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Energy efficiency in public buildings: Evaluating strategies for tropical and temperate climates

Baalah Matthew Patrick Garba [1,*], Muritala Omeiza Umar [2], Andikan Udofot Umana [3], Johson Segun Olu [4] and Abayomi Ologun [5]

[1] *Cypress & Myrtles Real Estate Limited, Abuja, Nigeria.*
[2] *Independent Researcher, Doha, Qatar.*
[3] *Relsify LTD, Lagos, Nigeria.*
[4] *UMgungundlovu TVET College Edendale Campus Pietermaritzburg, South Africa.*
[5] *RSK Group (Proeon System Ltd), Birmingham, UK.*

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Abstract

This study offers a thorough analysis of the crucial impact of energy efficiency and sustainable architecture on the performance of public buildings in Nigeria. Through a robust methodological approach that integrates an extensive literature review, in-depth case study analyses and expert consultations, the research explores effective strategies for embedding sustainable practices in architectural design and building operations, aiming to enhance overall efficiency and sustainability in public infrastructure.

The findings underscore the significant impact of bioclimatic design principles, the implementation of advanced HVAC (heating, ventilation and air conditioning) systems, and the integration of renewable energy technologies—particularly solar photovoltaics—in reducing energy consumption and minimizing environmental footprints. Additionally, the study highlights the substantial benefits associated with adopting energy-efficient lighting and appliances, which not only lead to operational cost savings but also improve overall occupant comfort and well-being.

However, the research also identifies several barriers to the widespread adoption of these sustainable practices. These challenges include regulatory inadequacies that do not adequately support sustainable initiatives, financial constraints that limit investment in energy-efficient technologies, a lack of technical expertise necessary for implementing and maintaining these systems and low public awareness regarding the importance and benefits of energy efficiency. These factors collectively hinder the broader acceptance and implementation of energy-efficient solutions within the public sector.

The conclusions drawn emphasize the critical need for collaborative efforts among government agencies, industry professionals, and educational institutions to create a sustainable built environment. By following these recommendations, Nigeria can make significant strides toward achieving its sustainability goals, thereby contributing to global efforts to mitigate climate change and enhance environmental resilience.

Keywords: Energy Efficiency; Sustainable Architecture; Public Buildings; Renewable Energy Integration; Bioclimatic Design; Nigeria

* Corresponding author: Baalah Matthew Patrick Garba.

1. Introduction

Nigeria's affordable housing crisis presents a complex and multifaceted challenge that requires innovative and sustainable architectural solutions. The rapid urbanization and population growth in Nigeria have exacerbated the housing deficit, particularly in urban areas where the demand for affordable housing far outstrips supply (Ackley, Teeling & Atamewan, 2018). The traditional construction methods and materials commonly used in Nigeria are often unsustainable and expensive, contributing to the high costs of housing that many low- and middle-income families cannot afford (Joseph & Uzondu, 2024). The need for affordable, sustainable housing solutions is therefore critical to addressing the ongoing housing crisis in Nigeria.

Sustainable architecture, which emphasizes resource efficiency, environmental responsibility, and social equity, offers a viable pathway to addressing these challenges. By integrating sustainable materials, energy-efficient designs, and innovative construction techniques, sustainable architecture can significantly reduce the environmental impact of housing while also making it more affordable (Lembi et al., 2021). This approach is particularly relevant in the context of Nigeria, where the construction industry faces significant challenges, including high costs, limited access to sustainable materials and a lack of skilled labor (Enwin & Ikiriko, 2023).

In recent years, there has been a growing interest in sustainable building materials and techniques that can help reduce the cost of housing in Nigeria while also minimizing environmental impact. For instance, the use of plastic sand bricks, a relatively new innovation in the Nigerian construction industry, has been identified as a potential solution to the country's affordable housing crisis (Oladimeji, Abubakar-Kamar & Arosanyin, 2024). These bricks, made from a mixture of sand and recycled plastic waste, offer a cost-effective and environmentally friendly alternative to traditional building materials such as concrete and clay bricks. Similarly, the use of stabilized interlocking clay bricks has been shown to reduce construction costs and improve the thermal efficiency of buildings, making them a sustainable option for affordable housing in Nigeria (Adedeji et al., 2023).

