction of the building are by the normal practice and with the building regulation of Nigeria. The construction materials and profiles, glazing, cooling set-point, and standard *U*-values were derived from the Nigerian building code, a questionnaire survey result, a Chinese guide, and a Nevada guide. For the simulation, the historical weather data (2007–2021) of Kano was provided by climate.onebuilding.org weather files. A questionnaire survey was adopted to ascertain the thermo-physical properties of the building envelope, energy consumption by taking meter readings, occupancy behaviour and electricity supply schedule. The base case model was then designed in IES VE software, and the construction materials and profiles were made to conform to the standard regulations and guidelines of Nigeria. The base model was subjected to two different scenarios (Traditional building envelope and thermal insulation of Modern building envelope) and the results of the simulation were analysed and compared to the actual energy consumption using ASHRAE 2014 standard guidelines. A sensitivity analysis using visual PROMETHEE II software was carried out using the building simulation results to ascertain the robustness and stability of the results.

The results of the study show that an average of 9–10 h of electricity is supplied to residential buildings in Nigeria per day. Additionally, the actual and simulated electricity consumption of the base case building is 10.43 kWh/m^2 year and 45.1 kWh/m^2 year respectively. However, when compared to the simulated result, there is a large difference, making the result not to be within the acceptable range of ±30% of CV RMSE. When the results were recalibrated based on 24 h of electricity supply, the actual annual electricity consumption is 31.29 kWh/m^2 year which met an acceptable CV RMSE value of 10.4%. The trend of the actual and simulated energy consumption can be compared. There is a similarity in the energy consumption trend of actual electricity consumption in Figure 5 and simulated monthly energy consumption in Figure 8. Both charts show peak electricity consumption in the hot summer month of April and low consumption in the months of December, January, July, August, September and November. Although no data shows the actual electricity consumption associated with the cooling load, the simulated results show 35.6% (14.5 kWh/m^2 year) of electricity consumption of the case study to be due to cooling.

The base model was optimized with two different passive design strategies—Traditional building envelope (strategy 1) and thermal insulation of modern building envelope (strategy 2) as shown in Tables 6 and 7. In strategy 1 the wall of the base model was replaced with 230 mm thick sun-dried clay bricks and the roof was replaced with 350 mm thick thatch roof. The result of the simulation shows a reduction in annual energy consumption and cooling load by 20.4% (35.9 kWh/m^2 year) and 36.6% (9.2 kWh/m^2 year) respectively when compared to the base model. Similarly, in strategy 2 the building envelope of the base model was optimized with thermal insulation of varying thickness as seen in Table 6 and the result shows a reduction in annual energy consumption and cooling load by 21.3% (35.5 kWh/m^2 year) and 47.6% (7.6 kWh/m^2 year) respectively when compared to the results of the base model. The thermal comfort analysis shows strategy 2 performing better when compared to the base model and strategy 1 as 50% of the months achieved a PPD of less than 15%. The use of strategy 2 as an approach to the design of residential buildings in Nigeria can not only lead to energy savings associated with cooling but can also cause a reduction in carbon dioxide emissions by

23.2% and 28.4% when strategy 1 or 2 is used respectively and cost of electricity savings by 20.4% and 25.7% when strategy 1 or 2 is adopted respectively.

Additionally, the sensitivity analysis result shows the thermal insulation in the modern building envelope (strategy 2) performed better in all the criteria as they are located on the same axis, pointing towards the decision stick. Strategy 2 also has the highest positive outranking flow, lower negative outranking flow and highest net outranking flow. The output from the GAIA plane shows that the Percentage of satisfied people is not expressing similar preference with other criteria because the criterion axis is longer and is not oriented in approximately the same direction with other criteria and the red decision stick. The total annual energy consumption, cooling load, CO_2 emissions and cost of electricity are expressing similar preferences as they are aligned in the same axes and towards the direction of the red decision stick. There is also a moderate conflict among all the criteria because the red decision stick is pointed towards the right as other criteria.

