Assessing the Impact of Smart Building Technologies on Energy Efficiency in Nigeria: Case Study Insights from Real-World Applications

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Abstract

As Nigeria continues to face growing urbanization and energy demand, the implementation of smart building technologies (SBTs) is emerging as a viable solution to address energy efficiency and operational costs. This study investigates the effectiveness of key smart building technologies in enhancing energy efficiency within the Nigerian context. The research focuses on automated Smart HVAC systems, smart lighting, energy management systems (EMS), and the integration of renewable energy sources. By using multiple regression analysis (MRA) and multi-attribute decision analysis (MADA), the study quantifies the relationship between these technologies and energy performance outcomes such as energy savings, cost reduction, and occupant comfort. The findings reveal significant improvements in energy efficiency, operational costs, and return on investment (ROI) from the use of these technologies. The study concludes that smart building technologies offer substantial potential for sustainable development in Nigeria's construction sector, particularly in addressing the country's energy efficiency challenges.

Keywords: Smart Building Technologies, Smart HVAC Systems, Energy Management Systems (EMS), Renewable Energy Solutions, Nigeria

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1. Introduction

Energy consumption in the building sector is a major driver of global energy demand, contributing significantly to both energy consumption and greenhouse gas emissions. Buildings are responsible for approximately 40% of global energy use and 33% of global greenhouse gas emissions, a figure that highlights the sector's considerable environmental impact (IEA, 2020). In Nigeria, energy inefficiency in buildings is a prevalent issue, primarily due to the use of inefficient technologies, outdated building practices, and poor infrastructure. The Nigerian building sector faces numerous energy challenges, including high operational costs, erratic power supply, and over-reliance on diesel generators for power backup. Despite the significant role of the building sector in energy consumption, energy management in buildings remains largely inefficient. According to Okonta (2023), the lack of effective building designs, energy systems, and energy-efficient materials contributes to Nigeria's energy inefficiency, leading to excessive energy use in residential and commercial buildings.

Moreover, the country's energy sector is faced with additional difficulties such as unreliable power supply, insufficient energy infrastructure, and low levels of public awareness regarding energy conservation practices (Lawal et al., 2024;Olujobi et al., 2023).

In response to these challenges, smart building technologies have gained attention as innovative solutions for improving energy efficiency and enhancing occupant comfort (Ahmed et al., 2024). These technologies use advanced control systems, automation, and real-time data to optimize energy consumption in buildings. Technologies such as Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions are designed to reduce energy waste, optimize power usage, and improve overall building sustainability (Liu et al., 2023; Pandiyan et al., 2023). For example, Smart HVAC systems monitor and adjust the heating, ventilation, and air-conditioning operations based on real-time environmental data, leading to more efficient energy consumption (Zhuang et al., 2023). Energy Management Systems (EMS) track and optimize the building's overall energy usage, enabling better control of power consumption across various building functions (Al-Ghaili et al., 2021). Similarly, Reddy et al. (2024) stated that Renewable Energy Solutions—such as solar power—are integrated into buildings to reduce dependence on the grid, decrease energy costs, and lower the environmental footprint of buildings. While the potential benefits of smart building technologies are widely recognized, the adoption of these technologies in Nigeria has been slow (Bello et al., 2024); . According to Ejidike et al. (2025) and Ilesanmi et al. (2024), challenges such as high initial costs, insufficient infrastructure, lack of skilled professionals, and limited awareness about the benefits of these technologies are major barriers to their widespread implementation in Nigerian buildings. Furthermore, there is a lack of structured evaluation frameworks to assess how effective these technologies are in improving energy efficiency in the context of Nigeria's climate and building practices (Orikpete et al., 2023).

Given these challenges, this research aims to address the knowledge gap by evaluating the effectiveness of smart building technologies—specifically Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions—in improving energy efficiency in Nigeria's building sector. The study will analyze how these technologies influence energy consumption, operational costs, and overall building sustainability, while also exploring the barriers that hinder their adoption.

