Developing a Context-Sensitive Operational Energy Management Framework for Tropical Public Office Buildings in Abuja, Nigeria

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Abstract: *Operating energy usage in tropical public office buildings in Nigeria remains a serious concern because to increased energy costs, intermittent grid supplies, and a reliance on mechanical cooling and backup power. This study looks into operational energy management in public office buildings in Abuja, Nigeria, with the goal of incorporating passive design, technology, and policy measures into a context-sensitive energy management framework. A structured questionnaire was distributed to building experts involved in public office building design and operations in order to conduct a quantitative cross-sectional study. The Relative Importance Index (RII) was used to prioritise essential parameters influencing operational energy usage, and Principal Component Analysis (PCA) was used to combine 16 energy-related variables into interpretable framework components. The RII data show that passive design methods dominate operational energy performance, with roof design and natural ventilation coming in first (RII = 0.88), followed by daylighting and material selection (RII = 0.86), and renewable energy integration (RII = 0.84). Smart automation systems and lighting controls have the lowest RII (<0.70). Adoption data show that natural ventilation is consistently used in practice (M = 3.88), whereas energy-efficient HVAC systems (M = 2.25) and solar integration (M = 2.19) are uncommon. PCA identified five components that explained 89.78% of the total variance: (1) thermal and material efficiency, (2) smart and renewable energy systems, (3) climate-responsive passive design, (4) envelope-HVAC integration, and (5) building morphology and roof design. The study concludes that effective operational energy management in Abuja's public office buildings necessitates a phased, policy-driven framework that prioritises passive design, improves envelope-system efficiency, and gradually integrates renewable and smart technologies through institutional support, capacity building, and enforceable standards.*

Keywords: Operational energy management; public office buildings; passive design; tropical buildings; Nigeria.

1. Introduction

Energy efficiency in buildings has become a major global issue as energy demand rises, operational costs rise, and the negative effects of climate change worsen. Energy, being a rare and valuable resource, requires efficient management to reduce waste and ensure long-term use [1]. Buildings use a significant amount of global energy, with non-residential and office buildings being among the most energy-intensive due to extended operating hours, high occupant densities, and reliance on mechanical systems [2-5]. In this context, operational energy management is defined as the systematic planning, monitoring, and optimisation of energy use during a building's operational phase, and it has emerged as a useful strategy for improving building performance and reducing energy waste [6]. Several authors [7-10] have suggested that operational energy savings in office buildings are increasingly being generated by integrated techniques that incorporate passive design optimisation, efficient systems, and governance mechanisms.

Climate conditions, infrastructure problems, and institutional constraints make operational energy management exceptionally difficult in developing countries, particularly in tropical regions. Nigeria continues to face persistent energy supply issues, growing electricity bills, and a heavy reliance on fossil fuel-powered generators. Only around 40% of the population is connected to the national electrical grid, forcing households and businesses to rely largely on diesel and petrol generators, which have severe environmental and economic consequences [11,12]. Buildings consume a significant portion of the country's energy supply, but policy attention has traditionally been focused on electricity generation, transmission, and distribution rather than how energy is used at the building level [13,14]. This narrow focus on demand-side management is rapidly being recognised as a significant policy gap in African urban sustainability transitions [15]. As a result of their high occupancy and cooling requirements, Nigerian public office buildings are particularly vulnerable to operational energy waste.

Anecdotal and empirical evidence point to an overreliance on air-conditioning systems to maintain indoor thermal comfort, with HVAC systems accounting for up to 70% of total building energy consumption [16]. This dependence leads to high operational costs and increased energy waste, which are difficult to sustain in an environment with variable power supply and limited maintenance capability. While several studies ([17-22] have investigated building energy consumption and sustainable design strategies in Nigeria, few have focused on operational energy management in public office buildings, particularly from a framework-development perspective. This is consistent with other data that public-sector building portfolios in emerging nations frequently lack formal operational energy planning and performance monitoring systems [23].

