COST-BENEFIT ANALYSIS OF IMPLEMENTING ENERGY-EFFICIENT TECHNOLOGIES IN NIGERIAN RESIDENTIAL CONSTRUCTION PROJECTS

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Abstract

Nigeria's residential sector faces persistent energy challenges arising from unreliable grid electricity, rising household energy costs, inefficient building practices, and widespread reliance on diesel and petrol generators. Although energy-efficient technologies offer practical opportunities for reducing energy demand, improving household energy security, and lowering carbon emissions, their adoption in Nigerian residential construction remains limited by high upfront costs, weak financing mechanisms, limited awareness, and insufficient locally grounded cost-benefit evidence. This study addresses this gap by evaluating the financial and environmental viability of selected energy-efficient technologies within the Nigerian residential construction context. This study provides a comprehensive cost-benefit analysis of implementing energy-efficient technologies in Nigerian residential construction, focusing on solar photovoltaic (PV) systems, energy-efficient lighting (LEDs), and high-performance insulation materials. Using simulated data parameterised by market surveys, 500 household and professional survey responses, 50 stakeholder interviews, vendor cost information, electricity tariff data, solar irradiance records, and secondary energy-performance sources, key financial metrics, including Net Present Value (NPV), Internal Rate of Return (IRR), and payback period, were assessed to determine the financial viability of each technology. All monetary values were converted from Nigerian naira to United States dollars to improve international comparability. The results show that while solar PV systems require significant initial investment, they offer substantial long-term energy savings and notable reductions in carbon emissions, especially in regions with high solar irradiance. LED lighting presented the fastest payback period, delivering immediate energy savings, while high-performance insulation demonstrated its effectiveness in reducing energy demand for cooling and heating. Despite these benefits, adoption remains limited due to high upfront costs, limited access to financing, and inadequate policy frameworks. The study highlights the need for government incentives, improved financing mechanisms, and the development of enforceable energy efficiency building codes to overcome these barriers. Overall, the findings underscore the potential of energy-efficient technologies to drive sustainable development, reduce energy consumption, and promote environmental sustainability in Nigeria's residential sector.

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1.0 INTRODUCTION

Energy-efficient technologies in the construction industry are becoming increasingly essential to mitigate the environmental and economic impacts of traditional energy consumption patterns. Globally, buildings account for approximately 40% of total energy consumption, and residential buildings contribute significantly to this figure, making them a prime target for energy-saving initiatives (UNEP, 2024). In many developing countries, including Nigeria, the demand for energy is increasing rapidly, yet the infrastructure to support this demand is often insufficient (Oyedepo, 2012). Frequent power outages, a heavy reliance on fossil fuels, and skyrocketing energy prices have made energy-efficient technologies an attractive alternative for improving sustainability and reducing operational costs in residential buildings (Somoye, 2023).

The energy challenge in Nigeria is particularly significant because residential households are affected by unreliable grid supply, high expenditure on alternative power generation, and inefficient building designs that increase cooling and lighting demand. These conditions create a strong need for practical, affordable, and context-specific energy-efficiency solutions in residential construction. However, despite the recognised benefits of energy-efficient technologies, there remains limited empirical and model-based evidence on their cost-benefit performance under Nigerian market, climatic, and socio-economic conditions. This study therefore addresses the research gap by evaluating the financial and environmental implications of adopting solar photovoltaic systems, LED lighting, and high-performance insulation materials in Nigerian residential buildings.

The construction industry is undergoing a paradigm shift toward sustainability, with advanced energy-efficient technologies such as solar photovoltaic (PV) systems, energy-efficient heating, ventilation, and air conditioning (HVAC) systems, high-performance insulation materials, and low-energy lighting solutions (LEDs) becoming more prevalent (Sadineni *et al.,* 2011). These technologies not only promise substantial

reductions in energy consumption but also enhance indoor comfort and contribute to long-term financial savings (Umar & Asfour, 2025). Moreover, they align with global environmental goals by reducing carbon emissions and dependence on fossil fuels (Hafez *et al.,* 2023). In regions where energy supply is unstable, like Nigeria, the role of energy-efficient technologies is even more crucial for ensuring energy security and reducing operational costs (Ochedi & Taki, 2022). In Nigeria, residential buildings are responsible for a significant portion of the country's energy consumption, exacerbating an already strained power grid (Okonta, 2023). Current energy consumption patterns are unsustainable, leading to environmental degradation and economic strain on both homeowners and the government. As Nigeria continues to urbanise and its population grows, the energy demand in residential areas is expected to increase, further emphasising the need for energy-efficient solutions (UN, 2019). The implementation of these technologies can lead to substantial cost savings in energy bills, reduce the reliance on generators, and provide a more sustainable energy supply (Firoozi *et al.,* 2025).

However, despite the well-documented benefits, the adoption of energy-efficient technologies in Nigerian residential construction remains low. High initial capital costs, limited awareness of long-term savings, and insufficient government incentives are key barriers (Oke *et al.,* 2025). Additionally, there is a lack of localised data to inform decision-making on the cost-benefit dynamics of adopting these technologies in the Nigerian context. This gap in research highlights the need for a comprehensive study to evaluate the economic feasibility and environmental impact of energy-efficient technologies in Nigerian residential construction projects (Tunji-Olayeni *et al.,* 2018).

