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EVALUATING THE IMPACT OF BUILDING ENVELOPE MATERIALS AND INSULATION ON ENERGY USE, THERMAL COMFORT, AND COST IN MULTI-FAMILY HOUSING IN ABUJA, NIGERIA

Isa Imam MAI

Master's Thesis

Supervisor

Asst. Prof. Dr. Ayşe Esra İDEMEN

İstanbul, 2025

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The thesis titled EVALUATING THE IMPACT OF BUILDING ENVELOPE MATERIALS AND INSULATION ON ENERGY USE, THERMAL COMFORT, AND COST, IN MULTI-FAMILY HOUSING IN ABUJA, NIGERIA, prepared by ISA IMAM MAI and submitted on 11/06/2025 has been **accepted unanimously** for the degree of Master of Science in Architecture.

Asst. Prof. Dr. Ayşe Esra İDEMEN
Supervisor

Thesis Defense Committee Members:

Asst. Prof. Dr. Ayşe Esra İDEMEN	Department of Architecture, Altınbaş University	
Asst. Prof. Dr. Can UZUN	Department of Architecture, Altınbaş University	
Prof. Dr. Ozan Önder ÖZENER	Department of Architecture, İstanbul Technical University	

I hereby declare that this thesis meets all format and submission requirements for a Master's thesis.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Isa Imam MAI

Signature

DEDICATION

In the name of Allah, the Almighty, the most merciful, the most gracious, the source of all strength and wisdom and sustenance, I humbly dedicate this thesis.

To my beloved parents, Alh, Ahmed Tijjani Mai and Late. Haj. Aishatu A.T Mai for their unwavering love, encouragement, prayers and sacrifices. Their confidence and faith in me have been my greatest motivation, and I am forever grateful for their endless support.

To my siblings especially Muhammad Inuwa Mai, for all your support, understanding and encouragement. And my friends who have supported and contributed to this research. Thank you for your endless words of encouragement.

And to my dearest fiance, Naja'atu Ibraheem Biu, your love and unwavering support have been my anchor through the highs and lows of this academic pursuit. Your patience, and understanding cannot be unmatched and I am forever grateful for your presence in my life.

PREFACE

I will like to start by giving my deepest gratitude to ReliaBuild Properties Limited for supporting this masters through a scholarship that made this educational path feasible. Your support has not only alleviated the financial burden, but also has been a great motivation and encouragement for me during my studies.

I'm especially grateful to my supervisor, Asst. Prof. Dr. Ayse Esra Idemen for her excellent guidance, patience and helpful contributions. Your guidance was a vital part in shaping this research and guiding me throughout every step of the thesis journey. I also thank Asst. Prof. Dr. Can Uzun whom, with his exciting and effective courses during the coursework, added depth to my new architectural interest.

Also, do note that during the coursework I have been inclined towards exploratory machine learning implementations in architectural realms but my love towards green sustainable Architecture took precedence. Without that love, this research might have gone in a very different direction. Over time, I hope to explore both of these interests together as a cross-point between smart technologies and sustainable solutions in architecture.

Finally, I want to acknowledge my family, friends, and all those who extended their support, encouragement, and belief in my capabilities during this academic endeavor. You have as much share in this achievement as I have.

ABSTRACT

EVALUATING THE IMPACT OF BUILDING ENVELOPE MATERIALS AND INSULATION ON ENERGY USE, THERMAL COMFORT, AND COST IN MULTI-FAMILY HOUSING IN ABUJA, NIGERIA

MAI, Isa Imam

M.Sc., Department of Architecture, Altınbaş University,

Supervisor: Asst. Prof. Dr. Ayşe Esra İDEMEN

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Global climate crisis has highlighted the pressing need for sustainable development, putting it at the centre of international discussion. The Paris Agreement serves as revolutionary international legal framework designed to power global efforts at combating climate change, setting global temperature targets increase to no more than 1.5^0C to 2^0 C less than pre-industrial levels. In order to keep up with this target, global emissions must be reduced by nearly 43% by 2030 and net-zero by 2050. Inarguably, two-third of total energy consumption and greenhouse gas emissions occur in building sector. Nigeria's energy demand far outweighs the supply with poorly designed buildings causing environmental degradation on one hand and economic hardship on the other, the nation's high reliance on non-renewable energy sources, frequent blackouts and rising demand for cooling provides opportunities for Alternative solutions. Net-zero Energy Buildings are one of the few ways to decarbonize an industry which is more energy-consuming than any other as they produce as much clean renewable energy as they demand annually. This research aims to create a simulation model that compares and analyses the energy performance of an Improved building envelope through material selection and insulation, to a conventional building envelope with respect to energy demand/consumption, thermal comfort and cost. by investigating the energy use pattern of buildings in Abuja and passive design strategies to reduce such energy use through envelope optimization. This study integrated qualitative and quantitative analytical approaches by comprehensive review of relevant literature and contextual data and the employment of a simulation-based approach using DesignBuilders EnergyPlus simulation engine to provide analysis on the energy performance two models. The Improved model show significant annual energy savings of up to 32.7%, average operative temperatures fell into acceptable ranges for thermal comfort, and annual CO_2 emissions decreased by as much as over 8 metric-tons.

Keywords: Building Envelope, Net-Zero Energy Building (NZEB), Energy Simulation, Passive Design, Thermal Comfort, Design Builder.

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ABBREVIATIONS

ACH	:	Air Changes per Hour
ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	:	Carbon Dioxide
COP	:	Conference of the Parties
DB	:	DesignBuilder
DCV	:	Demand-Controlled Ventilation
EPW	:	EnergyPlus Weather
ETC	:	Energy Transition Council (of Nigeria)
ETP	:	Energy Transition Plan (of Nigeria)
FCT	:	Federal Capital Territory
FCTEMIS	:	Federal Capital Territory Education Management System
FEC	:	Federal Executive Council
GHG	:	Green House Gas
GW	:	Giga Watt
HVAC	:	Heating, Ventilation and Air Conditioning
kWH	:	KiloWatt Hour
LSG	:	Light-to-Solar Gain Ratio
NBC	:	National Building Code (of Nigeria).
NCCAP	:	National Climate Change Action Plan (of Nigeria)

NCCC	:	National Council on Climate change (of Nigeria)
NZEB	:	Net-Zero Energy Building
PV	:	Photovoltaic
RC	:	Reinforced Concrete
SHGC	:	Solar Heat Gain Coefficient
uPVC	:	Unplasticized Polyvinyl Chloride
VLT	:	Visible Light Transmittance
WWR	:	Window-to-Wall Ratio

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The increasing serious global climate crisis has highlighted with ever greater urgency the pressing need for sustainable development, putting it at the centre of international discussion. With the intensifying environmental challenges, countries, organizations and decision makers have had to face the problem of creating strategies that backs green, low-carbon and flexible development. The need to take quick action to address climate change, reduce carbon footprints and promote sustainable practices has turned this into a key pillar of global policy making, economic planning and social development. The Paris Agreement, adopted in 2015 serves as revolutionary international legal framework designed to power global efforts at fighting climate change, setting ambitious targets for global temperature increase, aiming at ideally no more than 1.5^0 C or at worst under 2^0 C colder than pre-industrial levels, (The Paris Agreement, 2016). An assessment cycle is now started which makes it mandatory for each 5 years that every country should report on their work in promoting emissions reduction through ongoing auditing of responsibilities and fairness in discussion with others. The agreement calls for a major shift from fossil energy to such as marine energy, underlining all the potentials of technological innovation and economic growth that this can bring and at the same time the basic requirements for decreasing greenhouse gas emissions level (The Paris Agreement, 2016).

The Paris Agreement, (2016) also stated that in order to maintain average global temperatures rise below 1.5°C above pre-industrial level, the world must reduce global emissions by nearly 43% by 2030 and achieve net-zero emissions by 2050. The targets are not just ambitious, but vital limits which must be reached if we are to avoid the worst effects of climate change, in the likes of extreme weather, biodiversity loss and socio-economic disruptions. In this context, the building sector, in which noteworthy global energy consumption and CO_2 emissions occurs, has a leading role to play. Promoting Net-Zero Energy Buildings (NZEBs), particularly in developing regions undergoing rapid urban growth, such as Abuja, Nigeria, is a fundamental approach to harmonizing construction activities with global climate objectives. The built environment can play a vital role in driving down emissions and enacting broader sustainability initiatives through the optimization of building envelopes, promoting energy efficiency, and the embedding of renewable energy systems.

1.1.1 Energy Crisis and Fossil Fuel Dependence in Nigeria

It is difficult to balance Nigeria's energy demand and supply as demand far outweighs the supply. In response to these all-round challenges, experts suggest that a strategic turning point towards decentralized, renewable energy technologies is necessary, especially critical in rural areas and stand-alone systems, these tailored renewable solutions may not only stabilize the energy supply of such each location but also promote broader economic development (Ajao et al., 2009). Isa et al. (2013), reveals that Nigeria is in dire straits energy-wise, unable to provide effective usable energy, a deficiency typically ascribed to administrative incompetence and the country's energy infrastructure being underdeveloped. Hussaini (2019), wrote that Energy efficiency considerations in the housing sector of Nigeria remain largely underdeveloped, both in building design and conservation measures that are taken by end users. In Nigeria, energy demand far exceeds supply, leading to frequent power outages and heavy reliance on fossil fuel-based backup generators. This situation, which cannot be sustained, is one reason to explore alternative solutions, thus investigating Net-zero energy buildings as a possible option. In the face of a challenging future for Nigeria's energy landscape, it is time to implement net-zero energy building strategies as part of a focused campaign. Such measures not only could correct deficiencies in residential energy use, but also in the long run may serve to guide sustainable urban development. Thus, as modern construction methods are brought into line with net-zero targets, the stage could be set in Abuja for a different kind of future for housing in the nation all together: more resilient and environmentally friendly.

1.1.2 Net-Zero Energy Buildings as a Sustainable Solution

Whereas two-thirds of total energy consumption and greenhouse gas emissions occur in building construction, Net-zero Energy Buildings NZEBs are one of the few ways to decarbonize an industry which is more energy-consuming than any other. Their significance is more than merely a reduction in environmental impact; they also enhance energy security, reduce operational costs and contribute to long-term social and economic sustainability (Ahmed et al., 2022). This requires a variety of approaches to energy conservation: high-efficiency building design, passive and active renewable energy systems which are mutually beneficial, and the use of advanced building technologies such as smart grids and automation. In addition, energy storage plays an important role in maintaining stable, continuous energy supplies given the vagaries that may occur in on-site generation due to variations in the availability of renewable energy (Rosen, 2015). Case studies of individual NZEB projects have documented valuable insights into the difficulties of practical adoption: the barriers of technology unable to move forward with support; financial restrictions on its development and regulatory constraints. These case studies also point up positive solutions and methods. They help smooth the implementation process and ensure commitment from around all concerned parties (Reeder, 2016).

NZEB has become more and more visible as an alternative in Nigeria. Its design concept, that buildings produce as much energy as they consume by incorporating renewable energy technologies and energy-saving measures, supplies definite firepower for addressing Nigeria's present energy crisis. Studies show that adopting good building orientations and choosing suitable materials for construction can result in significant savings on cooling load together with a reduced total energy bill. Consequently, NZEBs are desirable from both environmental and economic standpoints as well as offering potential routes out of poverty (Nwaji et al., 2024).

Despite these advantages, a number of obstacles make it difficult to promote NZEBs widely across Nigeria. One of the pivotal issues is low awareness and skill levels among industry practitioners. This hampers the application of energy-efficient design principles. Moreover, a lack of standardized educational curricula and training programs means that there is gap in knowledge throughout the industry (Nduka et al., 2019). Conflicts with existing building policies and regulation frameworks make progress difficult. Many of today's guiding rules about construction do not deal with NZEBs specially required features, holding up even more advances for them (Nduka et al., 2019).

However, despite these challenges, NZEBs offer substantial benefits. Apart from reducing operational energy demands, such buildings help to increase energy infrastructure security and alleviate stresses on the already over-burdened Nigerian electricity grid. In addition, NZEBs can carry on economic competitiveness in the future, bringing long-term reductions in cost and large-scale employment to the construction sector while continuing to develop.

Also the way in which NZEBs address local land use issues should be emphasized, especially for cities, where rapid expansion without careful thought on the part of builders has effected environmental degradation (Nduka et al., 2019)

A comprehensive approach to NZEBs as proposed by Iwuagwu & Onyegiri (2019), is needed to achieve results for all. First, incorporating NZEB-focused courses on university curricula can develop a new generation of professionals equipped with the necessary expertise. Second, the use of passive energy strategies like improved natural ventilation, thermal insulation and strategic building orientation can reduce energy consumption in both new and old buildings. Finally, raising funding for energy-efficient buildings from both the private and public sectors are essential in moving NZEB technologies closer to market and ensuring that it's profitable for the long run. As pointed out by (Ohene et al., 2022), a NZEB is envisioned by reducing the rate of energy consumption of a building, and then utilize clean renewable energy for any remaining energy demands as shown in Figure 1.1. One of the main goals of buildings is to provide a refuge from the externalities of weather, the buildings envelope is primarily responsible for this duty in the building. Most energy consumed by buildings is as a result of HVAC (Heating ventilation & Air Conditioning).

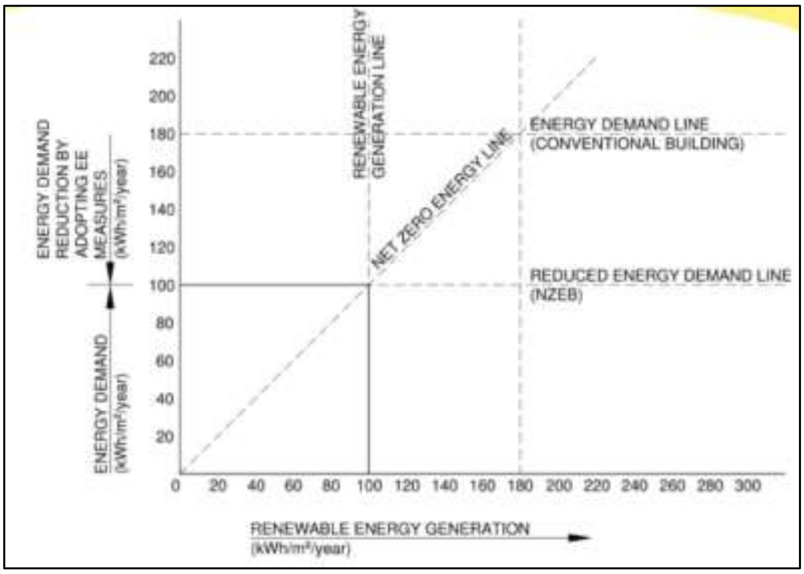


Figure 1.1: Ideal Concept of a NZEB Design (Ohene et al., 2022).

NZEBs offer an essential framework for addressing the country's persistent energy challenges. Given Nigeria's energy crisis, characterized by erratic electricity supply, high dependency on non-renewable sources, and significant energy inefficiencies, the implementation of NZEB principles can serve as a game-changer in achieving sustainable development. Optimizing building envelopes through advanced materials, passive design strategies, and renewable energy integration can significantly reduce energy demand and improve overall efficiency in residential and commercial structures.

1.2 PROBLEM STATEMENT AND RESEARCH QUESTIONS

With excessive energy usage and poorly designed buildings causing environmental degradation on one hand and economic hardship on the other, the building energy efficiency now seems to have become a pressing issue globally. The nation's high reliance on non-renewable energy sources, frequent blackouts and rising demand for cooling in severe weather have heightened problems in building air conditioning for people living in Nigeria when doubly compounded by the country's hot climate. A building’s envelope, which includes the exterior walls, roof, openings and insulation, has a major impact on how energy-efficient, thermally comfortable, and costly the building can be. The design and material composition of the envelope determine how much heat gain or loss occurs in the building, and thus affects energy use for heating and cooling. In Nigeria, a lot of buildings are still built without much concern for envelope optimization. This means that energy consumption is too high, as well as discomfort hours and carbon emissions remain higher than they should be, even on this background of vigorous advances in sustainable building technology. While some previous studies looked at many forms of energy efficiency, research on improving envelopes in Nigeria is still in short supply. There is also little actual confirmation as to how such efficiencies could help net-zero energy targets in line with our country`s climate conditions.

In order to address these outlined problems, we need to ask the questions.

a. How does the Nigerian building code outlined building envelopes and what are the most widely adopted building envelope systems in Abuja, Nigeria?

b. What are the energy use pattern of buildings in Abuja Nigeria and similar climates and what are the strategies to reduce the demand for such energies?

c. How does the energy consumption of an improved building envelope stack up against that of a common conventional one?

1.3 RESEARCH AIM AND OBJECTIVES

The primary purpose of this study is to improve the conventional building envelopes in Abuja, Nigeria by creating a simulation model that compares the energy performance of the improved building envelope to that conventional building envelope in order to reduce the energy demand/consumption and improve thermal comfort. This study will use energy performance simulation to illustrate graphically and vividly, how changes in a building envelope's components greatly affect the energy consumption and thermal comfort of residential buildings in Abuja, Nigeria. This aim is to be achieved by fulfilling the following objectives:

a. To outline the conventional building envelopes in Nigeria based on the National Building Code of Nigeria supplemented with Literatures.

b. To investigate the energy use patterns of buildings in Abuja and similar climates.

c. To find out strategies upon which building envelopes are improved to reduce the energy demand and improve thermal comfort from the consumption patterns investigated in (2) above.

d. To create a base model based on the conventional building envelope as well as an improved building envelope to measure the energy demand, thermal comfort, and cost of all scenarios.

1.4 SIGNIFICANCE OF THE STUDY

The findings of the study are expected to greatly influence Nigeria and other countries construction industry. In such times of rapid environmental change and sustainable energy concerns, building envelope improvement practices will help reduce energy usage, improve thermal comfort and at the same time offer programmes generating lots of ecological investments for construction industries. By offering a comprehensive review of envelope improvement technologies, this work provides some brief overview on net-zero energy building design in hot climates and high levels of solar radiation. These results will provide architects and other building professionals with a number of ideas based on hard data that can be used to create buildings that save energy potentially. It will also aid policymakers and urban planners in drafting regulations, laws, and standards that support ecological construction practices. It will also help to realize Nigeria's broader environmental and energy security objectives by reducing the country's over-reliance on non-renewable energy sources.

1.5 SCOPE OF THE STUDY

The study will be focused on showing how the choice of material and insulation will affect the energy performance thermal comfort and construction cost in the building envelope of a simple residential building in Abuja, Nigeria. This consideration will ensure that realistic and useful results will be obtained as energy performance simulations will be carried out with Design Builder software, using climate data and construction conditions in terms of materials and resources specific to Abuja, Nigeria.

1.6 RESEARCH METHOD

This study will adopt a comparative analysis methodology using energy performance models to assess how increasing the energy efficiency of a building envelope impacts energy efficiency. The energy performance of traditional and improved residential buildings will be simulated and assessed using Design Builder, which is a simulation program built on a platform of Energy Plus. The research shall compile data regarding typical standards in residential buildings, properties of building materials, and climate conditions concerning Nigeria. The analysis will focus on key performance metrics such as energy consumption, thermal performance, and cost-benefit analysis. The result of the simulation will be analysed to determine what envelope optimizations are most effective for energy consumption, and if possible, validate them using real energy use data.

1.7 THESIS OUTLINE

This study will focus on five chapters. The introduction gives a short background knowledge on the energy efficiency challenges in Nigeria and the avenue building envelope optimization provides towards the attainment of Net-zero energy buildings. The Literature

Review will review past studies conducted on net-zero energy buildings, point out gaps in the literature, and have a clear link to the methodology of the study. Specifics on research methodologies informing on ways to gather and analyse data, the simulation methods utilized, and the basic energy performance assessment standards will be addressed in the chapter on Research Methodology. We will demonstrate in the second part of this section how we will use Design-Builder software to compare conventional and streamlined building envelopes. The Results and Discussion section will present and discuss the results of the energy performance simulations, with specific comparisons between various building envelope designs and their influences on thermal comfort and energy consumption. The Study will finally conclude with recommendations for designing NZEBs building in Nigeria for actors and highlight further research potential on the subject matter.