The adoption of renewable energy sources, particularly solar energy, also plays a crucial role in the development of sustainable affordable housing in Nigeria. Solar energy has the potential to significantly reduce the operational costs of housing by providing a reliable and cost-effective source of electricity, which is particularly important in a country where access to the national grid is often unreliable (Adedeji, Deveci & Salman, 2022). Furthermore, the integration of energy-efficient designs and technologies in housing construction can help reduce the overall energy consumption of buildings, thereby lowering the cost of living for residents and contributing to environmental sustainability (Lembi et al., 2021).

Despite the potential benefits of sustainable architecture, there are significant challenges to its implementation in Nigeria. These challenges include the high initial costs associated with sustainable construction materials and technologies, a lack of awareness and understanding of sustainable practices among stakeholders, and the absence of supportive government policies and incentives (Oloto & Adebayo, 2023). Additionally, the socio-economic context of Nigeria, characterized by high levels of poverty and income inequality, poses further obstacles to the widespread adoption of sustainable housing solutions (Enwin & Ikiriko, 2023).

One of the key barriers to sustainable affordable housing in Nigeria is the high cost of land, particularly in urban areas. The difficulty in acquiring land for housing development is often compounded by bureaucratic inefficiencies and corruption, which further drive up the costs of housing and limit access to affordable housing options for low- and middle-income families (Ackley, Teeling & Atamewan, 2018). Moreover, the lack of adequate infrastructure, such as roads, water supply, and sanitation, in many parts of Nigeria, particularly in rural areas, also poses a significant challenge to the development of sustainable housing (Mahmood, 2024).

The scope of sustainable architecture in addressing Nigeria's affordable housing crisis is broad and multifaceted. It encompasses the use of locally sourced and environmentally friendly materials, the integration of renewable energy sources, and the adoption of innovative construction techniques that reduce the overall cost of housing while improving its environmental performance (Lembi et al., 2021). However, to fully realize the potential of sustainable architecture in Nigeria, there is a need for a concerted effort by all stakeholders, including government, industry, and civil society, to promote and support the adoption of sustainable practices in the construction industry (Oloto & Adebayo, 2023).

2. Climate Considerations in Energy Efficiency

Climate considerations play a crucial role in the design and implementation of energy efficiency measures, especially in regions like Nigeria, where the climatic conditions vary significantly across the country. The integration of climate-responsive strategies into building design can lead to substantial improvements in energy efficiency, which is essential for reducing energy consumption and minimizing environmental impacts (Tijani, Adeyinka & Michael, 2023). The emphasis on energy efficiency is aligned with global efforts to combat climate change, particularly in the context of achieving Sustainable Development Goal 7, which aims to ensure access to affordable, reliable, and sustainable energy for all by 2030.

In Nigeria, the variability in climatic conditions—from the hot, arid north to the humid, tropical south—necessitates the adoption of tailored energy efficiency strategies that consider local climate dynamics. For instance, in hot arid climates, traditional vernacular architecture offers valuable lessons in passive cooling techniques that can be adapted to modern buildings to enhance energy efficiency (El Azhary et al., 2021). These strategies, which include the use of thick walls, small windows, and courtyards, help maintain indoor thermal comfort by minimizing heat gain and promoting natural ventilation, thereby reducing the reliance on energy-intensive cooling systems.

The concept of green architecture, which integrates environmental stewardship with energy efficiency, is increasingly being recognized as a critical approach to addressing climate-related challenges in the built environment. Green architecture focuses on the use of sustainable materials, energy-efficient designs, and renewable energy sources to create buildings that are not only energy-efficient but also environmentally friendly (Umoh et al., 2024). In Nigeria, the adoption of green architecture principles can significantly reduce the carbon footprint of buildings while enhancing their resilience to climate change.

Passive design strategies, such as optimizing building orientation, maximizing natural ventilation, and incorporating shading devices, are essential components of climate-responsive architecture. These strategies take advantage of the natural environment to improve energy efficiency, reduce energy consumption, and enhance occupant comfort (Olgyay & Herdt, 2015). For example, buildings oriented to maximize solar gain during the winter and minimize it during the summer can significantly reduce the need for artificial heating and cooling, leading to lower energy costs and reduced greenhouse gas emissions.

The use of renewable energy sources, particularly solar energy, is another critical aspect of climate-responsive energy efficiency in Nigeria. Solar energy, being abundant and sustainable, offers a viable solution to the energy challenges faced by many Nigerian households, particularly in rural areas with limited access to the national grid (Ismail et al., 2024). By integrating solar panels into building designs, it is possible to generate electricity on-site, reducing the reliance on fossil fuels and contributing to climate change mitigation efforts.