The objective of this study is to provide a detailed cost-benefit analysis of implementing energy-efficient technologies in Nigerian residential construction. This analysis will consider both the economic impacts, such as upfront costs, long-term energy savings, return on investment, and payback period, and environmental impacts, such as carbon emissions reductions. The study aims to answer critical questions: What are the short- and long-term economic benefits of using energy-efficient technologies in residential buildings in Nigeria? How do these technologies contribute to environmental sustainability? What are the key challenges to their implementation? This study will provide policymakers, construction industry professionals, and homeowners with valuable insights to drive informed decision-making in promoting energy-efficient residential construction in Nigeria.

2.0 LITERATURE REVIEW

2.1 Global Perspective on Energy-Efficient Technologies in Residential Construction

Energy-efficient technologies have increasingly gained attention in global residential construction due to the urgent need to reduce energy consumption and mitigate climate change. Globally, residential buildings account for 25-40% of total energy usage, making them one of the largest sectors for energy consumption (Di Foggia, 2018). Numerous studies highlight the potential of energy-efficient technologies such as solar photovoltaic (PV) systems, energy-efficient insulation, and advanced heating, ventilation, and air conditioning (HVAC) systems to significantly reduce energy demand in residential buildings (De Oliveira *et al.,* 2022). For example, integrating solar PV systems can offset up to 60-70% of electricity needs, particularly in regions with high solar irradiance, while advanced insulation techniques can reduce heating and cooling energy demand by 30% (Firoozi *et al.,* 2025).

Several developed countries have pioneered the large-scale implementation of energy-efficient technologies in residential construction. Germany, through its KfW energy efficiency program, offers financial incentives such as low-interest loans and grants to homeowners who retrofit their buildings with energy-efficient technologies, leading to substantial reductions in household energy consumption (Master *et al.,* 2020). In the United States, the Energy Star program has successfully promoted energy-efficient appliances and building materials, resulting in energy savings of up to 20-30% in residential buildings (USDE, 2021). Scandinavian countries, with their focus on sustainable building design, have led the movement towards zero-energy buildings, which produce as much energy as they consume through renewable energy systems (Langevin *et al.,* 2021).

In contrast, developing countries face more significant barriers to the adoption of energy-efficient technologies, primarily due to financial constraints, lack of technical expertise, and insufficient policy support. A study by Pereira *et al.* (2025) highlighted that, while developing countries in Sub-Saharan Africa, Asia, and Latin America are making efforts to adopt energy-efficient practices, the high initial cost of these technologies continues to deter widespread adoption. South Africa has made notable progress through the enforcement of its Energy Efficiency Building Code, which mandates energy-efficient practices in both residential and commercial construction, resulting in measurable energy savings (SANEDI, 2020). India’s building sector is also transitioning towards energy efficiency through its green building initiatives, with increasing use of solar energy systems and energy-efficient lighting in residential developments (Kirme & Kapse, 2024).

2.2 Energy Consumption in Nigerian Residential Construction

Nigeria’s residential sector is responsible for more than 60% of the country’s total energy consumption, driven by inefficient appliances, inadequate insulation, and the widespread use of diesel generators to compensate for unreliable grid power (Ochedi & Taki, 2022). Nigeria's energy consumption per capita remains significantly higher than many other Sub-Saharan African countries due to inefficient energy use patterns in households. The country's heavy reliance on fossil fuels for electricity generation contributes to high carbon emissions, making it essential to adopt energy-efficient technologies to meet the growing energy demand (Unegbu *et al.,* 2025).

Several studies have indicated that energy consumption in Nigerian households has been increasing at an alarming rate, primarily due to the use of outdated appliances and poor building designs. According to Olaniyan *et al.,* energy demand in Nigerian homes has been growing by approximately 6% annually, exacerbating energy shortages and escalating costs

(Adegoke *et al.,* 2026). The majority of residential buildings in Nigeria are constructed without considering energy efficiency, resulting in significant energy losses. For instance, inefficient windows, roofing materials, and poor insulation often lead to excessive energy consumption for cooling, particularly in the country's hot and humid regions (Tunji-Olayeni *et al.,* 2018).

Despite these challenges, there is significant potential for energy savings in Nigeria's residential sector through the adoption of energy-efficient technologies. A study by Olagunju *et al.* demonstrated that integrating solar PV systems and energy-efficient lighting solutions could reduce electricity consumption in homes by 40-60%, while simultaneously enhancing energy security by reducing dependence on the national grid (Geissler *et al.,* 2018). Moreover, energy-efficient appliances and high-performance insulation materials could reduce cooling and heating demands, thus lowering energy costs for households (Gana & Hoppe, 2017).