2. LITERATURE REVIEW

2.1 OVERVIEW OF BUILDING ENVELOPES

Building envelopes are the primary barriers between indoor and outdoor environments and are responsible in many ways to enable buildings function properly. Such envelopes enhance thermal insulation, preventing variation between the temperatures of interior and exterior spaces whereas also forming a necessary barrier against wind forces, water intrusion and even other environmental elements (Wang et al., 2024). As well as protective functions, building envelopes are also critical in improving energy efficiency and comfort to inhabitants, and prolonging the life of buildings through minimising wear and degradation caused by prolonged exposure to extreme weather (Nouhaila & Bendriaa, 2023). Because of growing global pressures for sustainable and energy-efficient buildings, recent developments in technologies have enabled the development of smart building envelopes. These next generation systems can fully adjust themselves based on the changing environment, and achieve energy efficiency and indoor temperature control via real-time optimization (Wang et al., 2024). By thoroughly analysing heat transfer mechanisms, architects and engineer's familiar can improve building envelope system efficiencies by integrating passive design strategies including but not limited to solar energy capture and utilizations which are critical in minimizing heating and cooling energy demand (Hachem-Vermette, 2020). Ongoing research in the field is expanding on innovative strategies to enhance the performance of building envelopes with new materials, advanced insulation methods and smart control systems. This includes generating high-performance, environmental-friendly, and comfortable built environments that complement global sustainability objectives (Wang et al., 2024). The building envelope refers to all the various components that make up a building's outer shell; understanding building envelopes is an important aspect of building design that can help ensure structural integrity and energy efficiency. These components (Figure 2.1) include walls, which form the primary thermal barrier; roofs, that provide overhead shelter and heat-regulating characteristics; and floors, that influence thermal mass and insulation and fenestrations which includes openings such as doors and windows. It becomes extremely important that these principles are applied while designing fenestration of buildings or openings like windows, doors, etc., to provide a good balance in the amount of natural light, ventilation, thermal performance, etc., and many other factors associated with overall building comfort.

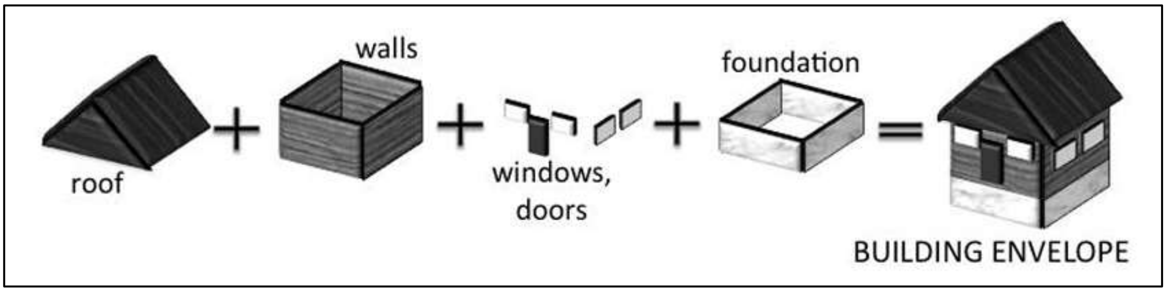


Figure 2.1: Components of the Building Envelope, (Khaled Mansouri & Sriti, 2019).

Insulating layers can also be added to the mentioned components to ensure efficient heat flow impedance from the walls to the outside (Abd-Rabo & Al-Temmamy, 2019). To optimize an efficient building envelope, an in-depth knowledge of heat transfer processes such as conduction, convection, and radiation and their interaction with each building material with respect to overall thermal performance is required (Goia et al., 2013). Criteria such as temperature fluctuation, relative humidity, solar radiation intensity and wind are determined depending on the climatic context, and should be taken into account in the design phase to ensure optimal performance of a building envelope(Abd-Rabo & Al-Temmamy, 2019). Excessive heat and moisture are the main enemies of buildings in hot and humid regions, which is why, in addition to reducing the solar heat gain to the most, the idea is to prevent solar heat or air movement in the building as much as possible to enable natural ventilation which indirectly leads to decreased cooling loads and energy demand levels, which is required for indoor thermal comfort (Abass et al., 2020). In colder climates, solar heat gain is typically maximized and the loss minimized to reduce heating energy needs and improve warmth within the home. An important parameter for achieving thermal effectiveness of the building envelope is the type of material used. In this regard, thermal emittance materials are very crucial; a material's ability to act as a barrier against unwanted heat transfer determines the level of stabilization of indoor temperatures over time and, of course, reduction in energy consumption, (Abass et al., 2020). But devices such as shading devices, reflective surfaces and insulated building elements, are a way to manage solar heat gain in very high solar irradiations regions like Abuja.

2.1.1 Overview of Building Envelopes in Nigeria

According to Ede et al. (2017) as cited by (Jegede & Taki, 2021), The right selection of building material and design strategies provides a high potential for improving building thermal comfort and energy efficiency like for instance in Nigeria, using indigenous materials like rammed earth and thatched roof provides better thermal function than the conventional modern counterparts. These classical materials effectively decreased indoor operative temperatures and decreased cooling energy demand; hence, their adaptation to the hot and humid climate conditions of Nigeria.

Further analyses conducted in simulation bolster these results, showing an 8% annual operative temperature decrease with the use of rammed earth walls and thatched roofing systems. This leads to longer durations of indoor thermal comfort, a reduction in reliance on mechanical cooling, and a significant potential reduction in CO_2 emissions linked with energy use. In addition, the use of these locally sourced materials has been proven to significantly reduce the overall cost of construction, offering an economically feasible and ecologically sustainable option compared to modern, high-energy materials (Jegede & A. Taki, 2021). Other than traditional materials, innovations in building envelope technologies including improved insulation, high-performance glazing systems, and green roofs emerged as viable strategies for mitigating cooling loads in tropical contexts, including Abuja(Agmada Bawa & Ukpabia, 2025). Beyond temperature control, these measures contribute to sustainability targets by minimizing energy use and ecological footprint. We would expect a more holistic approach to material selection, where thermal performance was one of a number of design variables along with structural strength, cost per tonne, and aesthetics. Therefore, as global temperatures continue to rise and solar radiation levels rise in tropical climates, there is a need for climate-responsive design principles in the building envelope construction to achieve energy-efficient, sustainable, and indoor thermal comfort, (Ede et al., 2017).

2.1.1.1 Building envelope standards in Nigeria

The National Building code of Nigeria (NBC) contains performance-related guidance and construction requirements for materials and systems in the building envelope. The standards aim to ensure safety, comfort, and environmental efficiency across the country's diverse climatic regions. This section covers the NBC's requirements for walls, roofs, and fenestration systems for housing.

Wall Systems

The NBC suggests that wall materials can include burnt clay bricks, concrete blocks (both solid and hollow), stabilized laterite blocks, and rammed earth, depending on what is available and appropriate to local conditions (NBC, 2006). In hot climates, the use of thermally heavy materials, including thick masonry walls, is encouraged to delay the penetration of heat and improve thermal comfort in the building interiors. While explicit U-values are omitted, the code places strong emphasis on durability, moisture resistance, and structural stability. Light-colored finishes are also recommended to reduce heat absorption, while external walls of residential buildings having three stories or less must offer a minimum fire-resistance rating of one hour (NBC, 2006).

Roof Systems

Roofing systems ought to be weatherproof, structurally stable, and acceptable for the specific climatic zone. Production of commonly approved materials such as corrugated galvanized or aluminum sheets, concrete roof slabs, clay tiles, and thatch for traditional architecture (NBC, 2006). The NBC point out the importance of proper ventilation of attic spaces and insulation below roof coverings to avoid overheating in residential buildings. Second, a pitched roof should have a slope of at least 30 degrees in order to facilitate water runoff. The inclusion of energy-efficient roof strategies like reflective coatings and green roofing systems is also promoted to improve thermal performance in accordance with sustainable building practices (NBC, 2006).

Fenestration Systems

According to NBC, doors, windows and other openings provide opportunities to balance natural lighting, ventilation, energy performance and security. The approved materials for fenestration are aluminum, uPVC, timber, and steel. There is no restriction on glazing, but in hot regions, tinted, reflective, or double-glazing is encouraged to reduce solar heat gain (NBC, 2006). While it does not provide specific U-factor or solar heat gain co-efficient (SHGC) values, the code recommends using shading devices such as overhangs, fins, and recessed windows to reduce glare and thermal load (Shahid & Karimi, 2022; Bano & Kamal, 2016). In residential applications, security measures such as window burglar-proof glass and security window frame reinforcement are also recommended.

2.1.1.2 Building envelopes in abuja, Nigeria

The building envelopes consists of mainly walls, floors, roofs, and fenestration (Openings such as doors and windows). (Mua'zu et al., 2019), outlined eight (8) wall types that are commonly used in Abuja studying their thermal performance of which they included the nine-inch sand-Crete blocks rendered with plaster, which is the most widely used building envelop in Nigeria and its often cladded with ceramic tiles or aluminium. Bricks are rarely used as well as insulation or cavity walls. Table 2.1 shows the types of walls highlighted. According to Amal and Halil (2017), as cited by Jegede & Taki (2021), the conventional roofing systems in Abuja involves the use of steel nails structural, fibre glass, long span aluminium roofing sheets, steel reinforcement, cement concrete roof, steel sections and galvanized metal sheets often nailed, bolted, or welded on steel trusses or well-seasoned timber with an extruded facia made of concrete, wood, steel, and other materials. However, the most widely used roofing system for residential buildings are Long span Aluminium roofing sheets, Galvanized metal sheet, and stone-coated Aluminium roofing sheets nailed on well-seasoned timber with a concrete or wooden facia as seen in Figure 2.9. The flooring system involves the use of steel reinforcement and structural steel or concrete often finished with ceramic tiles. The most common for residential buildings involves 150mm thick concrete slab under 50mm thick sand-cement screeding under ceramic tiles finish. For ground floors, the systems seats on a 300mm thick well compacted hardcore filling and at least 450mm well compacted laterite with a damp proof membrane (Fig. 2.9), (Amal and Halil, 2017: Jegede, 2021).

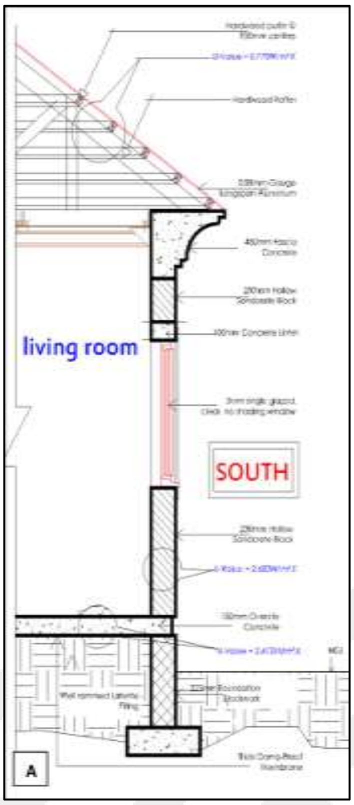


Figure 2.2: Showing Components of a Typical Building Envelopes For Residential Buildings In Abuja, Nigeria., (Jegede and Taki 2021).

Table 2.1: Wall Types for Building Envelopes in Nigeria. (Mu'azu et.al, 2019).

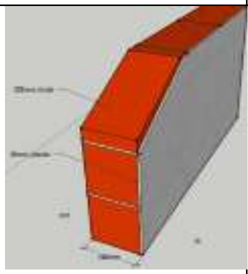
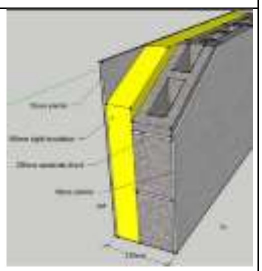
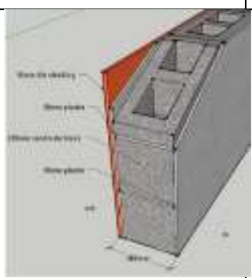
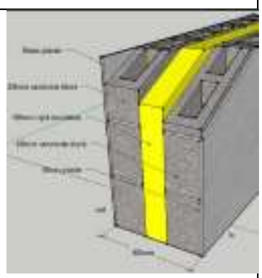
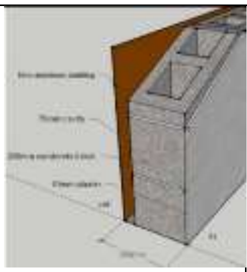
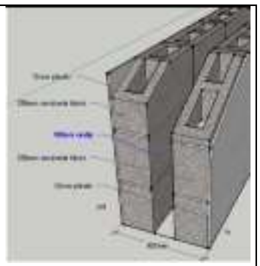
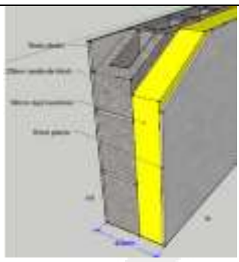
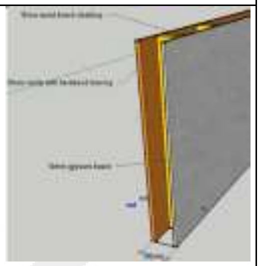
	General description	**Cross-Section**		**General description**	**Cross-Section**
Wall 1	Brick wall, plastered internally.		**Wall 5**	Externally insulated block wall with plaster on either face.	
Wall 2	External tile finish on block wall internally plastered.		**Wall 6**	Cavity block wall with center insulation and plasterd on both faces.	

Table 2.1: Wall Types for Building Envelopes in Nigeria. (Mu'azu et.al, 2019) (Table Continued).

Wall 3	External Aluminium clad finish on block wall internally plastered.		**Wall 7**	Cavity block wall with and plasterd on both faces.	
Wall 4	Internal Insulation on block wall plastered on either face.		**Wall 8**	Wooden wall with external wood voard and internal gypseum finish	

2.2 STUDY AREA

2.2.1 Geographical Location

According to the Federal Capital Territory Education Management System (FCTEMIS) (n.d), The Federal Capital Territory (FCT) is geographically nestled at the very heart of Nigeria between latitudes 8.25° and 9.20° north of the equator, and longitudes 6.45° and 7.39° east of the Greenwich Meridian. The FCT was formed as a federal territory in the North Central region (Figure 2.2) and is the country's capital and landmass of the administrative and political centre. There in the FCT lies Abuja which is Nigeria's first planned city and has been Nigeria's capital since it officially took over from Lagos on February 3, 1976. General Ibrahim Badamasi Babangida, who was President of Nigeria between 1985 and 1993, handed over the seat of government in Lagos to Abuja on December 12, 1991. The FCT was carved out of land from existing states, including old Kaduna, Kwara, Niger and Plateau states. The dominant chunk of the area was a carve-out of Niger State, whose central position and strategic prominence made it most available.

Figure 2.3: Map of Nigeria Showing the Six Geo-Political Zones (Adeyemi, 2017).

The FCT lies just north of the meet point between River Niger and Benue. It is bounded to the North and West by Niger State; to the northeast by Kaduna State; and to the east and south by Nasarawa State; and to the southwest by Kogi State. The FCT is composed of six Area Councils that include: Abaji, Abuja Municipal, Bwari, Gwagwalada, Kuje, and Kwali (Figure 2.3). Together, these councils represent a vast land area of around 7,290 km². However, this is primarily in the savannah, where the weather allows for good urbanism and agriculture.

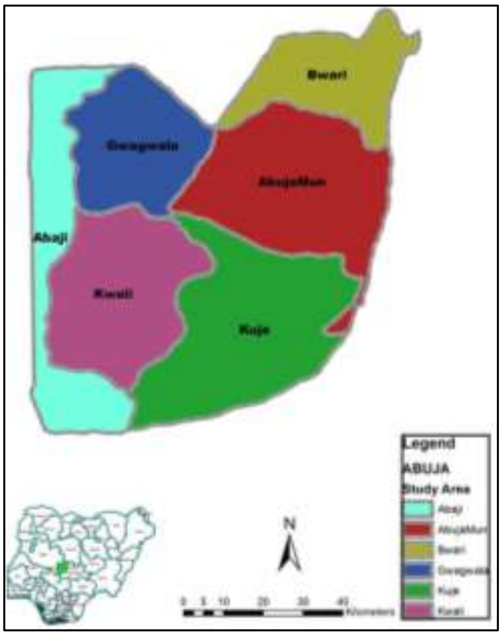


Figure 2.4: Map of Abuja Showing the Six Municipal Councils, (Oladimeji,2017).

2.2.2 Climate Data

According to Batagarawa (2013) as cited by Jegede & A. Taki, (2021), there are three different types of weather conditions that alter throughout the year in Abuja. November to March is the dry season with little rain, low humidity, and warm to hot daytime temperatures. The other main season is the wet season, from April to October during which humidity is at its peak, rainfall is very frequent in addition to the temperature being warm. The wet season includes downpours, especially around June and September, with thunderstorms. Moisture in the air helps create vegetation and replenish water sources, enabling agriculture in the area. In addition, there is a short but understandable harmattan season, generally between late December and early February. The Harmattan is a dry and dusty wind that has its source in the Sahara Desert, carrying fine dust particles over West Africa. According to Meteoblue (2025) climatic data, Abuja experiences hotter days from the months of October through May with mean daily temperatures ranging from 30^0C to 36^0 (Figure 2.4) raising concerns for thermal comfort, however the temperatures are relatively lower at nights through the years with a range of 21^0C to 25^0C. The average precipitation sits at 1342mm per annum.

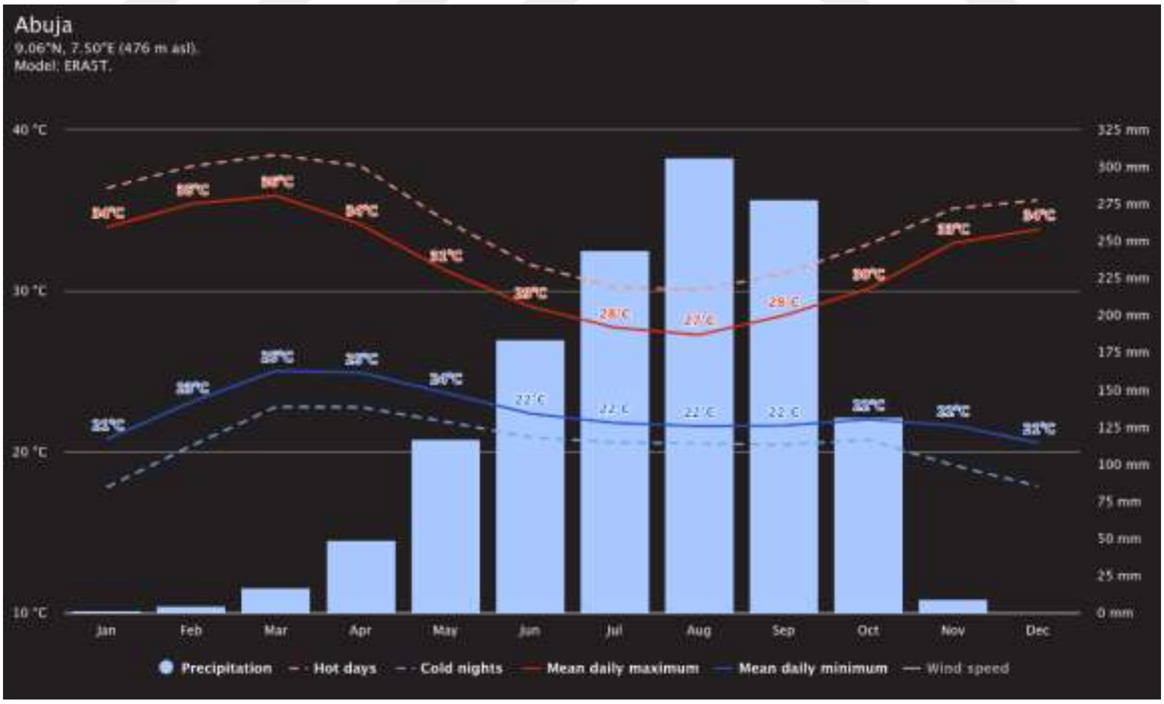


Figure 2.5: Average Temperature and Precipitation for Abuja, (Meteoblue,2025).

The cloudy, sunny and precipitation days of Abuja (Figure 2.5) shows huge potential for harnessing solar energy as there are only few over cast days in the months of June to September throughout the year, with the sunniest days in the Months of October to April and mostly partly cloudy for the remaining part of the year. The average daylighting for Abuja is 12 hrs per day. The wind rose for Abuja (Figure 2.6) shows the prevailing wind to be coming from the Sout-West direction allowing for opportunities to harness such winds for the required cross-ventilation for buildings in the region.