Although the Federal Ministry of Power, Works, and Housing, in collaboration with the Nigerian Energy Support Programme, introduced the Building Energy Efficiency Guideline in 2016, its application is primarily limited to new buildings and provides little guidance for managing energy use in existing public buildings. This gap emphasises the need for a context-sensitive operational energy management framework that includes design methodologies, technological solutions, and regulatory measures tailored to Nigeria's socioeconomic and climatic conditions. It further reinforces the case for evidence-based frameworks that can inform both new-build design decisions and targeted retrofit paths for existing public assets. [24]. Against this backdrop, the goal of this study is to develop an operational energy management framework for public office buildings in Abuja, Nigeria, by identifying key energy drivers, evaluating current design practices, researching energy sources, and synthesizing these findings into a practical and scalable framework.

2. Literature Review

2.1 Passive Design Strategies for Reducing Operational Energy in Tropical Public Buildings

Operational energy consumption in buildings refers to the amount of energy used throughout a building's functional phase, which includes heating, cooling, lighting, ventilation, and equipment use. Cooling and ventilation frequently dominate operating energy consumption in tropical climates due to high ambient temperatures, humidity levels, and increased sun radiation [25]. As a result, public office buildings in tropical environments frequently experience higher energy intensity, especially when designs fail to effectively respond to prevailing environmental circumstances. Passive design solutions are widely recognised as fundamental approaches to reducing energy demand in office and public buildings, particularly in warm areas. These tactics include building orientation, natural ventilation, daylighting, roof design, and material selection, all of which influence inside thermal conditions and lessen reliance on mechanical cooling systems.

Evidence from tropical Africa shows that optimised roof designs, suitable sun control, and effective ventilation paths can dramatically reduce cooling energy demand—often by up to 40% in some cases [26]. Similarly, better daylighting reduces dependency on artificial lighting while also improving occupant health and productivity, making it a dual-benefit design strategy in workplace environments [25]. Despite their recognised benefits, passive techniques are frequently used inconsistently in underdeveloped countries due to poor energy policy implementation and practitioners' lack of awareness of long-term operational benefits [27]. This inconsistency leads to design decisions that enhance thermal gains and need more mechanical cooling during operation. In Nigeria, this gap is crucial because public buildings frequently face energy limits and require practical, low-cost ways to minimise cooling demand without relying heavily on technology.

2.2 Energy Systems, HVAC Efficiency, Smart Controls, and Renewable Integration

While passive solutions lower baseline energy demand, long-term operational energy savings are increasingly dependent on efficient building energy systems and integrated technology. Office buildings consume a significant portion of worldwide operational energy due to their constant occupancy and reliance on mechanical and plug-load systems [28]. According to studies, office buildings might waste up to 30% of their energy due to inefficient systems, poor management practices, and inadequate integration of design intent and operational realities [29]. Such inefficiencies are especially obvious in tropical office buildings, where mechanical cooling is frequently required due to substantial internal heat gains, building form constraints, and user expectations.

Energy-efficient HVAC systems remain critical to minimising operating energy consumption, as cooling systems in workplaces often account for the majority of energy demand, especially in hot regions [16]. Without effective HVAC systems and optimisation, energy usage rises dramatically, increasing both operational costs and carbon emissions. Along with HVAC improvements, smart building automation and lighting control systems have been widely pushed around the world as mechanisms for enhancing energy monitoring, demand response, and operational optimisation [11]. However, the efficiency of these technologies is frequently limited by institutional constraints such as maintenance capacity, availability of technical experience, and inconsistent facility management practices, particularly in developing nations.

Renewable energy integration, particularly solar photovoltaic systems, has emerged as a critical pathway for reducing carbon emissions and boosting energy resilience in buildings. sun PV is becoming increasingly popular in Nigeria due to the country's high sun irradiation levels and the need to supplement inconsistent grid supply [30]. Nonetheless, adoption in public buildings is still limited due to high initial expenditures, a lack of financing channels, and inadequate technical support structures [31]. These problems demonstrate that technology-driven solutions necessitate not only technical viability, but also enabling policy and finance instruments for widespread application.