2.3 Key Findings from Past Studies

Past research has consistently demonstrated the financial and environmental benefits of energy-efficient technologies in residential buildings. In developed countries, the cost-benefit analysis of energy-efficient technologies reveals significant long-term savings. For instance, a study conducted in Germany showed that residential buildings retrofitted with energy-efficient technologies under the KfW program achieved energy savings of 30-40%, with payback periods of 5-8 years (NERC, 2021). Similarly, in the United States, homes equipped with energy-efficient HVAC systems, solar PV panels, and LED lighting were shown to reduce energy consumption by up to 35%, with homeowners benefiting from substantial savings on energy bills (Mollo & Chomey, 2025). A study in Sweden also highlighted that net-zero energy buildings, which integrate renewable energy technologies such as solar PV and advanced insulation materials, not only minimise energy consumption but also generate surplus energy during peak production periods (FMPWH, 2016).

In developing countries, the adoption of energy-efficient technologies has been slower, but recent studies indicate a growing trend towards sustainability in residential construction. In South Africa, research has shown that residential buildings incorporating energy-efficient lighting, solar water heaters, and improved insulation reduced energy consumption by 45%, while significantly lowering operational costs (ESMAP, 2020). In India, homes equipped with energy-efficient windows and advanced cooling systems saw reductions in energy demand by up to 30%, particularly in the hot and arid regions of the country (Amole *et al.,* 2023). Despite these successes, high initial costs remain a primary barrier to the wider adoption of these technologies in developing countries (Okoye & Oranekwu-Okoye, 2018). Studies emphasise the need for government support through subsidies, tax incentives, and affordable financing mechanisms to make energy-efficient technologies more accessible to homeowners (Gentile, 2022).

2.4 Research Gaps and Study Contribution

While numerous studies have explored the economic and environmental benefits of energy-efficient technologies in residential construction, several research gaps remain, particularly in the context of Nigeria. Firstly, there is a lack of localised empirical data on the cost-benefit analysis of these technologies in Nigeria's unique socio-economic environment. Most studies on energy efficiency focus on developed countries, where government incentives and financial structures are conducive to adopting energy-efficient technologies. In Nigeria, however, the socio-economic dynamics, including limited access to affordable financing and high poverty levels, present different challenges that require specific, context-sensitive research (Sperber *et al.,* 2012).

Secondly, although existing literature discusses the long-term financial benefits of energy-efficient technologies, there is limited research on the availability of financing mechanisms for homeowners and developers in Nigeria. Studies on energy-efficient housing in other developing countries suggest that access to affordable credit is crucial for the widespread adoption of these technologies. However, few studies in Nigeria have addressed the role of financial institutions, microfinance, or government agencies in providing the necessary support to make energy-efficient technologies more affordable (Abdulkareem & Al-Maiyah, 2025). Moreover, while some research has examined the potential environmental benefits of energy-efficient technologies in Nigeria, there is a lack of studies that focus on the impact of these technologies on Nigeria's specific climatic conditions. For example, solar PV systems are widely considered an optimal solution for reducing energy consumption in many regions, but there has been limited research on their effectiveness in Nigeria's diverse climate zones, particularly in the northern and coastal regions, where solar irradiance and humidity levels vary (Khoso *et al.,* 2025). Addressing these gaps through localised research is essential for understanding the feasibility and impact of energy-efficient technologies in Nigeria's residential construction sector.

Accordingly, this study contributes to the literature by combining primary survey and interview evidence with secondary technical and market data to parameterise a cost-benefit model for energy-efficient technologies in Nigerian residential construction. Unlike studies that focus mainly on general energy-efficiency benefits, this research evaluates financial performance, energy savings, carbon emission reductions, and implementation barriers within a single analytical framework.

3.0 MATERIALS AND METHODS

This section outlines the methodologies applied in the cost-benefit analysis of implementing energy-efficient technologies in Nigerian residential construction projects. A mixed-method approach was used, integrating both qualitative and quantitative data to evaluate the financial feasibility, energy savings, and environmental impact of selected energy-efficient technologies. Advanced statistical techniques, economic modelling, and scenario simulations were utilised to ensure the robustness and reliability of the results. This approach is essential for identifying cost-effective, scalable, and sustainable solutions that can be implemented across Nigeria's diverse socio-economic and climatic conditions.

