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Original Article

Adoption of Net Zero Energy Building Concepts and Energy Performance in Residential Buildings: A Sustainable Strategy in Affordable Housing Projects in Nairobi, Kenya

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Abstract *- Net Zero Energy Buildings (NZEBs) are designed to achieve energy efficiency, renewable energy integration, and decarburization, but their adoption in Kenya's affordable housing sector requires addressing local challenges. The study incorporates a privately developed project (Tilisi) and a government-led project (Pangani) to enable a comparative framework for understanding NZE impact of different development models, financing mechanisms, and regulatory frameworks on the adoption and performance of NZEB technologies. A mixed-methods survey research design was utilized, gathering data through questionnaires, interviews, and observations from 120 stakeholders, including residents, architects, engineers, and property managers. The findings indicate a significant lack of awareness regarding NZEB principles, with 95% of respondents unfamiliar with the concept and only 7% implementing NZEB features comprehensively. While all respondents had adopted some form of heating technology, suggesting a basic embrace of energy efficiency in this area, holistic NZEB integration remained minimal. Cooling strategies showed varied uptake, with 59% employing passive techniques, while mechanical cooling adoption was substantially lower. Further, regression analysis revealed a statistically significant positive relationship between the adoption of "Responsible Heating Controls" and overall NZEB integration ($\beta=0.346, p<0.001$). Furthermore, "Controlling Cooling" strategies demonstrated a positive impact on energy performance ($\beta=0.598, p<0.001$), whereas "Personal Control over Cooling" did not show a significant effect ($p>0.05$). The study concludes that despite a foundational acceptance of energy-efficient Heating, substantial barriers such as financial constraints, knowledge gaps, and low awareness impede the widespread adoption of comprehensive NZEB principles.*

Keywords *- Energy-efficient technologies, Heating and cooling strategies, Renewable Energy, Sustainable building practices, Sustainable Housing.*

1. Introduction

The shift towards clean energy in Kenya has recently gained momentum in various sectors owing to the growing energy demands amid demographic-led environmental challenges (Barngetuny, 2024). As a result, the Kenyan building sector has conceived several energy-saving strategies and products, such as green building and net-zero building concepts, to attain energy goals in 2030. However, the adoption of these energy solutions has been slow owing to the high costs of installation, regulatory red tape and technical limitations among local technicians (Ohene, 2024; Blom et al., 2025). Net Zero Energy Buildings (NZEBs) characterise structures that efficiently balance emission and removal of greenhouse gases in the atmosphere (Ahmed et al. 2022) over the course of a year. The concept focuses on strategies that produce energy from renewable sources such as solar PV, wind power, and geothermal energy (Jaysawal et al., 2022). Consequently, NZEBs minimize energy demand while maximizing on-site energy generation, resulting in minimal reliance on the grid and reduced environmental impact. Based on this understanding, the concept of energy performance is borne. It refers to the effectiveness of a building in utilizing energy, particularly in terms of reducing energy consumption through efficient design while maximizing on-site renewable energy generation to achieve net-zero energy consumption over a year (Wu & Skye, 2021).

In the United States, the concept of NZEBs is deeply rooted in the national construction practices to reduce the building sector's significant contribution to greenhouse gas emissions (Shrestha, 2016). This has led to the development of various NZEB models, such as Net-Zero Site Energy, Net-Zero Emissions, and Net-Zero Source Energy, each focusing on specific metrics of energy or emissions neutrality (Ahmed et al., 2022). The successful implementation of NZEBs requires a multi-dimensional approach that considers not only technological advancements but also economic feasibility, policy support and social equity (Kim & Lim, 2024). On the other hand, challenges to the adoption of these technologies include variability of solar resources and high upfront costs, which may be addressed through innovative financing mechanisms, supportive policies and public-private partnerships (Attia et al., 2022; Madadizadeh et al., 2024).

The European Union has established ambitious climate neutrality goals, with the Energy Performance of Buildings Directive (EPBD) accelerating the adoption of Nearly Zero-Energy Buildings (NZEBs) (Maduta et al., 2023). In this context, NZEBs are underpinned by stringent energy performance criteria, which emphasize high energy efficiency through decarbonization measures such as enhanced insulation, airtightness, and the combination of renewable energy sources (Magrini et al., 2020).

Despite these policy and practice efforts, many EU nations experience inconsistencies in implementation modalities. These challenges are more pronounced in Southern European countries, as they experience high primary energy demands, limited renovation rates, and insufficient integration of renewable energy sources (Olasolo-Alonso et al., 2023).