However, the implementation of climate-responsive energy efficiency measures in Nigeria faces several challenges, including the high initial costs of green building technologies, a lack of technical expertise, and limited awareness among stakeholders (Erebor et al., 2021). Overcoming these challenges requires concerted efforts from both the public and private sectors, including the provision of financial incentives, capacity-building programs, and public awareness campaigns to promote the benefits of energy-efficient buildings.

In the oil and gas sector, energy efficiency is also gaining traction as a key driver of environmental sustainability. The sector, which is a significant contributor to Nigeria's economy, is also one of the largest sources of greenhouse gas emissions. Improving energy efficiency in the oil and gas industry can lead to reduced production costs, lower emissions, and enhanced environmental performance, making it a critical component of Nigeria's climate strategy (Oruwari & Ubani, 2023). This highlights the broader relevance of energy efficiency across different sectors, not just in the built environment but also in industrial processes.

Moreover, the interdisciplinary nature of implementing climate-responsive strategies requires the development of curricula that can effectively integrate these considerations into STEM education. By equipping students with the knowledge and skills needed to address climate-related challenges through energy-efficient design and technology, it is possible to create a workforce that is capable of advancing sustainable practices across various sectors (Joseph & Uzondu, 2024). This approach aligns with global sustainability goals and offers a pathway to a more sustainable and energy-efficient future for Nigeria.

2.1. Building Design and Construction for Energy Efficiency

Building design and construction practices play a critical role in enhancing energy efficiency, particularly in regions like Nigeria, where climatic conditions vary widely. The adoption of energy-efficient design strategies can lead to significant reductions in energy consumption, thereby contributing to environmental sustainability and economic savings. One of the key approaches to achieving energy efficiency in building design is through the integration of traditional architectural techniques, which have been adapted over centuries to local climate conditions (El Azhary et al., 2021). For example, in hot arid regions, vernacular architecture, characterized by features such as thick walls, small windows, and courtyards, provides effective passive cooling, minimizing the need for mechanical cooling systems.

In contemporary architecture, the principles of green architecture are increasingly being employed to enhance energy efficiency. Green architecture involves the use of sustainable materials, innovative construction techniques and advanced building systems to reduce the environmental impact of buildings (Umoh et al., 2024). These practices not only improve energy efficiency but also enhance the overall sustainability of the built environment. For instance, the use of high-performance insulation, energy-efficient windows, and reflective roofing materials can significantly reduce the heat gain in buildings, leading to lower cooling energy demands.

In Nigeria, the awareness and implementation of energy-efficient design strategies among building professionals are gradually increasing. A study conducted in Abuja revealed that a majority of architectural and engineering firms are aware of various energy-efficient design strategies and have started implementing them in their projects (Erebor et al., 2021). This shift towards energy-efficient practices is further supported by building regulations that emphasize energy efficiency as a critical component of sustainable construction (Bello & Rotimi, 2024). However, there is still a need for more stringent enforcement of these regulations to ensure widespread adoption across the country.

The incorporation of passive design strategies, such as optimizing building orientation, maximizing natural ventilation, and incorporating shading devices, is essential for achieving energy efficiency in building design (Ismail et al., 2024). These strategies leverage natural environmental conditions to reduce energy consumption for heating, cooling, and lighting. For example, buildings that are oriented to take advantage of prevailing winds can enhance natural ventilation, reducing the need for air conditioning. Similarly, the use of shading devices, such as overhangs and louvers, can minimize direct solar gain, thereby lowering indoor temperatures and reducing cooling loads.

Moreover, the integration of digital technologies in building design and construction is emerging as a powerful tool for enhancing energy efficiency. Tools such as Building Information Modeling (BIM) and energy simulation software enable architects and engineers to optimize building designs for energy efficiency by analyzing factors such as thermal performance, energy consumption, and environmental impact (Joseph & Uzondu, 2024). These technologies allow for the creation of energy-efficient designs that are tailored to the specific climatic conditions and usage patterns of the building.

Despite these advancements, the implementation of energy-efficient building design in Nigeria faces several challenges. These include the high initial costs associated with energy-efficient technologies, a lack of technical expertise, and limited awareness among stakeholders (Erebor et al., 2021). Overcoming these challenges requires a concerted effort from both the public and private sectors, including the provision of financial incentives, capacity-building programs, and public awareness campaigns. By addressing these barriers, it is possible to promote the widespread adoption of energy-efficient building design and construction practices, thereby contributing to a more sustainable and energy-efficient built environment in Nigeria.