2.3 Governance, Policy Instruments, and Operational Energy Management Framework Models

Technical improvements alone are insufficient to provide long-term reductions in operational energy use, especially in public buildings where governance, procurement procedures, and institutional norms heavily influence outcomes. Formalised approaches to operational energy management, such as planning, monitoring, auditing, and continuous improvement, are becoming increasingly necessary. ISO 50001-compliant energy management systems are designed to facilitate systematic performance tracking, corporate responsibility, and continuing optimisation through periodic evaluations and remedial measures. Evidence from developing nations suggests that integrated frameworks incorporating passive design, building energy technologies, and governance systems are more beneficial than isolated interventions [32]. This is especially pertinent in Nigeria, where energy policy has traditionally prioritised generation and supply infrastructure over building-level energy consumption and waste management. As a result, there is still a shortage in operational frameworks designed specifically for public office buildings, particularly those that cover both new buildings and the enormous portfolio of current public assets.

Given the institutional role of public buildings in shaping urban sustainability and resource consumption, the creation of operational energy management frameworks should involve multi-stakeholder collaboration among design professionals, facility managers, government agencies, and energy organisations. Such frameworks are designed to provide practical direction on priority tactics (for example, passive-first design principles), phased adoption of advanced technologies, and supported governmental mechanisms such as standard enforcement, training, performance monitoring, and finance models. Addressing these governance factors is critical for creating context-sensitive solutions that can close the gap between design goals, technology adoption, and operational effectiveness in tropical public office buildings.

3. Methodology

3.1 Research Design and Approach

This study employed a quantitative, cross-sectional research design to examine operational energy management in public office buildings in Abuja, Nigeria. The approach was chosen to allow for a systematic assessment of professionals' perceptions, attitudes, and priorities regarding operational energy use, as well as to simplify the statistical reduction and structuring of many energy-related design parameters. The study uses the Relative Importance Index (RII) and Principal Component Analysis (PCA) to prioritise and minimise the dimensionality of operational energy management variables. This combined methodological approach is commonly used in built environment research to aid decision-making and framework creation. [33].

3.2 Study Area and Data Collection Instrument

The study was carried out in Abuja, Nigeria's Federal Capital Territory, which has a hot tropical climate, high solar radiation, and a fast expanding public building stock. Architects, engineers, facility managers, and energy consultants were among the respondents who worked directly on the design, construction, and operation of public office buildings. These categories were chosen because they have a significant impact on operational energy outcomes at both the design and operational stages. A systematic questionnaire was used to collect primary data after conducting a thorough study of the literature on building energy efficiency and operational energy management. The questionnaire included five sections that were consistent with the study's objectives: (i) Factors affecting operational energy consumption. (ii) Implemented design strategies (iii) Energy sources for operations. (iv) Options and limits for managing operational energy use. (v) Requirements for creating an operational energy management framework. Responses were collected using a five-point Likert scale, resulting in ordinal data suitable for RII computation and multivariate analysis.

3.3 Data Analysis

The Relative Importance Index (RII) was used to prioritise issues influencing operational energy use, design techniques, and energy sources. The RII values range from 0 to 1, with higher values indicating more perceived importance. PCA was used to reduce the 16 identified building design and operational factors to a smaller set of interpretable components that account for the majority of the variance in operational energy use. PCA helped to identify fundamental dimensions of operational energy management, organise correlated variables into coherent components, and provide a statistical foundation for creating the proposed conceptual framework. Two standard tests were used to assess appropriateness for PCA. (i) KMO's sample adequacy measure. (ii) The Bartlett sphericity test. The KMO value (0.3838) is lower than the typical 0.50 requirement, but Bartlett's test proved significant ($\chi^2 = 21152.47$, $p < 0.001$), showing adequate correlations among variables. Prior research has shown that PCA can provide useful insights in exploratory situations with small sample sizes, especially in developing-country studies [34]. Kaiser's criterion was used to keep components with eigenvalues of 1.0 or above. Varimax rotation with Kaiser normalisation was used to improve interpretability and decrease cross-loadings. Five components were recovered, accounting for 89.78% of the total variance, demonstrating high explanatory power.

