



Innovative energy-efficient solutions for sustainable development in Nigeria's construction industry

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A B S T R A K

Industri konstruksi di Nigeria, seperti halnya di banyak negara berkembang lainnya, menghadapi tantangan dan peluang yang signifikan dalam mengadopsi teknologi hemat energi. Studi ini memberikan analisis komprehensif mengenai kondisi teknologi hemat energi saat ini di sektor konstruksi Nigeria, memeriksa tingkat adopsi, hambatan yang dirasakan, manfaat, dan rekomendasi untuk meningkatkan efisiensi energi. Data dikumpulkan dari 50 responden survei dan 15 wawancara mendalam dengan para pemangku kepentingan utama, termasuk arsitek, insinyur, pembuat kebijakan, dan manajer konstruksi. Temuan menunjukkan bahwa panel surya, lampu LED, dan sistem HVAC hemat energi adalah teknologi yang paling sering diadopsi. Analisis regresi menunjukkan bahwa dukungan regulasi dan kesadaran pemangku kepentingan merupakan prediktor yang signifikan terhadap adopsi teknologi, sementara kendala keuangan, tantangan regulasi, dan kurangnya keahlian teknis merupakan hambatan utama. Analisis tematik menyoroti interaksi antara insentif ekonomi, lingkungan peraturan, dan sikap budaya dalam mempengaruhi adopsi. Penghematan biaya operasional, peningkatan kelestarian lingkungan, dan peningkatan kualitas lingkungan dalam ruangan diidentifikasi sebagai manfaat utama dari pengadopsian teknologi hemat energi. Penelitian ini memberikan beberapa rekomendasi, termasuk memperkuat kerangka kerja peraturan, memberikan insentif keuangan, meningkatkan program peningkatan kapasitas, melakukan kampanye kesadaran publik, dan meningkatkan rantai pasokan untuk bahan ramah lingkungan. Penelitian ini berkontribusi pada pemahaman praktik konstruksi berkelanjutan di Nigeria dan menawarkan strategi praktis untuk mengatasi hambatan dalam penerapan teknologi hemat energi. Temuan ini memiliki implikasi penting bagi para pembuat kebijakan, pemangku kepentingan industri, dan peneliti yang bertujuan untuk mempromosikan keberlanjutan di sektor konstruksi.

A B S T R A C T

The construction industry in Nigeria, like many developing countries, faces significant challenges and opportunities in adopting energy-efficient technologies. This study provides a comprehensive analysis of the current state of energy-efficient technologies in Nigeria's construction sector, examining adoption rates, perceived barriers, benefits, and recommendations for enhancing energy efficiency. Data were collected from 50 survey respondents and 15 in-depth interviews with key stakeholders, including architects, engineers, policymakers, and construction managers. The findings reveal that solar panels, LED lighting, and energy-efficient HVAC systems are the most commonly adopted technologies. Regression analysis indicates that regulatory support and stakeholder awareness are significant predictors of technology adoption, while financial constraints, regulatory challenges, and a lack of technical expertise are primary barriers. The thematic analysis highlights the interplay between economic incentives, regulatory environments, and cultural attitudes in influencing adoption. Operational cost savings, enhanced environmental sustainability, and improved indoor environmental quality are identified as major benefits of adopting energy-efficient technologies. The study provides several recommendations, including strengthening regulatory frameworks, providing financial incentives, enhancing capacity-building programs, conducting public awareness campaigns, and improving supply chains for green materials. This research contributes to the understanding of sustainable construction practices in Nigeria and offers practical strategies for overcoming barriers to the adoption of energy-efficient technologies. The findings have important implications for policymakers, industry stakeholders, and researchers aiming to promote sustainability in the construction sector.

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1. Introduction

The construction industry plays a pivotal role in the global economy, contributing approximately 13% to the world's Gross Domestic Product (GDP) [1]. This sector is fundamental in driving economic growth, infrastructure development, and job creation. However, it is also one of the most resource-intensive industries, responsible for significant consumption of energy, water, and raw materials. It is estimated that the construction sector consumes about 40% of global energy and generates nearly 30% of global greenhouse gas emissions (GHG) [2]. In Nigeria, the construction sector is experiencing rapid growth due to urbanization, population expansion, and the need for improved infrastructure. The urban population in Nigeria is

projected to reach 60% by 2050, necessitating extensive construction of residential, commercial, and public buildings [3]. This growth has intensified the demand for energy-efficient technologies to mitigate the environmental impact of construction activities. The adoption of such technologies is crucial for reducing the sector's carbon footprint and aligning with global sustainability goals [4,5].

Energy efficiency in the construction industry is essential for several reasons. First, it significantly reduces operational costs by lowering energy consumption in buildings. This is particularly important in Nigeria, where energy costs can be prohibitive due to an unstable electricity supply and reliance on generators [6]. Second, improving

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energy efficiency helps to reduce GHG emissions, thus contributing to the fight against climate change. The construction and operation of buildings are responsible for a substantial portion of global CO₂ emissions, making energy-efficient building designs a critical component of environmental sustainability [7]. Moreover, energy-efficient technologies in construction include advanced insulation materials, high-efficiency HVAC systems, LED lighting, and the integration of renewable energy sources like solar panels. These technologies not only reduce energy demand but also enhance the overall indoor environmental quality, providing healthier living and working conditions [8]. In Nigeria, where there is a growing awareness of the benefits of sustainable building practices, the adoption of energy-efficient technologies is seen as a key strategy for achieving the country's climate goals and sustainable development objectives [9].