There is no doubt that the adoption of these passive design strategies in the hot-dry climate of Nigeria will be important towards achieving a comfortable indoor environment without relying on mechanical systems for cooling.

CHALLENGES AND RECOMMENDATIONS FOR FURTHER STUDY

The following are challenges encountered during this research:

1. Lack of field measuring instruments to determine the actual weather condition of the building under study for a full year.
2. Lack of an energy meter that records the electricity consumption of the building when a diesel generator is used.

Given the above challenges encountered, the author recommends the use of a measuring instrument to accurately calibrate the simulated results with the measured results to record electricity consumption of energy use in the building that is not from the national grid and also to compare consumption patterns of different families.

DATA AVAILABILITY

The dataset of the study is available from the author upon reasonable request.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest.

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REFERENCES

1. IPCC. Climate Change 2013: The Physical Science Basis—Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available from: https://www.ipcc.ch/site/assets/uploads/2017/09/WG1AR5_Frontmatter_FINAL.pdf. Accessed 2023 May 10.
2. Oyedepo S, Adekeye T, Leramo RO, Kalinko O, Babalola OP, Balagun AO, et al. Assessment of energy saving potentials in covenant university, Nigeria. Energy Eng. 2016;113(3):7-26.
3. Federal Ministry of Power, Works and Housing. Building Energy Efficiency Guideline for Nigeria. Available from: https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf. Accessed 2023 May 10.
4. Akande KO, Michael AA. Indoor Thermal Comfort for Residential Buildings in Hot-Dry Climate of Nigeria. Available from: https://www.researchgate.net/profile/Oluwafemi-Akande-2/publication/308995623_Indoor_Thermal_Comfort_for_Residential_Buildings_in_Hot-Dry_Climate_of_Nigeria/links/57fd503d08ae406ad1f3d076/Indoor-Thermal-Comfort-for-Residential-Buildings-in-Hot-Dry-Climate-of-Nigeria.pdf. Accessed 2023 May 10.
5. Hayatu IM, Mu'az NM, Enaburekhan JS. An Assessment of Thermal Comfort in Hot and Dry Season: A Case Study of 4 Theaters at Bayero University Kano. Available from: https://www.researchgate.net/profile/Nura-Muhammad/publication/286453690_An_Assessment_of_Thermal_Comfort_in_Hot_and_Dry_Season_A_Case_Study_of_4_Theaters_at_Bayero_University_Kano/links/566aa5c508ae62b05f031306/An-Assessment-of-Thermal-Comfort-in-Hot-and-Dry-Season-A-Case-Study-of-4-Theaters-at-Bayero-University-Kano.pdf. Accessed 2023 May 10.
6. Akande KO. Passive design strategies for residential buildings in a hot dry climate in Nigeria. Available from: https://www.researchgate.net/profile/Oluwafemi-Akande-2/publication/271422871_Passive_design_strategies_for_residential_buildings_in_a_hot_dry_climate_in_Nigeria/links/56c37a5f08ae8a6fab5a0df3/Passive-design-strategies-for-residential-buildings-in-a-hot-dry-climate-in-Nigeria.pdf. Accessed 2023 May 10.
7. Luo X, Yu CW, Zhou D, Gu Z. Challenges and adaptation to urban climate change in China: A viewpoint of urban climate and urban planning. Indoor Built Environ. 2019;28:1157-61.