4. Results

4.1 Demographic Profile of Respondents

According to the demographic information for the professional questionnaire, 73% of the professionals are male, 26% are female, 56.7% have a master's degree, 33.3% have an HND/BSC, and 10% have a PhD; 46.7% are civil structural engineers, 23.3% are architects, 10% are service engineers, and 20% are facility managers. Among the professionals, 60% belong to MNSE, 20% to MNIA, and 10% to the MNIQS professional group. Overall, the demographic profile suggests that respondents have technical expertise and institutional relevance to operational energy management in public office buildings. The prevalence of male responders reveals a gender disparity in Nigeria's construction and building services sector, particularly in engineering and facility management professions. While this disparity may limit gender-based comparative insights, it is consistent with patterns documented across built environment professions in Sub-Saharan Africa and does not call into question the findings' technical validity. This distribution also shows that energy policy and professional development activities must purposefully increase participation and capability among under-represented groups in order to achieve long-term sector transformation. [10]. The majority of responders have postgraduate qualifications, indicating a reasonably high level of education. This boosts trust in their capacity to assess complicated issues including operational energy use, design methods, and energy governance frameworks. Professionally, civil/structural engineers lead the sample, followed by architects and facilities managers. The reduced representation of services engineers may explain why certain results place less focus on HVAC optimisation and smart controls, as these domains are frequently the domains of competence for building services experts. This emphasises the significance of diverse stakeholder involvement while developing operational energy frameworks for public buildings. [24]. Professional association enhances the credibility of responses since membership in recognised bodies (MNSE, MNIA, MNIQS) implies adherence to standards, ethical practice, and ongoing professional development. Overall, the demographic findings support the paper's fundamental argument: effective operational energy management in tropical public buildings necessitates the deliberate combination of passive design, technological systems, and regulatory processes.

4.2 Factors Contributing to Operational Energy Consumption

The RII research (Table 1) demonstrates that passive design solutions dominate operational energy performance in Abuja's public office buildings. Roof design and natural ventilation received the highest ratings (RII = 0.88), emphasising their importance in moderating indoor heat conditions. Daylighting and material selection were tightly related (RII = 0.86), illustrating the impact of envelope performance and spatial arrangement on energy demand. Renewable energy integration placed third (RII = 0.84), indicating a recognition of its potential despite limited deployment. Smart building automation, lighting controls, and water heating systems had the lowest RII (0.70), indicating minimal perceived importance and/or feasibility.

Table 1: Relative important index

Strategies adopted	$\sum W$	RII	Rank
Building orientation	108	0.72	8
Window Design and Placement	111	0.74	7
Building Shape and Form	114	0.76	6
Thermal Insulation	123	0.82	4
Roof design	132	0.88	1
Natural Ventilation	132	0.88	1
Day lighting	129	0.86	2
External shading Devices	105	0.70	9
Building envelope efficiency	114	0.76	6
Energy Efficient HVAC Design	123	0.82	4
Energy Efficient Lighting	120	0.80	5
Smart Building Automation System	102	0.68	10
Renewable energy integration	126	0.84	3
Material Selection	129	0.86	2
Water Heating and cooling system	99	0.66	11
Lighting controls and automation	93	0.62	12

4.3 Strategies Adopted in Practice to Reduce Operational Energy

Table 2 indicates the uneven adoption of energy-saving techniques. Natural ventilation had the highest adoption rate (Mean = 3.88; "used always"), indicating practitioners' preference for low-cost passive techniques.

Table 2: Strategies in practice to reduce operating energy usage in public office buildings.