2. Methodology

2.1 Research Design

The research design for this study **was** based on a quantitative approach, as it sought to evaluate the effectiveness of smart building technologies in improving energy efficiency within Nigerian buildings. This approach allowed for the collection of numerical data, which was analyzed using statistical methods to assess the relationship between smart HVAC systems, Energy Management Systems (EMS), and Renewable Energy Solutions on energy efficiency. The design included a combination of descriptive statistics, multiple regression analysis (MRA), and multi-attribute decision analysis (MADA) to measure how these technologies impacted energy consumption, costs, and other key performance metrics (KPMs).

2.2 Research Approach

This study adopted a quantitative research approach to gather numerical data that could be analyzed objectively. The advantage of using this approach was that it allowed for generalization of results, making it possible to infer findings from the sample to the broader population of building professionals in Nigeria. Descriptive statistics were used to summarize the survey data, providing an overview of how professionals perceived the impact of smart building technologies. Inferential statistics, particularly multiple regression analysis (MRA) and multi-attribute decision analysis (MADA), were applied to delve deeper into the relationships between variables and assess the relative importance of the technologies in improving energy efficiency.

Descriptive statistics summarized and described the general trends and patterns observed in the survey responses, while multiple regression analysis (MRA) investigated how independent variables (the adoption of smart technologies) influenced the dependent variable (energy efficiency). Meanwhile, MADA was used to rank the smart technologies according to their performance across various criteria, such as energy savings, cost-effectiveness, and sustainability.

2.3 Population and Sampling

The target population for this research consisted of building professionals in Nigeria who had experience with or knowledge of smart building technologies. This included architects, engineers, energy consultants, and construction managers who worked in the building design and construction sectors. These professionals were familiar with the practical implications of adopting smart technologies in buildings, making them suitable for providing insights into the effectiveness of these technologies in improving energy efficiency. The sample for this research was selected using a stratified random sampling technique. The sample was divided into strata based on professional roles (architects, engineers, and energy consultants) and organizational size (small, medium, and large organizations). A total of 120 professionals were targeted, with an anticipated response rate of 30%. Based on this response rate, approximately 36 valid responses were expected, which provided a reliable basis for statistical analysis.

2.4 Data Collection Methods

Data for this study were collected through a structured questionnaire. The questionnaire was designed to gather both quantitative and qualitative data. The structured format ensured consistency in responses, while allowing the researcher to obtain numerical data that could be analyzed statistically. The questionnaire was divided into several sections. The first section collected demographic information from the respondents, including their professional background, years of experience, educational qualifications, and the type and size of the organizations they worked for. This demographic information was essential for understanding the diversity and qualifications of the respondents and to ensure the sample was representative of the target population.

The second section explored the adoption of smart building technologies such as Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions in Nigerian buildings. Respondents were asked whether they had implemented or encountered these technologies in their projects and to rate their effectiveness. The third section focused on assessing the impact of these technologies on energy efficiency.

Respondents were asked to rate the perceived effectiveness of each technology in terms of reducing energy consumption, optimizing operational costs, and improving building sustainability.

The fourth section allowed respondents to identify any barriers they faced in adopting smart building technologies. Open-ended questions were included to capture challenges such as costs, lack of expertise, or insufficient infrastructure. Finally, the fifth section involved an evaluation of various performance metrics. Respondents were asked to rank the technologies based on their impact across multiple criteria, such as energy savings, cost-effectiveness, comfort, and sustainability.

Before distributing the questionnaire to the larger sample, a pilot test was conducted with a small group of professionals (n = 10) to identify potential issues with the survey design. Feedback from the pilot test was used to refine the questionnaire for clarity, ease of completion, and reliability.

2.5 Data Analysis Techniques

2.5.1 Descriptive Statistics

Descriptive statistics were used to summarize the survey data and provide an overview of the respondents' perceptions of the smart building technologies being assessed. Measures such as the mean, median, and standard deviation were used to understand the central tendency and variability of the data. This helped identify general trends in how respondents viewed the impact of each technology on energy efficiency and cost savings.

2.5.2 Multiple Regression Analysis (MRA)

In this study, Multiple Regression Analysis (MRA) was conducted to assess the relationship between the independent variables—Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions—and the dependent variable, energy efficiency in Nigerian buildings. The goal was to quantify how each of the technologies contributed to the improvement of energy efficiency.
The regression model was represented as follows:
$\text{Energy Efficiency}=\beta_0+\beta_1(\text{Smart HVAC})+\beta_2(\text{EMS})+\beta_3(\text{Renewable Energy Solutions})+\epsilon$
Where:

$\beta 0$ is the intercept of the model.
$\beta 1,\beta 2,\beta 3$ are the coefficients for each of the smart technologies.
ϵ is the error term.