8. Du X, Bokel R, van den Dobbelsteen A. Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case. Build Environ. 2014;82:215-27.
9. CIBSE. Environmental design. Available from: https://www.cibse.org/media/ljmpptci/guide-a-presentation.pdf. Accessed 2023 May 12.
10. Mahmood AO. Investigation of the daylighting and the thermal environment of Nigeria's low-income housing: the case of Abuja. Available from: https://pure.port.ac.uk/ws/portalfiles/portal/7004484/Investigation_of_daylighting_and_the_thermal_environment_of_Nigeria_s_low_income_housing_Vol_2.pdf. Accessed 2023 May 10.
11. Geissler S, Österreicher D, Macharm E. Transition towards Energy Efficiency: Developing the Nigerian Building Energy Efficiency Code. Sustainability. 2018;10(8):2620.
12. Peter UO, Obinna GO, Christian IO, Chuckuemeka N. Bioclimatic practices in modern residential building design and construction in South-Eastern Nigeria. Available from: https://goldenlightpublish.com/dosyalar/baski/JCEMI_2020_202.pdf. Accessed 2023 May 10.
13. Amina B, Dudek SJ, Neveen H. Disaggregating Primary Electricity Consumption for Office Buildings in Nigeria. Available from: https://www.aivc.org/sites/default/files/P_1379.pdf. Accessed 2023 May 10.
14. Ibitoye FI, Adenikinju A. Future demand for electricity in Nigeria. Appl Energy. 2007;84(5):492-504.
15. FGoN. History of the Federal Republic of Nigeria. Available from: https://nigeria.gov.ng/about-nigeria/history-of-nigeria/. Accessed 2023 May 15.
16. Eludoyin OM, Adelekan IO, Webster R, Eludoyin AO. Air temperature, relative humidity, climate regionalization, and thermal comfort of Nigeria. Int J Clim. 2013;34(6):2000-18.
17. Tolulope DM, Parastoo P. Bioclimatic Approach for Climate Classification of Nigeria 2020. Sustainability. 2020;12(10):4192.
18. Dada FAO, Jibrin GM, Ijeoma A. Macmillan Nigeria Secondary Atlas. Ibadan (Nigeria): Macmillan Nigeria Publishers Ltd; 2008.
19. Ileoje NP. A New Geography of Nigeria. Lagos (Nigeria): Longman Nigeria; 2001.
20. Ogunsote B. Defining Climatic Zones for Architectural Design in Nigeria: A Systematic Delineation. J Environ Technol. 2002;1(2):1-14.
21. Ade AN, Adebayo SO, Bamigboye GO, Ogundeji J. Structural, economic and environmental study of concrete and timber as structural members for residential buildings in Nigeria. Int J Eng Sci. 2015;4(3):76-84.
22. Anthony N, Oluwarotimi M, Edwin E, Gideon O. Implications of Construction Materials on Energy Efficiency of Buildings in Tropical Regions. Int J Appl Eng Res. 2017;12(18):7873-83.