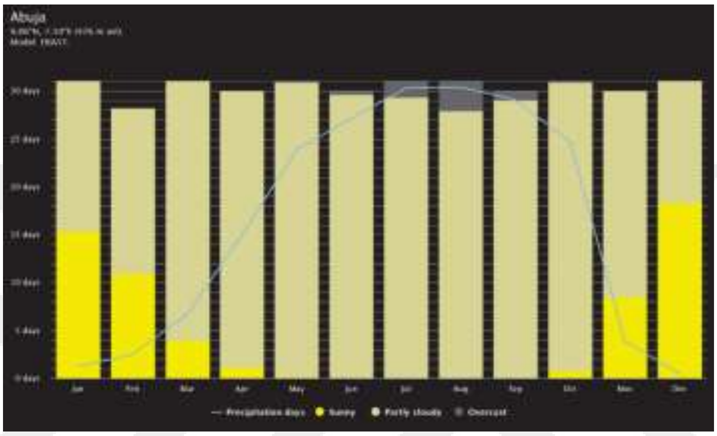


Figure 2.6: Average Cloudy Sunny and Precipitation Days for Abuja, (Meteoblue,2025).

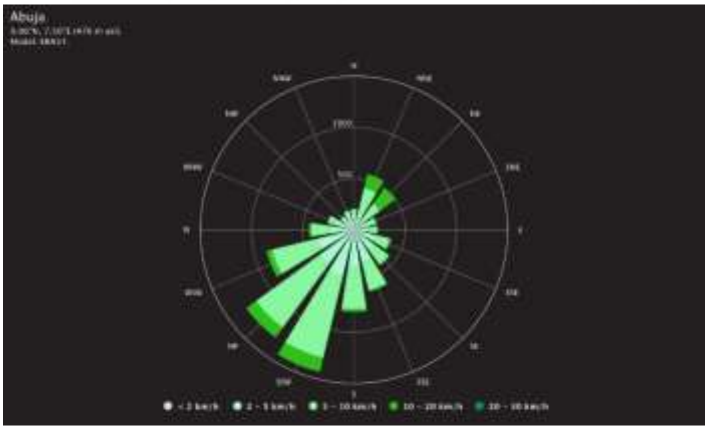


Figure 2.7: Wind Rose for Abuja, (Meteoblue,2025).

2.2.3 Climate Change Act of Nigeria

Former President Muhammadu Buhari, on November 2021, signed the Climate Change Bill into law creating grander legal structures upon which Nigeria's response to climate change is anchored. The passed legislation that will help the country shift towards its climate goals, with the intention of long-term environmental sustainability, economic stability, and resiliency to climate change impacts. Its enactment is in sync with Nigeria's commitment made at the 26th Conference of the Parties (COP 26) in Glasgow where the President signed Nigeria to the net-zero carbon emissions target for 2060. To support this commitment, the Climate Change Act establishes a wider national target of reaching net-zero emissions between 2050 and 2070 (Nigeria's Climate Change Act, 2021). One of the major aspects of the law is to require the Nigerian government to create a National Climate Change Action plan that provides a framework and concrete steps for Nigeria to realize its climate goals. The Act also mandates the development of a five-year carbon budget, detailing measurable annual targets for emissions reductions. These, thus, require the validation and approval of the Federal Executive Council (FEC) for governmental oversight and accountability. Importantly, the Act indicates that the first carbon budget should have been set and approved by November 2022. The Act establishes the National Council on Climate Change (NCCC) to supervise the execution of the Climate Change Action Plan. This new institution would coordinate national climate policies, unify sectorial strategies, and help Nigeria to achieve its climate goals. Alongside overseeing the operations of the Climate Change Fund, the financial mechanism that supports actions on climate. The Fund's financing would be set in Parliament through legislation and would be used to cover the operational cost of the Council and for specific climate related projects, comprising adaptation and mitigation activities. And at the global level, the Council will work in close collaboration with the Federal Ministry of Environment to align climate action with economic sectors. It will also determine and apply priority adaptation measures to heighten Nigeria's resilience to climate change impacts.

The Act also places certain obligations on the private sector. It mandates that all private organizations with 50 or more personnel create and enforce measures to achieve the annual carbon emissions reduction target specified in the National Climate Change Action Plan (NCCAP). Additionally, such entities are required to designate a Climate Change Officer to oversee the tracking, documentation, and reporting of compliance with these targets. Should businesses not align with the outlined emissions reduction schedules, they could be subject to regulatory action, such as fines. It provides a robust framework that will help Nigeria in its transition to a low carbon economy and through these legal and institutional mechanisms, it once again highlights its commitment to climate action including international and national development goals shaped around it. It guarantees the engagement of both governmental and private sector actors in the country's path toward environmental sustainability and resilience from the threats posed by global climate change, (Nigeria's Climate Change Act, 2021).

2.2.3.1 Nigeria's energy transition plan (ETP)

According to the National Council on Climate change (NCCC, 2022), the Nigerian government executed the Energy Transition Plan (ETP), as a strategy to put the country on a net-zero trajectory towards 2060 as well as freeing 100 million Nigerians from poverty. Prepared in 2021 with assistance from the COP26 Energy Transition Council (ETC), the ETP built the groundwork for former President Muhammadu Buhari's pledge to carbon neutrality, made official at the 26th Conference of the Parties (COP26) in Glasgow. The ETP focuses on five energy sectors, namely:

a. Power: The switch to green on Nigeria's electricity grid.

b. Cooking: Decreasing dependence on traditional biomass fuels such as firewood and charcoal.

c. Oil and Gas: Transitioning to cleaner production techniques and lessens flaring.

d. Transport: The increase in use of electric vehicles and alternative fuels.

e. Industries: Promoting green making and sustainable energy consumption in industrial processes.

The Nigeria's ETP is projected to incur an estimated cost of about $1.9 trillion for infrastructure development, technology deployment and policy execution over multiple decades.

This is a stepwise strategy to shift away from heavy carbon fuels like firewood, diesel, and petrol to gas, which is relatively less polluting interim energy. The country hopes, over a long period to completely switch to renewable and cleaner forms of energy by 2060. One of the key features of the ETP is its potential to create a significant amount of economic growth and jobs. The plan forecasts that around 340,000 jobs will be created by 2030, and predicts that 840,000 people will work in the sector by 2060. The job market will be driven mainly by renewable energy generation, clean cooking, and transportation.

Nigeria's total Green House Gas (GHG) emissions in 2020 was 275 Mt CO_2e in which energy consumption and industry contributed 65% of GHG emissions. The ETP sets the following vision statements to halt the growth of anthropogenic CO_2 emissions, consistent with the 1.5°C global warming target and to accelerate the transition towards becoming carbon neutral:

a. Installed electricity capacity by 2050 to 250 GW, with more than 90% from clean energy (solar/wind/hydro/other renewables).

b. More than 80% of Nigeria’s vehicle fleet electrified, facilitating emission reductions from the transport sector.

c. Over 80% of the population adopting clean cooking solutions, reducing dependence on nature-polluting traditional biomass fuels.

Through this revolutionary plan, Nigeria seeks to revolutionise its energy sector, promote sustainable economic growth, and play a prominent role in the global fight against climate change, (NCCC 2022).

2.2.4 Housing Typologies in Nigeria

Villa Afrika (2020), published 9 housing typologies in Nigeria (Figure 2.7) of which included a mansion (Figure 2.7a), which are large luxurious home usually above 450 m^2 in size and indicate a level of magnificence in size and style beyond what is considered normal in a given area. A bungalow (Figure 2.7b), which is typically a one storey home relatively small in size, not expensive to build and maintain thereby becoming the affordable housing option for the working-class Nigerian. Apartment or flats (Figure 2.7c) which comprises of many houses stacked on each other and side by side sharing a common access point and utilities like gyms, play areas, and roof tops. A penthouse (Figure 2.7d) which is an apartment unit at the top of a multi-storey building or a hotel often seen in major cities like Lagos, Abuja, and Port-Harcourt. A terrace housing or row housing (Figure 2.7e) which are usually set on two or three floors per unit connected side by side for a row down a block or road but are mostly found inside a gated estate in Nigeria. Terraces are more affordable than their semi-detached or stand-alone replica which makes it more desirable in places like Lagos and Abuja. A semi-detached (Figure 2.7f) comprises of two houses sharing a single wall between them with one house being the exact mirror of the other. It can be a single floor or multiple floors but most often not more than two suspended floors. This housing typology is slightly cheaper than a detached stand alone. Detached houses (Figure 2.7g) refers to houses that stand alone on their own without being connected to another, but not big enough to be called a mansion and usually gated in a compound of their own. These houses are usually found in major cities like Abuja, Lagos, kano, Kaduna, etc. A duplex (Figure 2.7h) in the Nigerian context simply refers to a single storey home usually for a single family but can also accommodate 2 families in an apartment like style but not more than one storey. The Traditional houses (Figure 2.7i) are found in the rural parts of Nigeria, the major construction materials are mud walls and thatched roofs but the style, pattern and construction techniques vary with the location and traditions of the various ethnic groups in Nigeria.

Figure 2.8: Housing Typologies in Nigeria; (a) Mansion, (b) Bungalow, (c) Flats, (d) Pent-House, (e) Terrace, (f) Semi-detached, (g) Detached, (h) Duplex, (i) Traditional Houses, (Villa Afrika, 2020).

Adegoke (2022), investigated the housing preference of Nigerians by studying two states in each geopolitical zones to choose from flats, bungalows, semi-detached and detached houses, where he found out that 89% of Nigerians prefer to live in a flat or bungalow as shown in the figure below (Figure 2.8). In all, about 58% of the population chose flats, about 31% chose bungalows, only about 4% of all the beneficiaries chose detached houses while 7% choose semi–detached houses. Further analysis showed that the beneficiaries preferred

2-bedroom Flat; at 26.5%, then 3-bedroom at 26.4% while 17.7% chose 3-bedroom bungalow. Only about 13% of the population chose 2-bedroom bungalow; while 5.5% made 1-bedroom bungalow their choice. 3-bedroom semi-detached and 4-bedroom semi-detached were chosen by 4% and 3% respectively. Those that choose 4-bedroom detached and 5-bedroom detached houses were 2.3% and 1.5% respectively.

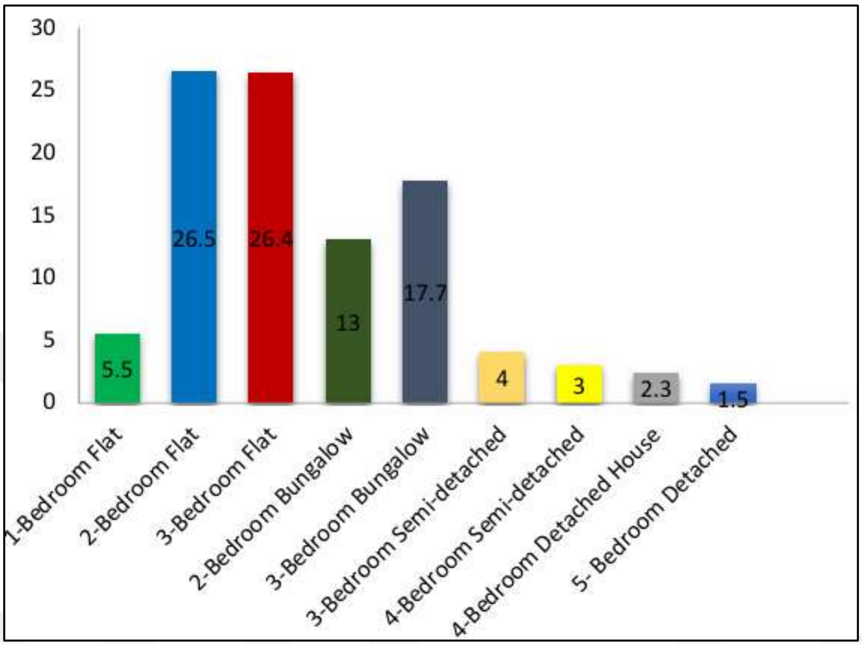


Figure 2.9: Housing Preference of Nigerians, (Adegoke,2023).

2.2.5 Energy Use Pattern in Abuja's Buildings

Significant energy demand for cooling & lighting has been reported in the cases of both commercial & residential buildings in Nigeria, with particular reference to Abuja. Research shows that energy consumption in office buildings is mainly determined by cooling systems which represent from 40% to 59% of total energy use while lighting accounts for 12%–28% of total energy demands (Batagarawa et al., 2011; Mu'azu, 2015).

A case study on the University of Abuja corroborates these findings as cooling systems are found to account for nearly 48% of the total energy consumption at the university, with lighting representing 28%. Collectively (Figure 2.10), these two factors were responsible for 76% of the university's overall energy use (Evuti et al., 2020). On a global scale, air conditioning systems are reportedly responsible for consuming more than 40% of total energy used for buildings, and thus a major contributor to greenhouse gas emissions (A. &

O. K., 2023). With the hot climate, Abuja heavily depends on energy-intensive cooling systems, highlighting the need for energy-efficient strategies in building design and operation. Passive design strategies and the use of energy-efficient equipment hold a great opportunity in Nigeria to minimize energy consumption in buildings further. For example, a study carried out at the University of Abuja revealed that replacing 40W light bulbs with 25W types would lead to an annual reduction in energy use of 154,854 kWh ((Evuti et al., 2020)).

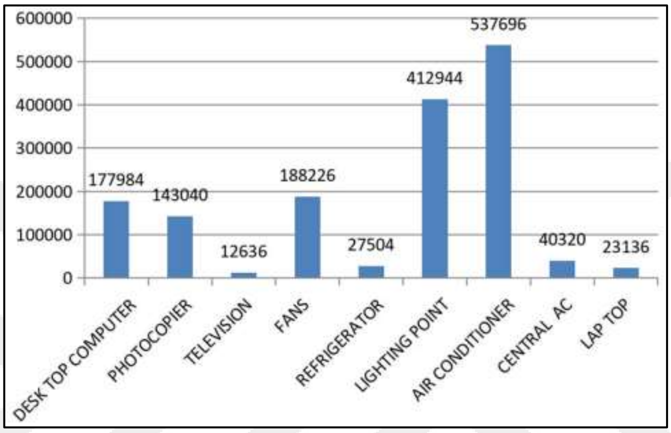


Figure 2.10: Annual Total Energy Consumption of all Appliances in the University of Abuja in KWh, (Evuti et al.,2020).

Moreover, the inclusion of passive design components like increased natural ventilation, proper building orientation, and adequate insulation can lower cooling energy demand by 20% in the case of office buildings (Mu'azu, 2015). Not only do these strategies reduce energy consumption, they are also a win for sustainability by providing an environmental benefit for buildings. This reality, in addition to high demand for cooling and lighting needs, dictates a dire need for the adoption of energy-efficient solutions and passive architectural designs as a feasible means of addressing energy consumption, operational expenses, and environmental sustainability in the built environment of Nigeria.

2.3 STRATEGIES FOR OPTIZING BUILDING ENVELOPES

Optimization of building envelopes for net-zero energy buildings in tropical climates such as that of Abuja is a balancing act across design strategies and material choices. Adding insulation, installing high-performance glazing, and implementing green roofs can help to reduce cooling energy usage (Bawa & Ukpabia, 2025). According to Jegede & Taki (2021), the use of local materials for floors, walls and roofs has proved to reduce annual operative temperatures by 8%, enhance thermal comfort and reduce cost of construction by 41.81%. Adopting passive design features, such as natural ventilation, sun-shading, daylighting and improved envelope airtightness, can achieve 48-50% energy demand reduction, and the remaining energy demand can be met using solar PV systems for operational energy (Ohene et al., 2022). Studies have been found in the commercial sector that have shown advanced passive cooling strategies to have an energy savings of 19.1% - 27.6% and are a candidate solution for greater sustainability in office space (Abdur-Rahman Musa & Abdullahi, 2018). Combining these strategies can enhance energy efficiency, reduce operational costs, and improve thermal comfort for tropical climate buildings, providing useful insights for architects, engineers, and policymakers aiming for sustainable urban development solutions.

2.3.1 Passive Design Strategies

Passive design is a strategy where design problems are reduced primarily through the building design not depending on additional electrical or mechanical equipment to do it; this is also an aspect of energy consumption reduction as the early phase of NZEBs, this strategy is a tool for opposing the external climatic condition through design, i.e. allowing heat gain in cold region and minimizing heat gain in hot regions by passive cooling, and proper thermal zoning (Singh et al, 2020). Passive design involves some aspect of site planning, orientation, horticulture, building external body, and building materials (Singh et al, 2020). Shehadi (2020), Showed that solar heat gain can be reduced by proper orientation of the building, the use of shading devices to block solar penetration during the summer and allow solar penetration through the winter, thermal insulation on building envelopes, and vegetation. Cavity walls, thermal mass, external reflective coating can be used to repel heat from solar radiation and prevent heat gain in the building (Singh & Syal, 2020). Passive cooling can be achieved through adequate opening of windows as well as their positioning and orientation to allow in maximum cross ventilation. According to (Singh & Syal, 2020), radiant cooling, direct and indirect evaporative cooling, and geothermal exchangers are the strategies for achieving passive cooling for NZEBs. Ohene et al (2022), Wrote that the use of light-coloured materials and cool roofs, High-performance glazing and having good

Natural ventilation can play a vital role in reducing heat gains in buildings as seen in the Figure below (Figure 2.11).

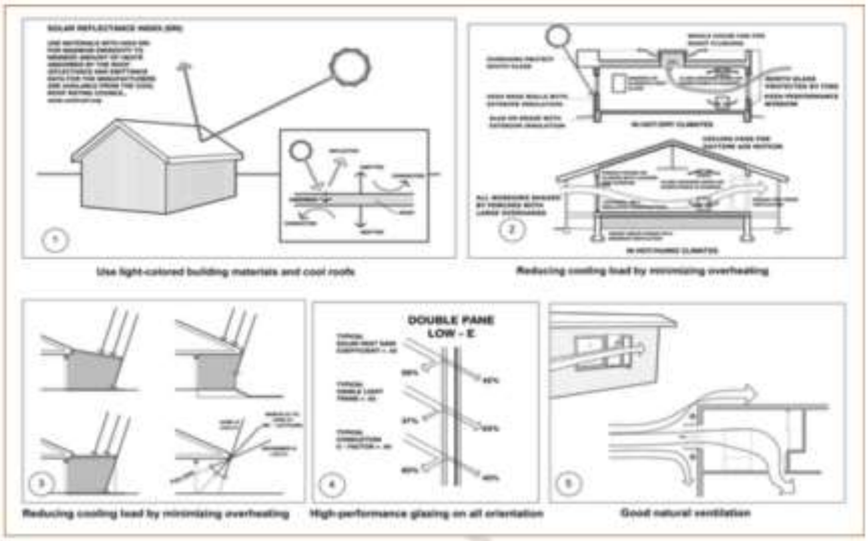


Figure 2.11: Passive Design Strategies, (Ohene et al, 2022).

2.3.1.1 Building orientation

Building orientation emphasize its importance in reducing heat gain and improving energy effectiveness through research. Abdul et al. (2024), wrote that facades facing the east and west are most susceptible to excessive heat gain, which can compromise thermal comfort and devalue worker performance in office buildings. Placing a building in an east–west orientation, so that its long faces face north and south (Figure 2.12), can significantly reduce building solar exposure and building heat gain (García et al., 2018). The energy consumption estimate for a 270° orientation was 10.5% lower than that of the 0° orientation (Alkali et al., 2021), which is significant when adjusting building orientation to optimize cooling loads. Simulation-based studies suggest that when combined with high-performance glazing and shading devices, the strategic orientation would reduce solar heat gains by 29.45% and achieve 1.90% reduction in annual operative temperatures through natural ventilation (Ochedi & Taki, 2019).

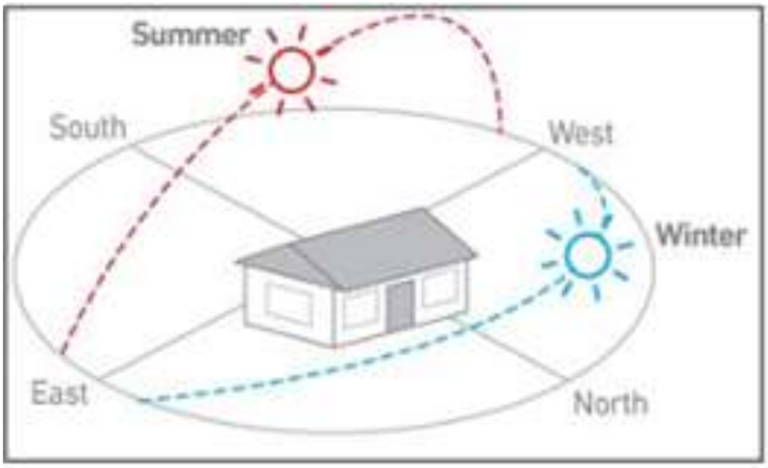


Figure 2.12: Typical Building Orientation for Tropical Climates Like Abuja, (Jegede & Taki, 2021)

This highlights the need for implementing several design alternatives to arrive at the best possible energy performance in tropical attack zones such as Abuja in other to arrive at an optimal design outcome. Intelligent building orientation, along with passive design features, can dramatically reduce energy demand, improving both comfort and sustainability of indoor environment.