Strategies adopted	Not used	Rarely used	Sometimes	Used always	Predominantly used	Mean value	Decision
LED Lighting	14 (13.7)	10 (9.8)	18 (17.6)	46 (45.1)	14 (13.7)	3.35	Sometimes
Natural ventilation	4 (3.9)	10 (9.8)	20 (19.6)	28 (27.5)	40 (39.2)	3.88	Used always
Energy Efficient HVAC system	14 (13.7)	58 (56.9)	20 (19.6)	10 (9.8)	0	2.25	Rarely used
Building insulation	24 (23.5)	44 (43.1)	24 (23.5)	10 (9.8)	0	3.06	Sometimes
Solar Energy integration	10 (9.8)	4 (3.9)	62 (60.8)	22 (21.6)	4 (3.9)	2.19	Rarely used

LED lighting (Mean = 3.35) and building insulation (Mean = 3.06) were occasionally used, showing a partial but inconsistent compliance with energy efficiency principles. However, energy-efficient HVAC systems (Mean = 2.25) and solar energy integration (Mean = 2.19) were infrequently used, showing that high-impact interventions are still limited in normal practice. This pattern implies that capital-intensive techniques encounter ongoing challenges, such as high costs, ineffective procurement structures, and a lack of technical skills [10, 23].

4.4 Sources of Operational Energy Consumption

Table 3 shows that electricity from the national grid is the dominant energy source (RII = 0.749), indicating a reliance on the centralised supply network. Diesel generators and solar power both placed second (RII = 0.533), showing that energy instability persists and supply alternatives are only somewhat diversified. The ongoing reliance on diesel is consistent with larger findings that energy resilience in public buildings frequently relies on self-generation in the face of grid unreliability [10].

Table 3: Relative Important Index

Strategies adopted	$\sum W$	RII	Rank
Electricity from the National grid	191	0.749	1
Diesel Generator	136	0.533	2
Solar Power	136	0.533	2

4.5 PCA Results: Total Variance Explained and Component Extraction

The PCA results (Table 4) show that five extracted components account for 89.78% of total variance, showing that the reduced component structure is highly explanatory.

Table 4: Total variance Explained

	Initial Eigenvalues		
Component	Total	% of Variance	Cumulative %
1	4.7544	28.69	28.69
2	3.8117	23.0	51.69
3	2.902	17.51	69.21
4	2.3491	14.18	83.38
5	1.0606	6.40	89.78
6	0.6426	3.88	93.66
7	0.4948	2.99	96.64
8	0.4389	2.65	99.29
9	0.1173	0.71	1.000
10	0.000	0.000	0.000
11	0.000	0.000	0.000
12	0.000	0.000	0.000
13	0.000	0.000	0.000
14	0.000	0.000	0.000
15	0.000	0.000	0.000
16	0.000	0.000	0.000

The first component accounts for 28.69% of variance, the second and third contribute 23.0% and 17.51%, respectively, while the fourth and fifth contribute 14.18% and 6.40%. Table 5 shows the rotated component matrix, which validates five coherent component clusters that indicate energy-related design and operational aspects. This includes: (i) Thermal performance and material efficiency, (ii) Smart and renewable energy systems, (iii) Climate-responsive passive design, (iv) Integrating envelope and HVAC efficiency, (v) Building morphology and roof design. This tight clustering enables the creation of a comprehensive operational energy management framework for Abuja's public office buildings.

Table 5: Rotated Component Matrix[a]