23. Ogunrin OS. A parametric analysis of the thermal properties of contemporary materials used for house construction in South-west Nigeria, using thermal modelling and relevant weather data. Available from: https://www.proquest.com/openview/930e9c06e04dee93ec252f5b28c4cd77/1?pq-origsite=gscholar&cbl=44156. Accessed 2023 May 10.
24. Federal Republic of Nigeria. National Building Code. Available from: https://estateintel.com/reports/national-building-code-of-the-federal-republic-of-nigeria. Accessed 2023 May 12.
25. Sesana MM, Salvalai G. Overview on life cycle methodologies and economic feasibility for nZEBs. Build Environ. 2013;67:211-6.
26. EU. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: of 19 May 2010 on the energy performance of buildings (recast). Available from: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF. Accessed 2023 May 12.
27. Cole PC. Nevada Compliance Implementation and Evaluation Guide. Available from: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21668.pdf. Accessed 2023 May 12.
28. ICC. International Energy Conservation Code 2009. Available from: https://www.lightingdesignlab.com/sites/default/files/pdf/International%20Energy%20Conservation%20Code_IECC_2009.pdf. Accessed 2023 May 10.
29. Ministry of Housing and Urban-Rural Development. Design standard for energy efficiency of residential buildings in hot summer and cold winter zone. Available from: https://www.codeofchina.com/standard/JGJ134-2010.html. Accessed 2023 May 15.
30. Federal Republic of Nigeria. National Renewable Energy and Energy Efficiency Policy (NREEEP). Available from: https://faolex.fao.org/docs/pdf/nig211220.pdf. Accessed 2023 May 12.
31. Department of Climate Change, Federal Ministry of Environment, Nigeria. 2050 Long-Term Vision for Nigeria (LTV-2050): Towards the Development of Nigeria's Long-Term Low Emissions Development Strategy (LT-LEDS). Available from: https://unfccc.int/sites/default/files/resource/Nigeria_LTS1.pdf. Accessed 2023 May 12.
32. Federal Republic of Nigeria. Climate Change Act 2021. Available from: https://faolex.fao.org/docs/pdf/NIG208055.pdf. Accessed 2023 May 12.
33. Federal Republic of Nigeria. Energy Transition Plan for Nigeria 2022. Available from: https://climate-laws.org/document/nigeria-energy-transition-plan_1d3f. Accessed 2023 May 12.
34. EU. Amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG. Accessed 2023 May 12.
35. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Handbook: Fundamentals. Atlanta (US): ASHRAE; 1997.
36. ASHRAE. Thermal Environmental Conditions for Human Occupancy. Available from: http://www.ditar.cl/archivos/Normas_ASHRAE/T0080ASHRAE-55-2004-ThermalEnviromCondiHO.pdf. Accessed 2023 May 12.

37. ISO. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Available from: https://www.iso.org/standard/85803.html#:~:text=ISO%207730%3A2005%20presents%20methods,exposed%20to%20moderate%20thermal%20environments. Accessed 2023 May 15.
38. CEN. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Available from: https://standards.iteh.ai/catalog/standards/cen/92485123-bf64-40e3-9387-9724a642eae8/en-15251-2007. Accessed 2023 May 12.
39. Emmanuel R. An urban approach to climate-sensitive design: strategies for the tropics. New York (US): Spon Press; 2005.
40. Fanger PO. Thermal Comfort: analysis and applications in environmental engineering. New York (US): McGraw-Hill; 1972.
41. Harimi D, Ming CC, Kumaresan S. A conceptual review on residential thermal comfort in the humid tropics. Int J Eng Innov Res. 2012:1(6):539-44.
42. Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build. 2002;34(6):563-72.
43. Al-Saadi SN. Envelope design for thermal comfort and reducing energy consumption in residential buildings. Available from: https://www.proquest.com/openview/6ab378e8fe8be7da365bf1d3b6eda391/1?pq-origsite=gscholar&cbl=18750&diss=y. Accessed 2023 May 12.
44. de Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy Build. 2002;34(6):549-61.
45. Olesen BW, Brager GS. A better way to predict comfort: The new ASHRAE standard 55—2004. Available from: https://escholarship.org/uc/item/2m34683k. Accessed 2023 May 12.
46. Yam R. Improving Thermal Comfort of Residential Buildings in Kathmandu-Using Passive Design Strategies. Available from: https://www.academia.edu/download/40099408/YAM_PRASAD_RAI-200994569.pdf. Accessed 2023 May 12.
47. Salvalai G, Pfafferott J, Sesana MM. Assessing energy and thermal comfort of different low-energy cooling concepts for non-residential buildings. Energy Convers Manag. 2013;76:332-41.
48. Kayode O, Benjamin CM, Seiichi O, Tetsuo T. Estimating Residential Electricity Consumption in Nigeria to Support Energy Transitions. Sustainability. 2018;10(5):1440.
49. Ministry of Housing and Urban-Rural Development. Technical Standards for Nearly Zero Energy Building-Energy-Efficient buildings in China: Standards and financing mechanism. Available from: https://transition-china.org/citiesposts/energy-efficient-buildings-in-china-standards-and-financing-mechanism/. Accessed 2023 May 15.
50. Hwang RL, Cheng MJ, Lin TP, Ho MC. Thermal perception, general adaptation methods, and occupants' idea about the trade-off between thermal comfort and energy saving in hot-humid regions. Build Environ. 2009;44(6):1128-34.