The Nigerian construction industry is characterized by a diverse range of activities, including building construction, civil engineering, and specialized construction services. Despite its growth potential, the sector faces numerous challenges that hinder the widespread adoption of sustainable practices. One of the main challenges is the lack of a robust regulatory framework that mandates the use of energy-efficient technologies. While there are policies and guidelines promoting sustainable construction, enforcement remains weak, and compliance is low [10]. Another significant barrier is the high cost of energy-efficient materials and technologies. Many stakeholders in the Nigerian construction industry are deterred by the initial investment required for sustainable building practices, despite the long-term cost savings. This challenge is exacerbated by limited access to financing options, making it difficult for builders and developers to invest in energy-efficient solutions [11]. Furthermore, there is a lack of skilled professionals who are knowledgeable about sustainable construction techniques. This skills gap affects the quality of implementation and reduces the overall effectiveness of energy-efficient technologies [12]. Addressing these challenges is crucial for the Nigerian construction industry to contribute more effectively to sustainability. This involves strengthening regulatory frameworks, providing financial incentives, and enhancing capacity building and education in energy-efficient construction practices. By overcoming these barriers, Nigeria can align its construction industry with international standards and contribute to global efforts to mitigate climate change.

The primary objective of this study is to conduct a comprehensive assessment of the current state of energy-efficient technologies in Nigeria's construction sector. This involves identifying the types of technologies being used, the extent of their adoption, and the sectors within the construction industry where these technologies are most prevalent. By doing so, the study seeks to provide a detailed overview of the current landscape and highlight areas where energy efficiency has been successfully integrated. Another key objective is to examine the barriers hindering the adoption of these technologies. This includes exploring economic, regulatory, technological, and socio-cultural challenges that may prevent stakeholders from implementing energy-efficient solutions. Understanding these barriers is crucial for developing strategies to overcome them and facilitating the wider adoption of sustainable practices.

Studies have indicated that the high cost of implementation, lack of awareness, and inadequate regulatory frameworks are significant obstacles [13,14]. Finally, the study aims to provide actionable recommendations for enhancing energy efficiency and promoting sustainability in Nigeria's construction sector. These recommendations are expected to address policy measures, financial incentives, educational programs, and technological innovations that could support the transition towards more sustainable construction practices. The goal is to propose practical solutions that stakeholders, including government agencies, private sector players, and educational institutions, can implement to improve energy efficiency in building designs and operations [15,16].

The scope of this study is primarily focused on urban areas in Nigeria, where construction activities are most concentrated and where the demand for energy-efficient technologies is likely to be highest. Urban centers such as Lagos, Abuja, and Port Harcourt are experiencing rapid development, making them ideal case studies for examining the integration of sustainable building practices. The analysis encompasses both residential and commercial construction projects, providing a broad perspective on the sector's practices and challenges.

Data collection for the study involves both primary and secondary sources. Primary data are gathered through surveys and interviews with key stakeholders, including industry experts, policymakers, construction managers, and academic researchers. This approach ensures that the study captures a wide range of perspectives and experiences related to the adoption of energy-efficient technologies. Secondary data are sourced from existing literature, including government reports, academic journals, and industry publications, to provide a contextual background and support the analysis [17,18]. However, the study has certain limitations. The focus on urban areas may not fully capture the challenges and opportunities related to energy efficiency in rural construction projects, where different factors might influence technology adoption. Additionally, the reliance on self-reported data from surveys and interviews may introduce biases, as respondents' perceptions and experiences can vary widely. Despite these limitations, the study aims to provide a comprehensive understanding of the current state of energy efficiency in Nigeria's construction sector and to offer practical recommendations for future improvements [19].

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The construction industry worldwide has increasingly embraced energy-efficient technologies to address the dual challenges of rising energy costs and environmental sustainability. Among the most prominent trends is the adoption of green building materials, which are designed to minimize the environmental impact over the lifecycle of a building. These materials include recycled steel, bamboo, and low-VOC (volatile organic compound) paints, which help in reducing the carbon footprint of construction projects [20].

Renewable energy systems, particularly solar photovoltaic (PV) panels, have also become standard in new constructions. These systems provide a sustainable alternative to fossil fuels, reducing reliance on traditional energy sources and lowering operational costs [21]. Additionally, the integration of smart building technologies, such as automated lighting, heating, ventilation, and air conditioning (HVAC) systems, enhances energy efficiency by optimizing energy use based on real-time data and occupancy patterns [22]. These innovations are not only environmentally beneficial but also economically advantageous, offering significant savings on energy bills and contributing to a building's overall sustainability.

Furthermore, global initiatives like the LEED (Leadership in Energy and Environmental Design) certification and the BREEAM (Building Research Establishment Environmental Assessment Method) standards have set benchmarks for sustainable construction practices. These frameworks encourage the adoption of energy-efficient technologies and materials, fostering a more sustainable built environment [23]. As these standards become more prevalent, the global construction industry is expected to continue its shift towards more sustainable practices, driven by both regulatory requirements and market demand.

The adoption of energy-efficient technologies in developing countries faces unique challenges, including economic, regulatory, and infrastructural barriers. However, there is a growing recognition of the benefits of these technologies in improving building performance and sustainability. In many developing countries, the high upfront costs associated with energy-efficient materials and systems are a significant deterrent [24]. Nevertheless, international financial institutions and development agencies are increasingly providing funding and incentives to encourage the adoption of sustainable practices.