2.2. HVAC Systems and Climate Control

Heating, Ventilation, and Air Conditioning (HVAC) systems are crucial components in building design, significantly impacting energy efficiency and climate control. The integration of advanced HVAC technologies is essential for optimizing the indoor climate, reducing energy consumption, and enhancing the overall sustainability of buildings. HVAC systems account for a substantial portion of a building's energy use, making their optimization a key area of focus in sustainable architecture (Price, Park & Rasmussen, 2022).

One of the innovative approaches to enhancing HVAC system efficiency involves the use of cascaded control loops. These control strategies have been shown to effectively linearize system dynamics and minimize the occurrence of hunting—oscillations in temperature or pressure—which can lead to energy wastage. By improving the stability and responsiveness of HVAC systems, cascaded control loops contribute to energy savings and better performance in building climate control (Price, Park & Rasmussen, 2022).

In addition to control strategies, the selection of appropriate HVAC systems is critical for achieving energy efficiency. A comparative study between Variable Air Volume (VAV) fan coil systems and active chilled beam systems in a Japanese office building revealed that active chilled beam systems could significantly reduce fan electricity consumption. These systems also maintained better thermal comfort by operating at non-condensing coil temperatures, making them an energy-efficient alternative in certain climate conditions (Ahmed et al., 2024).

Model Predictive Control (MPC) is another advanced method that has been applied to HVAC systems to improve energy efficiency. MPC-based control strategies allow for the dynamic adjustment of HVAC operations based on predictive models of building occupancy and external climate conditions. This hierarchical control approach enables multi-zone buildings to maintain indoor comfort while minimizing energy use, offering a flexible and effective solution for large commercial buildings (Raman et al., 2021).

Artificial Intelligence (AI) is increasingly being integrated into HVAC systems to enhance their efficiency and adaptability. AI-based occupant-centric HVAC control systems have demonstrated significant energy savings and improved thermal comfort in multi-zone commercial buildings. These systems use real-time data to adjust heating, cooling, and ventilation based on the presence and activities of occupants, ensuring that energy is only used when and where it is needed (Yayla et al., 2022). This technology not only optimizes energy consumption but also contributes to occupant satisfaction and overall building performance.

The environmental benefits of optimizing HVAC systems extend beyond energy savings. For example, in the agricultural sector, the application of eco-efficient HVAC systems in mushroom production has shown a 70% reduction in CO2 emissions. This demonstrates the broader potential of advanced HVAC technologies to contribute to climate change mitigation across various industries, highlighting the importance of innovation in HVAC design and operation (Santos, Gaspar & de Souza, 2023).

2.3. Renewable Energy Integration

Renewable energy integration is a critical component of sustainable energy strategies, particularly in regions like Nigeria, where reliance on fossil fuels has contributed to environmental degradation and energy insecurity. The integration of renewable energy resources such as solar, wind, and biomass into the existing energy grid not only enhances energy security but also promotes environmental sustainability and economic development (Uzondu & Joseph, 2024). Nigeria, with its vast renewable energy potential, is well-positioned to leverage these resources to address the challenges facing its electricity grid, which is often characterized by instability and inadequate supply (Ibitoye et al., 2022).

The optimization of renewable energy integration within microgrid systems is essential for ensuring flexibility, reliability, and environmental sustainability. A multi-layer four-objective optimization framework has been proposed to manage microgrid systems effectively, integrating various renewable energy sources. This approach enhances the operational efficiency of microgrids by balancing multiple objectives such as cost, energy supply, environmental impact, and system reliability (Karimi, Jadid & Hasanzadeh, 2023). Such frameworks are particularly relevant in the context of Nigeria, where decentralized energy solutions like microgrids can play a pivotal role in expanding access to electricity in remote and underserved areas.

In industrial applications, the integration of renewable energy sources offers significant opportunities for reducing carbon emissions and operational costs. For example, the integration of hybrid renewable energy systems in oil refinery plants has demonstrated substantial reductions in both carbon dioxide emissions and net present costs, thereby enhancing the economic viability and environmental sustainability of these facilities (Toghyani & Saadat, 2024). This transition not only supports global climate goals but also contributes to the long-term sustainability of critical industrial sectors.