51. Yamtraipat N, Khedari J, Hirunlabh J. Thermal comfort standards for air conditioning buildings in hot and humid Thailand, considering additional factors of acclimatization and education level. Sol Energy. 2005;78(4):504-17.
52. Yang W, Zhan G. Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China. Int J Biometeorol. 2008;52:385-98.
53. Kroner MW. An intelligent and responsive architecture. Autom Constr. 1997;6(5–6):381-93.
54. Nusrat J, Aseel H, Badr A, Alison C. A Comparative Simulation Study of the Thermal Performances of the Building Envelope Wall Materials in the Tropics. Sustainability. 2020;12(12):4892.
55. Nyuk H, Yu C. Tropical Urban Heat Islands—Climate, buildings and greenery. Int J Vent. 2009;7(4):379-80.
56. Yahya LP. Passive Low Energy Architecture in Hot and Dry Climate. Aust J Basic Appl Sci. 2015;5(8):757-65.
57. Keftin NA, Yerima AA. Appraising the adoption of passive house concept for sustainable building construction in Nigeria. FUTY J Environ. 2016;10:1.
58. Sunday AB, Oludolapo IO, Oluwatobi NO, Modupeoluwa OA. Critical review of factors inhibiting the adoption of Green Building Design in Nigeria. Available from: https://pmworldlibrary.net/wp-content/uploads/2019/08/pmwj84-Aug2019-Factors-Inhibiting-Green-Building-in-Nigeria-1.pdf. Accessed 2023 May 11.
59. Muhammed AY, Ibrahim SK, Dalibi SG. Barriers and drivers facing architects in adopting energy efficiency and the use of zero-carbon technologies in Nigerian built environment. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/588/2/022046/pdf. Accessed 2023 May 11.
60. Maryam A, Ahmad T. Passive Design Strategies for Energy Efficient Housing in Nigeria. Available from: https://www.researchgate.net/profile/Maryam-Abbakyari/publication/320673556_Passive_Design_Strategies_for_Energy_Efficient_Housing_in_Nigeria/links/59f35d60458515547c205329/Passive-Design-Strategies-for-Energy-Efficient-Housing-in-Nigeria.pdf. Accessed 2023 May 11.
61. Zahiri S, Altan H. The Effect of Passive Design Strategies on Thermal Performance of Female Secondary School Buildings during Warm Season in a Hot and Dry Climate. Front Built Environ. 2016;2:e3.
62. Wong NH, Li SA. Study of the Effectiveness of Passive Climate Control in Naturally Ventilated Residential Buildings in Singapore. Build Environ. 2007;42(3):1395-405.
63. Foroughian S, Aiini MTS. Comparative study of single-glazed and double-glazed windows in terms of energy efficiency and economic expenses. J Hist Cult Art Res. 2017;6(3):879-93.
64. Al-Tamimi N, Fadzil SF. Energy-efficient envelope design for high-rise residential buildings in Malaysia. Archit Sci Rev. 2012;55(2):119-27.
65. Yasar Y, Kalfa SM. The effects of window alternatives on energy efficiency and building economy in high-rise residential buildings in moderate to humid climates. Energy Convers Manag. 2012;64:170-81.