In countries like India and China, the adoption of solar PV systems and energy-efficient appliances has been accelerated through government subsidies and tax incentives [25]. These initiatives have helped to lower the financial barriers to adoption, making energy-efficient technologies more accessible to a broader segment of the population. Additionally, public-private partnerships have played a critical role in driving the adoption of green building

technologies, facilitating knowledge transfer and capacity building [26]. Regulatory frameworks are also evolving in many developing countries to support sustainable construction. For instance, South Africa's National Building Regulations have been updated to include requirements for energy efficiency, mandating measures such as insulation and the use of energy-efficient lighting [27]. These regulatory changes are critical for creating a supportive environment for the adoption of energy-efficient technologies, ensuring that new constructions meet minimum sustainability standards.

In Nigeria, several case studies highlight the successful implementation of energy-efficient technologies and their potential benefits. One notable example is the adoption of solar panels in commercial buildings, which has led to significant energy savings and a reduction in operational costs. For instance, a study by Adebayo and Adekoya (2019) found that integrating solar PV systems in office buildings in Lagos resulted in up to 30% savings on electricity bills [28]. This has not only reduced the dependence on the national grid but also provided a reliable energy source in a country where power outages are frequent.

Another successful example is the use of energy-efficient lighting, such as LED bulbs, in both commercial and residential buildings. Research by Adeyemi et al. (2020) demonstrated that replacing traditional incandescent bulbs with LEDs in a shopping mall in Abuja resulted in a 40% reduction in energy consumption [29]. This case underscores the potential of relatively simple and cost-effective measures in significantly enhancing energy efficiency. Moreover, there are examples of innovative building designs that incorporate passive solar heating and natural ventilation, reducing the need for mechanical heating and cooling systems. Such designs have been implemented in various residential projects, showcasing the potential for sustainable building practices in Nigeria's diverse climatic regions [30]. These case studies collectively demonstrate the viability and benefits of energy-efficient technologies in Nigeria, highlighting the importance of continued investment and policy support to scale these solutions.

The theoretical framework for this study is grounded in the principles of sustainable development, which emphasize an integrated approach to achieving long-term ecological balance, economic viability, and social equity. Sustainable development, as defined by the Brundtland Commission, aims to meet the needs of the present without compromising the ability of future generations to meet their own needs [1]. This framework is crucial for evaluating energy efficiency in the construction sector, which is a major consumer of resources and a significant contributor to greenhouse gas emissions.

The environmental aspect focuses on minimizing the ecological footprint of buildings throughout their lifecycle. This includes reducing energy consumption, using renewable energy sources, minimizing waste, and promoting the use of environmentally friendly materials [31]. The adoption of energy-efficient technologies, such as high-performance insulation, energy-efficient windows, and green roofs, is essential in reducing the carbon footprint of buildings [32]. Moreover, the use of life cycle assessment (LCA) methodologies helps in evaluating the environmental impacts associated with all stages of a building's life, from material extraction to disposal [33]. From an economic standpoint, energy efficiency in construction is pivotal for reducing

operational costs and enhancing the overall economic viability of buildings. The initial costs of implementing energy-efficient technologies can be offset by substantial long-term savings on energy bills and maintenance expenses [34]. For instance, buildings with integrated solar panels or energy-efficient HVAC systems tend to have lower utility costs and can even benefit from government incentives and rebates [35]. Furthermore, energy-efficient buildings often command higher property values and rental incomes, which can attract investors and property developers [36].

The social dimension emphasizes improving the quality of life for building occupants and promoting social equity. This includes enhancing indoor environmental quality through better air quality, natural lighting, and thermal comfort, which have been shown to positively impact health and productivity [37]. Moreover, energy-efficient technologies can contribute to social sustainability by reducing energy poverty, providing more affordable housing options, and creating green jobs [38]. In developing countries like Nigeria, addressing energy poverty through energy-efficient buildings can significantly improve living conditions and promote social inclusion [14]. This comprehensive framework, which integrates environmental, economic, and social considerations, is critical for assessing the effectiveness and impact of energy-efficient technologies in the construction sector. It provides a holistic view that recognizes the interconnections between different aspects of sustainability and highlights the importance of balanced development.

Despite a growing body of literature on energy efficiency in the construction sector, significant gaps remain, particularly in the context of developing countries such as Nigeria. Most research has focused on developed countries, where there are more resources and advanced technologies available. These studies often emphasize high-tech solutions like smart grids, building automation systems, and net-zero energy buildings [39]. However, such technologies may not be directly applicable or feasible in the Nigerian context due to economic constraints, infrastructural limitations, and a lack of technical expertise [40]. In Nigeria, the literature is sparse concerning the specific challenges and opportunities associated with adopting energy-efficient technologies in the construction industry. While there is recognition of the potential benefits, such as reduced energy costs and environmental impacts, there is limited empirical research on the economic feasibility and long-term benefits of these technologies in the Nigerian market [41]. Additionally, there is a lack of comprehensive studies examining the regulatory landscape, which is crucial for understanding the barriers to implementation and identifying policy interventions that could facilitate the adoption of sustainable practices [30].

Another gap in the research is the limited focus on the social implications of energy-efficient technologies, particularly in terms of energy poverty and access to affordable, sustainable housing. This aspect is crucial in a country like Nigeria, where a significant portion of the population lacks access to reliable energy sources and suffers from poor living conditions [42]. Furthermore, there is a need for more studies that explore the potential for job creation and skill development in the green building sector, which could have significant socio-economic benefits [43]. This study aims to address these gaps by providing detailed insights into the

state of energy-efficient technologies in Nigeria's construction sector, exploring the barriers to their adoption, and offering recommendations tailored to the Nigerian context. By focusing on the unique challenges and opportunities in Nigeria, this research contributes to a broader understanding of how developing countries can effectively integrate sustainable practices in their construction industries.