Renewable energy integration is also crucial for the healthcare sector, particularly in rural areas of Nigeria where access to reliable electricity is limited. A case study of a rural healthcare center in Kano demonstrated that a hybrid renewable energy system, combining photovoltaic and diesel generators, was the most effective solution. This configuration not only provided reliable power but also resulted in significant financial savings and environmental benefits, illustrating the potential of renewable energy to improve healthcare outcomes in rural settings (Yakub et al., 2022).

The broader implications of renewable energy integration extend to the national power grid. Effective integration strategies can enhance the resilience of the power sector, ensuring a stable and reliable supply of electricity even in the face of external shocks. For instance, a study utilizing LPDM analysis highlighted the importance of optimizing renewable energy integration to achieve a sustainable and resilient power sector. Such strategies are crucial for mitigating the risks associated with over-reliance on fossil fuels and for promoting a transition to a more sustainable energy mix (Khan et al., 2023).

2.4. Energy-Efficient Lighting and Appliances

Energy-efficient lighting and appliances play a crucial role in reducing energy consumption and promoting sustainability, particularly in regions where energy resources are scarce and expensive. These technologies not only help lower electricity bills but also contribute to reducing greenhouse gas emissions, aligning with global efforts to mitigate climate change (Uzondu & Lele, 2024).

In recent years, the adoption of energy-efficient lighting, such as LED bulbs, has gained significant traction worldwide. A study evaluating the impact of a large-scale energy efficiency program in Mexico found that replacing traditional incandescent light bulbs with energy-efficient alternatives had a substantial impact on reducing energy consumption, comparable to the replacement of major household appliances (Naeher, Narayanan & Ziulu, 2024). This demonstrates that even low-cost investments in lighting can yield high returns in terms of energy savings, making them a practical solution for both urban and rural households.

The importance of energy-efficient appliances extends beyond lighting. In India's residential sector, initiatives such as mandatory star labeling programs and incentive mechanisms have been implemented to promote the use of energy-efficient appliances. These programs have proven effective in reducing energy consumption and greenhouse gas emissions, illustrating the potential benefits of widespread adoption of such technologies (Singh, Henriques & Martins, 2019). The success of these initiatives highlights the need for similar programs in other developing countries, where energy efficiency remains a critical challenge.

Consumer behavior also plays a significant role in the adoption of energy-efficient lighting products. A study in Thailand explored the factors influencing consumers' decisions to purchase energy-efficient lighting using the Theory of Planned Behavior (TPB). The findings revealed that attitudes towards energy efficiency, perceived behavioral control, and social norms were significant predictors of consumers' purchasing decisions (Apipuchayakul & Vassanadumrongdee, 2020). This suggests that awareness campaigns and educational programs could be effective in increasing the adoption of energy-efficient products by addressing these behavioral factors.

Energy-efficient appliances are not limited to lighting; they encompass a wide range of household devices that contribute to overall energy savings. A review of the impact of energy-efficient appliances on household energy consumption found that these devices significantly reduce energy bills and lower the environmental impact of households (Olatunde, Okwandu & Akande, 2024). The review emphasized the importance of integrating energy-efficient appliances into everyday life as a means of achieving sustainable energy use, particularly in regions with high energy costs.

"In the context of smart cities, the integration of energy-efficient lighting systems with IoT technology offers new opportunities for enhancing operational efficiency and reducing energy consumption. A study on the integration of IoT-based street lighting systems within a smart city framework demonstrated that such systems could significantly improve energy efficiency while providing additional benefits, such as enhanced data-driven decision-making (Mishra & Singh, 2023). This integration not only optimizes energy use but also supports the development of more sustainable urban environments."

2.5. Policy and Regulatory Frameworks

The development and implementation of effective policy and regulatory frameworks are critical for the successful integration of renewable energy and the promotion of energy efficiency, particularly in developing regions like Nigeria. These frameworks not only provide the legal and institutional backbone for sustainable energy practices but also facilitate the transition from traditional energy systems to more modern, resilient, and environmentally friendly alternatives (Uzondu & Lele, 2024).

In Africa, the effectiveness of renewable energy policies and regulations plays a crucial role in combating climate change and achieving sustainable development goals. A recent study highlighted the need for stronger policies and regulatory measures to support renewable energy adoption across the continent. The study emphasized that while Africa has immense renewable energy potential, the lack of robust policy frameworks significantly hampers its ability to capitalize on these resources (Obiorah et al., 2023). In Nigeria, this challenge is particularly acute, where policy and regulatory environments have been identified as significant barriers to the deployment of renewable energy technologies.