In contrast, Asian nations are driving the adoption of Zero Energy Buildings (ZEBs) through ambitious decarbonisation goals and regional cooperation, such as the Asia-Pacific Economic Cooperation's (APEC) efforts to promote ZEBs and achieve energy intensity reduction targets (Zhang et al., 2021). Leading economies like China, Japan, and South Korea are spearheading ZEB development with their commitments to carbon neutrality by 2050/2060. For instance, China has developed a hierarchical framework encompassing ultra-low energy buildings, nearly ZEBs, and ZEBs as progressive goals for upgrading building energy codes (Yang et al., 2019), while Japan emphasizes the integration of renewable energy systems, such as solar power and geothermal heat, into renovated and new buildings to meet ZEB standards (Kuwahara et al., 2022). These government-led initiatives and policy frameworks demonstrate the importance of consistent implementation and monitoring in achieving climate neutrality goals, as highlighted by the need for harmonized policies, enhanced renewable energy integration, and innovative financing mechanisms to make NZEBs and ZEBs more accessible and affordable (Gonzalez-Caceres, Lassen & Nielsen, 2020).

Despite significant progress, challenges to ZEB adoption in Asia persist. High initial costs remain a significant barrier, particularly for renewable energy systems and high-performance building materials (Ahmed et al., 2022). Moreover, policy gaps, such as inadequate enforcement mechanisms and a lack of standardized building codes, hinder the widespread implementation of ZEBs. Zhang et al. (2021) identify the need for comprehensive frameworks addressing financing, standardization, and cross-sector collaboration within APEC economies to overcome these challenges. In China, Yang et al. (2019) emphasize the need for widespread adoption of ultra-low energy buildings and ZEBs, covering at least 50% of the total floor area by 2050.

The adoption rate of NZEBs in many African building settings is slowly rising as member states continue to advocate for decarbonisation strategies. In the context of Ghana, NZEB is a concept that has been explored through retrofitting existing buildings, demonstrating that passive design strategies like natural ventilation, daylighting, and enhanced envelope airtightness can drastically reduce energy demand by up to 50% (Ohene, Hsu, & Chan 2022). Solar photovoltaics (PV) are also employed to meet remaining energy needs, creating a balance in energy generation-consumption needs in buildings (Ohene, Hsu, & Chan, 2022). Similarly, in Sub-Saharan Africa, including Cameroon, Senegal, and Côte d'Ivoire, adopting NZEBs faces challenges such as high energy consumption, inadequate building energy standards, and limited access to financing (Mohammed et al., 2023). However, strategies such as conducting baseline assessments, establishing energy codes, creating financing mechanisms, and raising awareness are key pathways to transition towards NZEBs (Mohammed et al., 2023). As African nations continue to experience growing energy demand, rapid urbanization, and the need to address climate change, NZEBs offer a sustainable solution for affordable housing projects.

Despite the clear environmental and economic benefits of NZEBs, challenges persist in their adoption, particularly in the MENA (Middle East and North Africa) and Sub-Saharan Africa regions that have hot climates and high reliance on fossil fuels (Attia et al., 2022; Ohene, Hsu, & Chan 2022). In these regions, the lack of energy efficiency standards for buildings and the high upfront costs of implementing NZEB strategies have hindered their widespread adoption (Al-Saeed & Ahmed, 2018). However, the concept's potential is evident, as seen in simulation results from MENA countries, where improving building fabric and utilizing solar PV has led to significant reductions in energy consumption (Al-Saeed & Ahmed, 2018). To overcome these barriers, a comprehensive approach is necessary, including revising and aligning building energy standards to contemporary best practices, piloting NZEB projects, and scaling up the adoption of renewable technologies. Ultimately, by integrating these strategies, African nations can move towards a more sustainable future, reducing energy consumption and CO2 emissions while addressing the growing demand for energy-efficient buildings (Mohammed et al., 2023; Ohene et al., 2022).

Kenya's affordable housing initiative emerged as a key government strategy to tackle the country's growing housing deficit and provide decent shelter for its burgeoning population (Kieti, 2020). Recognizing the significant gap between housing demand and supply, particularly for low and middle-income earners, the government launched this ambitious program. This policy addresses rapid urbanization, informal settlements, and the need for improved living standards by facilitating the construction of affordable homes nationwide.

Incorporating NZEB principles, such as improved energy efficiency through passive design, solar energy systems, and rainwater harvesting, in this scheme may help reduce long-term energy costs for residents. Moreover, by using locally sourced, sustainable materials, these projects can support economic development while minimizing the sector's ecological footprint.