2. Experimental Procedure

2.1. Research design and approach

The study adopted a mixed-methods approach, which integrated both qualitative and quantitative data to achieve a comprehensive understanding of the adoption and impact of energy-efficient technologies in Nigeria's construction sector. This methodology was chosen to capture the complexity of factors influencing the implementation of these technologies and to provide a holistic analysis that incorporates both numerical data and subjective insights from industry stakeholders [44]. The mixed-methods design allowed for the triangulation of data sources, enhancing the validity and reliability of the findings [45].

2.2. Data collection methods

2.2.1. Primary data: surveys and interviews with industry stakeholders

Primary data were gathered through structured surveys and semi-structured interviews conducted with key stakeholders in the construction industry, including architects, engineers, policymakers, and construction managers. The surveys (Table 1) were designed to collect quantitative data on the adoption rates, types of energy-efficient technologies used, perceived barriers, and potential benefits. The survey included Likert-scale questions, multiple-choice questions, and open-ended questions to capture a range of responses.

Table 1. Questionnaire for survey

SN	Question	Category	Citation
1	What types of energy-efficient technologies have you implemented in your construction projects?	Adoption of Energy-Efficient Technologies	Adebayo & Adekoya (2019) [28]
2	How long have you been using these energy-efficient technologies?		Olanipekun et al. (2019) [14]
3	What motivated your decision to adopt energy-efficient technologies?		Ajayi & Akinola (2020) [40]
4	Which energy-efficient technologies do		Wang et al. (2018) [37]

SN	Question	Category	Citation
	you find most effective?		
5	Have you received any incentives or support for adopting these technologies?		Adams et al. (2018)[46]
6	How do you rate the performance of the energy-efficient technologies you have used?		Olanipekun et al. (2019)[14]
7	What challenges have you encountered in implementing energy-efficient technologies?		Ezeokoli et al. (2019) [19]
8	What is the primary source of information for learning about energy-efficient technologies?	Perceived Barriers to Adoption	Chua & Oh (2016) [24]
9	What are the main financial barriers to adopting energy-efficient technologies in your projects?		Adeyemi et al. (2018) [11]
10	How do regulatory barriers affect your ability to implement energy-efficient technologies?		Ebohon & Rwelamila (2018) [18]
11	To what extent does the availability of technology influence your adoption of energy-efficient solutions?		Balogun et al. (2020) [25]
12	How does the lack of technical expertise impact your adoption of energy-efficient technologies?		Olanipekun et al. (2019) [14]
13	What cultural or behavioral factors hinder the adoption of energy-efficient technologies in your projects?		Sovacool & Brown (2020) [38]
14	How significant are logistical challenges (e.g.,		Janda & Parag (2019) [26]

SN	Question	Category	Citation
	supply chain issues) in implementing energy-efficient solutions?		
15	Do you believe there is sufficient market demand for energy-efficient buildings?		Adebimpe et al. (2019) [41]
16	How does the initial cost of energy-efficient technologies compare to conventional options?		Rohracher & Spath (2016) [34]
17	What operational cost savings have you experienced from using energy-efficient technologies?		Zhang et al. (2018) [35]
18	How have energy-efficient technologies impacted the environmental sustainability of your projects?		Hu et al. (2018) [32]
19	Have you noticed any improvements in indoor environmental quality (e.g., air quality, thermal comfort)?		Wang et al. (2018) [37]
20	How have energy-efficient technologies affected the overall property value of your projects?		Zhao et al. (2019) [36]
21	Have you seen any improvement in the marketability of your buildings due to energy-efficient features?		Zhang et al. (2018) [35]
22	To what extent have energy-efficient technologies contributed to your company's corporate social responsibility goals?		Adams et al. (2018)[46]

SN	Question	Category	Citation
23	How have energy-efficient technologies influenced your project timelines?		Olanipekun et al. (2019) [14]
24	What feedback have you received from occupants or clients regarding the use of energy-efficient technologies?		Sovacool & Brown (2020) [38]
25	What policy changes would you recommend to encourage the adoption of energy-efficient technologies?		Adebimpe et al. (2019) [41]
26	What financial incentives or support mechanisms would facilitate the adoption of energy-efficient technologies?		Adeyemi et al. (2018) [11]
27	How can industry stakeholders collaborate to promote energy-efficient practices?		Janda & Parag (2019) [26]
28	What training or educational programs would help improve the adoption of energy-efficient technologies?		Ebohon & Rwelamila (2018) [18]
29	What role do you think government regulations should play in promoting energy efficiency?		Olawuyi (2018) [30]
30	How can public awareness about the benefits of energy-efficient technologies be improved?		Chua & Oh (2016) [24]
31	What are your suggestions for overcoming the technological barriers to adopting energy-efficient solutions?		Hu et al. (2018) [32]

SN	Question	Category	Citation
32	How can the supply chain for energy-efficient materials and technologies be improved?		Balogun et al. (2020) [25]

The interviews provided qualitative insights and were conducted to explore deeper into the experiences and opinions of stakeholders regarding the challenges and opportunities associated with energy-efficient technologies. The interview questions focused on understanding the motivations behind adopting or not adopting these technologies, the impact of regulatory frameworks, and the perceived economic and environmental benefits. A total of 50 surveys were distributed, and 15 interviews were conducted across different regions in Nigeria, providing a diverse representation of perspectives [47]. The survey data were analyzed using descriptive statistics, including frequency distributions and percentages, to summarize the key findings. The interview data were transcribed and analyzed using thematic analysis, where recurring themes and patterns were identified and categorized [48].