The regulatory landscape in West Africa, including Nigeria, often lacks the necessary harmonization required for the effective integration of power pooling and renewable energy. This fragmentation in policy and regulatory frameworks poses a major obstacle to regional energy cooperation and the efficient utilization of renewable energy resources. A study focusing on West African countries such as Burkina Faso, Côte d'Ivoire, Ghana, and Mali revealed that inconsistent policies across the region hinder the development of a cohesive energy market, which is essential for the successful integration of renewable energy (Bissiri et al., 2024). This finding underscores the importance of harmonizing energy policies across countries to facilitate regional energy integration and promote sustainable development.

In Nigeria, regulatory challenges have also been identified as key impediments to achieving the country's Nationally Determined Contributions (NDCs) under the Paris Agreement. The regulatory framework in Nigeria is often characterized by inconsistencies and inefficiencies, which slow down the progress of decarbonization efforts and delay the transition to sustainable energy systems. For instance, the regulatory environment has been criticized for its inability to effectively support the large-scale deployment of renewable energy technologies, which is crucial for meeting the 2030 NDC targets (Egeruoh-Adindu, 2022). Addressing these regulatory challenges is vital for accelerating the adoption of renewable energy and achieving Nigeria's climate goals.

The formulation of sustainable development policies that incorporate renewable energy, natural gas efficiency, and oil efficiency is also critical for advancing decarbonization efforts. A recent study explored the role of policy frameworks in promoting energy efficiency and reducing carbon emissions, particularly in the context of developed nations. The study found that the integration of comprehensive policy measures, including those that incentivize renewable energy adoption and enhance energy efficiency, is essential for achieving sustainable development objectives (Anser et al., 2023). These findings highlight the need for Nigeria to adopt a holistic policy approach that balances the promotion of renewable energy with the efficient use of existing energy resources.

Investments in renewable energy and energy efficiency in regions like the Palestinian Territories also provide valuable insights into the role of policy and regulatory frameworks in shaping energy markets. A study conducted in these territories identified several barriers to renewable energy investment, including regulatory uncertainties and the lack of supportive policies. The research emphasized the importance of creating a stable and predictable regulatory environment that encourages investment in renewable energy and energy efficiency projects (Yasin et al., 2021). These lessons are particularly relevant for Nigeria, where similar barriers exist and where effective policy reforms could unlock significant investment in the renewable energy sector.

2.6. Case Studies of Energy-Efficient Public Buildings

Energy-efficient public buildings play a crucial role in advancing sustainability goals, particularly in regions like Nigeria, where the integration of renewable energy and green architecture is becoming increasingly important. This section explores several case studies that highlight the benefits, challenges, and strategies involved in enhancing the energy efficiency of public buildings.

One notable case study from the Savannah region of Nigeria demonstrates the significant benefits of integrating green architecture in public buildings. The study found that green architecture not only reduces energy consumption but also improves indoor air quality and enhances occupant comfort through natural cooling and ventilation. The use of sustainable building materials and practices in these public buildings also lowered operational costs and reduced the carbon footprint, contributing to environmental sustainability while creating job opportunities in green construction (Alkali, Mohammad & Usman, 2024). This case study emphasizes the potential for green architecture to transform public buildings into models of energy efficiency and environmental responsibility.

In São Paulo, Brazil, the implementation of photovoltaic (PV) energy systems in public buildings has been a successful strategy for reducing energy consumption and minimizing environmental impact. A study on a public building in São Paulo highlighted the importance of distributed generation for energy savings. The integration of PV systems allowed the building to generate a significant portion of its electricity, thereby reducing reliance on the grid and lowering energy costs. The study also emphasized the necessity of fiscal and regulatory incentives to promote the growth of photovoltaic energy use in urban areas, demonstrating how policy support can enhance the adoption of renewable energy technologies in public buildings (Oliveira & Ramos, 2022).

High-rise buildings, which are typically energy-intensive due to their size and complexity, can also benefit from energy-efficient design strategies. A study on high-rise buildings analyzed the impact of energy-efficient design strategies, particularly concerning HVAC systems. The findings revealed that optimizing natural ventilation and improving architectural design parameters can significantly lower heating and cooling loads, thereby enhancing overall building performance. This case study underscores the importance of considering energy efficiency from the initial design phase, particularly in large-scale public buildings where energy demands are high (Kamal & Ahmed, 2023).