2.3.2 Materials and Insulation

The selection of materials in the construction of building envelopes is a matter of great importance that affects the thermal comfort and energy efficiency of a building. According to (Kumar et al., 2022), the fundamental criteria that provides for energy efficiency during the material selection process are factors such as thermal conductivity, solar absorption rates, and thermal mass. Selecting the most suitable envelope materials, however, requires a systems approach that includes not only technical specifications but many other design criteria as Alkasar & Yahya, (2023) highlighted, which encompasses physical characteristics, socio-cultural importance, environmental effect, and the structural function features of the building, which differ across the context and the aim of buildings.

In hot arid areas like those in the Middle East and North Africa, multilayered and well-insulated building envelope systems have been very efficient. For example, double rows of red bricks in wall systems (Figure 2.13) increase indoor thermal comfort through a reduction in rate of thermal flow (Khaled Mansouri & Sriti, 2019). Kumar et al. (2022), wrote that sophisticated and innovative materials such as smart windows with switchable optical properties, changeable reflective coatings, and dynamic insulation can also play a vital role in optimizing building envelope performance in the nearest future. Designing efficient building envelopes delivers significant energy savings and thermal comfort benefits in climates like Abuja, Nigeria, that is characterized by tropical climatic features. According Jegede and Taki (2021), locally sourced and indigenous materials such as cavity brick walls and clay roofing tiles insulated with reed thatch (Figure 2.14) with low thermal transmittance (U-values) for building components (floor, wall roofs, etc.), are capable of reducing annual operative temperatures by about 8% when compared to the use of exotic materials.

These results do not only better thermal comfort in warmer climates but also lowers CO_2 emissions, cooling loads, and construction costs, making it both a sustainable and economical solution.

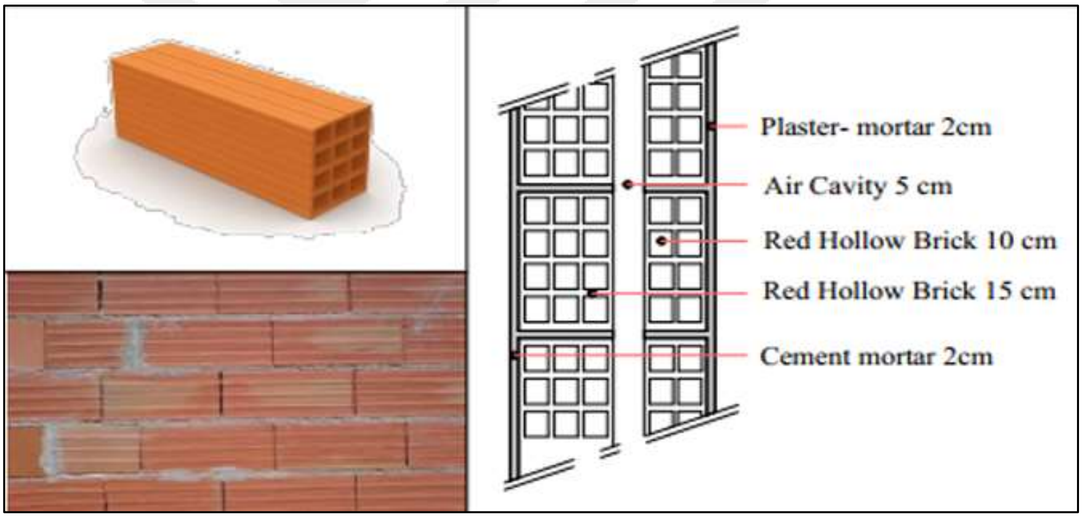


Figure 2.13: Double Red Brick Wall, (Khaled Mansouri & Sriti, 2019).

Furthermore, additional strategies such as using advanced insulation methods, energy-efficient glazing systems, and green roofing solutions (Figure 2.15) can also help reduce the amount of energy needed for cooling, particularly in hotter climates (Bawa & Ukpabia, 2025). It is essential to note that energy performance and indoor comfort in buildings is widely proven to be significantly influenced by the choice of materials and construction techniques used; for example, the energy performance and indoor comfort metrics of a rammed earth wall with thatched roofing (Figure 2.16) outperformed modern approaches such as the use of shipping containers or buildings with glass façade and concrete roofs in a study conducted by (Ede et al., 2017). Even certain insulation products such as the polyurethane boards have proven to save up to 9% on electricity consumption for its cooling application, thus presenting a low-cost retrofitting alternative for residential and commercial buildings (Alegbe & Hammed, 2024).

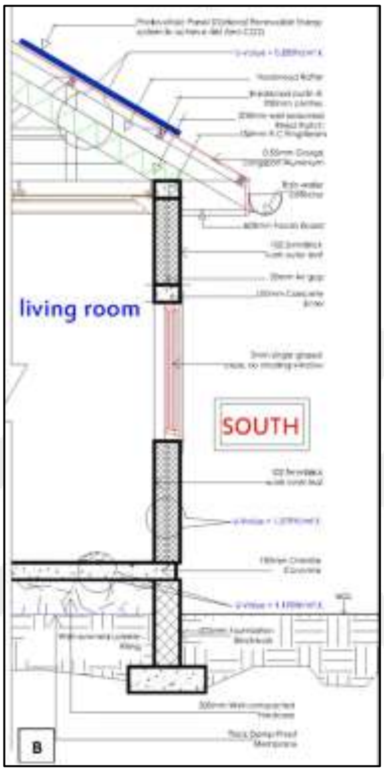


Figure 2.14: Proposed Optimized Construction Guideline to Increase Thermal Comfort and Reduce Cooling Loads, (Jegede and Taki, 2022).

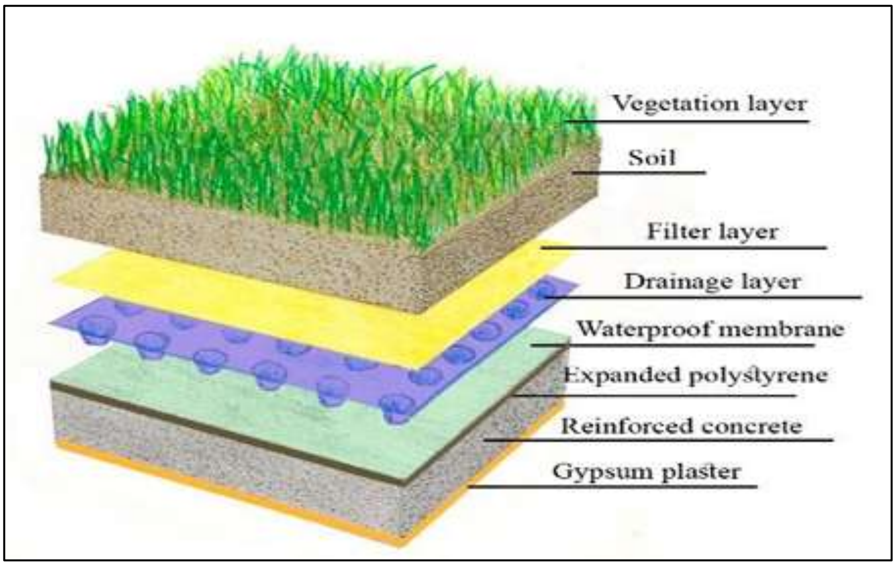


Figure 2.15: Layers of Green Roof System, (Bawa and Ukpabia 2025: Ragab & Abdelrady, 2020)

Figure 2.16: Rammed Earth Wall, (Ede et al., (2017).

All these findings reinforce each other as they highlight key necessities in material choice and design of building envelope that significantly make impact on environmental responsiveness and thermal efficiency. Beyond improving occupant well-being, this also aligns with initiatives around sustainability and energy conservation.

2.3.2.1 Thermal bridges

Thermal bridges represent specific zones within a building's envelope where there is a disproportionately high rate of heat transfer, leading to significant energy losses. These areas are critical concerns in the design and performance NZEBs, as they can undermine overall thermal efficiency. Thermal bridges typically form at the intersections and junctions of structural elements such as where façades meet intermediate floor slabs creating pathways for unwanted heat flow (Romero et al., 2021). As NZEBs increasingly incorporate thicker insulation to reduce energy consumption, the relative influence of thermal bridges on total energy demand becomes even more pronounced, highlighting their importance in high-performance buildings ((Berggren & Wall, 2011). Adopted for Ayse Esra Idemen ARCH 311 lecture notes from Altinbas University Istanbul, Figure 2.17 and Figure 2.18 shows some common thermal bridges and solutions respectively.

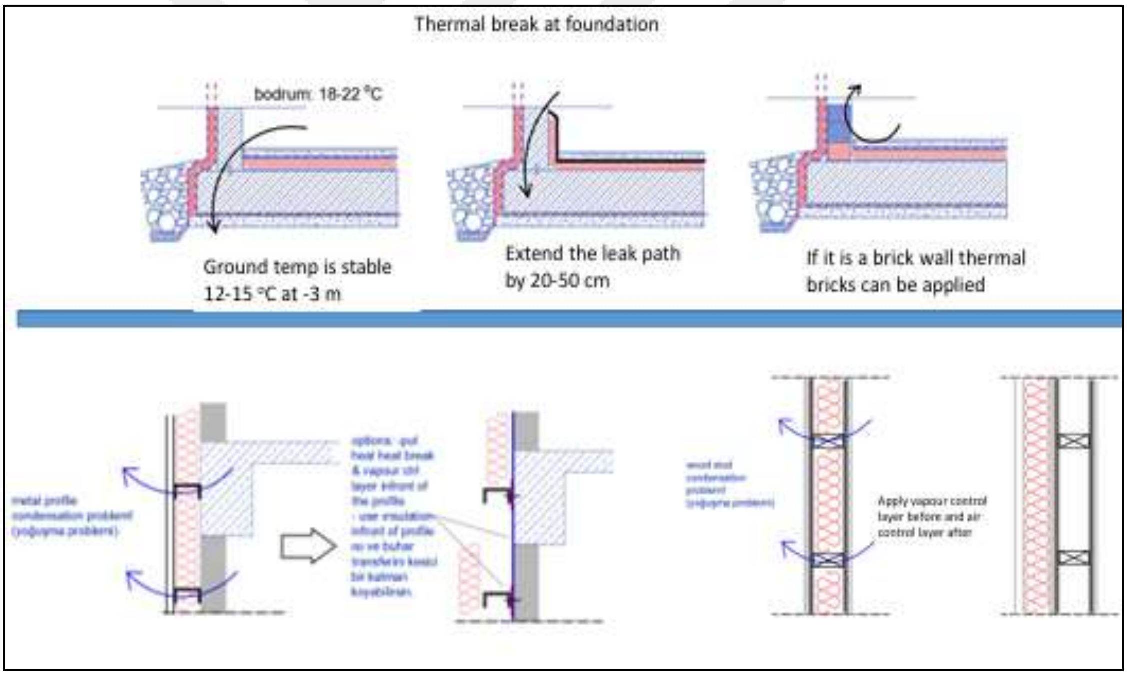


Figure 2.17: Thermal Bridge Examples and Possible Solutions for Foundations.

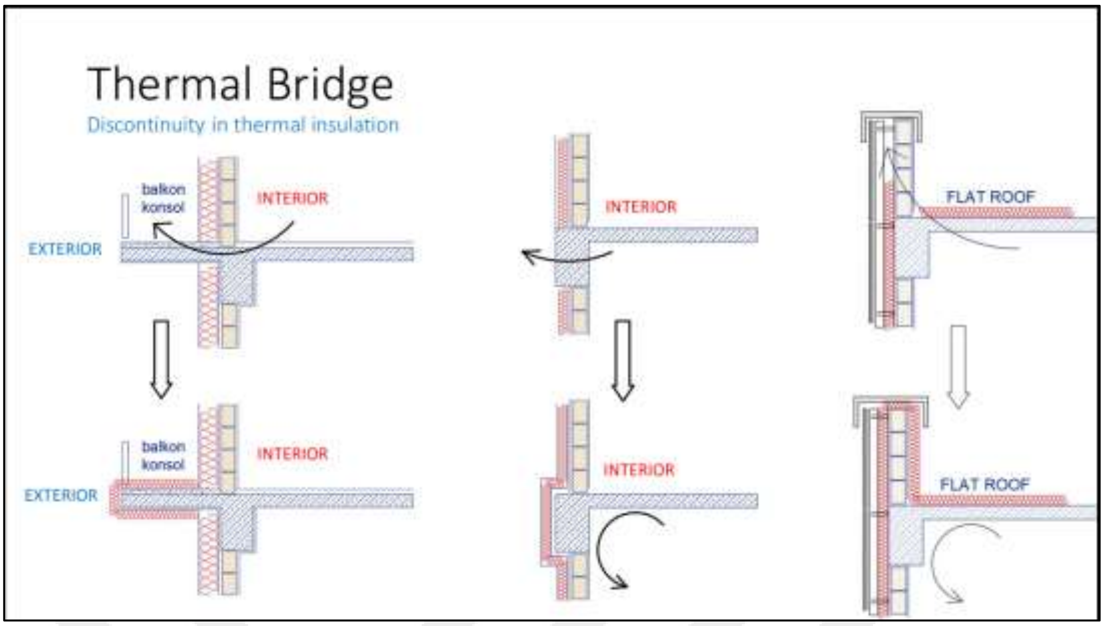


Figure 2.18: Thermal Bridge Examples and Possible Solutions for Walls.

2.3.3 Fenestration and Solar Shading

The energy performance of buildings, particularly in the tropics, relies heavily on the fenestration, which is the design of individual openings in the building envelope such as windows and skylights, along with their orientation and placement. These areas, which face continuous solar radiation and heat gain, derive substantial benefits of performance from the optimization of fenestration parameters. Shahid & Karimi (2022), determined that the components of fenestration design such as window-to-wall ratio (WWR), glazing type, orientation, and the use of shading devices significantly affect the total energy demand of the building. Of these, the WWR is usually regarded as the most important factor affecting thermal performance. According to research conducted by Shahid & Karimi (2022) and (Fang & Cho, 2019), reducing WWR promotes lesser unwanted heat gain, thus making lower WWR buildings more energy-efficient in the hot climates where excessive solar exposure can overburden the cooling systems. According to (Gupta & Deb, 2023), when proper WWR is combined with appropriate high-performance glazing and insulation techniques, substantial improvements in energy savings in tropical architecture are achieved. To create an effective fenestration system, multiple performance parameters need to be evaluated including the U-value (heat transfer coefficient), Solar Heat Gain Coefficient (SHGC), Light-to-Solar Gain (LSG) ratio, and Visible Light Transmittance (VLT). U-value (thermal transmittance) measures the rate of heat transfer through the fenestration, measured in W/m^2K, and it is a quantity that is expected to be low in order to achieve high energy efficiency of the product, thereby reducing the heat that flows from the outside to inside. SHGC measures the percentage of solar radiation (directly or indirectly) that comes through a window and is admitted as heat. This coefficient varies from 0 to 1, with lower values indicative of improved solar heat rejection and better thermal performance. The LSG ratio is calculated by taking VLT/SHGC, which shows how much natural light is transmitted relative to solar heat. An LSG greater than 1 means that a glazing system admits more daylight than solar heat gain, which is an advantage in energy-saving designs. The Visible Light Transmittance (VLT) itself denotes the quantity of daylight that passes through the glass, affecting both the levels of illumination and visual comfort in indoor spaces (Alyahya & Nawari, 2018:U.S. Department of Energy). It should also be noted that shading components that include overhangs, louvers and vertical fins significantly also play an important role in controlling SHGC as well as light penetration aside from glazing properties. These devices alleviate cooling loads by blocking direct solar radiation from hitting the glass surfaces directly, particularly during peak sun hours (Shahid & Karimi, 2022); Bano & Kamal, 2016).

These attractive design elements produce a potentially substantial energy-saving opportunity when properly incorporated and optimized. Per Gupta and Deb (2023), net energy consumption for buildings is reduced by 60%, in a worst-case scenario, as a result of holistic fenestration optimization through the adoption of ideal WWR settings, advanced glazing systems and/or effective shading. These efficiencies not only reduce operating costs, but also contribute to wider ambitions in sustainable development and climate resilience. Research on window-to-wall ratio (WWR) in hot-humid climates shows that the ideal values differ depending on building type and orientation. For offices WWR at about 10% was identified to provide the best thermal comfort (Alibaba, 2016). In contrast, (Shaeri et al., 2019) reported 20–30% for north-facing and 20–50% for south-facing facades. Ayoosu et al. (2021), found that 30% ideal for lecture theaters for daylighting Vijay Kumar et al., (2020), analyzed WWR of 5%, 10%, 15%, and 20% for residential buildings in order to evaluate the effect of these values on energy use and daylighting. In conclusion, results underscore the necessity of a mindful selection of WWR in order to achieve an appropriate balance between thermal comfort, energy performance and natural lighting, with optimal levels usually lying between 10% and 30% keeping in mind solar orientation and direct solar radiation.

2.3.3.1 High performance glazing

High-Performance Glazing Systems are essential in ensuring energy efficiency and thermal comfort in buildings, especially considering the needs of NZEBs, (Moghaddam et al., 2023). Advanced glazing technologies have been proven to be an essential factor in minimizing energy use and carbon dioxide (CO_2) emissions, with their effects covered on a European Union scale (Bakker, 2019). But with great benefits in high-performance glazing comes a potential downside too, occupants may also be forced to use more blinds or shading systems, faced with issues such as too much glare and over lit areas due to overuse of natural light or poor design. This can increase the use of artificial lighting and/or cooling, and hence offset the expected energy savings (Byrd, 2012). This proves that a comprehensive, balanced approach is crucial for glazing system selection. The energy performance, indoor thermal comfort, cost-effectiveness, and environmental impact are integrated factors that should be addressed to ensure that the mentioned glazing does not affect negatively the performance of building contributing with unwanted inefficiencies on building performance (Moghaddam et al., 2023). Mirrahimi et al, (2015) as cited by Bawa and Ukpabia (2025) outlined a series of glazing build up and their characteristics as shown in the table 2.2.

Table 2.2: Glazing Build up and Their Characteristics. (Ukpabia 2025; Mirrahimi et al, 2015).

Glazing type	**No. of panes**	**Visible transmittance**	**Shading coefficient**	**Solar Heat Gain coefficient**	**U-value (W/m^2K)**
Single-glazed clear 6 mm	1	0.88	0.95	0.81	6.4
Single-glazed tinted 6 mm	1	0.65	0.73	0.62	6.0
Double-glazed clear 6/12/6 mm	2	0.78	0.81	0.70	2.74
Double glazed clear low-e 6/12/6 mm	2	0.74	0.65	0.56	1.78

2.3.4 Air Tightness and Ventilation

The methods of ventilation and airtightness play very important factor in increasing efficiency and sustaining the indoor environmental quality in modern buildings. When designed appropriately and correctly, they play a major role in minimising total building energy usage. Increased airtightness, specifically, limits uncontrolled air loss, reducing the demand placed on heating, ventilation and air conditioning (HVAC) systems. This is particularly important for NZEBs, which focus on energy efficiency in the first instance (Liu et al., 2019). Despite that clear benefit, many current building designs still do not maximize the combined effectiveness of airtightness and ventilation. Research suggests a significant proportion of mechanically ventilated dwelling units are more air permeable than the mechanical systems are designed to deliver (Crawley et al., 2019). Unfortunately, this omission frequently results in unwarranted energy loss and a drop in indoor air quality. Airtight construction should always be followed by appropriate ventilation strategies to maximize the benefits of airtight construction. When these two sides are treated in combination at design stage, they can result in a remarkable energy demand decrease and at the same time improve indoor air quality through regulated and adequate intake of fresh air (Crawley et al., 2019). In relatively hot, humid climates where the cooling loads are generally high, a dual strategy is found to work effectively: Maintaining airtightness in air-conditioned zones to reduce heat and moisture ingress and implementing natural or mechanical night-time ventilation in non-air-conditioned spaces to spillage built-up warmth. This is a well-documented way to reduce energy demand for cooling and enhance human thermal experience (Uno et al., 2012). Ventilation systems have remained at the forefront of energy saving technology. More modern systems like demand-controlled ventilation (DCV) modulate airflow rates based on occupancy and indoor air quality, avoiding wasted energy. ‘Decentralized’ can enable better local control while minimizing duct losses, which is particularly important for retrofit projects. Normally, earth-to-air heat exchangers utilize the constant underground temperature to precondition incoming air, reducing the energy required to heat or cool. Lastly, high-efficiency heat recovery systems capture thermal energy from burnt air, enabling it to precondition incoming fresh air and contributing significantly to overall HVAC energy savings (Amanowicz et al., 2023).