The potential of NZEBs to address energy poverty and promote sustainable development is well established by Mohammed et al. (2023). However, the extent to which these concepts are being integrated into government-led affordable housing projects in Kenya and the factors influencing their adoption remain largely unexplored. This study aims to bridge this knowledge gap by investigating the current level of NZEB integration within government-led affordable housing projects in Nairobi, Kenya, while simultaneously examining the challenges and opportunities associated with their implementation.

Literature shows that while there is global recognition of net-zero concepts and associated environmental and economic benefits, their adoption faces persistent challenges, particularly in developing nations like Kenya (WEF, 2021). Key challenges include technical aspects, economic feasibility, and policy frameworks for NZEBs in developed economies (Ohene, 2024; Barngetuny, 2024; Mohammed et al., 2023). Additionally, while several studies show that NZEB concepts are inherently linked to energy performance, some present a somewhat mixed or indirect relationship.

While some aspects of NZEB implementation, such as passive design strategies or solar PV integration, consistently show a strong positive correlation with improved energy performance (Ohene, Hsu, & Chan, 2022), there is a lack of literature showing universally positive relationship across active and renewable energy systems. This study examines the direct relationship between the various NZEB concepts, including active systems, and actual energy performance in a specific local context.

The additional concern lies in the limiting contextual focus of NZEB studies targeting residential buildings. Many studies have been conducted outside or within Africa, but not specifically in Kenya. For instance, research highlights NZEB development and implementation in the United States (Shrestha, 2016; Kim & Lim, 2024), the European Union (Maduta et al., 2023; Magrini et al., 2020; Olasolo-Alonso et al., 2023), and Asian nations like China, Japan, and South Korea (Zhang et al., 2021; Yang et al., 2019; Kuwahara et al., 2022). While these provide valuable insights into global progress, they operate within vastly different policy environments, regulatory frameworks, economic conditions, and climatic variations compared to Kenya.

Even within Africa, studies often focus on regions outside Kenya, such as Ghana (Ohene, Hsu, & Chan, 2022; Ohene, 2024) or broader Sub-Saharan African countries like Cameroon, Senegal, and Côte d'Ivoire (Mohammed et al., 2023). While these studies identify common challenges like high energy consumption, inadequate building energy standards, and limited access to financing and propose strategies for transition (Mohammed et al., 2023), their findings are shaped by their specific local contexts. Policies and incentives effective in one African nation may not be directly transferable to Kenya's unique socio-economic and political landscape, which faces challenges in financing the net-zero transition, including high capital costs, regulatory uncertainty, and limited local expertise (Barngetuny, 2024).

Therefore, this study's novelty lies in its focused investigation into the underexplored components of NZEB adoption within government-led affordable housing projects, specifically in Nairobi, Kenya. Examining the current level of NZEB adoption, challenges, and opportunities within Kenya's affordable housing scheme (Kieti, 2020) may provide insights that are directly relevant to policy formulation and practical implementation in an urbanizing developing economy, addressing the local specificities that broader or geographically disparate studies cannot fully capture.

2. Materials and Methods

2.1. Study Area

The study was conducted in two distinct residential developments in Kenyan counties of Kiambu and Nairobi. The first, Tilisi Developments in Kiambu County, represented the private, affordable housing project in Kiambu County. In contrast, the Pangani Affordable Housing Project in Nairobi County represented the public housing scheme under Nairobi Metropolitan Area (NMA). Tilisi Developments, a master-planned, mixed-use community in Limuru (-1.15841, 36.64804), represents high-end residential areas with world-class infrastructure. Conversely, the Pangani project (-1.26801, 36.83578) focuses on affordable housing, catering to low-end residential needs. These locations were selected due to the high concentration of newly constructed residential buildings, allowing a comparative analysis of operational net-zero energy building (NZEB) concepts. Only residential buildings were targeted to ensure population homogeneity.

2.2. Research Design

A survey incorporating qualitative and quantitative approaches was utilized to evaluate the integration of NZEB principles and their role in enhancing sustainability in affordable housing. The study used the mixed-methods approach, as recommended by Dawadi, Shrestha and Giri (2021). This approach ensured that quantitative methods provided numerical insights while qualitative methods offered in-depth explanations, validating findings across both modes of inquiry. Data collection involved recording information on residential buildings' design, construction, and management aspects. Quantitative analysis determined the degree of NZEB element incorporation using statistically measurable parameters, while qualitative analysis captured the barriers and challenges of adopting energy-efficient technologies.