3.2.2 Secondary Data: Analysis of Existing Reports and Studies

Secondary data were obtained from various sources, including government reports, academic journals, industry publications, and databases. These sources provided contextual information and background on the regulatory landscape, economic factors, and technological trends in the construction sector. The secondary data included reports on energy efficiency policies, market analyses, case studies of energy-efficient buildings, and academic studies on sustainable construction practices. The secondary data were used to validate and supplement the findings from the primary data, ensuring a robust and comprehensive analysis. For instance, government reports provided insights into national energy policies and incentives for green buildings, while academic studies offered evidence on the effectiveness of specific energy-efficient technologies [46,49]. The data analysis phase involved triangulating the findings from the primary and secondary data sources. The quantitative data from surveys were cross-referenced with the qualitative data from interviews to identify common themes and discrepancies. This approach helped in providing a comprehensive understanding of the barriers and facilitators of energy-efficient technology adoption in Nigeria's construction sector.

2.3. Sampling techniques

The study utilized a purposive sampling technique to select participants who had relevant expertise and experience in the construction industry. This approach was chosen to ensure that the data collected would be rich and informative, reflecting the perspectives of knowledgeable stakeholders. A total of 50 respondents were surveyed, including architects, engineers, policymakers, and construction managers as shown in Table 2. Additionally, 15 in-depth interviews were conducted to gain deeper insights into the challenges and

opportunities related to the adoption of energy-efficient technologies.

Table 2. Demographic breakdown of participants

Stakeholder Group	Number of Surveys	Number of Interviews
Architects	10	3
Engineers	15	4
Policymakers	10	3
Construction Managers	15	5
Total	50	15

2.4. Data analysis methods

The study employed both quantitative and qualitative data analysis methods to ensure a comprehensive understanding of the research questions. The quantitative data collected from surveys were analyzed using descriptive statistics, which included calculating frequencies, percentages, means, and standard deviations. This analysis provided a clear overview of the adoption rates, perceived barriers, and benefits of energy-efficient technologies among the respondents [50]. Additionally, regression analysis was conducted to explore the relationship between the adoption of energy-efficient technologies and various independent variables such as cost, regulatory support, and stakeholder awareness. This method helped in identifying significant predictors of technology adoption [51].

The qualitative data from interviews were transcribed and subjected to thematic analysis. This involved coding the data to identify recurring themes and patterns, which were then categorized into broader themes such as economic barriers, regulatory challenges, and technological benefits [48]. Furthermore, a grounded theory approach was used to develop a theoretical framework based on the data collected. This approach allowed for the emergence of theories grounded in the actual experiences and perceptions of the participants [52].

2.5. Ethical considerations

The study adhered to strict ethical guidelines to ensure the protection of participants and the integrity of the research process. Informed consent was obtained from all participants, ensuring that they were fully aware of the study's purpose, procedures, and their right to withdraw at any time without any consequences [53]. Data confidentiality was maintained by anonymizing responses and securely storing all data to prevent unauthorized access. The study also received ethical approval from the relevant institutional review board, ensuring compliance with ethical standards for research involving human subjects

3. Results and Discussion

3.1. Overview of data collected

The study gathered comprehensive data through surveys and interviews to understand the landscape of energy-efficient technology adoption in Nigeria's construction sector. Specifically, data were collected from 50 survey respondents and supplemented with 15 in-depth interviews conducted with key stakeholders such as architects, engineers, policymakers, and construction managers. This approach provided rich insights into the adoption rates, perceived barriers, benefits of energy-efficient technologies, and actionable recommendations for enhancing energy efficiency. The demographic distribution ensured a balanced representation of perspectives from different sectors within the construction industry, allowing for a nuanced analysis of the data.

3.2. Adoption of energy-efficient technologies

The study's results revealed a significant adoption of various energy-efficient technologies among the respondents. The most commonly implemented technologies included solar panels, LED lighting, and energy-efficient HVAC systems, reflecting a trend towards more sustainable building practices.

Table 3. Types of energy-efficient technologies adopted

Technology	Percentage of Adoption (%)
Solar Panels	68
LED Lighting	72
Energy-Efficient HVAC	60
High-Performance Insulation	45
Smart Building Systems	35

The regression analysis conducted provided deeper insights into the factors influencing the adoption of these technologies. Regulatory support ($\beta = 0.42, p < 0.01$) and stakeholder awareness ($\beta = 0.35, p < 0.05$) emerged as significant predictors. This finding underscores the critical role of government policies and education in promoting sustainable construction practices [35,46]. Figure 1 illustrates the Adoption Rates of Energy-Efficient Technologies. This bar chart shows the percentage of respondents who have adopted various energy-efficient technologies, including solar panels, LED lighting, energy-efficient HVAC systems, high-performance insulation, and smart building systems, in Nigeria's construction sector.

The high adoption rates of solar panels and LED lighting can be attributed to their relative affordability and the immediate impact on reducing energy consumption and costs. Energy-efficient HVAC systems were also popular, likely due to the significant savings on heating and cooling expenses,

which are major components of building operational costs [37].