Overall, they emphasize that building design for ventilation and airtightness must be multifaceted, but a unified approach is skeletal to designing well-performing building envelopes. When implemented correctly they can not only facilitate energy efficiency and thermal comfort, but improved indoor environments as well and are vital goals in the advancement of sustainable, high-performance buildings.

2.4 THERMAL COMFORT

According to ASHRAE standards, the thermal comfort for occupancy in tropical climates is achieved at 26^0C, however, research shows that occupants in tropical climates have higher threshold for thermal comfort. For instance, studies of thermal comfort in tropical areas suggest that ASHRAE Standard 55 may not be totally applicable for such climates. Studies in Malaysia, Singapore and Thailand reported neutral temperatures in line with those found in our work of 28.5 C under naturally ventilated feeding and resting areas, which are above those recommended by ASHRAE (Maarof & Jones, 2009). ASHRAE standards were not met in many of the classrooms in Hawaii, yet over 80% of the occupants found naturally ventilated and mechanically conditioned spaces acceptable, (Kwok, 1990). Similarly, non-ASHRAE compliant office buildings in Sri Lanka are felt as comfortable by occupants, (Rodrigo et al., 2022). A study in Cameroon found that optimal worker performance was achieved when thermal sensation ranged from -0.5 to 0.5, while productivity declined at temperatures above 28°C (M. K. Nematchoua, 2018). These findings suggest that people in tropical climates often have different thermal comfort preferences and tolerances compared to those in temperate zones, highlighting the need for region-specific comfort standards.

A number of variables, such as air temperature, relative humidity, and local climate conditions, influence thermal comfort in Nigeria and other tropical areas. According to research, Nigeria has experienced an increase in thermal stress since 2000, especially in the country's south and northwest, (Eludoyin et al., 2014). Indoor comfort is greatly impacted by a building's thermal performance, which is determined by design factors such thermal mass, window placement, shading, and construction materials. Because their ideal interior operating temperature is typically greater than 28°C, residents of many residential structures commonly feel thermal discomfort (Adaji et al., 2017). Nigeria's varied climate zones necessitate the use of several thermal indices for evaluating thermal comfort. In order to capture the combined effects of temperature and humidity on human comfort, commonly used indices include the Effective Temperature (ET), Temperature-Humidity Index (THI), and Relative Strain Index (RSI) (Eludoyin et al., 2014).

3. RESEARCH METHODOLOGY

3.1 RESEARCH DESIGN

This study adopts a mixed-methods research design, integrating both qualitative and quantitative analytical approaches to investigate the impact of building envelope material and insulation on energy consumption, cost, and thermal comfort in residential buildings in Abuja-Nigeria, within a tropical climate context. The qualitative method involved a comprehensive review of relevant literature and contextual data using secondary sources such as academic journals, textbooks, and previous studies. This process provided an in-depth understanding of sustainable design strategies suitable for tropical climates and helped to identify key research gaps in building envelope performance. The quantitative component employed a simulation-based approach using DesignBuilder, which utilizes the EnergyPlus simulation engine. This phase involved modelling and analysing the energy performance of two building envelope scenarios: a baseline model with conventional envelope materials and an alternative model with improved envelope configurations based on insights from the literature review. The simulation results were used to compare and evaluate parameters such as annual energy consumption, construction cost, energy cost, and thermal comfort.

By combining qualitative insights with quantitative performance data, this research design ensures a robust and holistic understanding of how envelope optimization can contribute to achieving energy efficiency and comfort in tropical residential buildings. The research design can further be understood using the figure below (Figure 3.1).

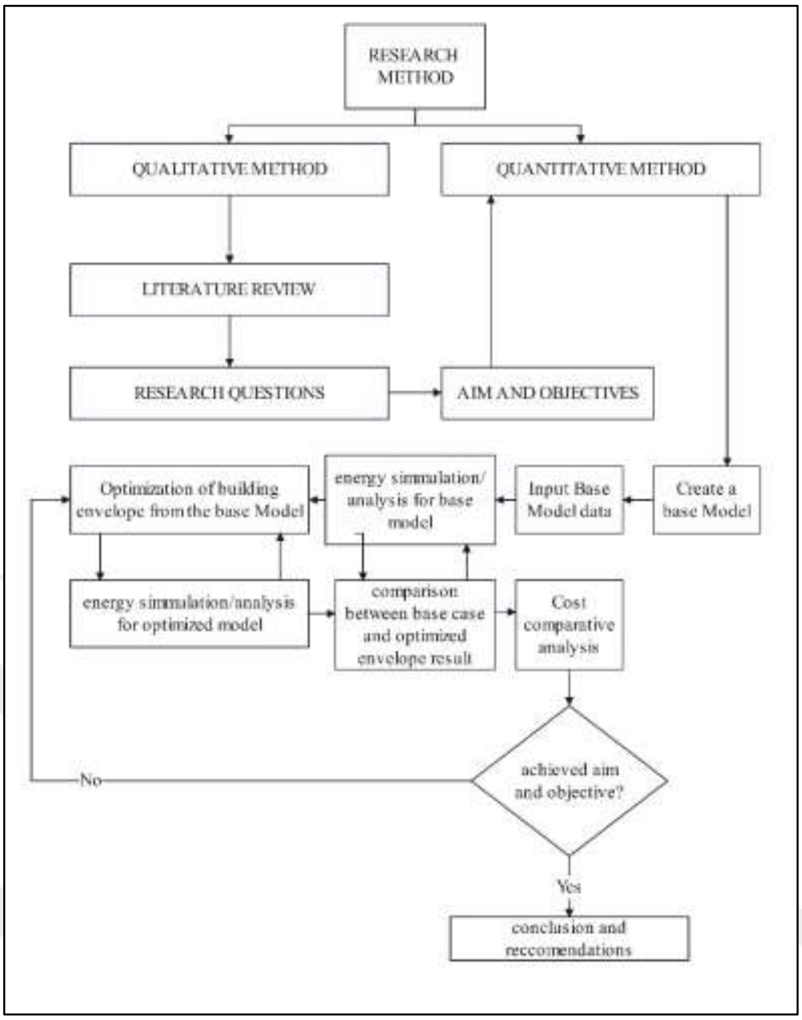


Figure 3.1: Research Design Flow Chart, (Aurthor: EdrawMax 2025).

3.2 DATA COLLECTION

Achieving the objectives of this study involves the utilization of secondary data and simulation generated data.

For the qualitative phase, collection of data was based on secondary data collection methods in the phase of extensive review of literature including peer-reviewed journal articles, reports, books, and case studies. These were vital for gaining insights into sustainable building envelope best practices, climate-responsive design principles, and energy efficiency measures relevant to tropical climates.

Data collection in the quantitative phase was performed via dynamic simulations using DesignBuilder with the EnergyPlus engine. The inputs for the simulation depended on the climate data for Abuja, Nigeria (derived from typical weather files), building geometry, construction materials, and occupancy schedules. For residential building envelopes, two building envelope conditions were built: the baseline model, which represented the conventional construction practices, obtained from the Nigerian Building Code (NBC) and supplemented with customary envelope construction practices obtained for the literature review, and the improved model, which consolidated improvements for the envelope, as indicated in the literature review. The flat data for energy consumption, operative temperature, cooling load, and CO_2 emissions allowed comparative analysis between each simulation output.

Integrating data from specialized literature with simulation-derived data for the evaluation of the impact of building envelope optimization for a tropical climate also ensures that the methodology is thoughtful and efficient.

3.2.1 Data Analysis

Data analysis was performed using qualitative interpretation and quantitative performance evaluation, in accordance with the mixed-methods approach.

For its qualitative component, the data retrieved from the literature review was thematically analyzed to recognize common strategies, materials, and principles of design to optimize building envelopes in tropical climates. Informed by these insights, envelope features considered in the simulation phase included building envelope include insulation types, glazing systems and shading techniques.

While for the Quantitative Analysis, the results of simulation ran using DesignBuilder were analyzed. Annual energy consumption, operative indoor temperature, cooling loads, and CO_2 emissions as primary performance metrics were interpreted based on the data extracted for both baseline and optimized building model. In order to compare the optimized envelope design, these parameters were then analyzed. The differences in performance was highlighted using graphical and tabular representations, percentage change calculations helped quantify the improvements in energy efficiency and thermal comfort.

By employing this dual-layered analysis approach, the research aimed at fostering energy-efficient and climate-responsive architecture, especially assessing the role of strategic envelope design in enhancing building performance in a tropical climate context.

3.3 DESIGN PROPOSAL

For the purpose of this research, a duplex three-bedroom block of flats of the semi-detached format for four (4) families with a floor area of $292m^2$ was designed by the Author upon which the conventional and improved building envelope were imposed for the simulations to be carried out. The block of flats was chosen because based on research conducted as seen in the literature review of this study, it is the most preferred housing typology amongst the residents of Abuja and Nigeria at large. This housing typology also offers economical sustainability which means it will reach most of the population thereby making it more feasible to achieve NZEBs in Nigeria by 2070. The semi-detached form of the block of flats was chosen because most often than not, it gives a rectangular shape, and in combination with the duplex format becomes a cuboid providing a more suitable building form for proper orientation as studied to be the first phase towards achieving NZEBs. The floor plan, sections and elevation of the design proposal can be seen in Figure 3.2.

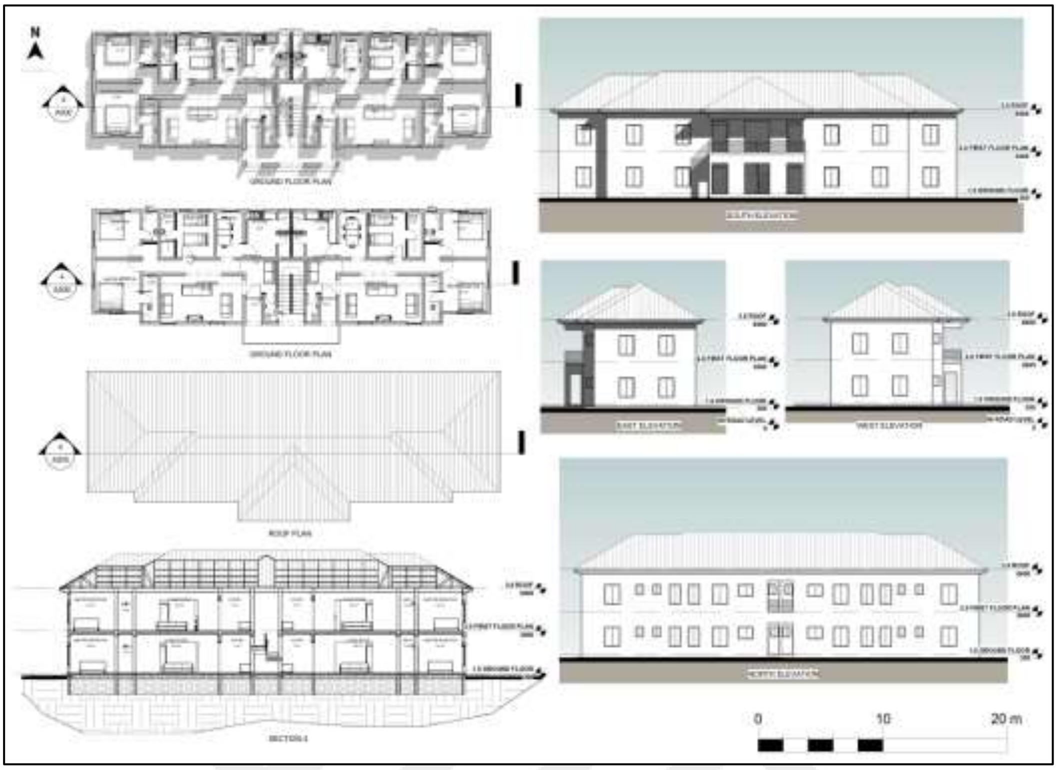


Figure 3.2: Design Proposal (Authors Sketch; Revit 2024).

3.4 SIMULATION SOFTWARE: DESIGN-BUILDER

DesignBuilder (DB) is a performance simulation tool for evaluating and optimizing building energy performance. It enables the assessment of parameters such as orientation, material choice, ventilation, glazing, and lighting, all of which can enable energy-efficient design (Choudhary, 2015); Zhang, 2014). In early design stages, DB is successful in designing sustainable buildings to minimize energy consumption (Choudhary, 2015). As a result, it helps to correlate the architectural principles into the quantitative energy data, leading towards the modifications of the designs for progress (Pawar & Kanade, 2018) Widely used to evaluate commercial buildings, DB can measure against predefined benchmarks like Energy Conservation Building Code (Choudhary, 2015; Pawar & Kanade, 2018). In hot arid climate regions, discrepancies of the order of 1–5°C between DB outputs and real-world measurements have been reported, suggesting some accuracy limitations (Moussa & Moawad, 2020).

3.4.1 Energy Simulation Using Design Builder

Energy simulations were conducted using DesignBuilder, a graphical interface that works with the EnergyPlus simulation engine, in order to assess the energy performance of the building envelopes. First, a digital representation of the buildings was constructed, as information about geometry, zoning and layout was determined based on desired specifications (Figure 3.3). The project location was set to Abuja, Nigeria, and the relevant EnergyPlus Weather (EPW) weather file was uploaded to import the local climate. Construction materials (conventional and optimized design strategies) were assigned to the envelope elements such as walls, roofs, floors, and glazing. Activity type, internal gains, occupancy pattern, lighting, equipment, and HVAC schedules of the building were provided to represent typical usage scenarios. Where relevant, HVAC parameters and natural ventilation strategies, including airtightness and night ventilation, were set. Simulations were conducted for both baseline and optimized envelope model, and results were obtained, including annual energy consumption, cooling loads, and CO_2 emissions. These outputs were obtained and examined in comparison to determine the performance of the optimal envelope strategies in improving the energy efficiency and thermal comfort in the context of a tropical climate.

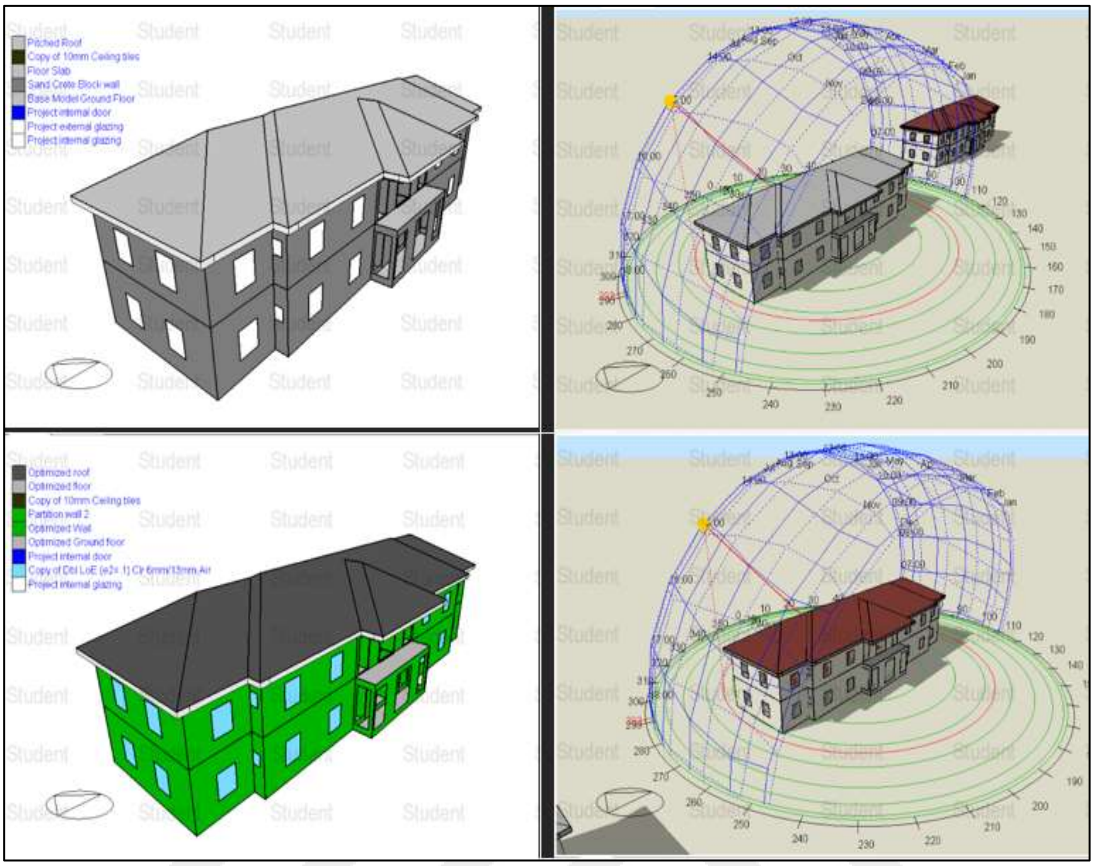


Figure 3.3: Envelope Geometry of Base Model and Optimized Model in Design Builder (Authors Sketch; Design Builder).

3.5 SIMULATION SCENARIOS

The scenarios were evaluated in the DesignBuilder software to analyze the influence of different parameters, including wall and roof composition, thermal insulation classes, glazing types. The baseline model depicts a conventional house built using common design methods in Nigeria, while the succeeding scenario incorporates optimized envelope strategies from the literature review and contextual exploration. The purpose of these scenario is to highlight design solutions that are cost-effective, thermally comfortable, and energy-efficient, providing insight into how one can achieve net-zero energy targets in the Nigerian context. These improvements are then evaluated based on the simulation results of each scenario regarding energy consumption, indoor thermal comfort, and carbon emissions.

3.5.1 Regular Envelope Simulation

The ground floor of the conventional building envelopes is comprised of 150mm thick concrete site overcast on 300mm thick hardcore filling laid on well compressed laterite earth having a combined U-value of 1.19 W/m^2K. The external walls are made up of 230mm sand-Crete hollow blocks with 25mm thick plaster on either side giving a total thickness of 280mm and a U-Value of 1.98 W/m^2K. The glazing of windows and other glazed openings are made with 6mm thick single clear glazing without shading. The roofing system comprises of a 0.55mm long span corrugated aluminium roofing sheet, nailed on well-seasoned hard wood timber, with a concrete facia as shown in Figure 3.4 while table 3.1 shows the details of each components material.

Table 3.1: Building Envelope Components of Base Model with Their Corresponding U-Values. (NBC 2006, Jegede 2021, and Ukpabia 2025; Mirrahimi et al, 2015).

Envelope component	**Description**	**U–value (W/m^2K)**
Ground floor	150 mm Oversite Concrete on a damp-proof membrane on 300mm hard core on well ramped Laterite.	1.19
External walls	230mm sand-Crete hollow blocks with 25mm thick plaster on either side (Figure 3.5).	1.98
Glazing	6mm thick single clear glazing	5.78
Roof	0.55mm long span aluminium roofing sheet, nailed on well-seasoned hard wood timber, with a 600mm concrete facia overhang.	7.14

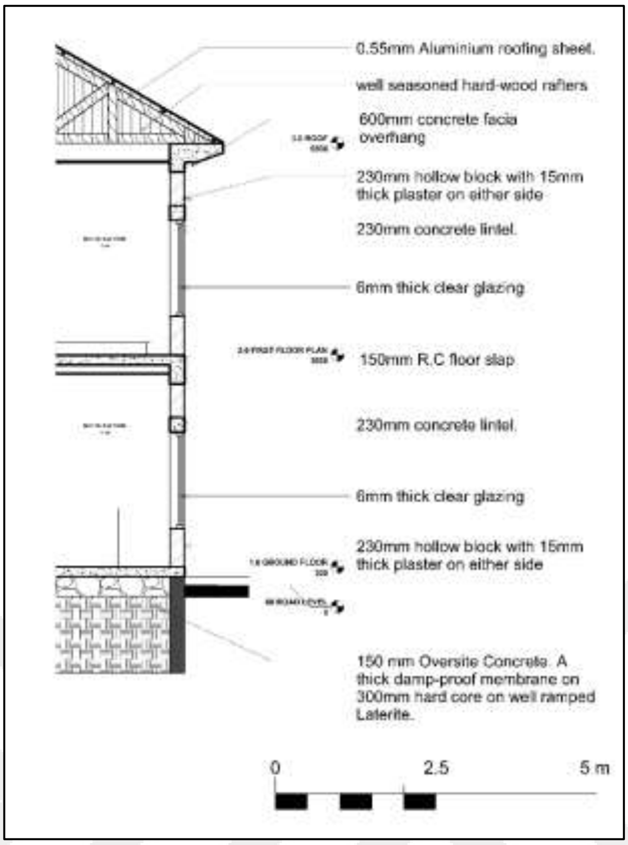


Figure 3.4: Envelope Detail of the Base Model, (Authors Sketch; Revit 2024).