	Component				
	1	2	3	4	5
Building Orientation	-0.23058	-0.29388	**0.64717**	0.30716	0.13292
Window Design and Placement	0.52554	-0.23450	**0.56490**	-0.21058	0.39017
Building Shape and Form	0.46838	0.16912	0.29559	-0.28950	**0.76193**
Thermal Insulation	**0.86592**	0.31138	-0.16541	0.07748	-0.34778
Roof design	-0.16811	0.49840	0.06860	-0.01193	**0.81390**
Natural Ventilation	0.17903	-0.11612	**0.91398**	0.09670	0.11489
Day Lighting	0.11416	0.18551	**0.97481**	-0.15860	0.02612
External Shadng Devices	**-0.69314**	0.24050	-0.29764	-0.09676	-0.11983
Building Envelope Efficiency	0.01746	0.03383	0.01536	**1.00771**	0.05012
Energy-Efficient HVAC Design	0.07532	0.06329	0.16714	**0.81562**	-0.12226
Energy Efficient Lighting	-0.75457	-0.05939	-0.32461	-0.26762	-0.26606
Smart Building Automation System	0.30323	**0.96192**	-0.00496	-0.04076	0.01550
Renewable Energy Integration	0.09268	**0.84132**	-0.34863	0.28397	0.18376
Material Selection	**0.87548**	0.23285	-0.11448	-0.18359	0.01036
Water Heating and cooling sustems	0.05716	**0.42227**	0.26829	-0.59976	0.26914
Lighting controls and Automation	-0.07783	**0.76241**	0.02196	-0.13792	0.18158

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

5. Discussion

The rankings of roof design, natural ventilation, and daylighting show that passive design solutions are the most important elements determining operational energy performance in Abuja's public office buildings. High solar radiation and elevated ambient temperatures necessitate careful roof and envelope design to reduce heat gains and cooling loads. This is consistent with research showing that passive techniques can significantly reduce cooling energy demand in tropical locations [26,35]. Recent global assessments have also emphasised that passive-first solutions remain critical for achieving scalable energy reduction in the building sector, particularly in emerging economies. [9,24]. While PCA and RII studies emphasis the relevance of HVAC efficiency, insulation, and renewable energy integration, these approaches are underutilised in reality. This disparity is most likely caused by financial constraints, a lack of technical experience, and lax enforcement of energy efficiency regulations, according to [27,31]. The data implies that "high-impact strategies" necessitate supporting institutional structures, such as lifecycle procurement, commissioning requirements, and routine energy auditing, in order to progress from awareness to adoption. [23,33]. Smart building technologies and automation emerged as discrete PCA components, but they rated low in both RII and reported adoption rates. Although the global literature identifies automation as a significant driver of energy efficiency and operational performance

(IEA, 2020), the usefulness of such systems in Nigerian public buildings is limited by maintenance, expertise, and cost limitations. This strengthens the rationale for a staged adoption strategy: first, consolidate passive techniques, then boost efficiency standards for HVAC and envelope systems, and last, expand renewables and smart controls as capacity increases.

6. Implications of the Study

6.1 Framework Implications

Using RII rankings and PCA component structure, Abuja's energy management should prioritise: (i) Passive-first design with climate-responsive measures, (ii) Efficiency-driven envelope-HVAC optimisation, (iii) Phased implementation of renewables and smart technologies, and (iv) Policy-enabled support through standards, incentives, and capacity building. This comprehensive understanding directly influenced the design of the suggested operational energy management system. This study contributes to knowledge by providing empirical evidence on operational energy drivers in Nigerian public office buildings, demonstrating the value of RII-PCA integration in framework development, and proposing a context-sensitive operational energy management framework for tropical developing economies.

6.2 Policy Implications for FCDA and the Federal Ministry of Power

The findings have immediate consequences for Nigeria's public-sector energy governance, particularly FCDA and the Federal Ministry of Power. FCDA should integrate passive design criteria into development control, set minimum envelope and HVAC performance standards, institutionalise building-level energy management techniques, and prioritise phased retrofit programs for existing public buildings. The study recommends that the Federal Ministry of Power prioritise demand management over supply expansion, implement building-level energy management systems aligned with global best practices, encourage renewable energy adoption through targeted incentives and financing, and invest in capacity development and technical training.

7. Toward an Integrated National Framework

Overall, the data suggest that operational energy management in Nigeria's governmental office buildings cannot be accomplished purely through technological deployment. Instead, a coordinated framework is required that incorporates passive architectural design, efficient building systems, renewable energy uptake, and institutional governance. For FCDA and the Ministry of Power, this means coordinating planning rules, energy policies, finance mechanisms, and capacity-building activities to achieve the common goal of reducing operational energy usage. Such integrated approaches are consistent with global energy transition policies that prioritise demand reduction, efficiency, and clean energy substitution in public infrastructure portfolios.