2.3. Sampling and Data Collection

The sampling frame consisted of 120 respondents, which comprised 90 households residing in the targeted building projects, 10 architects, 5 quantity surveyors, 10 property managers and 5 engineers who were actively involved in residential projects within Tilisi and Pangani affordable housing projects. To maintain uniformity, both private and public residential premises were sampled. Using simple random sampling, 90 households (75% of the target population) were selected, consistent with Dawadi et al. (2021) recommendation for a minimum sample size of 30 to ensure greater representation and statistical robustness in reported findings.

2.4. Data Analysis

The qualitative data was summarised and thematically analysed. This involved systematically identifying recurring patterns, themes, and meanings within the textual data. Specifically, the responses were coded to categorize similar ideas, opinions, and experiences related to the affordable housing scheme. These codes were then grouped into broader themes, which allowed the extraction of detailed insights and nuanced explanations on respondent perceptions, challenges, and policy ramifications on NZEB adoption. Statistical analysis was conducted using SPSS 20 (IBM Corp., United States).

The analysis included the generation of frequency distribution tables to describe the characteristics of the sample and variables of interest. Linear regression analysis was performed to examine relationships and quantify the effect of predictors on response variables. The significance of the regression models and individual predictors was assessed at a 5% significance level.

3. Results and Discussion

3.1. Descriptive Analysis of Awareness and Adoption of Near-Zero Energy Building (NZEB) Concepts

The results of the frequency tables of the NZEBs are presented in Table 1. This table presents the number (n) and percentage (%) of respondents falling into three categories for each concept: "Yes" (indicating adoption or awareness), "No" (indicating non-adoption or lack thereof), and "Not Aware" (indicating a lack of knowledge about the concept).

Ninety-five percent of respondents reported no awareness, with only 5% indicating some level of familiarity. This suggests a substantial knowledge gap regarding NZEB strategies in the Nairobi Metropolitan area, which could hinder the adoption of these sustainable building practices. In terms of incorporating NZEB design concepts into the design and construction of their residential buildings, the results presented in Table 1 indicated a clear adoption gap.

Only 7% of respondents reported integrating such concepts into their residential buildings. 49% chose not to adopt NZEB design concepts, while 44% were not in a position to make that choice due to a lack of information. The results in Table 1 suggest that adopting NZEB concepts in residential buildings, particularly in affordable housing projects in Nairobi, is severely hampered by a profound lack of awareness.

From Table 1, all respondents (100%) reported adopting some form of NZEB heating mechanisms in their homes, indicating that heating solutions have become a foundational aspect of sustainable residential design in the area and could potentially serve as a model for other energy-saving initiatives in the housing sector. The results regarding energy-efficient practices show a near-even split, with a slight majority (51%) adopting some measures while a substantial portion (48%) has not, indicating a moderate but incomplete adoption of energy-saving practices.

In assessing the variable of energy consumption, 22% admitted to using electricity, which is associated with high energy consumption bills, while only 1% used solar energy, which is associated with low energy consumption bills. The low uptake of solar energy, despite its potential for cost savings, may be attributed to barriers such as high initial investment costs, lack of awareness of its benefits, or limited access to solar technology and installation services.

In relation to the NZEB Cooling Concepts (Mechanical), from Table 1, 25% of respondents reported adopting the concepts, while a majority (75%) were unaware of them. This suggests a relatively low adoption rate for mechanical cooling strategies within the NZEB framework, potentially due to factors like cost, complexity of installation or lack of information about available options.

Table 1. Respondent Perceptions on NZEBs

Variable Item	Yes (n/%)	No (n/%)	Not Aware (n/%)
Awareness of NZEB	4 (5%)	0 (0%)	71 (95%)
NZEB Design Concepts Incorporated	5 (7%)	37 (49%)	33 (44%)
NZEB Heating Concepts	75 (100%)	0 (0%)	0 (0%)
Adopt energy efficiency practices	38 (51%)	36 (48%)	1 (1%)
High Energy Consumption Bills (Electrical)	16 (22%)	0 (0%)	59 (78%)
Low Energy Consumption Bills (Passive Solar)	1 (1%)	74 (99%)	0 (0%)
NZEB Cooling Concepts (Mechanical)	19 (25%)	0 (0%)	56 (75%)
NZEB Cooling Concepts (Natural/Passive)	44 (59%)	0 (0%)	31 (41%)
Heating/Cooling Control Mechanisms	75 (100%)	0 (0%)	0 (0%)
Provision for HVAC Upgrades	50 (67%)	5 (6%)	20 (27%)
Adequate Daylight and Natural Light	56 (75%)	19 (25%)	0 (0%)
Adequate Artificial Light	41 (55%)	15 (20%)	19 (25%)
Measures for Reducing Energy Bills	75 (100%)	0 (0%)	0 (0%)
Utilization of Renewable Energy Technologies	17 (22.67%)	58 (77.33%)	0 (0%)
Incorporated Energy Star Rated Appliances	18 (24%)	57 (76%)	0 (0%)
High-Efficiency Light Fixtures Installed	19 (25.33%)	56 (74.67%)	0 (0%)