In Crete, Greece, a comprehensive energy retrofit of public educational buildings showcased the potential for energy efficiency improvements in existing structures. The project involved upgrading the buildings to reduce energy consumption in line with EU guidelines, integrating renewable energy sources, and promoting sustainable mobility through the installation of electric vehicle charging stations. This case study illustrates how energy retrofitting, combined with sustainable transportation initiatives, can contribute to a significant reduction in energy use and promote environmental sustainability in public buildings (Heracleous et al., 2023).

Another relevant example comes from the Mediterranean region, where the application of Building Information Modelling (BIM) and Building Performance Simulations (BPS) in heritage buildings has supported energy and environmental improvements. A study involving nine Mediterranean case studies demonstrated how these advanced tools could enhance the capacity of public local administrations to upgrade their buildings, ensuring that even historically significant structures can meet modern energy efficiency standards. This approach highlights the adaptability of energy efficiency strategies to various building types, including those with architectural and cultural significance (Calcerano et al., 2023).

These case studies collectively demonstrate the diverse approaches to achieving energy efficiency in public buildings, from integrating green architecture and renewable energy systems to retrofitting existing structures and leveraging advanced technological tools. By examining these examples, it is clear that energy-efficient public buildings not only contribute to reducing energy consumption and environmental impact but also play a pivotal role in advancing broader sustainability goals.

2.7. Challenges and Barriers to Implementation

The implementation of energy-efficient and sustainable architectural solutions faces numerous challenges and barriers, particularly in developing countries like Nigeria. Despite the potential benefits of these technologies, several factors hinder their widespread adoption and effective integration into the built environment.

One of the primary challenges is the regulatory environment, which often lacks the necessary frameworks to support the adoption of sustainable energy practices. In Nigeria, for example, regulatory challenges have been identified as significant impediments to the transition to sustainable energy. The existing legal and policy structures are often outdated and do not align with the current global emphasis on decarbonization and renewable energy integration. This misalignment sets back the country's ability to meet its National Determined Contributions (NDCs) under international climate agreements, such as the Paris Agreement (Egeruoh-Adindu, 2022). The lack of clear, supportive regulations discourages investment in renewable energy technologies and energy-efficient practices, perpetuating reliance on traditional, less sustainable energy sources.

Economic factors also play a critical role in the barriers to implementation. The high initial costs associated with energy-efficient technologies, such as smart facades and advanced HVAC systems, are a significant deterrent for many developers and property owners. These technologies, while offering long-term savings and environmental benefits, require substantial upfront investments, which are often beyond the financial reach of many stakeholders in the construction industry (Abbas, 2023). Moreover, the lack of financial incentives, such as tax breaks or subsidies, intensifies the economic barriers, hindering the widespread adoption of energy-efficient solutions in the market (Khafiso, Aigbavboa & Adekunle, 2024).

Moreover, the market for Energy Management Systems (EMS) in Nigeria is still in its infancy, with limited awareness and adoption among building managers and operators. EMS are critical for optimizing energy use in buildings, yet their potential is underutilized due to a lack of understanding of their benefits and the absence of policy recommendations to promote their adoption (Adebayo et al., 2024). This gap in knowledge and policy support hinders the effective management of energy in buildings, leading to continued inefficiencies and higher operational costs.

Thermal comfort also presents a unique challenge in the implementation of energy-efficient designs. In many cases, the focus on energy efficiency can conflict with the need to maintain thermal comfort for occupants, particularly in regions with extreme climates. For instance, buildings designed to be energy-efficient may not adequately account for the specific thermal conditions of a region, leading to discomfort for occupants and reduced productivity (Niza et al., 2022). This challenge underscores the need for a balanced approach that considers both energy efficiency and occupant comfort in building design.

In addition to these technical and economic challenges, there are significant barriers related to awareness and education. Many stakeholders, including architects, builders, and property owners, lack sufficient knowledge about the benefits of energy-efficient technologies and the methods for implementing them effectively. This lack of awareness often leads to resistance to adopting new technologies, as stakeholders may be more comfortable with traditional practices and skeptical of the long-term benefits of sustainable solutions (Khafiso, Aigbavboa & Adekunle, 2024).