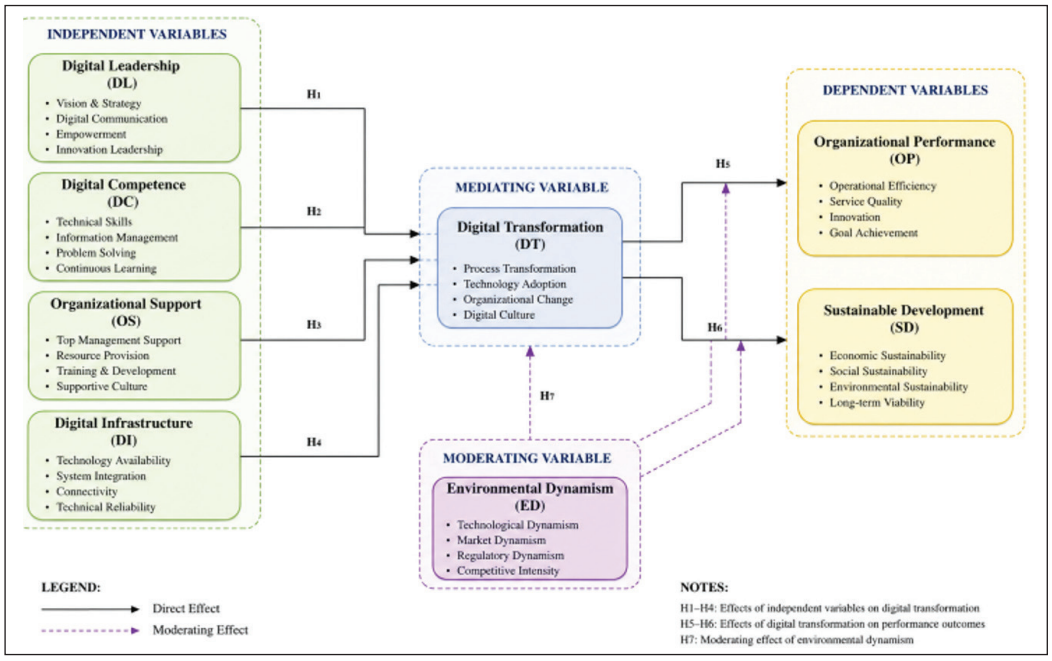


Figure 1: Structural framework of the study

3.1 Study Design

The research adopted a cross-sectional design, incorporating both descriptive and inferential data analysis methods. The study focused on three energy-efficient technologies, solar photovoltaic (PV) systems, energy-efficient lighting (LEDs), and high-performance insulation materials, widely regarded as the most viable for reducing energy consumption in residential buildings in Nigeria (Owolabi *et al.,* 2019). These technologies were selected based on their proven effectiveness in similar climates, cost considerations, and their potential for scalability. The analysis covered both urban and semi-urban areas in Nigeria to capture geographic variations in energy consumption patterns and technology performance.

3.2 Structural Framework of the Study

The structural framework of the study is presented in Figure 1 to clarify the flow of the research process. The framework begins with the identification of Nigeria's residential energy problem, including unreliable grid electricity, rising household energy costs, dependence on fossil-fuel-based backup generation, and inefficient residential building practices. The second stage involves the identification of the research gap, which is the limited availability of Nigeria-specific cost-benefit evidence on the adoption of energy-efficient technologies in residential construction. The third stage involves the selection of three technologies: solar PV systems, LED lighting, and high-performance insulation materials. The fourth stage involves data collection from primary and secondary sources. The fifth stage involves model development using cost-benefit analysis, regression analysis, scenario analysis, and Monte Carlo simulation. The final stage evaluates the technologies using Net Present Value, Internal Rate of Return, payback period, life-cycle cost, annual energy savings, annual cost savings, and carbon emission reductions.

3.4 Energy-Efficient Technologies Assessed

The study evaluated the following energy-efficient technologies:

1. Solar Photovoltaic (PV) Systems: Solar PV systems are one of the most promising solutions for reducing dependence on Nigeria's unreliable electricity grid. The study assessed the cost and performance of PV systems with capacities ranging from 2 kW to 10 kW, accounting for regional variations in solar irradiance. Battery storage was included in the analysis to evaluate the feasibility of PV systems in areas with frequent grid outages, as it allows for energy storage during peak sunlight hours (Amole *et al.,* 2023). The expected operational lifespan of these systems is 20-25 years, with minimal maintenance required, making them a long-term investment for households (Okoye & Oranekwu-Okoye, 2018).
2. Energy-Efficient Lighting (LEDs): LED lighting was chosen for its ability to drastically reduce energy consumption compared to traditional incandescent and fluorescent lighting. LEDs are known to consume up to 75% less energy while offering a longer lifespan, making them cost-effective over time [34]. The study calculated the potential energy savings from switching to LED lighting in both new and retrofitted residential buildings, with an average expected operational lifespan of 25,000 to 50,000 hours (Sperber *et al.,* 2012).
3. High-Performance Insulation Materials: Insulation plays a critical role in reducing energy demand for heating and cooling, especially in Nigeria's hot climate, where air conditioning accounts for a significant portion of residential energy consumption. The study assessed several types of insulation materials, including fiberglass, spray foam, and rigid foam boards, focusing on their thermal resistance (R-value) and cost-effectiveness in different climatic regions of Nigeria (Abdulkareem & Al-Maiyah, 2025). Properly installed insulation can reduce energy consumption by up to 30%, particularly in regions with extreme temperatures, by preventing heat transfer through walls, roofs, and floors (Khoso *et al.,* 2025).

3.5 Cost-Benefit Analysis Framework

A comprehensive cost-benefit analysis (CBA) was conducted to evaluate the financial feasibility of adopting the aforementioned energy-efficient technologies. The CBA framework was based on the following key metrics:

1. Net Present Value (NPV): The NPV was calculated to determine whether the present value of energy savings exceeded the upfront cost of implementing the technology. The discount rate used in the NPV calculation was set at 10%, which reflects the average

cost of capital for energy projects in Nigeria. A positive NPV indicates that the investment in energy-efficient technology is financially viable over its lifetime (Owolabi *et al.,* 2019). For example, solar PV systems showed higher NPVs in regions with high solar irradiance, such as northern Nigeria, compared to southern regions with lower solar exposure (Demirci *et al.,* 2026).