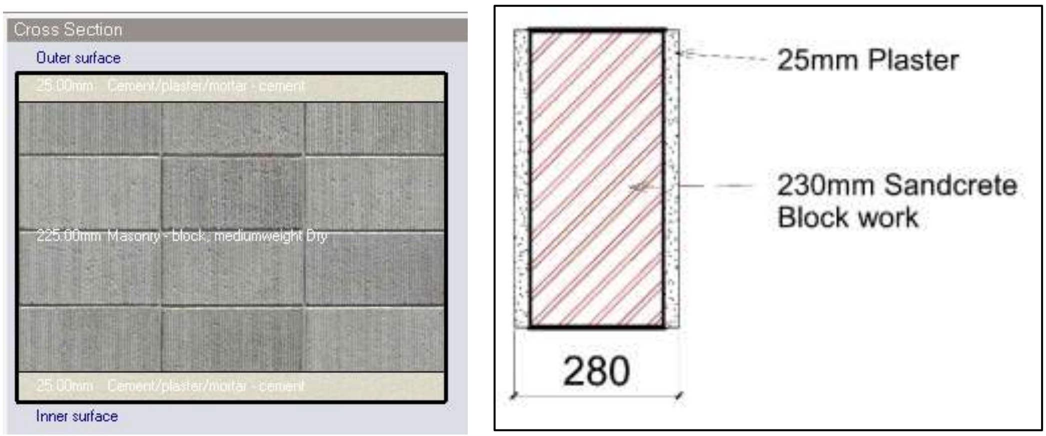


Figure 3.5: Wall Cross Section of Base Model (Authors Sketch; Design Builder & Revit).

3.5.2 Improved Envelope Simulation

The optimized envelope components (Figure 3.6) comprised of ground floor made of terrazzo floor finish, on 50mm thick sand-cement screed, on 150mm expanded polystyrene insulation on 150mm thick concrete oversite on 300mm hardcore resting on well compacted laterite. The walls are made of double bricks having 102.5mm brick on either side with a 150mm expanded polystyrene insulation in between. The glazing for windows has been changed to double glazed clear low-e 6/13/6 mm glazing. The roof comprised of clay tile roofing sheet insulated with 150mm thick polystyrene. Figure 3.6 and table 3.2 best describes this model.

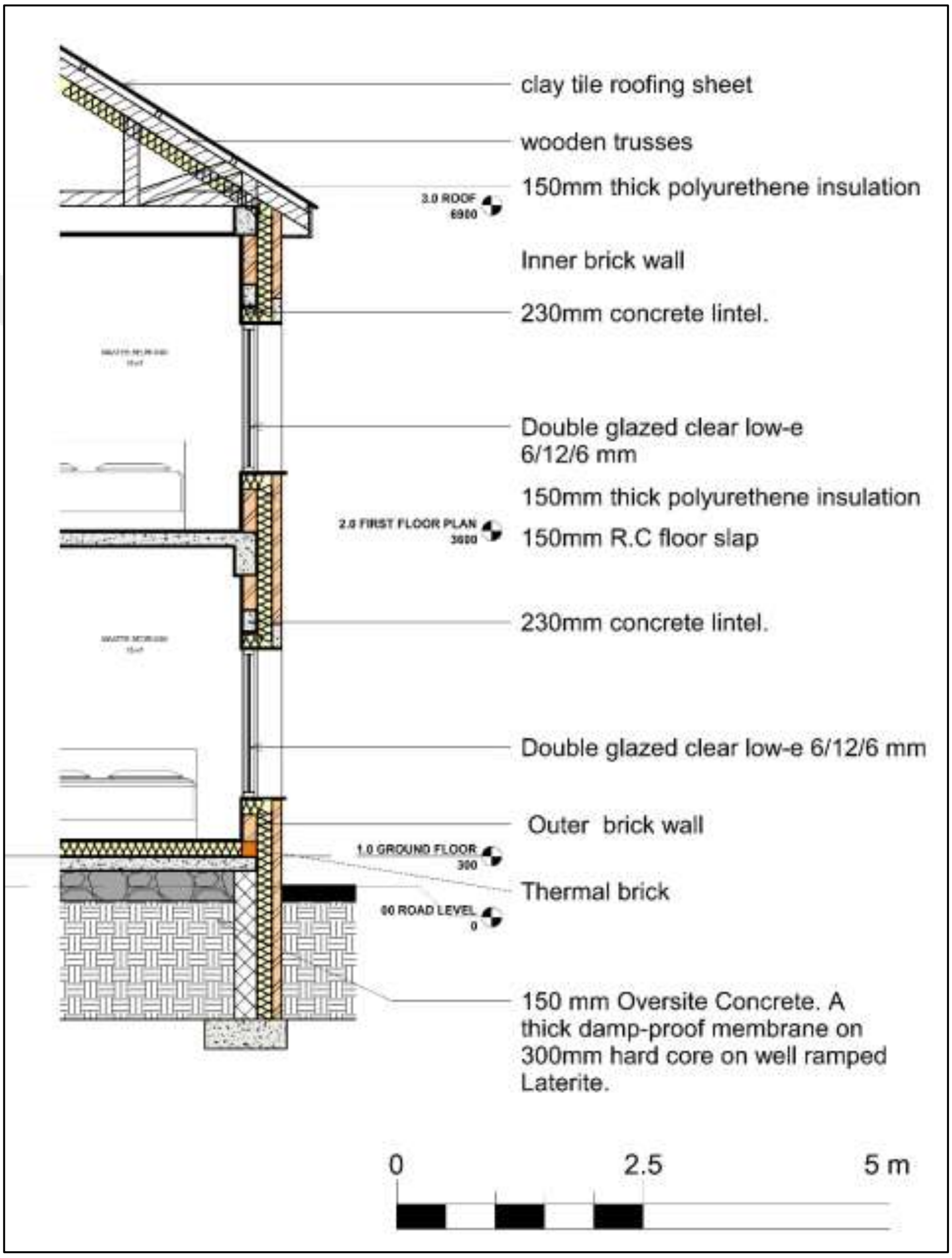


Figure 3.6: Envelope Detail of Improved Model, (Authors Sketch; Revit 2024).

Table 3.2: Building Envelope Components of the Improved Model with their Corresponding U-Values.

IMPOROVED MODEL		
Envelope component	**Description**	**U–value (W/m²K)**
Ground floor	Terrazzor finish, on 50mm sand-cement floor screed, on 150mm expanded polysterene insulation, on 150 mm Oversite Concrete on a damp-proof membrane on 300mm hard core on well ramped Laterite. (Figure 3.7).	0.22
External walls	102.5 mm inner + 150mm expanded polystyrene insulation + 102.5mm outer cavity brick wall rendered with 25mm plaster on either side. (Figure 3.8).	0.21
Glazing	Double glazed clear low-e 6/13/6 mm glazing	1.76
Roof	Clay tiles roofing sheet, nailed on well-seasoned hard wood timber, with a sandwiched 150mm thick EPS insulation, and a 600mm wooden facia overhang.	0.21

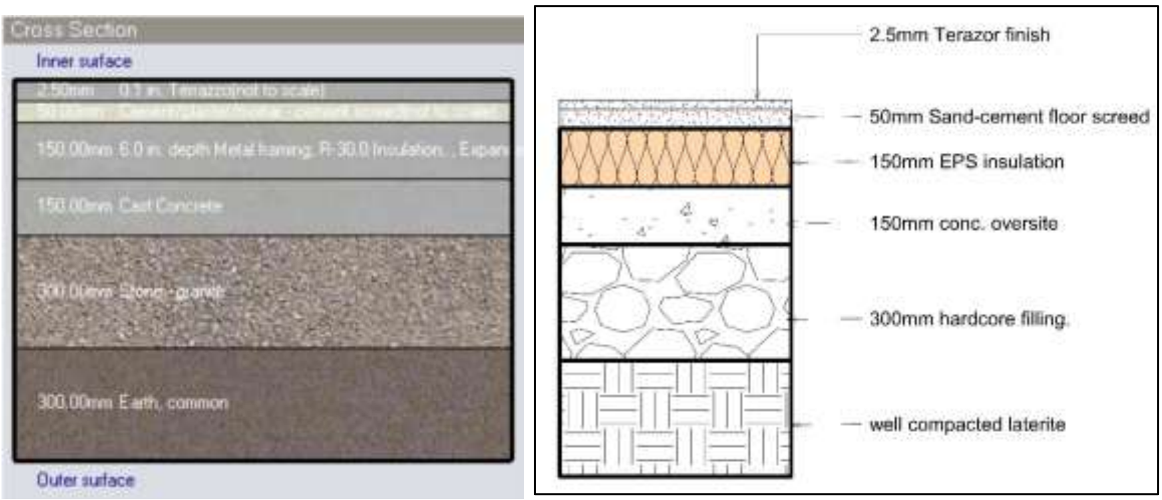


Figure 3.7: Cross Section of the Improved Ground Floor (Authors Sketch; Design Builder).

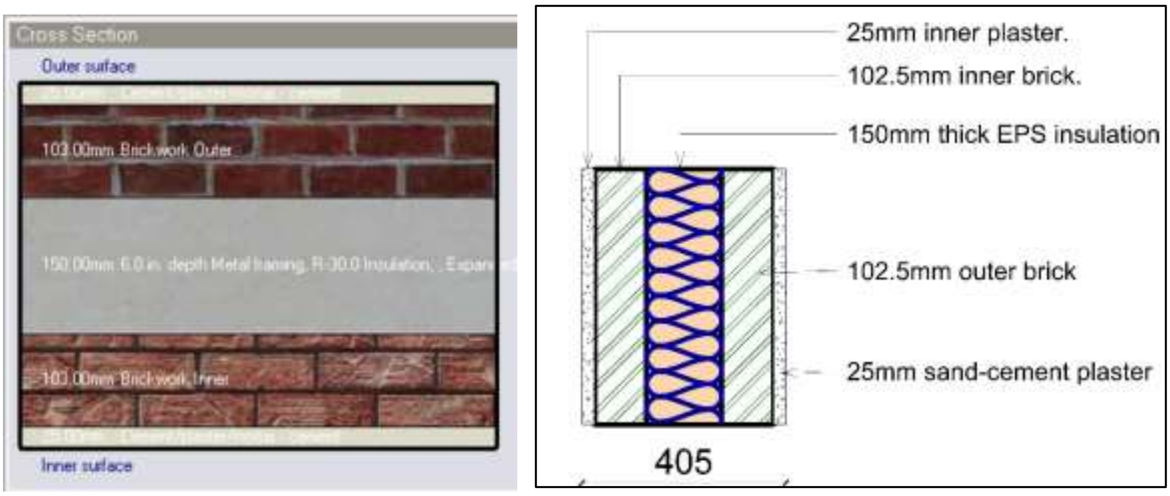


Figure 3.8: Cross-Section of the Improved Wall System (Authors Sketch; Design Builder).

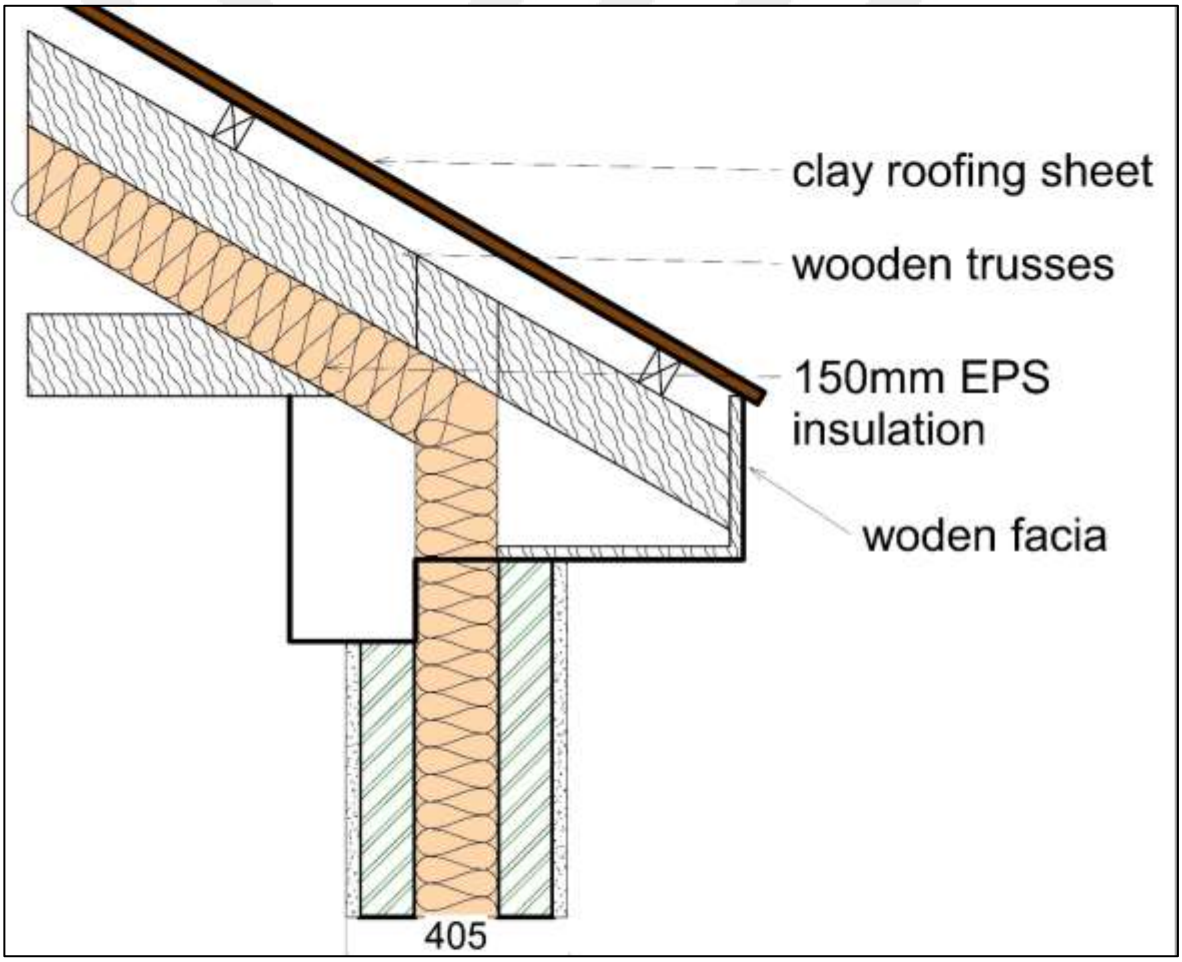


Figure 3.9: Improved Roof Cross Section (Authors Sketch; Revit).

4. RESULT AND DISCUSSIONS

The simulation was performed on an average three-bedroom duplex block of flats (four families in a semi-detached arrangement) located in Abuja, Nigeria. To ensure consistency between the models, key assumptions were applied as shown in table 4.1. The climate data (hourly weather data) was derived from Typical Meteorological Year (TMY) for Abuja.

Table 4.1: Key Constants for the Simulations.

PARAMETER	BASELINE MODEL	IMPROVED MODEL
Cooling system	split-unit (heating is not applicable)	split-unit (heating is not applicable)
Cooling set point	24^0C	24^0C
Cooling set back	28^0C	28^0C
Occupancy density	0.0215 per m^2	0.0215 per m^2
Lighting load	5 W/m^2	5 W/m^2
Air Infiltration rate	0.7 ACH	0.3 ACH
Simulation period	Jan – Dec	Jan - Dec
Orientation	East - West	East - West
Energy Tarrif	$0.145/kWh	$0.145/kWh

4.1 PERFORMANCE OF THE BUILDING ENVELOPES

The base model, which represents typical construction practice in Nigeria, shows an annual total energy consumption of about 44,067 kWh. Cooling represented the majority of this demand at 28,127 kWh, followed by lighting at 8,565 kWh and equipment/miscellaneous loads at 7,375 kWh as shown in the chart below (Chart 4.1). Energy consumptions peaked in March with about 4,900 kWh consumption on record largely due to extreme heat and dependence on air conditioning, and least in August with 2,130 kWh as shown in Figure 4.1. Carbon emission reported at about 26,705 kg, ranging from 1,290 kg in August to 2,967 kg in March, (Figure 4.2). Based on the simulation, the base model exhibits a total of about 8,360 discomfort hours, worst from July to September as a result of high humidity accompanied by high temperatures as seen in Figure 4.3 with operative temperatures ranging from 27^0C to 31^0C, and relative humidity ranging from 27% to 77%.

Chart 4.1: Energy Consumption Pattern of Base Model.

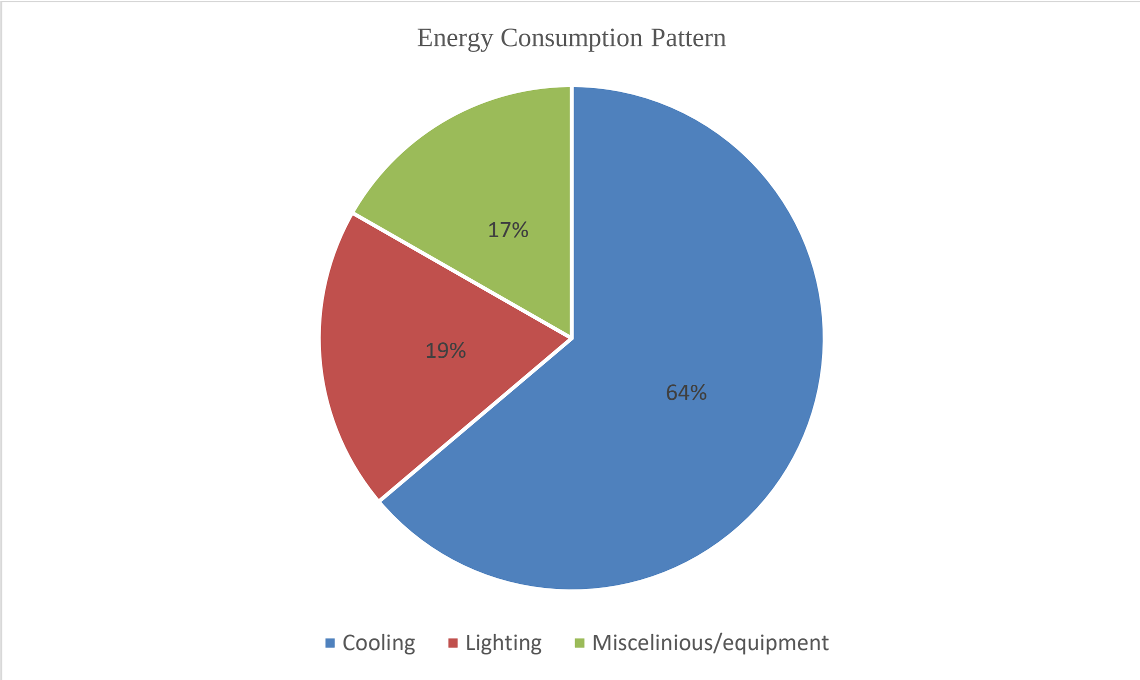


Figure 4.1: Monthly Energy Consumption of the Base Model (Design Builder).