Similarly, 59% of respondents reported using natural/passive NZEB cooling concepts, compared to 41% unaware. This indicates a greater reliance on natural ventilation, shading, and other passive strategies, often more accessible and cost-effective than mechanical systems. Table 1 also indicates that all respondents reported using some form of heating/cooling control systems. This universal adoption suggests that while the *type* of control mechanism may vary (e.g., thermostats, manual adjustments), the concept of regulating indoor temperature is widely practised.

The results in Table 1 further show that a majority (67%) of respondents affirmed that their buildings have provisions for HVAC (Heating, Ventilation, and Air Conditioning) upgrades. This suggests that many buildings may have been designed with future integration of sophisticated climate control in mind, potentially easing the pathway for adopting more energy-efficient and comfortable systems. However, the notable 27% of respondents who were unaware of these provisions highlight a critical gap in communication and understanding. This lack of awareness could stem from insufficient information sharing by developers or landlords, inconspicuous provisions, or varying levels of resident engagement with building features.

Only a small fraction (6%) reported no provision for HVAC upgrades. Additionally, most (75%) respondents reported having adequate daylight and natural light in their buildings (Table 1). This is a positive finding, as natural light contributes to energy efficiency and occupant well-being (reference). Twenty-five percent of respondents reported a lack of adequate natural light, suggesting potential areas for improvement in building design or renovation. However, over half (55%) of respondents felt their buildings had adequate artificial lighting. While this is a majority, it indicates that a substantial portion (45% - combining the "No" and "Not Aware" categories) perceive deficiencies in their artificial lighting. This suggests possible issues with lighting quality, energy efficiency, or overall design.

The results in Table 1 further show that all the respondents reported having measures in place to reduce energy bills (75, 100%). This suggests a widespread concern about energy costs and a general awareness of the need to take action to conserve energy. Regarding utilization of renewable energy technologies, the results show that only 22.67% of respondents reported utilizing renewable energy technologies. This indicates a significant gap between awareness of energy conservation and adopting more sustainable energy solutions. The high percentage (77.33%) of non-utilization of renewable energy technologies suggests potential barriers to adoption, which may likely be linked to high initial costs of installation, lack of information or access to technology, regulatory bottlenecks, and lack of incentives or support programs. Further, similar to renewable energy, only 24% of respondents reported using Energy Star-rated appliances. This suggests that while respondents may be aware of energy-saving practices, they were not actively investing in energy-efficient appliances, indicating potential gaps in upfront costs and awareness. As a result, only 25% of respondents reported having high-efficiency light fixtures installed in their premises, indicating a relatively low adoption rate in spite of the associated long-term cost-effectiveness and accrued environmental benefits.

3.2. Multiple Linear Regression to Establish the Relationship between NZEB Heating Concepts and Level of Adoption

Multiple linear regression analysis was conducted to investigate the relationship between the adoption of Net Zero Energy Building (NZEB) practices (dependent variable) and various NZEB heating control strategies (independent variables), as well as quantify the strength and direction of these relationships. The analysis aimed to determine the strength and direction of these relationships, specifically examining how these heating-related factors influence the likelihood and extent of broader NZEB adoption.

The regression model is represented by Equation (1) given by,

$$AL = 0.823 + 0.132 \times (RHM) - 0.223 \times (CH) + 0.122 \times (MHF) \cdots\cdots (1)$$

Where AL, the adoption level, measures the overall NZEB adoption by respondents. RHM, or responsible heating controls, quantifies adopting related NZEB strategies. CH refers to controlling Heating and measuring the adoption of heating control strategies. MHF is the monitoring heating frequency, which reflects the adoption of strategies for monitoring heating activity. The model demonstrated a strong fit with $R = 0.872$, $R^2 = 0.760$, and an adjusted $R^2 = 0.750$. The model was significant ($p \leq 0.05$) at a 95% significance level.

The analysis revealed a statistically significant positive relationship between "Responsible Heating Controls" and "Adoption Level" ($\beta = 0.346$, $t = 5.141$, $p < 0.001$), indicating that increased adoption of responsible heating controls is associated with higher overall NZEB adoption. However, a statistically significant negative relationship was observed between "Controlling Heating" and "Adoption Level" ($\beta = -0.748$, $t = -11.04$, $p < 0.001$), suggesting that a greater focus on specific heating controls might inadvertently correlate with lower adoption of broader NZEB practices. This could stem from a concentration of efforts on single solutions, perceived sufficiency, cost trade-offs, or a limited understanding of the holistic nature of NZEB. Finally, while "Monitoring Heating Frequency" exhibited a positive coefficient ($\beta = 0.141$), its relationship with "Adoption Level" was not statistically significant ($t = 1.863$, $p = 0.067$), indicating that simply monitoring heating habits may not strongly predict overall NZEB implementation, potentially due to other more influential factors or measurement limitations.