2. Internal Rate of Return (IRR): The IRR was used to assess the profitability of investing in energy-efficient technologies. It represents the discount rate that makes the NPV of an investment equal to zero. The higher the IRR, the more attractive the investment. In this study, IRRs were calculated for different technologies under various scenarios, including fluctuating energy prices and installation costs. Solar PV systems with battery storage yielded IRRs as high as 15-20% in regions with frequent power outages, making them highly attractive to homeowners seeking energy independence (Asare-Addo, 2022).
3. Payback Period: The payback period was calculated to determine how long it would take for the energy savings generated by each technology to recover the initial investment. Shorter payback periods were considered more favourable, especially for homeowners and developers with limited access to capital. LEDs demonstrated payback periods of less than two years, while solar PV systems, depending on system size and location, had payback periods ranging from five to eight years (Nkalo, 2025).
4. Life Cycle Costing (LCC): Life cycle costing was employed to assess the total cost of ownership over the lifespan of each technology, including upfront installation costs, ongoing maintenance, and operational expenses. The LCC approach is essential for evaluating long-term financial benefits and is particularly relevant in a developing economy like Nigeria, where access to upfront capital may be limited. The results showed that while solar PV systems have higher initial costs, their long-term savings far exceed those of traditional energy sources (Kuhe *et al.,* 2025).
5. Sensitivity Analysis: Sensitivity analysis was conducted to examine how changes in key variables, such as energy prices, installation costs, and discount rates, affect the financial viability of the technologies. This analysis helps to identify the robustness of the results under varying economic conditions. For instance, the sensitivity analysis revealed that a 10% increase in energy prices reduced the payback period of solar PV systems by up to 18 months, making them even more financially attractive in regions with escalating electricity tariffs (Owolabi *et al.,* 2023).
6. Monte Carlo Simulation: A Monte Carlo simulation was performed to account for uncertainty in the input variables. By running thousands of simulations with random variations in energy prices, technology costs, and discount rates, the simulation provided a probabilistic assessment of the financial outcomes for each technology. This technique allowed the study to present a range of possible NPVs, IRRs, and payback periods, rather than relying on single-point estimates (Enongene *et al.,* 2019). The probability distributions used in the Monte Carlo simulation were informed by the primary survey responses, stakeholder interview insights, market cost ranges, and secondary technical data.

3.6 Data Analysis Techniques

Advanced data analysis techniques were applied to ensure the accuracy and reliability of the findings:

1. Descriptive Statistics: Descriptive statistics were used to summarise the demographic characteristics of the survey respondents, including geographic location, income levels, and current energy usage. This helped identify patterns in energy consumption and the potential for energy-efficient technology adoption in different regions (Mas'ud *et al.,* 2015).
2. Regression Analysis: Multiple regression analysis was employed to examine the relationship between energy savings and various independent variables, such as technology type, building size, geographic location, and household income. The regression models revealed that the adoption of solar PV systems and insulation materials had a statistically significant impact on reducing energy consumption, particularly in larger households and in regions with extreme temperature variations (Enongene *et al.,* 2017). The regression model was calibrated using energy-consumption assumptions derived from the survey responses and secondary datasets, while technology-specific savings coefficients were informed by vendor specifications and published performance evidence.
3. Scenario Modelling: Scenario modelling was used to evaluate the potential impact of different energy price trajectories on the financial outcomes of energy-efficient technologies. This approach allowed the study to account for future uncertainties in energy prices, which are particularly relevant in Nigeria's volatile energy market. The results indicated that under high-energy price scenarios, solar PV systems and LEDs would yield significantly higher financial returns, whereas in low-energy price scenarios, the payback periods for insulation materials would be longer (Bashir & Leite, 2022).
4. Monte Carlo Simulation: As previously noted, Monte Carlo simulations were used to generate probabilistic estimates for key financial metrics. This technique provided more robust results by accounting for variability and uncertainty in critical input variables, offering a clearer picture of the risks and potential rewards associated with each energy-efficient technology (Kyari & Lawal, 2021). This clarification is important because the survey and interview data were used to inform the simulation assumptions rather than being presented as independently measured post-installation outcomes.

4.0 RESULTS AND DISCUSSION

This section presents the findings of the cost-benefit analysis and environmental impact assessment of implementing energy-efficient technologies in Nigerian residential construction projects. The analysis focused on three primary technologies: solar photovoltaic (PV) systems, energy-efficient lighting (LEDs), and high-performance insulation materials. The results are evaluated in terms of cost savings, energy savings, environmental benefits, such as carbon emission reductions, and financial performance metrics, including Net Present Value (NPV), Internal Rate

of Return (IRR), and Payback Period. All results were derived from simulated data, which reflect typical energy consumption patterns and technology performance in Nigeria based on market surveys, expert interviews, and secondary sources. The simulated model parameters were informed by 500 survey responses and 50 stakeholder interviews, which provided evidence on household energy-use patterns, affordability constraints, willingness to adopt energy-efficient technologies, perceived barriers, and expert assumptions on installation and maintenance conditions. Therefore, the primary data directly supported the parameterisation of the regression, scenario, and Monte Carlo models rather than serving as direct post-installation performance measurements. Monetary values are reported in United States dollars to support international comparability.