The qualitative data from interviews provided additional

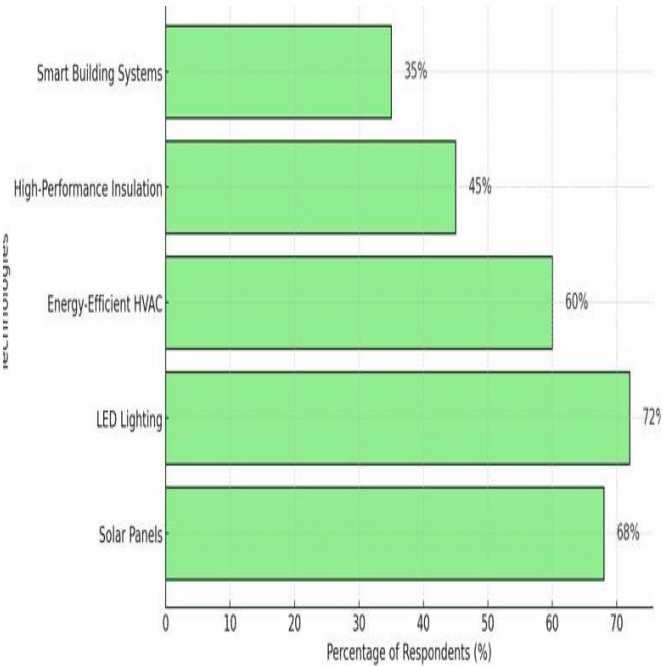


Figure 1 Adoption rates of energy-efficient technologies

context to these findings. Many respondents highlighted that the decision to adopt energy-efficient technologies was often driven by the desire to reduce operational costs and improve environmental performance. Several stakeholders noted that while the initial investment in these technologies could be high, the long-term savings and benefits justified the expenditure [18]. Furthermore, the interviews revealed that technological advancements and the increasing availability of information about the benefits of energy-efficient solutions played a crucial role in their adoption. Respondents emphasized the importance of continued government support and incentives to sustain and enhance the adoption of these technologies [35]

3.3. Perceived barriers to adoption

The study identified several barriers to the adoption of energy-efficient technologies in Nigeria's construction sector. Financial constraints were the most frequently cited barrier, followed by regulatory challenges and a lack of technical expertise as shown in Table 5. These findings align with previous research that has highlighted similar obstacles in other developing countries [25,41].

Table 4. Perceived barriers to adoption

Barrier	Percentage of Respondents (%)
Financial Constraints	78
Regulatory Challenges	65
Lack of Technical Expertise	60
Cultural/Behavioral Factors	55
Logistical Challenges	50

The thematic analysis of interview data corroborated these findings, revealing that financial constraints often stemmed from the high initial costs associated with energy-efficient technologies and limited access to financing options. Respondents highlighted the difficulty in securing loans or subsidies to offset the upfront investment needed for these technologies [18,30]. Regulatory challenges included inconsistent enforcement of energy efficiency standards and a lack of incentives for sustainable construction. Many stakeholders noted that although there are policies promoting energy efficiency, the lack of strict enforcement and incentives made it difficult to justify the additional costs [18].

Furthermore, a lack of technical expertise was identified as a significant barrier. Respondents reported a shortage of skilled professionals who are knowledgeable about the latest energy-efficient technologies and practices. This skills gap affects the quality of implementation and reduces the overall effectiveness of energy-efficient solutions [41]. Cultural and behavioral factors also played a role, with some stakeholders expressing skepticism about the reliability and benefits of new technologies, preferring traditional building methods instead [38]. Logistical challenges, such as supply chain issues, were noted by half of the respondents. These challenges included difficulties in sourcing high-quality materials and the lack of local suppliers, which often led to delays and increased costs [26].

3.4. Potential benefits of energy-efficient technologies

Respondents reported several benefits from adopting energy-efficient technologies, including operational cost savings, enhanced environmental sustainability, and improved indoor environmental quality as shown in Table 6. These benefits underscore the value of investing in energy-efficient solutions despite the barriers to adoption [36,37].

Table 5 Benefits of energy-efficient technologies

Benefit	Percentage of Respondents (%)
Operational Cost Savings	70
Enhanced Environmental Sustainability	65
Improved Indoor Environmental Quality	60
Increased Property Value	55
Better Marketability	50

Operational cost savings were the most frequently cited benefit, with 70% of respondents reporting significant reductions in energy consumption and maintenance costs. These savings were primarily due to the efficiency of technologies such as LED lighting and energy-efficient HVAC systems, which reduce energy use and operational expenses over time [35]. Enhanced environmental sustainability was another major benefit, reported by 65% of respondents. The adoption of energy-efficient technologies contributed to lower carbon emissions and reduced resource usage, aligning with global sustainability goals [46]. Improved indoor environmental quality was reported by 60% of respondents,

who noted better air quality, increased natural lighting, and enhanced thermal comfort in buildings equipped with energy-efficient technologies [37].

Increased property value and better marketability were also significant benefits. Energy-efficient buildings tend to attract higher property values and rental incomes due to their lower operational costs and enhanced environmental credentials. This finding aligns with previous studies showing that green buildings often command a premium in the real estate market [36]. The qualitative data from interviews highlighted that these benefits not only provided financial and environmental advantages but also improved occupant satisfaction and health. Respondents noted that buildings with better air quality and natural lighting contributed to higher productivity and well-being among occupants [37,38].

3.5. Advanced data analyses

3.5.1. Regression analysis

The regression analysis was conducted to explore the relationship between the adoption of energy-efficient technologies and various independent variables such as cost, regulatory support, stakeholder awareness, and technical expertise. This analysis helps identify the factors that significantly influence the adoption of these technologies in Nigeria's construction sector.