The regression results offer fascinating insights into NZEB adoption. The positive association between responsible heating controls and overall NZEB adoption suggests that focusing on responsible practices can effectively promote broader NZEB implementation. This position aligns with global calls for behavioral change in achieving energy efficiency (Ma et al., 2024). However, the study observed a negative relationship between "Controlling Heating" and adoption levels. This could be due to inefficient implementation or a perception among users that complex controls detract from comfort, potentially discouraging the adoption of other NZEB features, a similar challenge observed in the Ghanaian context (Ohene, 2024). The mixed relationship where not all NZEB components show a positive effect is consistent with Ohene, Hsu, and Chan's (2022) study in many West African nations.

In terms of civil engineering practices, the results may promote certain aspects of NZEB adoption in Kenya's affordable housing projects, given the barriers of high initial costs, regulatory hurdles, and limited local technical expertise (Barngetuny, 2024; Ohene, 2024; Blom et al., 2025). Prioritization should be given to NZEB packages that integrate passive design elements like optimized natural ventilation and improved insulation with efficient active systems and renewable energy generation, as suggested by (Ürge-Vorsatz et al., 2020). Furthermore, the observed positive link between "Responsible Heating Controls" and energy performance highlights the value of promoting broader energy-conscious behaviors through user-friendly guides and awareness campaigns, which helps overcome the "lack of public awareness" barrier, as suggested by Ohene (2024). Given the limited impact of monitoring, interventions should focus on direct strategies to address financial and technical barriers that inhibit adoption.

3.3. Multiple Regression to Establish the Relationship between the Level of Adoption and NZEB Cooling Concepts

A multiple linear regression analysis investigated the relationship between energy performance (dependent variable) and various NZEB cooling strategies (independent variables). The following equation represents the regression model:

$$EP = 0.149 + 0.377 \times (CC) + 0.036 \times (PCOC) + 0.776 \times (MCF) \quad (2)$$

Where Energy Performance (EP) is quantified as the percentage reduction in total energy costs over a defined period compared to a Baseline Building—a typical, code-compliant residential building in Nairobi Metropolitan representing common pre-NZEB practices—calculated using actual energy consumption data, CC (Controlling Cooling) represents the level of active management of cooling systems, measured as a composite index based on the presence and usage of technologies like programmable thermostats and smart cooling systems. PCOC (Personal Control Over Cooling) assesses how occupants can independently adjust cooling settings within their spaces based on survey responses about thermostat access and perceived control. Lastly, MCF (Monitoring Cooling Frequency) quantifies how occupants track their cooling system usage, assessed by the reported use of energy monitoring systems or active tracking of cooling runtime.

The regression model had a moderate fit ($R = 0.490$, $R^2 = 0.240$, Adjusted $R^2 = 0.208$, $F(3, 71) = 7.483$, $p < 0.001$) to the data. The results had a statistically significant ($p \leq 0.05$) positive relationship between energy performance and both controlling cooling strategies ($\beta = 0.598$, $t = 4.301$, $p < 0.001$) and monitoring cooling frequency ($\beta = 0.568$, $t = 4.102$, $p < 0.001$), suggesting that increased adoption of these strategies is associated with better energy performance. However, no significant ($p>0.05$) relationship was found between personal control over cooling and energy performance ($\beta = 0.055$, $t = 0.527$, $p = 0.6$). The moderate R^2 value suggests that other factors, beyond those included in the model, had an influence on the energy performance. The non-significant impact of personal cooling control on energy performance suggests that in NZEB adoption, simply providing more control to residents may be less effective than focusing on automated cooling technologies and inherent system efficiencies.

The multiple linear regression analysis reveals important relationships between NZEB cooling strategies and energy performance. The statistically significant positive relationships between energy performance and both "Controlling Cooling" (adoption of technologies like programmable thermostats) and "Monitoring Cooling Frequency" (use of tracking systems on operational runtime of cooling systems) suggest that these strategies are effective in improving energy performance.