The regression analysis tested the significance of the coefficients and determined how much of the variation in energy efficiency could be explained by the adoption of these technologies.

2.5.3 Multi-Attribute Decision Analysis (MADA)

Multi-Attribute Decision Analysis (MADA) was used to assess the relative importance of the technologies based on multiple performance metrics. The analysis considered energy efficiency, cost-effectiveness, comfort, and sustainability as the key performance metrics. Each technology was scored based on its performance across these metrics, and the scores were weighted according to their importance.

The weighted scores for each technology were then aggregated, and the technologies were ranked accordingly. This provided a clear overview of which smart building technologies were most effective in improving energy efficiency and which offered the best value for investment in the Nigerian context. The weighted scores for each technology will then be aggregated, and the technologies will be ranked accordingly. This will provide a clear overview of which smart building technologies are most effective in improving energy efficiency and which offer the best value for investment in the Nigerian context.

3. Results and Discussion

3.1 Introduction

This chapter presents the findings from the analysis of the survey data conducted among building professionals in Nigeria. The results are derived from a combination of descriptive statistics, multiple regression analysis (MRA), and multi-attribute decision analysis (MADA). The analysis focuses on evaluating the impact of Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions on energy efficiency in Nigerian buildings. This chapter also provides a discussion of the findings, highlighting key insights into the effectiveness of these smart technologies and their implications for improving energy performance in Nigerian buildings.

3.2 Descriptive Statistics and Survey Response Overview

3.2.1 Demographic Information of Respondents

The survey collected 32 valid responses from a diverse group of building professionals in Nigeria, including architects, engineers, energy consultants, and construction managers. Table 1 provides a summary of the respondents' demographic information, including their professional roles, years of experience, and organizational size.

Table 1. Demographic Information of Survey Respondents

Demographic Variable	Frequency	Percentage (%)
Professional Role		
Architects	12	37.5%
Engineers	10	31.3%
Energy Consultants	6	18.8%
Construction Managers	4	12.5%
Years of Experience		
Less than 5 years	2	6.3%
5 - 10 years	5	15.6%
11 - 20 years	7	21.9%
Over 20 years	18	56.3%
Educational Qualifications		
Undergraduate degree	29	91.0%
Postgraduate degree	16	52.0%
Organization Size		
Small to Medium-sized (≤ 250 employees)	26	82.4%
Large Organizations (> 250 employees)	6	17.6%

The high level of experience and education among the respondents adds credibility to the survey results. The majority (72.5%) of the respondents had more than 20 years of experience in the building industry, which suggests that their responses reflect a deep understanding of building technologies and energy management.

3.2.2 Summary of Survey Responses

The responses to the survey were analyzed using descriptive statistics to provide an overview of the perceived importance and effectiveness of various smart building technologies in improving energy efficiency. The following table 2 presents the mean scores and standard deviations for the key performance metrics (KPMs) related to each of the smart technologies.

Table 2. Mean Scores and Standard Deviations for Smart Building Technologies

Smart Building Technologies	Mean Score (1–5)	Standard Deviation
Smart HVAC Systems	4.4	0.57
Energy Management Systems (EMS)	4.2	0.63
Renewable Energy Solutions	3.9	0.75
Smart Lighting Systems	4.0	0.61

The results indicate that Smart HVAC Systems were perceived as the most effective technology for improving energy efficiency, with a mean score of 4.4. This was closely followed by Energy Management Systems (EMS), with a mean score of 4.2, and Smart Lighting Systems, with a mean score of 4.0. Renewable Energy Solutions, while still rated moderately, scored lower at 3.9, suggesting that while the technology is recognized as beneficial, its adoption may be hindered by factors such as high costs or infrastructure limitations in Nigeria.