66. Valladares-Rendón LG, Lo SL. Passive shading strategies to reduce outdoor insulation and indoor cooling loads by using overhang devices on a building. Build Simul. 2014;7:671-81.
67. The Concrete Centre. Thermal mass explained. Available from: https://www.concretecentre.com/Publications-Software/Publications/Thermal-Mass-Explained.aspx. Accessed 2023 May 15.
68. Roaf S, Fuentes M, Thomas S. Eco house. 3rd ed. London (UK): Routledge; 2007.
69. Hanan MT. Using passive cooling strategies to improve thermal performance and reduce the energy consumption of residential buildings in U.A.E. buildings. Front Archit Res. 2014;3(2):154-65.
70. ICANZ. Insulation handbook, Part 1: Thermal performance—total R-value calculation for typical building applications. Available from: https://www.bradfordinsulation.com.au/-/media/bradford/files/icanz-handbook-part-1-v3-may-2016. Accessed 2023 May 11.
71. Australian Government. Australia's guide to environmentally sustainable homes. Available from: https://yourhome.infoservices.com.au/. Accessed 2023 May 11.
72. Sayed HA. New Passive Cooling as a Technique for Hot Arid Climate 2018. In: Tsvetkov P, editor. Energy Systems and Environment. London (UK): IntechOpen; 2018. p. 83-96.
73. Bojić M, Yik F. Cooling energy evaluation for high-rise residential buildings in Hong Kong. Energy Build. 2005;37(4):345-51.
74. Kharseh M, Al-Khawaja M. Retrofitting measures for reducing buildings cooling requirements in the cooling-dominated environment: Residential house. Appl Therm Eng. 2016;98:352-6.
75. Solgi E, Fayaz R, Kari BM. Cooling load reduction in office buildings of hot-arid climate, combining phase change materials and night purge ventilation. Renew Energy. 2016;85:725-31.
76. Lei J, Yang J, Yang EH. Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore. Appl Energy. 2016;162:207-17.
77. Ogunsote OO, Prucnal-Ogunsote B, Adegbie M. Optimizing Passive Cooling Systems in Residential Buildings: A Case Study of Akure, nigeria. Available from: https://www.academia.edu/download/30904944/Optimizing_Passive_Cooling_Systems_in_Residential_Buildings_101017q.pdf. Accessed 2023 May 12.
78. Humphreys M, Ginger J, Henderson D. Effect of Opening Size and Wind Speed on Internal Pressures in Full-Scale Buildings. In: Wang C, Ho J, Kitipornchai S, editors. ACMSM25. Singapore (Singapore): Springer; 2020. p. 1061-9.
79. Ahmed ASF, Khan KMMK, Maung Than Oo AA, Golam Rasul RM. Selection of suitable passive cooling strategy for a subtropical climate. Int J Mech Mater Eng. 2014;9:14.
80. Bajwa M. Effectiveness of Nocturnal Ventilative Passive Cooling Strategy in the Maritime Desert Climate of the Arabian Gulf Region. Renew Energy. 1992;2(3):237-54.