Essentially, implementing advanced cooling controls and actively monitoring cooling energy usage leads to demonstrable cost savings (reference). However, the lack of a significant relationship between "Personal Control Over Cooling" (occupant ability to adjust settings) and energy performance implies that simply giving occupants control over their cooling environment doesn't necessarily translate into better energy performance. This might be because occupants lack the knowledge or motivation to use controls effectively, or the available control systems are not designed to facilitate optimal energy usage.

The moderate R^2 value (0.24) indicates that the model, focusing on cooling control and monitoring, only explains a quarter of the variance in energy performance, underscoring the significant influence of other uncaptured factors. As highlighted in the literature on NZEB adoption in Africa (Mohammed et al., 2023; Ohene, Hsu, & Chan, 2022), these likely include inadequate building energy standards and limited access to financing, which can hinder the implementation of comprehensive NZEB measures beyond cooling technologies. Furthermore, the impact of passive design strategies, such as enhanced insulation, natural ventilation, and daylighting, which significantly reduce overall energy demand (Ohene et al., 2022), are not accounted for in the current model. Therefore, achieving optimal energy performance in buildings necessitates a more holistic approach to NZEB adoption that extends beyond cooling strategies and considers these crucial additional influences related to regulatory frameworks, financial constraints, and fundamental building design principles.

3.4. Discussion

The analysis revealed a substantial gap among respondents between awareness and adoption of Net Zero Energy Building (NZEB) concepts. A striking 95% reported no familiarity with NZEB, with only 7% having integrated NZEB concepts into their homes. This low level of awareness is a primary contributor to the low adoption rate despite the well-established sustainability benefits of NZEB design, including energy efficiency and reduced environmental impact (Ohene, 2024; Ma et al., 2024). This mirrors findings in other contexts where limited public awareness is a significant barrier to NZEB uptake (Ohene, 2024). Our findings also align with broader literature identifying financial constraints, lack of technical knowledge, and resistance to new construction methods as major impediments to adoption (Ahmed et al., 2022; Zhang et al., 2021). These results underscore the need for policies that reduce upfront costs and enhance access to training and technical expertise for both individuals and organizations. For example, energy efficiency initiatives in the EU emphasize the importance of financial incentives and subsidies to overcome such barriers (Maduta et al., 2023). In Kenya, addressing high capital costs and limited local expertise is crucial, and strengthening financial mechanisms like green bonds and carbon markets, currently underutilized, may likely facilitate related solutions (Barngetuny, 2024).

The findings revealed that 100% of respondents reported using some form of NZEB heating solution despite low overall NZEB awareness. This suggests that heating solutions could serve as an effective entry point for promoting broader NZEB adoption, as they represent a universal need within residential settings. Our regression analysis showed that responsible heating controls had a positive and statistically significant impact on adoption (($p \leq 0.05$), suggesting that promoting mindful usage practices can genuinely enhance overall NZEB integration. This aligns with the understanding that behavioral changes are crucial alongside technological advancements for energy efficiency (Ma et al., 2024). Conversely, "Controlling Heating" mechanisms negatively and statistically significantly impacted adoption. This result suggests that implementing certain control strategies, particularly if complex or perceived as restrictive, might inadvertently hinder overall NZEB adoption. This could occur if controls are implemented in isolation without considering the holistic NZEB approach, or their interaction with other systems is counterproductive. This relationship between specific NZEB indicators and overall energy performance is consistent with the mixed findings noted in the broader literature, where not all components demonstrate a universally positive effect across diverse operational contexts (Ohene, Hsu, & Chan, 2022). This highlights a critical contradiction: while there is a need for energy-efficient features, overly complex or poorly integrated controls can paradoxically become a barrier, rather than a solution, for occupants.

Regarding cooling, the limited adoption of mechanical cooling likely stems from cost constraints and Nairobi's relatively mild climate. However, a significant majority of respondents (59%) reported using natural/passive cooling strategies. This is a positive finding, as passive cooling can significantly reduce energy consumption and enhance comfort, leveraging natural conditions instead of mechanical systems. This contrasts with lower adoption rates for other NZEB technologies like solar photovoltaic (PV) systems for electricity generation, energy-efficient windows and insulation, and advanced lighting controls. The control over cooling also showed a significant positive impact on energy performance, indicating that robust control mechanisms are effective in minimizing energy waste in cooling systems. In contrast, while monitoring the frequency of heating actions showed a modest positive relationship, it was not statistically significant ($p>0.05$), suggesting its influence on overall NZEB adoption is limited without complementary measures. However, regular monitoring of cooling-related actions was found to greatly enhance energy performance, emphasizing the importance of advanced monitoring systems to ensure consistent energy savings for cooling, distinguishing its impact from heating monitoring.