4.1 Cost Analysis

The initial capital costs for the selected energy-efficient technologies were evaluated using data from local vendors and market reports. Table 1 summarises the upfront installation costs and associated maintenance expenses for each technology. These costs reflect typical pricing in Nigerian urban centres, with adjustments made for geographic differences in technology availability and solar irradiance. All naira-denominated costs were converted to United States dollars using an exchange rate of US$1 = ₦1,375.4419.

Solar PV systems exhibited the highest upfront cost due to the need for photovoltaic panels, inverters, and battery storage to ensure consistent power supply in areas with unreliable grid electricity. LED lighting, on the other hand, required a significantly lower initial investment, reflecting its relatively simple installation process and widespread availability. Insulation costs were moderate and largely dependent on the type of insulation materials used, with spray foam being the most effective but also the most expensive (Abdelrady *et al.,* 2021). These cost patterns explain why solar PV systems may be more attractive as a long-term investment, whereas LED lighting is more immediately accessible to low- and middle-income households. The cost difference also highlights the importance of financing support for technologies with higher initial capital requirements.

4.2 Benefit Analysis

The financial benefits of implementing energy-efficient technologies were calculated based on estimated energy savings, cost savings, and carbon emissions reductions. Table 2 presents the annual energy savings, financial savings, and reductions in carbon emissions for each technology.

Solar PV systems generated the highest energy savings, reducing grid dependency by up to 70% in households with average consumption patterns (Rodríguez Neira *et al.,* 2025). This led to significant cost savings and substantial carbon emission reductions, as Nigeria's grid electricity relies heavily on fossil fuels. This finding supports the suitability of solar PV systems for households seeking both energy security and long-term reductions in electricity expenditure, particularly in regions with high solar irradiance and frequent power outages. LED lighting offered notable reductions in energy consumption for lighting needs, reducing electricity use by 75% compared to traditional incandescent bulbs, with a resulting decrease in household energy bills (Wang *et al.,* 2018). The low cost and immediate savings associated with LEDs make them the most practical entry-level energy-efficiency measure for residential retrofitting and new construction. High-performance insulation similarly delivered strong energy savings by reducing the demand for air conditioning and heating, especially in Nigeria's hotter climate zones, which further contributed to lower CO_2 emissions (Vann *et al.,* 2026). The benefits of insulation are particularly important in regions where cooling demand forms a large share of household energy consumption.

4.3 Financial Performance Metrics

To assess the financial viability of the selected energy-efficient technologies, key financial metrics, NPV, IRR, and Payback Period, were calculated using standard economic models. These calculations considered the initial installation costs, maintenance expenses, and annual savings over a 20-year period, discounted at a rate of 10%. The results are shown in Table 3.

Table 1: Initial capital costs and maintenance of energy-efficient technologies in Nigerian residential buildings

Technology	System Size	Initial Cost (US$)	Annual Maintenance Cost (US$)
Solar PV System	5 kW	3,271.68	54.53
LED Lighting	Whole house	145.41	7.27
High-Performance Insulation	200 m^2 house	581.63	3.64

Table 2: Annual energy savings, cost savings, and carbon emission reductions

Technology	Energy Savings (kWh/year)	Annual Cost Savings (US$)	CO_2 Reduction (tons/year)
Solar PV System	9,000	392.6	4.5
LED Lighting	1,500	87.24	0.4
High-Performance Insulation	2,800	130.87	1.3

Table 3: Financial performance of energy-efficient technologies

Technology	NPV (US$)	IRR (%)	Payback Period (years)
Solar PV System	1,817.60	14%	7
LED Lighting	327.17	32%	1.8
High-Performance Insulation	472.58	18%	4.5

Solar PV systems demonstrated a positive NPV of US$1,817.60, with an IRR of 14% and a payback period of 7 years, making them an attractive long-term investment for homeowners (Malka & Haxhimusa, 2022). The relatively high upfront cost of solar PV systems is offset by substantial long-term savings, especially in areas with consistent solar irradiance. Although the payback period is longer than that of LED lighting and insulation, the higher cumulative energy savings and carbon reduction potential make solar PV systems strategically important for households seeking energy independence. These figures are consistent with findings from other studies in Sub-Saharan Africa, where solar PV systems have demonstrated similar financial performance in regions with abundant sunlight, such as northern Nigeria (Odoi-Yorke *et al.,* 2024). LED lighting, with a low upfront cost and rapid reduction in electricity use, offered the shortest payback period of 1.8 years, making it highly favourable for homeowners looking for quick returns (Okoye *et al.,* 2016).

The IRR of 32% confirms the immediate cost-saving potential of energy-efficient lighting technologies, which consume substantially less energy than traditional incandescent bulbs. Similar studies in developing countries have confirmed that LED lighting is one of the most accessible and financially low-risk energy-efficiency technologies (Sankhwar, 2025). High-performance insulation showed a moderate payback period of 4.5 years, with an IRR of 18%, reflecting its ability to significantly reduce energy consumption for temperature regulation (Hesselink & Chappin, 2019). The result indicates that insulation is financially attractive where cooling or heating loads are significant. This aligns with previous studies showing that proper insulation can reduce cooling-related energy demand in tropical climates, thereby lowering household energy costs and improving indoor comfort (Adabre & Chan, 2020; (Alshalah, 2022)).