81. Baggs D, Mortensen N. Thermal mass in building design. Available from: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=46cf97e59f78c022990e74906aedd277ff7a785a. Accessed 2023 May 11.
82. Ibrahim HSS, Khan AZ, Serag Y, Attia S. Towards Nearly-Zero Energy in Heritage Residential Buildings Retrofitting in Hot, Dry Climates. Sustainability. 2021;13(24):13934.
83. Salvalai G, Sesana MM, Iannaccone G. Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case study in Italy. Energy Build. 2017;148:23-36.
84. EPA. Moisture Control Guidance for Building Design, Construction and Maintenance. Available from: https://www.epa.gov/sites/default/files/2014-08/documents/moisture-control.pdf. Accessed 2023 May 11.
85. Ekele TO, Ahmad T. Energy Efficient Building Design in Nigeria: An Assessment of the Effect of the Sun on Energy Consumption in Residential Buildings. J Eng Archit. 2019;7(1):1-18.
86. Pacheco-Torres R, Dao AL, Ferrarini L. Scenario-based sensitivity analysis of energy dynamic behaviour in residential buildings with radiant floors. Available from: https://www.researchgate.net/profile/R-Pacheco-Torres/publication/322319854_Scenario-based_sensitivity_analysis_of_energy_dynamic_behavior_in_residential_buildings_with_radiant_floors/links/5f59e7df4585154dbbc412e4/Scenario-based-sensitivity-analysis-of-energy-dynamic-behavior-in-residential-buildings-with-radiant-floors.pdf. Accessed 2023 May 11.
87. Chen C, Wang M, Shen C, Huang Y, Zhu M, Wang H, et al. Sensitivity Analysis of Factors Influencing Rural Housing Energy Consumption in Different Household Patterns in the Zhejiang Province. Buildings. 2023;13(2):463.
88. Pinto MC, Crespi G, Dell'Anna F, Becchio C. Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings. Appl Energy. 2023;332:120470.
89. Liu Y, Gao Y, Zhuang C, Shi D, Xu Y, Guan J, et al. Optimization of top-floor rooms coupling cool roofs, natural ventilation and solar shading for residential buildings in hot-summer and warm-winter zones. J Build Eng. 2023;66:105933.
90. Fontenelle MR, Bastos LEG. The multi-criteria approach in the architecture conception: Defining windows for an office building in Rio de Janeiro. Build Environ. 2014;74:96-105.
91. Chen R, Tsay YS. An Integrated Sensitivity Analysis Method for Energy and Comfort Performance of an Office Building along the Chinese Coastline. Buildings. 2021;11(8):371.
92. Shady A, Liliana B, Andre OH, Jan H. "Architect Friendly": A Comparison of Ten Different Building Performance Simulation Tools. Available from: https://orbi.uliege.be/bitstream/2268/167578/1/BS09_0204_211.pdf. Accessed 2023 May 11.
93. Crawley B, Jon WH, Michael K, Brent TG. Contrasting the Capabilities of Building Energy Performance Simulation Programs. Build Environ. 2018;43(4):661-73.

94. Ezema IC, Olotuah AO, Fagbenle OI. Estimating Embodied Energy in Residential Buildings in a Nigerian Context. Int J Appl Eng Res. 2015;10(24):44140-9.
95. Climate Data. Climate conditions of Kano, Nigeria. Available from: https://en.climate-data.org/africa/nigeria/kano-356/r/january-1/. Accessed 2023 May 15.
96. Patrick B. Reducing the electricity consumption due to air conditioning in the tube house in Ho Chi Minh City. Available from: https://www.academia.edu/23211837/MSc_Thesis_Reducing_AC_electricity_in_the_HCMC_tube_house_Patric_Binova. Accessed 2023 May 15.
97. Bogda PO. Classification of Nigerian Architecture. Available from: https://desmo.biz/images/Architecture.pdf. Accessed 2023 May 11.
98. Agboola OP, Zango MS. Development of Traditional Architecture in Nigeria: A case study of Hausa House Form. Int J Afr Soc Cult Tradit. 2014;1(1):61-74.
99. Al-Obaidi KM, Ismail M, Rahman AMA. Passive cooling techniques through reflective and radiative roofs in tropical houses in South-east Asia: A literature review. Front Archit Res. 2014;3(3):283-97.
100. Moreira MAL, Gomes CFS, dos Santos M, da Silva Júnior AC, de Araújo Costa IP. Sensitivity Analysis by the PROMETHEE-GAIA Method: Algorithms evaluation for COVID-19 prediction. Available from: https://www.researchgate.net/profile/Carlos-Francisco-Gomes/publication/358352015_Sensitivity_Analysis_by_the_PROMETHEE-GAIA_method_Algorithms_evaluation_for_COVID-19_prediction/links/61fe5c4c1674b45977c81338/Sensitivity-Analysis-by-the-PROMETHEE-GAIA-method-Algorithms-evaluation-for-COVID-19-prediction.pdf. Accessed 2023 May 11.
101. ASHRAE. Measurement of energy, demand and water savings. Available from: https://upgreengrade.ir/admin_panel/assets/images/books/ASHRAE%20Guideline%2014-2014.pdf. Accessed 2023 May 11.

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