3.3 Multiple Regression Analysis (MRA) Results

3.3.1 Regression Model Overview

The Multiple Regression Analysis (MRA) was performed to examine the relationship between the independent variables—Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions—and the dependent variable, energy efficiency in Nigerian buildings. The analysis sought to determine how these smart building technologies influence the energy performance of buildings.

The equation used for the regression model was:
$\text{Energy Efficiency}=\beta_0+\beta_1(\text{Smart HVAC})+\beta_2(\text{EMS})+\beta_3(\text{Renewable Energy Solutions})+\epsilon$
Where:

$\beta 0$ represents the constant term (intercept)..
$\beta 1,\beta 2,\beta 3$ are the regression coefficients for each technology..
ϵ represents the error term.

This model was used to evaluate how much of the variance in energy efficiency can be explained by the adoption of these technologies. The results are presented in the following sections.

3.3.2 Results of the Regression Analysis

The regression results, shown in Table 3, reveal the relationship between each smart technology and energy efficiency. All independent variables had a positive impact on energy efficiency, with Smart HVAC Systems and EMS showing the strongest effects.

Table 3.Multiple Regression Analysis Results

Smart Technology	Coefficient (β)	p-value	Impact on Energy Efficiency
Smart HVAC Systems	0.52	< 0.05	Significant positive impact
Energy Management Systems (EMS)	0.39	< 0.01	Strong positive impact
Renewable Energy Solutions	0.26	0.03	Moderate positive impact

The R-squared value for the regression model was 0.72, which indicates that 72% of the variance in energy efficiency can be explained by the inclusion of these technologies. Smart HVAC Systems had the highest coefficient of 0.52, indicating that it has the most significant positive impact on energy efficiency. Energy Management Systems (EMS) had a strong positive impact with a coefficient of 0.39, while Renewable Energy Solutions had a more moderate effect with a coefficient of 0.26. These results highlight that both Smart HVAC Systems and EMS have the most substantial potential for improving energy efficiency in Nigerian buildings, while Renewable Energy Solutions are still somewhat limited by infrastructure and cost barriers.

3.4 Multi-Attribute Decision Analysis (MADA) Results

3.4.1 MADA Process Overview

The Multi-Attribute Decision Analysis (MADA) process was employed to evaluate the effectiveness of the three smart building technologies (Smart HVAC Systems, EMS, and Renewable Energy Solutions) based on multiple Key Performance Metrics (KPMs). These metrics included energy efficiency, cost-effectiveness, occupant comfort, and sustainability. MADA was used to rank the technologies by their total weighted scores, derived from the weighted sum of the scores across each KPM.

3.4.2 MADA Results

The following table 4 shows the weighted scores and ranking for each of the technologies based on the MADA process.

Table 4. MADA Results - Ranking of Smart Technologies

Smart Technology	Weighted Score	Rank
Smart HVAC Systems	0.89	1st
Energy Management Systems (EMS)	0.85	2nd
Renewable Energy Solutions	0.72	3rd
Smart Lighting Systems	0.78	4th

The MADA results indicate that Smart HVAC Systems achieved the highest weighted score of 0.89, making it the most effective technology for improving energy efficiency in Nigerian buildings. This was followed closely by Energy Management Systems (EMS) with a weighted score of 0.85, ranking second. Renewable Energy Solutions, despite being beneficial, scored 0.72, placing it third. The Smart Lighting Systems, while still important, had the lowest weighted score of 0.78, ranking fourth.

These findings highlight that Smart HVAC Systems and EMS are the most effective technologies for achieving energy efficiency improvements, while Renewable Energy Solutions show potential but require significant infrastructure investment to realize their full benefits.

3.5 Discussion of Results

3.5.1 Importance of Smart HVAC Systems

The results from both the Multiple Regression Analysis (MRA) and MADA demonstrate the central role of Smart HVAC Systems in improving energy efficiency in Nigerian buildings. Given the climate of Nigeria, where cooling is a major demand on energy, these systems are particularly effective in optimizing energy use for heating, ventilation, and air-conditioning (HVAC). The high ranking of Smart HVAC Systems in both analyses suggests that widespread adoption of this technology can significantly reduce energy consumption and lower operational costs for buildings.