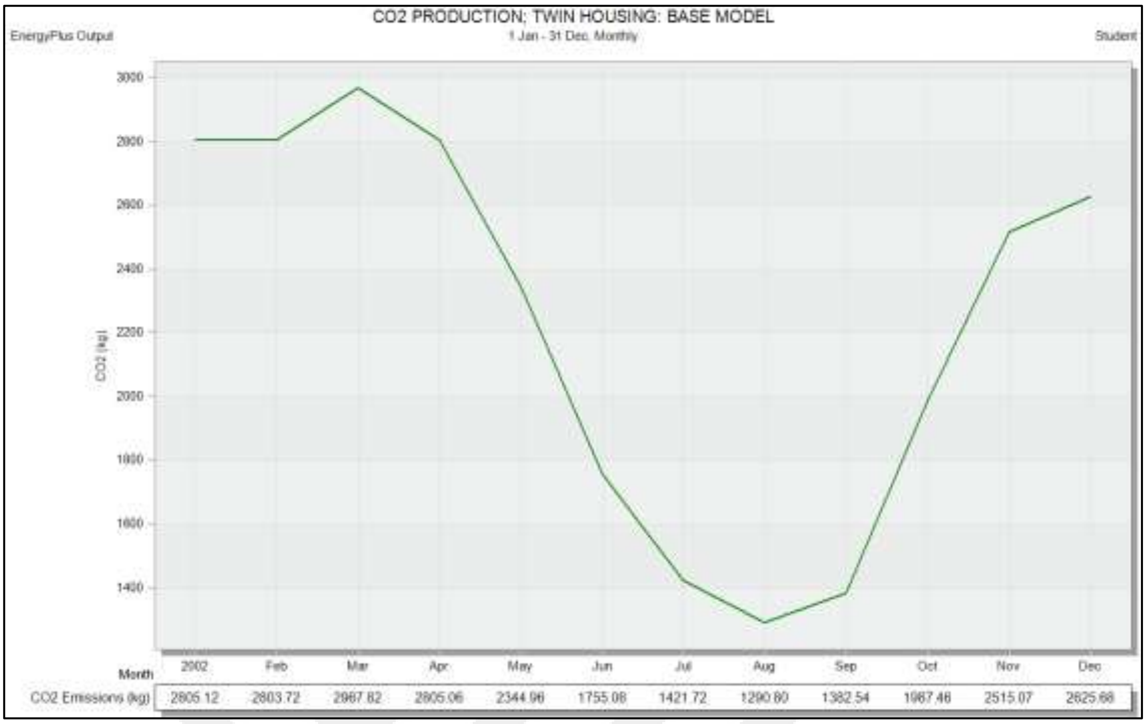


Figure 4.2: Monthly Carbon Emission of the Base Model (Design Builder).

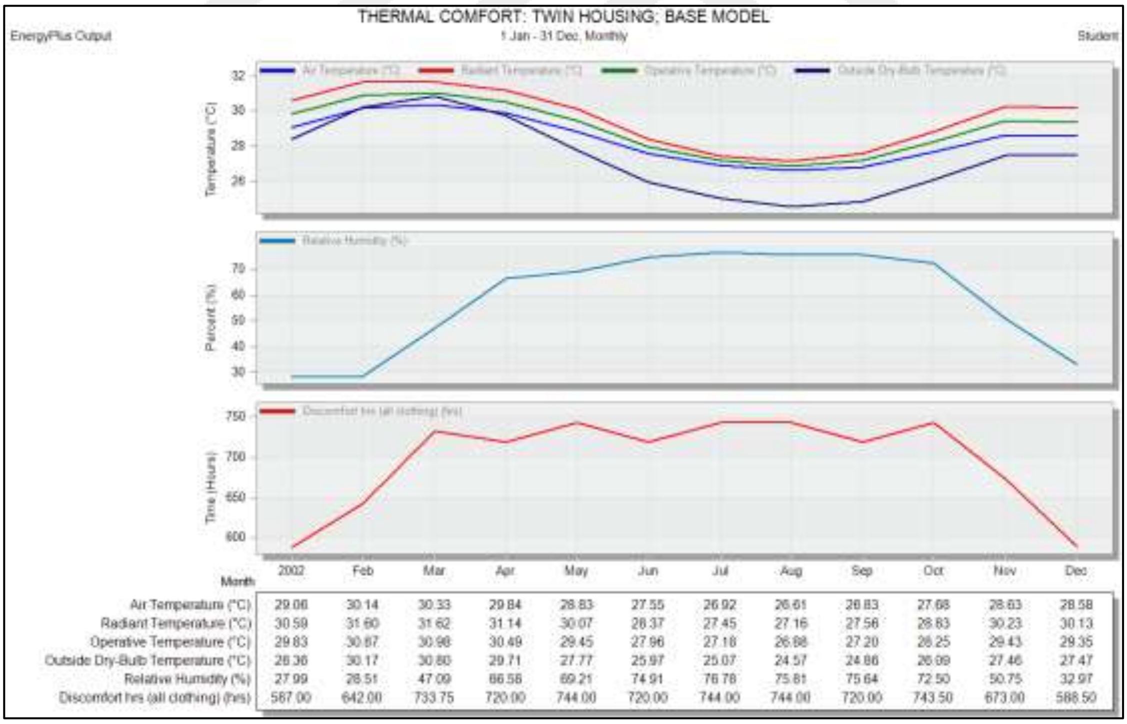
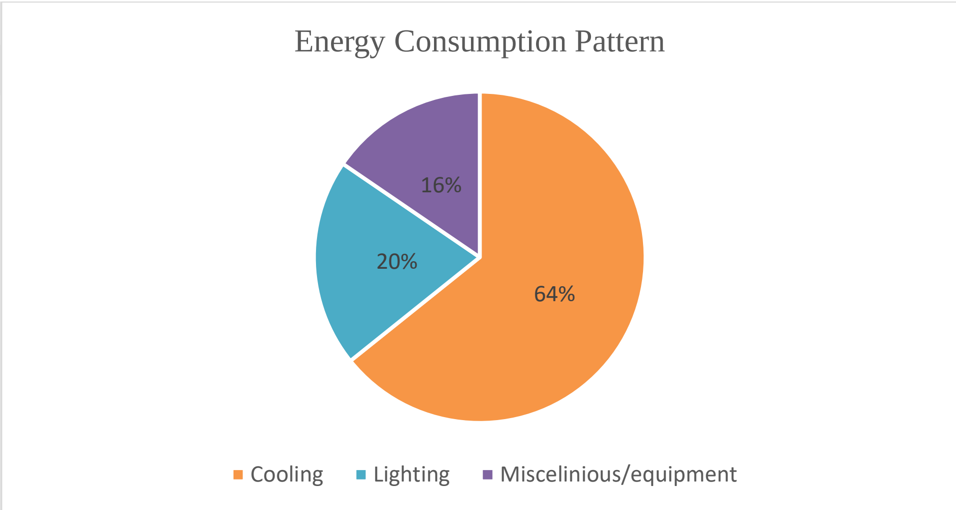


Figure 4.3: Thermal Comfort Parameters of the Base Model (Design Builder).

The energy performance of the optimized Model showed a total annual energy consumption of 29,620 kWh. Cooling decreased to 19,027 kWh, and lighting and equipment used 6015, kWh and 4,578 kWh of energy respectively, (Chart 4.2). Similarly, energy consumption peaked in March with 3,335 kWh consumed, and least in August with 1,550 kWh consumed as seen in Figure 4.4. Carbon emission reported a total of 17,950 kg ranging from 937 kg in August to 2021 kg in March as shown in Figure 4.5. Discomfort hours returned at a total of 7,414 hrs with operative temperatures ranging from 260C to 290c and relative humidity from 29% to 76%, (Figure 4.6)

Chart 4.2: Energy Consumption Pattern of the Improved Model.



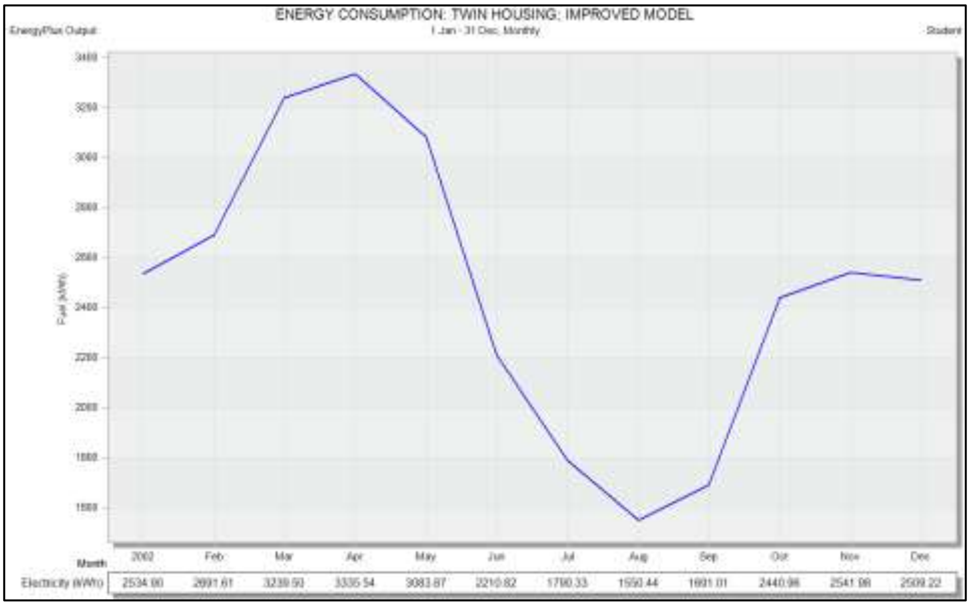


Figure 4.4: Monthly Energy Consumption of the Improved Model (Design Builder).

Figure 4.5: Monthly Carbon Emission of the Improved Model (Design Builder).

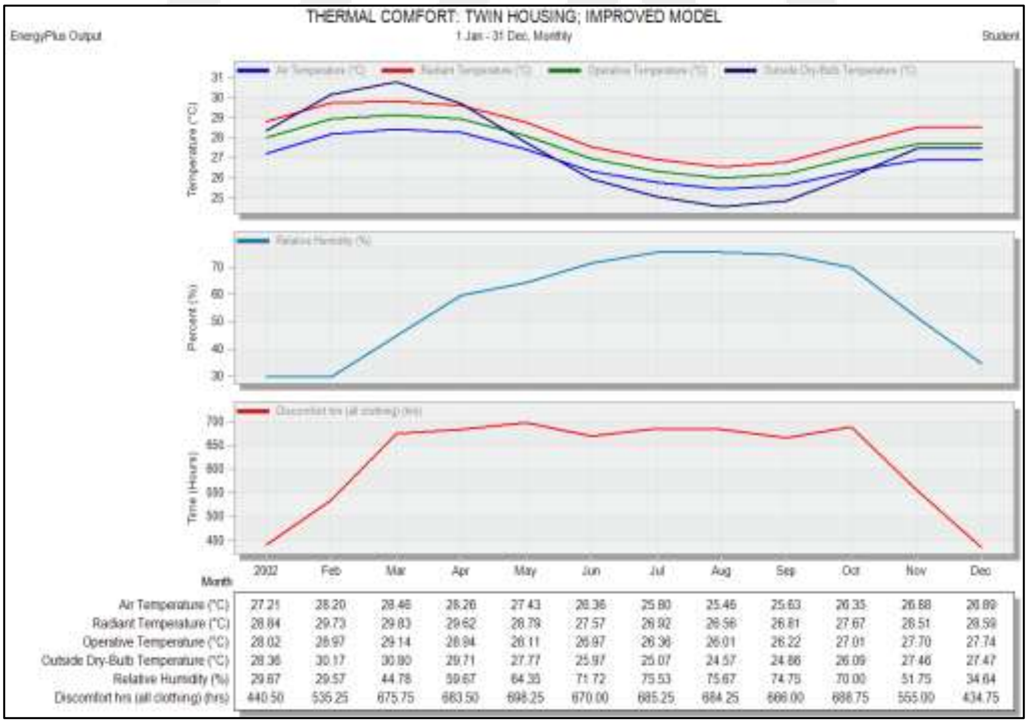


Figure 4.6: Thermal Comfort Parameters of the Base Model (Design Builder).

Based on the simulation results, the total annual energy cost for the base model, and the improved model is approximately $6,390.00 and $4,295.00 respectively, and construction cost to be approximately $202,917.00 (151,556.00 GBP) and $219,971.00 (164,293.00 GBP). Break down of the construction cost can be seen in Table 4.2.

Table 4.2: Construction Cost of Both Models.

Description	Base model	Improved Model
Sub Structure	$43,036.08 (32,143.00 GBP)	$43,036.08 (32,143 GBP)
Super Structure	$42,740.18 (31,922.00 GBP)	$56,522.76 (42,216.00 GBP)
Glazing	$7,337.14 (5,480 GBP)	$10,650.90 (7,955.00 GBP)
Surface Finishes	$109,804.05 (82,011.00 GBP)	$109,761.21 (81,979.00 GBP)
Total Cost	$202,917.45 (151,556.00 GBP)	$219,970.95 (164,293.00 GBP)

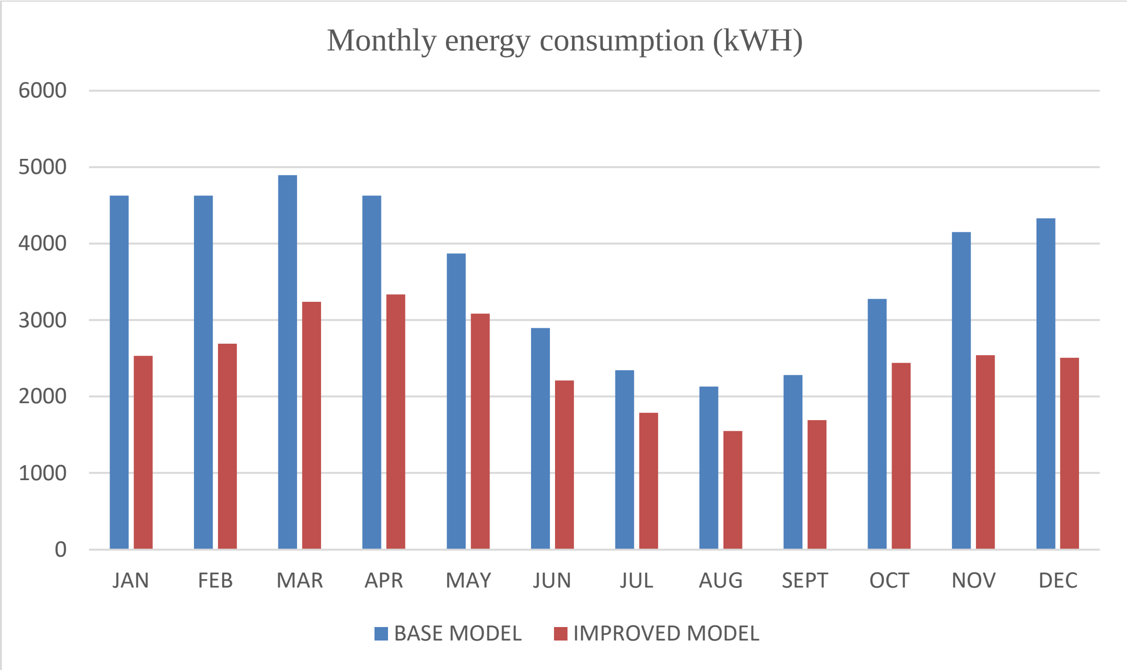
4.2 COMPARISON AND ANALYSIS

4.2.1 Energy, Carbon and Comfort Analysis

The simulation results show the significance of envelope optimization on energy performance and thermal comfort. The baseline model (Conventional Nigerian 230 mm sand-crete walls, single glazing and aluminum roofing) displayed the highest energy consumption at 44,067 kWh per year, and thermal discomfort hours at 8,360hrs per annum. This is mainly a result of its thermal transmittance, and hence low capacity to restrict heat gain; causing higher reliance on active cooling systems.

The combination of double wall with insulation with a clay tile insulated roof system for the improved model reduced energy consumptions to 29,620 kWh/year, outperforming the baseline by a percentage change of 32.7%. The choice of material with lower U-values, and adopting insulation with double walling offered additional thermal mass, low thermal transmittance thereby reducing solar gain, all of which are factors in stabilizing internal temperatures and reducing active cooling loads. The thermal comfort simulation showed that the improved model reduces thermal discomfort hours by 11% from 8,360 hours to 7,414 hours. The results for both models can best be described by Chart 4.4. These reductions also align with improvements in thermal comfort, where the operative indoor temperature dropped from an average 29°C in the baseline to 27.6°C in the improved model, staying within the ASHRAE comfort zone (24–28°C) for tropical buildings.

Chart 4.3: Comparison of Energy Consumption Between Base Model and the Optimized Model.



Based on the simulations, the improved model has the lower carbon emission by about 33% from 26,705 kg to 17,950 kg as shown in Table 4.3 below. The progression from baseline to the improved model reflects a total reduction of over 8 tonnes of CO_2 per year, reinforcing the potential for envelope optimization in climate mitigation strategies.

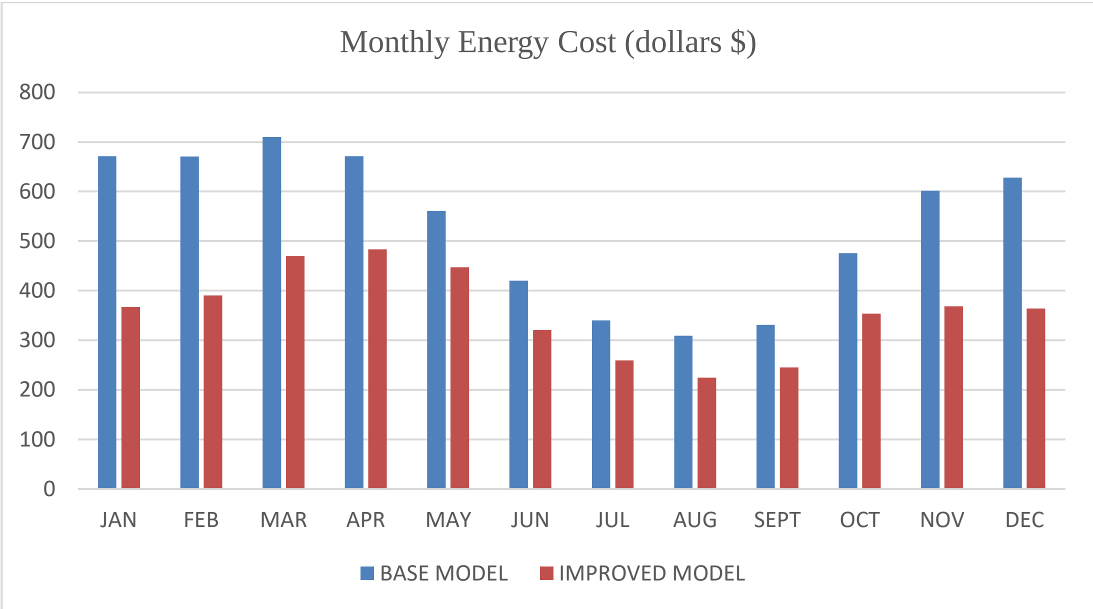
Table 4.3: Simmulated Annual Carbon Emmissions.

Model	Annual Energy Consumption (kWH)	Annual CO_2 Emissions (Kg)
Base Model	44,067	26,705
Improved Model	29,620	17,950

4.2.2 Cost Analysis

The significance of envelope optimization, in terms of economic performance is self-evident when converting the energy performance results into cost values based on an annual electricity price (derived from a tariff of $0.145 / kWh). The base model had the highest cost at about $6,390.00 per year due to its high cooling demand. By comparison, the highest performing layout, the improved model, would cost just $4,295.00, yielding a maximum savings of $2,095.00/yr. Chart 4.6 shows the monthly energy consumption of each model.

Chart 4.4: Monthly Energy Cost for Both Models.



These numbers demonstrate the long-term economic advantage of employing better envelope materials and passive design techniques, especially in hot-humid specifications, as is the case for Abuja. This directly reduces energy costs translating to reduced operational expenses, which can gradually offset the cost of implementing these strategies. The construction cost however, showed that the improved model is more expensive to build by about 8% with the difference of $17,054.00. However, with the $2,095.00 energy cost saving per year, it will take less than 10 years to recoup the initial cost difference.

5. CONCLUSION

5.1 SUMMARY OF KEY FINDINGS

This study investigated how improved building envelope strategies like material choice and insulation affects the energy performance, thermal comfort and construction cost of residential buildings in Nigeria's tropical climate, using a three-bedroom duplex block of flats as a case study. By means of a literature review, contextual analysis, and simulation-based modelling in Design Builder, the research drew comparisons between a baseline model (built with conventional Nigerian materials and design practices) and an improved model incorporating materials, insulation, and innovative passive design strategies. Results indicated that the choice of material and insulating the building envelope plays a considerable role on energy performance and indoor environment quality. The base case, using conventional materials like the 230mm sand crete hollow block with 25mm thick sand cement plaster render on each side, single glazing, and aluminum roofs without insulation, provided a system with high demand for cooling energy use, high operative temperature, higher discomfort hours, energy cost and greater carbon emissions.