8. Limitations and Future Research

8.1 Limitations

This study gives empirical insights into operational energy management in Abuja's public office buildings; nevertheless, numerous limitations must be acknowledged when interpreting the findings. First, the study used a cross-sectional questionnaire survey to gather perceptions and reported practices at a specific moment in time. As a result, causal interpretations of links between design techniques, adoption patterns, and operational energy outcomes are restricted, and longitudinal research is not feasible. Second, sample size and composition may limit generalisability. Although respondents were experienced professionals with significant institutional affiliations, civil/structural engineers and architects dominated the distribution, with services engineers and energy specialists accounting for a very modest fraction. This may impact the prioritisation of passive methods over advanced mechanical and automation-based solutions. Furthermore, the gender distribution was biased (73% male), reflecting sectoral reality but limiting interpretation of gender-diverse professional experiences.

Third, the PCA results should be interpreted with caution because the Kaiser-Meyer-Olkin (KMO) value is low (KMO = 0.3838), indicating insufficient sampling adequacy. The Bartlett's Test of Sphericity was significant ($p < 0.001$), indicating appropriate correlations for factor extraction. However, the low KMO suggests that the recovered component structure may be susceptible to sample extension and different measurement conditions. As a result, the PCA-derived framework should be regarded as an exploratory yet valuable model that requires further confirmation. Finally, this study did not incorporate direct metered operational energy data (such as electricity bills, sub-metering logs, or energy simulation results). As a result, conclusions reflect professional judgements and reported adoption patterns rather than measured building energy performance. This limits the ability to measure absolute energy savings from certain design strategies or operational changes.

9. Future Research

Future research should expand on these findings in four major directions. First, researchers should broaden their sample size and diversity by include more stakeholders, such as government project managers, procurement officers, policy regulators, and a greater representation of building services engineers and energy consultants. This will increase the statistical appropriateness of PCA and boost framework robustness. Second, future study should use measurable operational energy data from public office buildings, such as power bills, generator fuel consumption records, and submetering systems, in order to validate perception-based findings and quantify energy usage intensity (EUI). Combining surveys with energy audits and monitoring might result in more robust evidence-based policy recommendations. Third, future research should use confirmatory approaches like Confirmatory Factor Analysis (CFA) or Structural Equation Modelling (SEM) to validate the PCA-derived component structure and test direct and indirect pathways that connect passive design, technology adoption, and policy mechanisms to operational energy outcomes. Finally, comparative studies across other Nigerian cities (e.g., Lagos, Kaduna, Port Harcourt) and public building typologies (e.g., hospitals, universities, courts) are recommended to assess the framework's transferability and support the development of national-scale operational energy management standards.

10. Conclusion

This study sought to develop an operational energy management framework for public office buildings in Abuja, Nigeria, with the goal of minimising operational energy consumption through an integrated assessment of design factors, professional practices, energy sources, and management decisions. The study uses a mix of RII and PCA to give empirical evidence on the factors that influence operational energy utilisation in a tropical developing country scenario. The findings indicate that passive design tactics, specifically roof design, natural ventilation, daylighting, and building shape, are the most influential drivers of operational energy performance in Abuja's public office buildings. Advanced solutions including energy-efficient HVAC systems, smart automation, and renewable integration are underutilised due to financial, technical, and institutional constraints. PCA consolidated sixteen factors into five coherent components: thermal/material efficiency, smart/renewable systems, passive design, envelope-HVAC integration, and morphology/roof design, revealing the multidimensionality of operational energy performance. The findings show a disparity between perceived relevance and practical execution, emphasising the necessity for a formal operational energy management framework backed by policy enforcement, institutional capability, and a phased technology transfer. Overall, the study provides a context-sensitive, evidence-based framework for energy reduction initiatives in Abuja and other tropical developing cities.

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Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this study.

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