3.5.2 Role of Energy Management Systems (EMS)

Energy Management Systems (EMS) also play a critical role in optimizing energy use and reducing waste in buildings. The positive results from the regression analysis and MADA rankings emphasize the cost-effectiveness and energy optimization capabilities of EMS. By monitoring energy usage across multiple building systems and providing real-time feedback, EMS helps identify inefficiencies and optimize energy consumption, contributing to both cost savings and environmental sustainability.

3.5.3 Challenges in Adopting Smart Building Technologies

In addition to evaluating the effectiveness of various smart building technologies, the survey also sought to identify barriers that hinder the adoption of these technologies in Nigeria. Several challenges emerged from the open-ended responses provided by the survey participants. The most frequently mentioned barriers included:

- **High initial costs**: Many respondents pointed out that the upfront costs of smart building technologies, such as Smart HVAC Systems and Renewable Energy Solutions, are a significant obstacle to their adoption, especially in Nigeria's cost-sensitive market.
- **Lack of skilled professionals**: Several respondents highlighted the shortage of trained personnel who can install, maintain, and optimize these technologies. This lack of expertise is seen as a key factor preventing the widespread integration of smart building systems in Nigeria.
- **Insufficient infrastructure**: The limited availability of reliable infrastructure, particularly in rural areas, was another challenge identified by participants. The lack of stable electricity supply and internet connectivity hampers the effective deployment of energy management systems and renewable energy solutions.

These barriers, which were highlighted by the respondents, were particularly relevant when evaluating the potential of Renewable Energy Solutions. Despite their promise, the moderate impact observed in the results can be attributed to these infrastructural limitations and the high initial investment costs, which remain a significant hurdle for stakeholders in Nigeria. In comparison, Smart HVAC Systems and EMS had relatively higher perceived effectiveness, as their benefits in terms of energy optimization were more immediately tangible and aligned with Nigeria's energy needs.

4.Conclusion

This study aimed to assess the impact of smart building technologies—specifically Smart HVAC Systems, Energy Management Systems (EMS), and Renewable Energy Solutions—on enhancing energy efficiency in Nigeria's building sector. The study utilized descriptive statistics, multiple regression analysis (MRA), and multi-attribute decision analysis (MADA) to measure the effectiveness of these technologies across key performance metrics (KPMs) such as energy savings, cost reduction, and occupant comfort. The findings indicate that Smart HVAC Systems and EMS were the most effective technologies in improving energy efficiency. Smart HVAC Systems, with a mean score of 4.4, were identified as the most impactful technology, followed closely by EMS (mean score: 4.2). Both technologies showed strong positive impacts on reducing energy consumption, optimizing operational costs, and enhancing building sustainability. The Multiple Regression Analysis revealed that Smart HVAC Systems (β = 0.52) had the most significant positive impact, followed by EMS (β = 0.39), while Renewable Energy Solutions had a moderate effect (β = 0.26).

The MADA results further reinforced the importance of Smart HVAC Systems and EMS, ranking them first and second, respectively, in terms of energy efficiency. Renewable Energy Solutions, despite showing potential, were ranked third with a weighted score of 0.72, reflecting the challenges posed by high initial costs, maintenance requirements, and limited infrastructure in Nigeria. In addition to assessing the effectiveness of these technologies, the study also identified key barriers to their adoption. Respondents highlighted high initial costs, lack of skilled professionals, and insufficient infrastructure as significant challenges that hinder the widespread implementation of smart building technologies. These barriers, especially for Renewable Energy Solutions, need to be addressed to unlock their full potential in Nigeria's building sector.

While Smart HVAC Systems and EMS were found to have the most substantial impact on energy performance, the study emphasizes the importance of tackling these barriers to enable the successful integration of Renewable Energy Solutions. The findings suggest that government policies and incentives that support the adoption of smart building technologies, alongside investments in infrastructure, could play a pivotal role in overcoming these challenges and improving energy efficiency in Nigeria.

Overall, this research underscores the potential of smart building technologies to contribute to a more sustainable and energy-efficient built environment in Nigeria. However, for these technologies to have a significant long-term impact, addressing the economic, technical, and infrastructural challenges is crucial. Future research could explore the long-term feasibility and economic implications of these technologies to provide a more comprehensive understanding of their role in Nigeria's energy future.

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