In contrast, the improved model showed significant performance improvements with 32.7% annual energy savings due to double brick walls, polyurethane insulation, and clay tile roofing sheet with insulation. Also, average operative temperatures fell into acceptable ranges for thermal comfort, and annual CO_2 emissions decreased by over 8 metric-tons, and energy cost fell be over $2,000 with less than a 10 year payback on construction cost.

These findings validate the effectiveness of NZEB design principles in tropical environments such as Abuja, contributing to the global pursuit of minimizing emissions from built infrastructure. The research shows that, with just a bit of consideration for climate, simple changes to material specification, insulation and envelope configuration can lead to significant environmental, economic, and health gains.

5.2 CONTRIBUTION TO KNOWLEDGE

This research provides important evidence of the potential real-world feasibility of Net-Zero Energy Buildings (NZEBs) in tropical climates like that of Abuja, Nigeria. The results of the study can serve as empirical evidence of how the choice of material and insulation of building envelopes can be a supportive measure to achieve the sustainable energy goals of the country, by modeling and comparing the previously constructed types of envelopes utilizing a data set of working construction conditions along with real-world climate data. It also fills a localized knowledge gap by providing a framework for policymakers, architects, and urban planners in building multi-family housing developments in Nigeria.

The study was restricted to only one housing typology (a three-bedroom duplex block for four families) and used simulation outputs for comparison rather than validation with built environments. Material assumptions were made using data from the literature which doesn't always capture real-world performance, especially when occupancy or maintenance conditions vary. Also, the analysis assessed only residential envelopes, not commercial or mixed-use buildings.

Other building envelope parameters like Window to Wall Ratio (WWR), solar shading, and Air tightness, should also be considered in further research on this subject. Additional field-based performance monitoring should also be integrated into simulations to confirm the predictions. Generalization should involve wider typologies such as commercial, institutional buildings. Finally, photovoltaic panels can be added as renewable energy systems to provide an integrated model for near zero energy building. It would also be useful to conduct research on the economic feasibility and payback period of large schemes as well as the cost of optimizing the building envelope in relation to the energy savings as to whether it is worthy economically, to implement such optimizations in Nigerian housing policy. Furthermore, with enough research on this subject giving rise to adequate data-sets, the optimization of building envelopes itself can be optimized by the use of machine learning to quickly and efficiently calculate and recommend the best envelope optimization practices for a given area using its climatic data.

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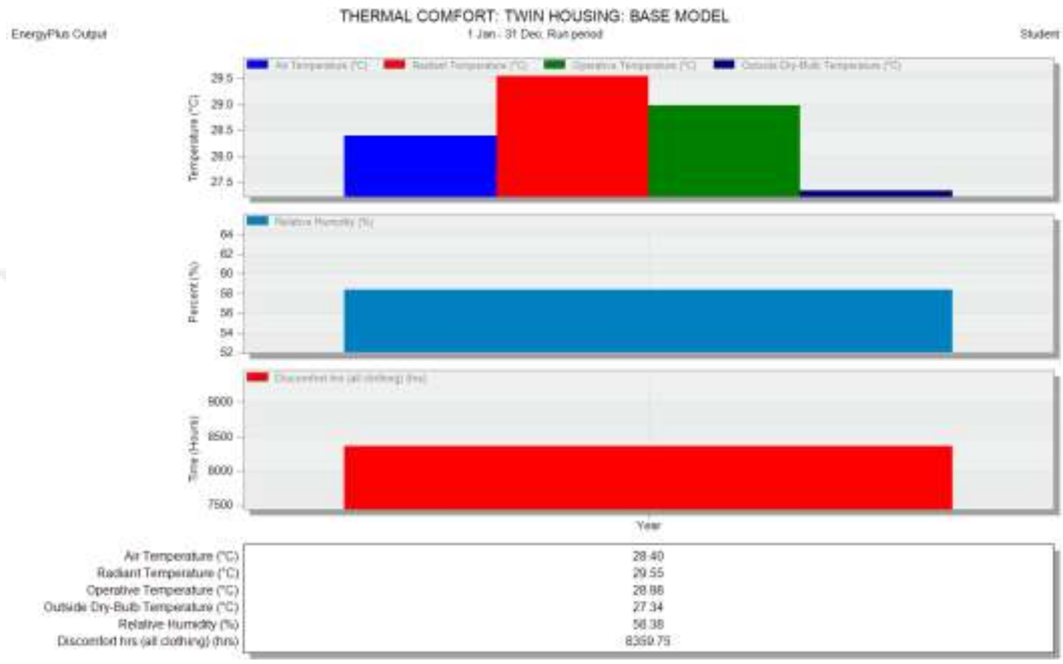
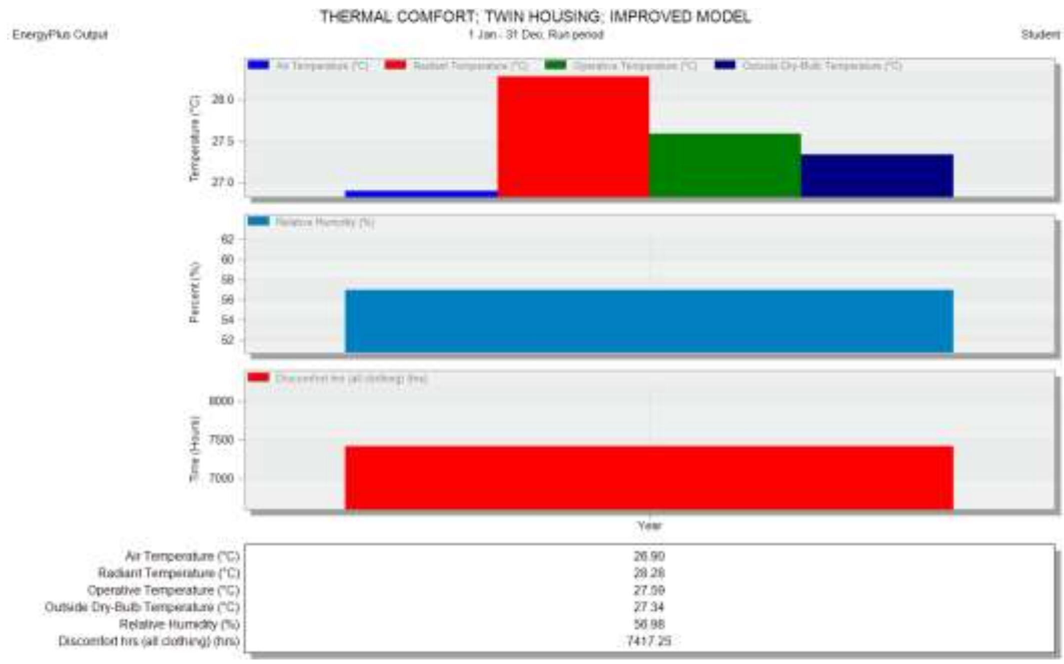
APPENDIX A

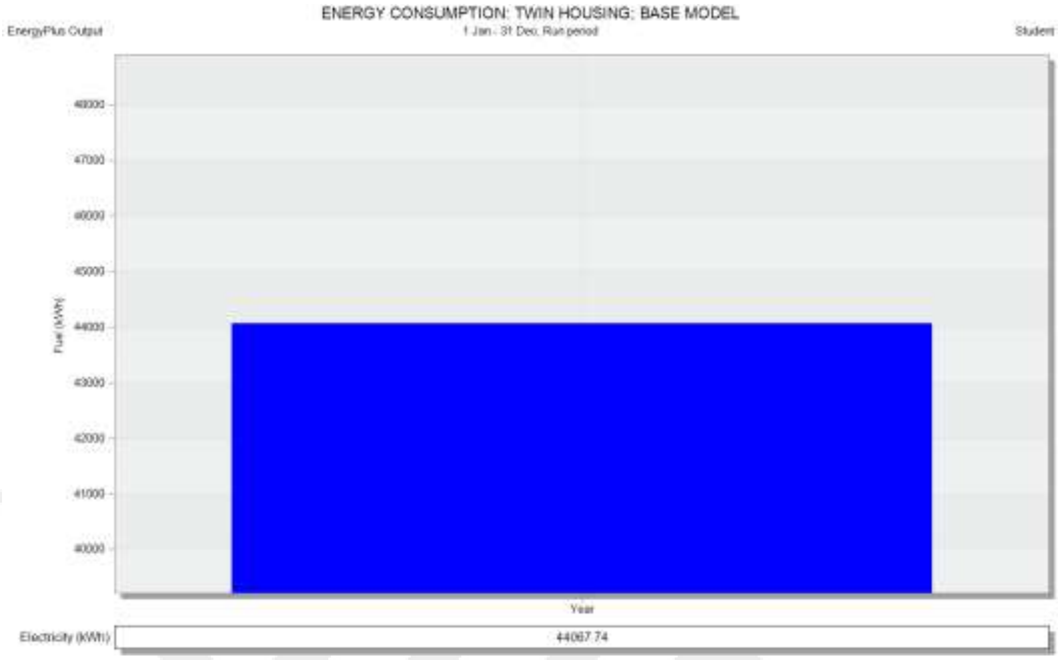
MONTHLY DATA OF BUILDING ENVELOPES MODELS

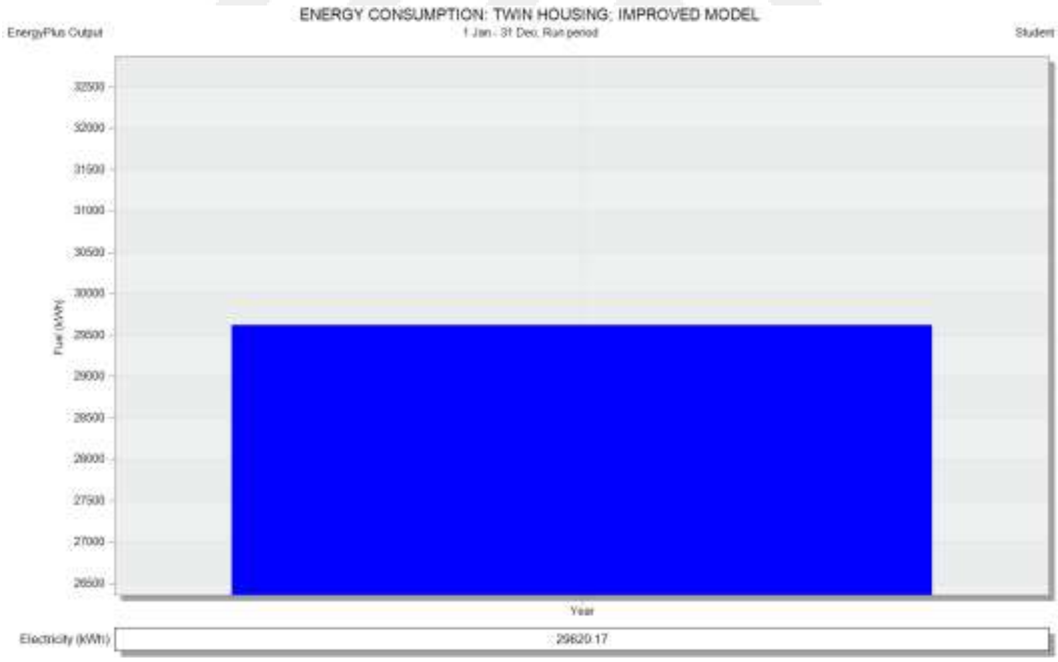
A.1 AVERAGE THERMAL COMFORT DATA



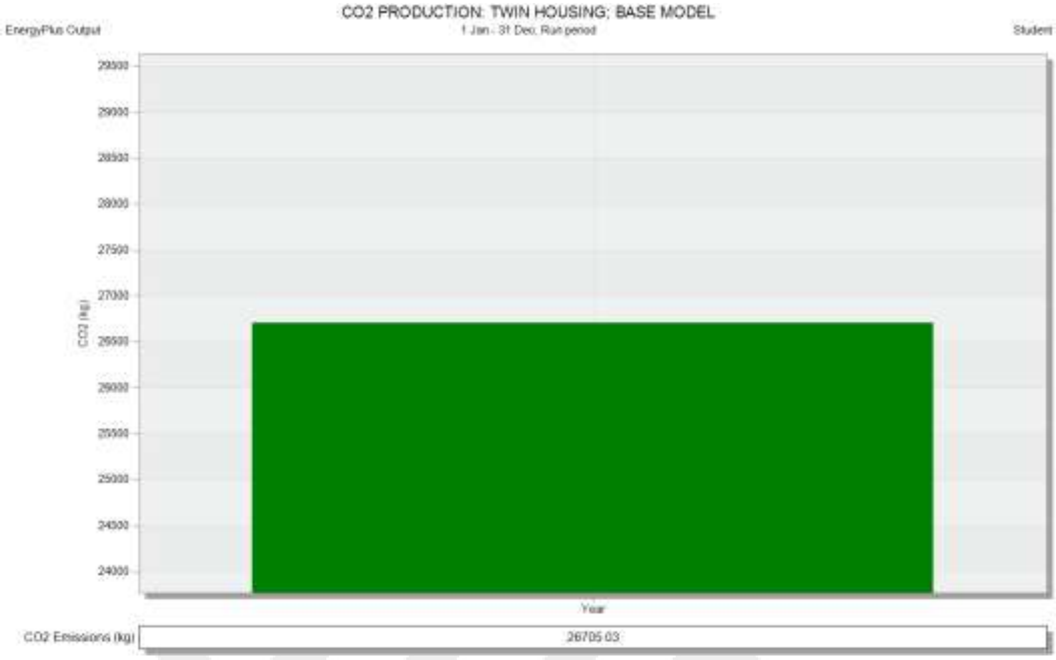


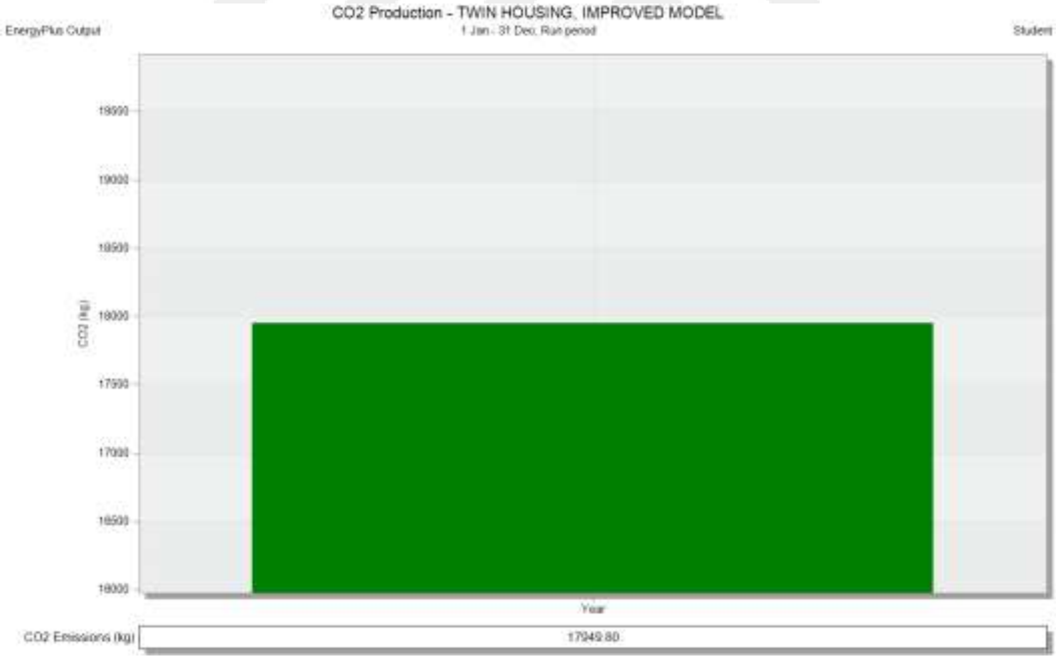
A.2 TOTAL ANNUAL ENERGY CONSUMPTIONS





A.3 TOTAL ANNUAL CARBON EMISSION





A.4 TOTAL CONSTRUCTION COST: BASE MODEL

Construction Costs for: BASE MODEL

Calculation description:

Reporting method: Basic

The estimated building construction cost data shown below is based on 'per gross internal floor area' costs of services, sub-structure and frame construction. The cost of constructions and glazing is based on the 'per surface area' cost data from the constructions and glazing database. Surface finish costs are also calculated from actual building surface areas and entered surface finish per area costing data.

Is the user's responsibility to ensure that input data is checked and the basis for the calculations is understood.

Structure Costs	Floor Area (m2)	Cost (GBP)
Sub Total	835.5	175,455

HVAC Costs	Floor Area (m2)	Cost (GBP)
Sub Total	835.5	51,042

Lighting Costs	Floor Area (m2)	Cost (GBP)
Sub Total	835.5	30,625

Sub-Structure Costs	Floor Area (m2)	Cost (GBP)
Sub Total	292.2	32,143

Super Structure Cost	Construction Area (m2)	Cost (GBP)
Project internal mass	21.6	4,536
Project internal door	16.2	647
Floor Slab_Reversed	271.8	6,795
Base Model Ground Floor	292.2	3,506
Sand Crete Block wall	669.9	6,699
Copy of 10mm Ceiling tiles	292.2	2,338
Floor Slab	75.2	1,880
Copy of 10mm Ceiling tiles_Reversed	292.2	2,338
Pitched Roof	397.8	3,182
Sub Total	2329.1	31,922

Glazing Cost	Surface Area (m2)	Cost (GBP)
Project internal glazing	0.4	54
Project external glazing	106.4	5,426
Local shading		0
Blinds and internal shades		0
Sub Total		5,480

Renewables Cost	Area (m2)	Cost (GBP)
PV Panels	0.00	0
Solar Hot Water Panels	0.00	0
Wind Turbines	0.00	0
PV Electrical		0
Wind Turbine Electrical		0
Sub Total		0

Surface Finish Costs	Surface Area (m2)	Cost (GBP)
Walls	890.9	34,772
Floors	575.5	25,897
Ceiling	575.5	21,342
Sub Total		82,011

Building Total Cost (GBP)		**408,677**

A.5 TOTAL CONSTRUCTION COST: IMPROVED MODEL

Construction Costs for: IMPROVED MODEL

Calculation description:

Reporting method: Basic

The estimated building construction cost data shown below is based on 'per gross internal floor area' costs of services, sub-structure and frame construction. The cost of constructions and glazing is based on the 'per surface area' cost data from the constructions and glazing database. Surface finish costs are also calculated from actual building surface areas and entered surface finish per area costing data.

Is the user's responsibility to ensure that input data is checked and the basis for the calculations is understood.

Structure Costs	**Floor Area (m2)**	**Cost (GBP)**
Sub Total	805.1	169,062

HVAC Costs	**Floor Area (m2)**	**Cost (GBP)**
Sub Total	805.1	49,652

Lighting Costs	**Floor Area (m2)**	**Cost (GBP)**
Sub Total	805.1	29,791

Sub-Structure Costs	**Floor Area (m2)**	**Cost (GBP)**
Sub Total	292.2	32,143

Super Structure Cost	**Construction Area (m2)**	**Cost (GBP)**
Project internal door	16.6	662
Optimized floor_Reversed	271.4	10,856
Optimized Ground floor	292.2	5,844
Optimized Wall	446.2	13,387
Partition wall 2	224.3	1,794
Copy of 10mm Ceiling tiles	292.2	2,338
Copy of 10mm Ceiling tiles_Reversed	292.2	2,338
Optimized floor	75.2	3,008
Optimized roof	397.8	1,989

Sub Total	2308.1	42,216

Glazing Cost	**Surface Area (m2)**	**Cost (GBP)**
Copy of Dbl LoE (e2=.1) Clr 6mm/13mm Air	105.3	7,901
Project internal glazing	0.4	54
Local shading		0
Blinds and internal shades		0
Sub Total		7,955

Renewables Cost	**Area (m2)**	**Cost (GBP)**
PV Panels	0.00	0
Solar Hot Water Panels	0.00	0
Wind Turbines	0.00	0
PV Electrical		0
Wind Turbine Electrical		0
Sub Total		0

Surface Finish Costs	**Surface Area (m2)**	**Cost (GBP)**
Walls	869.5	34,778
Floors	575.1	25,878
Ceiling	575.1	21,323
Sub Total		81,979

Building Total Cost (GBP)		**412,798**