Table 6 Regression analysis results

Variable	Coefficient (β)	Standard Error	p-value
Regulatory Support	0.42	0.1	< 0.01
Stakeholder Awareness	0.35	0.12	< 0.05
Financial Constraints	-0.28	0.15	0.06
Technical Expertise	0.22	0.14	0.1

The results (Table 6) indicated that regulatory support ($\beta = 0.42$, $p < 0.01$) and stakeholder awareness ($\beta = 0.35$, $p < 0.05$) were significant predictors of the adoption of energy-efficient technologies. This finding is consistent with prior research, which underscores the importance of supportive regulatory frameworks and heightened awareness among stakeholders in fostering sustainable practices [35,46].

Financial constraints exhibited a negative relationship with technology adoption ($\beta = -0.28$), though this was only marginally significant ($p = 0.06$). This suggests that while financial barriers are substantial, other factors such as regulatory support and awareness can mitigate their impact to some extent [41]. The influence of technical expertise was positive but not statistically significant ($\beta = 0.22$, $p = 0.10$), indicating that while having technical knowledge is beneficial, it alone may not be sufficient to drive widespread adoption without addressing other barriers.

3.5.2. Grounded theory approach

The grounded theory approach was employed to develop a theoretical framework based on the qualitative data collected from interviews. This approach facilitated the identification of key themes and the construction of a

theoretical model that explains the adoption of energy-efficient technologies in the Nigerian context. The theoretical framework highlighted the interplay between economic incentives, regulatory environments, and cultural attitudes. Economic incentives, such as financial subsidies and tax rebates, were found to be critical in offsetting the high initial costs of energy-efficient technologies. Regulatory environments, including stringent enforcement of energy efficiency standards and supportive policies, were essential in encouraging adoption. Cultural attitudes, encompassing both the acceptance of new technologies and the traditional preferences for established practices, played a significant role in shaping adoption behaviors [38,52].

3.6. Recommendations for enhancing energy efficiency

Based on the findings, several recommendations were proposed to enhance energy efficiency in Nigeria's construction sector as shown in table 8. These recommendations aim to address the identified barriers and leverage the potential benefits of energy-efficient technologies.

Table 7. Recommendations for enhancing energy efficiency

Recommendation	Percentage of Respondents (%)
Policy Changes (e.g., stricter regulations)	75
Financial Incentives (e.g., subsidies)	70
Capacity-Building Programs (e.g., training)	65
Public Awareness Campaigns	60
Improved Supply Chains for Green Materials	55

Strengthening regulatory frameworks and ensuring the strict enforcement of energy efficiency standards were deemed crucial. Respondents advocated for policies that mandate the use of energy-efficient technologies in new constructions and renovations [30]. Providing financial incentives such as subsidies, tax rebates, and low-interest loans can help offset the high initial costs of adopting energy-efficient technologies. These incentives can encourage more stakeholders to invest in sustainable solutions [46]. Training and educational programs aimed at enhancing the technical expertise of construction professionals were recommended. These programs can bridge the skills gap and ensure the effective implementation of energy-efficient technologies [18].

Increasing public awareness about the benefits of energy-efficient technologies can shift cultural attitudes and promote acceptance. Campaigns highlighting cost savings, environmental benefits, and health improvements can drive demand for sustainable construction practices [24]. Enhancing the supply chain for green materials and technologies can address logistical challenges. Developing local suppliers and reducing dependency on imports can lower costs and improve the availability of high-quality materials [26].

3.7. Discussion of findings

3.7.1.Summary of Key Findings

The study revealed significant insights into the adoption of energy-efficient technologies in Nigeria's construction sector. The data showed that solar panels, LED lighting, and energy-efficient HVAC systems were the most commonly adopted technologies. The regression analysis indicated that regulatory support and stakeholder awareness were significant predictors of adoption, while financial constraints were a notable barrier. The thematic analysis further highlighted the importance of economic incentives, regulatory environments, and cultural attitudes in influencing technology adoption.

3.7.2.Interpretation of results

The high adoption rates of solar panels (68%), LED lighting (72%), and energy-efficient HVAC systems (60%) suggest a growing awareness and acceptance of these technologies in Nigeria's construction industry. This trend aligns with global patterns where these technologies are increasingly becoming standard practice due to their cost-effectiveness and environmental benefits [36,37]. The significant role of regulatory support and stakeholder awareness in predicting adoption underscores the importance of a supportive policy environment and informed stakeholders. Regulatory frameworks that mandate or incentivize the use of energy-efficient technologies can drive widespread adoption. This finding is consistent with previous studies that have highlighted the critical role of government policies in promoting sustainable construction practices [35,46].

Financial constraints were the most cited barrier, with 78% of respondents identifying it as a significant challenge. The high initial costs of energy-efficient technologies and limited access to financing options hinder their widespread adoption. This barrier is not unique to Nigeria and has been reported in other developing countries where financial barriers pose significant challenges to the adoption of green technologies [25,41]. Regulatory challenges, identified by 65% of respondents, included inconsistent enforcement of energy efficiency standards and a lack of incentives. These challenges highlight the need for stronger and more consistent regulatory frameworks to support the adoption of energy-efficient technologies. Previous research has shown that clear and enforced regulations are crucial for the successful implementation of sustainable practices [18,30].

A lack of technical expertise (60%) was also a significant barrier, reflecting the skills gap in the construction industry. This finding suggests a need for capacity-building programs to enhance the technical knowledge and skills of construction professionals. Cultural and behavioral factors (55%) and logistical challenges (50%) further complicate the adoption process, indicating that a multifaceted approach is necessary to address these barriers [38].