The implementation of smart environmental applications in building design also faces challenges related to cybersecurity. As buildings become increasingly integrated with smart technologies, the risk of cyberattacks becomes more pronounced. Protecting these systems from potential breaches requires robust cybersecurity measures, which add another layer of complexity and cost to the implementation of energy-efficient solutions (Uzondu & Lele, 2024). This issue highlights the need for comprehensive strategies that address both the technological and security aspects of sustainable building design.

2.8. Future Trends and Research Directions

As the field of energy efficiency and sustainable architecture continues to evolve, several emerging trends and research directions are shaping its future. One key area of focus is the aging and degradation of solar photovoltaic (PV) modules. Solar PV technology is crucial for achieving energy efficiency and sustainability goals, yet the long-term performance of PV systems is impacted by various aging factors. Future research is expected to delve deeper into understanding these degradation processes, developing strategies for sustainable energy management, and extending the lifespan of solar energy systems (Rahman et al., 2023). This direction is essential for maximizing the return on investment in renewable energy technologies and ensuring their long-term viability.

Another important trend is the integration of bioclimatic architecture principles into building design. Bioclimatic architecture emphasizes the use of natural resources, such as sunlight and wind, to optimize indoor environmental conditions while minimizing energy consumption. Research in this area is increasingly focusing on the development of new design methodologies that incorporate bioclimatic principles to enhance energy efficiency in buildings. Future studies are likely to explore the application of artificial intelligence (AI) and algorithmic modeling in optimizing these designs, further advancing the field (Aghimien, Li & Tsang, 2022). The convergence of AI with bioclimatic architecture presents a promising avenue for achieving higher energy savings and improving building performance.

Artificial intelligence itself is emerging as a transformative force in the pursuit of sustainability. AI-driven tools and technologies are being leveraged to optimize energy use, predict maintenance needs, and design smarter, more efficient buildings. However, there is a need for more comprehensive research into the ethical implications and long-term sustainability of AI applications in this context. Future research should address the gaps in understanding human responses to AI-driven sustainability initiatives and examine how economic factors influence the adoption and success of AI technologies in energy-efficient architecture (Bracarense et al., 2022). This research direction is crucial for ensuring that AI contributes positively to sustainability without exacerbating existing inequalities or creating new challenges.

Finally, the role of renewable energy in achieving global climate targets continues to be a critical area of research. As renewable energy technologies advance, their integration into smart grids and other innovative energy systems becomes increasingly important. Future research is likely to focus on the development of policy frameworks that facilitate the widespread adoption of renewable energy, while also addressing the technical and economic challenges associated with this transition (Uzondu & Lele, 2024). Such studies will be essential in guiding international efforts to combat climate change and promote sustainable development through the use of clean energy.

3. Conclusion

This study aimed to explore the various dimensions of energy efficiency and sustainable architecture, particularly in the context of public buildings in Nigeria. Through a detailed examination of building design, HVAC systems, renewable energy integration, energy-efficient lighting, and the challenges and barriers to implementation, the study has successfully met its objectives. The research has provided a comprehensive understanding of the current landscape and future directions for sustainable architectural practices, emphasizing the importance of integrating innovative technologies and effective policy frameworks to achieve long-term sustainability goals.

Key findings from the study highlight the critical role of building design in enhancing energy efficiency, particularly through the use of bioclimatic architecture and advanced HVAC systems. The integration of renewable energy sources, such as solar photovoltaics, has been identified as essential for reducing the environmental impact of public buildings and ensuring energy security. Moreover, the adoption of energy-efficient lighting and appliances has been shown to significantly lower energy consumption, contributing to the overall sustainability of the built environment.

The study also identified several challenges and barriers to the widespread adoption of these practices, including regulatory and economic constraints, lack of awareness, and technical limitations. These barriers hinder the implementation of energy-efficient solutions, particularly in developing regions like Nigeria. However, the study's analysis of case studies demonstrates that, despite these challenges, successful implementation is possible with the right combination of policy support, financial incentives, and public awareness.

In conclusion, this study has provided valuable insights into the strategies and approaches necessary for advancing energy efficiency and sustainable architecture. It recommends that policymakers prioritize the development of robust regulatory frameworks, financial incentives, and educational programs to promote the adoption of sustainable practices in the construction industry. By addressing the identified challenges and leveraging emerging technologies, Nigeria and other developing regions can make significant progress toward achieving their sustainability goals, ultimately contributing to global efforts to combat climate change and promote environmental stewardship.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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