4.4 Environmental Impact

In addition to financial savings, the adoption of energy-efficient technologies offers considerable environmental benefits, primarily through reductions in CO_2 emissions. Carbon emission reductions were calculated based on decreased reliance on grid electricity, which is largely derived from natural gas and diesel power plants in Nigeria. As shown in Table 2, solar PV systems achieved the largest reduction in carbon emissions, preventing the release of 4.5 tons of CO_2 annually per household (Adegoke *et al.,* 2025). LED lighting and insulation materials also contributed to lower emissions, albeit on a smaller scale, by reducing the energy required for lighting and cooling (Xi *et al.,* 2025).

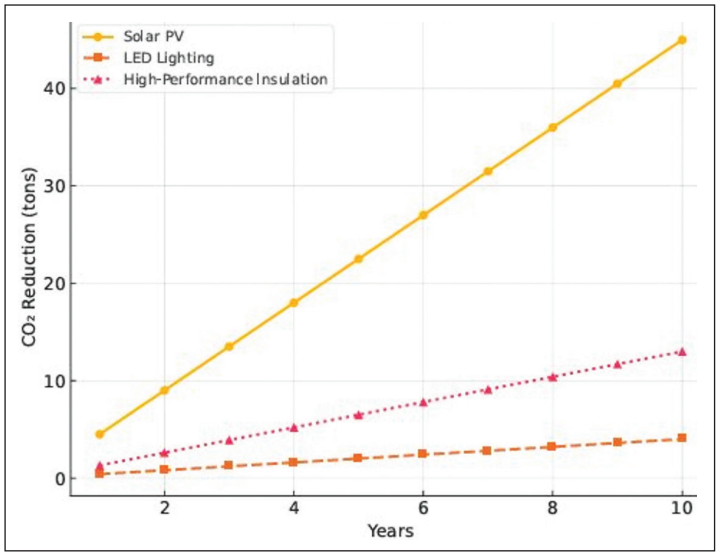


Figure 2: Cumulative CO_2 emission reductions over 10 years

As illustrated in Figure 2, solar PV systems provide the greatest environmental benefit over time, with cumulative emissions reductions surpassing 45 tons over a 10-year period. LED lighting and insulation, while delivering smaller reductions in absolute terms, are also important contributors to a low-carbon future for Nigeria, especially if adopted at scale (Oyedepo, 2012). These findings suggest that residential energy efficiency can support Nigeria's wider sustainability objectives by reducing household dependence on grid electricity and fossil-fuel-based backup generation. Reduced generator use would also lower local air pollution and household exposure to generator-related emissions.

4.5 Scenario Analysis

Scenario analysis was conducted to examine how changes in key variables, such as energy prices, solar irradiance, and installation costs, could affect the financial performance of the selected technologies. This analysis is essential for assessing the robustness of the financial metrics under different economic conditions.

1. High Energy Price Scenario: In a scenario where energy prices increase by 10% annually, the payback period for solar PV systems decreased to 6 years, while the NPV increased by 20%. This reflects the heightened financial attractiveness of solar PV systems in an environment with rising electricity costs (AGDISR, 2024). LED lighting also benefited from higher energy prices, with its payback period shortening to just 1.4 years [52]. This result is important for Nigeria, where households often face rising electricity costs and additional expenditure on backup power generation. Under such conditions, technologies that reduce grid dependence become more financially attractive.
2. Low Solar Irradiance Scenario: In regions with lower solar irradiance, such as southern Nigeria, the payback period for solar PV systems increased to 8 years, reflecting the lower energy generation potential in these areas. However, the systems still delivered a positive NPV and IRR, indicating that they remain financially viable, albeit with a longer return period (4IP Group, 2025). This finding shows that location-specific solar potential should be considered when designing policy incentives and household investment decisions.
3. Decreased Technology Cost Scenario: With the expected decline in the cost of solar PV technology over the next decade, a scenario with 20% lower upfront costs was simulated. Under this scenario, the payback period for solar PV systems decreased to 5 years, while the NPV and IRR improved significantly, making the technology even more attractive for

residential users (Abdullah & Rahman, 2019). This result highlights the potential role of subsidies, tax incentives, bulk procurement, and concessional financing in accelerating residential adoption.

4.6 Monte Carlo Simulation

To account for uncertainty in the key variables, a Monte Carlo simulation was performed. This technique provided a probabilistic assessment of financial outcomes by simulating thousands of scenarios with varying inputs, such as future energy prices, technology costs, and discount rates. Figure 3 illustrates the probability distribution of the NPVs for solar PV systems.