The results underscore stakeholder engagement's importance in bridging the identified gap between awareness and adoption. Collaborative strategies involving a broad range of stakeholders are crucial for creating a supportive ecosystem that encourages the adoption of energy-efficient technologies (Olasolo-Alonso et al., 2023; Mohammed et al., 2023). Targeted awareness initiatives, especially for builders and policymakers, are essential to enhance their capacity to drive adoption. Such initiatives, drawing lessons from successful programs in other developing nations, could include community workshops for homeowners, training programs for builders on sustainable construction techniques, and policy briefs for government officials highlighting the economic and environmental benefits of NZEBs (Ohene, 2024; Mohammed et al., 2023). Adapting these strategies to Kenya requires considering existing infrastructure, local expertise, and cultural factors. For instance, leveraging community networks and incorporating local building practices into training programs could be vital for effective implementation, echoing the importance of targeted outreach in driving technological uptake and policy changes (Ohene et al., 2022).

The low adoption of renewable energy technologies, with only 22.67% of respondents utilizing them, highlights a significant gap despite existing policies, such as Kenya's requirement for solar water heating in new buildings. This indicates that while some policy frameworks are in place, persistent financial constraints, limited availability of diverse renewable energy technologies beyond solar water heating (like solar PV for electricity), and potentially insufficient awareness or enforcement of existing regulations continue to hinder broader uptake (Barngetuny, 2024; Kim & Lim, 2024). This aligns with challenges in other developing economies where upfront costs and access to financing are major impediments (Barngetuny, 2024). Furthermore, the minimal utilization of passive solar systems for Heating and lighting, despite a relatively higher adoption of natural/passive cooling (59%), points to a significant underutilization of readily available solar resources for Heating. This suggests a potential lack of widespread knowledge and expertise in passive solar design principles among Kenyan building professionals and a prevailing focus on conventional building methods. Integrating passive solar design, a readily available and cost-effective resource, into residential design is essential for maximizing energy efficiency in affordable housing projects. The fact that a significant portion of respondents are not yet prioritizing energy efficiency, despite its potential to reduce operational costs and environmental impact, underscores the urgent need for greater emphasis on integrating these fundamental passive solar design features and other energy-efficient technologies into Kenya's affordable housing initiatives.

An inclusive and stakeholder-guided approach is recommended to accelerate NZEB adoption in Kenya's affordable housing sector. The study proposes developing integrated NZEB roadmaps and policy frameworks prioritizing innovative design over isolated technologies. Additionally, overcoming financial barriers necessitates targeted subsidies, green mortgages, green bonds and carbon markets to attract investment, as recommended by Barngetuny (2024). Furthermore, capacity building and awareness campaigns should be enhanced to address the prevalent lack of knowledge, which may call for professional training on NZEB benefits. Further, efforts promoting passive design principles and locally appropriate technologies, capitalizing on natural cooling preferences and maximizing readily available solar resources for Heating and lighting should be incentivized. This will facilitate the adoption of sustainable, local materials to reduce costs and environmental impact. Future research opportunities may target investigating "Controlling Heating" concepts, detailed cost-benefit analyses of NZEB integration in Kenya's affordable housing, and assessing the long-term effectiveness of policy and incentive programs.

4. Conclusion

This study of the Nairobi Metropolitan area reveals a critical juncture for NZEB adoption within Kenya's housing sector, particularly the affordable segment. While a surprising ubiquity of some NZEB heating solutions exists, a pervasive lack of awareness and the low integration of comprehensive NZEB design principles represent significant barriers to achieving widespread sustainable building practices. Financial limitations and insufficient technical expertise further compound this challenge. The acknowledged importance of reducing energy bills, however, signals an underlying motivation for change that may be leveraged.

This study recommends that to effectively promote NZEB in the affordable housing sector and the broader residential market across Kenya, a multi-pronged approach is essential. Robust awareness campaigns tailored to residents and practitioners are needed to bridge the significant knowledge gap. Simultaneously, accessible financial incentives, such as subsidies and green loans, are crucial to overcome initial cost barriers, especially for affordable housing projects. Developing and enforcing clear, context-specific NZEB guidelines and providing comprehensive technical training for building professionals will ensure quality implementation. Encouraging the integration of passive design principles from the outset and adopting readily available energy-efficient technologies can significantly reduce operational costs. Pilot projects showcasing successful NZEB implementations within the Kenyan context, particularly in the affordable segment, will be instrumental in demonstrating feasibility and building confidence across the industry. Ultimately, a concerted effort involving the government, financial institutions, the construction industry, and homeowners is necessary to mainstream NZEB practices and unlock a more sustainable and affordable housing future for Kenya.

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