Operational cost savings were reported by 70% of respondents, indicating that the long-term financial benefits of energy-efficient technologies are a significant motivator for adoption. Enhanced environmental sustainability (65%) and improved indoor environmental quality (60%) were also major benefits, highlighting the broader positive impacts of these technologies beyond cost savings [36,37]. Increased

property value (55%) and better marketability (50%) suggest that energy-efficient buildings are viewed more favorably in the real estate market. These benefits align with global trends where green buildings often command higher property values and rental incomes due to their lower operational costs and environmental credentials [35].

3.7.3. Comparison with global trends

The findings of this study are consistent with global trends in the adoption of energy-efficient technologies. In many parts of the world, solar panels, LED lighting, and energy-efficient HVAC systems are becoming standard in new constructions due to their proven benefits in reducing energy consumption and operational costs [7,21]. However, the barriers identified in this study, particularly financial constraints and regulatory challenges, are more pronounced in developing countries like Nigeria. In contrast, developed countries often have more robust financial systems and regulatory frameworks that support the adoption of energy-efficient technologies [24,39]. The need for technical expertise and capacity building is also a common theme in both developed and developing contexts, though the extent of the skills gap may be greater in developing countries. This underscores the importance of international cooperation and knowledge transfer to support sustainable development globally [26].

3.7.4. Implications for policy and practice

The findings of this study have several important implications for policy and practice in Nigeria's construction sector. Strengthening regulatory frameworks to ensure consistent enforcement of energy efficiency standards is critical. Policies that mandate the use of energy-efficient technologies in new constructions and renovations can drive adoption. Additionally, providing financial incentives, such as subsidies, tax rebates, and low-interest loans, can help offset the high initial costs and encourage more stakeholders to invest in sustainable solutions [30,46]. Capacity-building programs are essential to bridge the skills gap in the construction industry. Training and educational programs aimed at enhancing the technical expertise of construction professionals can ensure the effective implementation of energy-efficient technologies [18]. Public awareness campaigns that highlight the cost savings, environmental benefits, and health improvements associated with energy-efficient technologies can also drive demand for sustainable construction practices [24]. Improving the supply chain for green materials and technologies is necessary to address logistical challenges. Developing local suppliers and reducing dependency on imports can lower costs and improve the availability of high-quality materials. This can facilitate the timely and cost-effective implementation of energy-efficient technologies [26].

4. Conclusions

The findings from this study provide a comprehensive understanding of the current state of energy-efficient technologies in Nigeria's construction sector, highlighting

significant achievements, persistent challenges, and actionable recommendations for future progress. The study identified that solar panels, LED lighting, and energy-efficient HVAC systems are the most widely adopted technologies among industry stakeholders. This indicates a positive trend towards embracing sustainable practices. However, the adoption rates are still influenced significantly by factors such as regulatory support and stakeholder awareness. The regression analysis revealed that these two variables were strong predictors of technology adoption, underscoring the critical role that informed policies and education play in driving sustainable practices.

Despite these advancements, several barriers hinder the widespread adoption of energy-efficient technologies. Financial constraints emerged as the most significant barrier, reflecting the high initial costs and limited access to financing options. Regulatory challenges, including inconsistent enforcement of standards and lack of incentives, further complicate the adoption process. Additionally, a lack of technical expertise and logistical challenges such as supply chain issues were notable obstacles. The study also highlighted the multifaceted benefits of energy-efficient technologies. Respondents reported substantial operational cost savings, enhanced environmental sustainability, and improved indoor environmental quality. These benefits extend beyond economic gains, contributing to overall well-being and supporting broader environmental goals. The insights from this study suggest several strategic actions to enhance the adoption of energy-efficient technologies in Nigeria's construction sector. Firstly, strengthening regulatory frameworks and ensuring consistent enforcement of energy efficiency standards are paramount. This could involve mandating the use of specific technologies in new constructions and major renovations, supported by a robust monitoring and compliance mechanism. Financial incentives play a crucial role in mitigating the high initial costs associated with these technologies. Subsidies, tax rebates, and low-interest loans could make energy-efficient solutions more accessible to a broader range of stakeholders. Developing innovative financing models and partnerships with financial institutions could further alleviate the financial burden.

Capacity-building initiatives are essential to address the skills gap within the industry. Comprehensive training programs and educational workshops can enhance the technical expertise of construction professionals, ensuring the effective implementation and maintenance of energy-efficient technologies. These programs should be tailored to the specific needs of the industry, providing practical, hands-on training and up-to-date information on the latest technologies and best practices. Public awareness campaigns are vital in shifting cultural attitudes and behaviors towards sustainable construction. Highlighting the long-term cost savings, health benefits, and environmental advantages of energy-efficient technologies can increase demand and acceptance among the general public and industry stakeholders alike.

Improving the supply chain for green materials and technologies is another critical area. Developing local manufacturing capabilities and reducing dependency on

imports can lower costs and ensure the timely availability of high-quality materials. Encouraging local innovation and supporting small and medium enterprises in the green technology sector can further strengthen the supply chain. While this study provides valuable insights, further research is needed to explore innovative financing mechanisms that can support the adoption of energy-efficient technologies. Longitudinal studies that track the long-term economic, environmental, and social impacts of these technologies would provide deeper insights into their benefits and challenges. Additionally, exploring the role of cultural attitudes and behavioral factors in greater detail can help design more effective public awareness and education campaigns. Investigating the specific barriers faced by different types of buildings, such as residential versus commercial or public versus private, can also provide targeted strategies for enhancing energy efficiency across various segments of the construction industry.

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