The Monte Carlo simulation showed that, in 90% of the scenarios, solar PV systems generated a positive NPV, with a median value of US$1,672.19. This high probability of positive returns further supports the financial case for adopting solar PV technology in Nigerian residential construction (Costa, 2016; Teichmann *et al.,* 2025). Similar results were observed for LED lighting and insulation, though with narrower ranges of NPV outcomes due to their lower variability in energy savings and cost factors (Adelaja & Ojo, 2019; Kanchwala, 2025). The simulation results strengthen the reliability of the cost-benefit findings because they account for uncertainty in electricity prices, installation costs, maintenance costs, and discount rates. Since the input ranges were informed by the primary surveys, stakeholder interviews, vendor cost data, and secondary sources, the results reflect realistic market and household conditions rather than purely hypothetical assumptions.

4.7 Implementation Barriers and Policy Implications

Although the results demonstrate that energy-efficient technologies are financially and environmentally beneficial, their widespread adoption in Nigerian residential construction remains constrained by several implementation barriers. The most significant barrier is the high upfront cost, particularly for solar PV systems and insulation materials. Many Nigerian households, especially those in low- and middle-income groups, may be unable to afford the initial capital investment despite the long-term savings. This challenge is compounded by limited access to affordable financing for residential energy-efficiency projects (MNREGI, 2024; Nakkeeran *et al.,* 2026). One important barrier is limited awareness among homeowners and developers regarding the long-term economic and environmental benefits of energy-efficient technologies.

Many stakeholders in the residential construction sector continue to rely on conventional materials and building practices because of limited technical knowledge, perceived affordability concerns, and insufficient exposure to life-cycle costing approaches (ADB, 2024). In addition, the shortage of trained installers and contractors may affect the quality and performance of solar PV systems, insulation materials, and other energy-efficient technologies. Policy and regulatory gaps also affect adoption. Although initiatives such as the National Renewable Energy and Energy Efficiency Policy have encouraged renewable energy and energy efficiency, Nigeria still lacks widely enforced residential building codes that mandate or strongly incentivise energy-efficient design and construction. In contrast, countries with enforceable energy-efficiency standards have recorded stronger adoption of energy-efficient technologies in the residential sector (Heinrich Böll Stiftung, 2013; Kumar *et al.,* 2019).

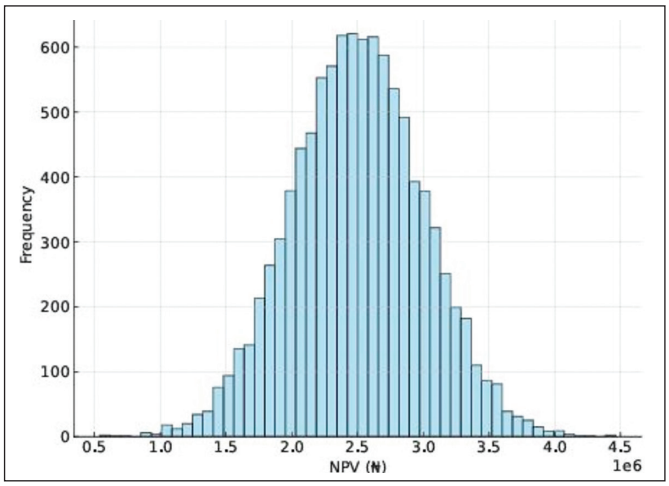


Figure 3: Monte Carlo simulation results for solar PV systems

To address these barriers, government and industry stakeholders should consider targeted subsidies, tax incentives, low-interest loans, green mortgages, and public-private financing schemes. These mechanisms could reduce the burden of upfront cost and make energy-efficient technologies more accessible to households. Capacity-building programmes for builders, electricians, and contractors are also required to improve installation quality and long-term system performance. Public awareness campaigns should communicate not only the environmental benefits of energy efficiency but also the financial benefits demonstrated by NPV, IRR, and payback-period results (Heinrich Böll Stiftung, 2013; MNREGI, 2024; MNREGI, 2024). Finally, the development and enforcement of energy-efficiency building codes would help mainstream solar PV systems, LED lighting, and insulation materials in new residential construction (Kumar *et al.,* 2019).

5.0 CONCLUSION

The study evaluated the economic and environmental viability of solar photovoltaic systems, LED lighting, and high-performance insulation materials in Nigerian residential construction. The findings show that all three technologies can reduce household energy consumption, lower energy costs, and contribute to carbon-emission reduction, although their financial performance differs by investment cost, energy-saving potential, and climatic suitability. Solar PV systems produced the highest long-term energy and emission benefits, particularly in areas with strong solar irradiance, but their adoption is constrained by high upfront cost. LED lighting offered the shortest payback period and represents the most immediately affordable energy-efficiency option for households. High-performance insulation provided moderate but important benefits by reducing cooling demand, especially in hotter regions.

In line with the study objectives, the results confirm that energy-efficient technologies are financially viable and environmentally beneficial for Nigerian residential buildings when evaluated over their life cycle. However, adoption will

depend on supportive policies, affordable financing, public awareness, technical capacity, and enforceable energy-efficiency building standards. The study therefore recommends targeted subsidies, low-interest green financing, capacity-building for installers and builders, and the integration of energy-efficiency requirements into residential building codes. Future studies should validate these simulated findings using monitored energy-performance data from completed residential buildings across Nigeria's climatic zones.

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Danjuma Saleh Yawas	Data validation, visualisation, supervision and formal analysis
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