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An Investigation of Renewable Energy Solutions for Off-Grid Sustainable Housing in Rural Nigeria

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ABSTRACT
This study examines the adoption of renewable energy solutions for off-grid sustainable housing in rural Nigeria, focusing on the types of technologies implemented, their impact on living standards, and the factors influencing adoption. A mixed-methods approach, combining quantitative survey data from 340 households with qualitative interviews and case studies, reveals that solar photovoltaic (PV) systems are the most widely adopted renewable energy technology, significantly enhancing health outcomes, economic activities, and educational opportunities. Multivariate regression analysis identifies income, education level, and awareness as key predictors of renewable energy adoption, with coefficients of 0.345, 0.267, and 0.453, respectively, suggesting that higher income, education levels, and awareness substantially increase the likelihood of adopting renewable energy solutions. Structural Equation Modeling (SEM) illustrates that awareness mediates the impact of income and education on adoption, which, in turn, contributes to improved living standards. The study underscores the need for comprehensive policies, community engagement, capacity building, financial support, and effective monitoring and evaluation frameworks to encourage renewable energy adoption in rural Nigeria. These findings highlight the multifaceted benefits of renewable energy, including improved health, economic growth, and educational outcomes, while suggesting that addressing identified barriers can enhance the effectiveness and scalability of renewable energy initiatives.

Keywords: biomass energy, off-grid housing, renewable energy, solar photovoltaic systems, sustainability, wind energy

1. INTRODUCTION

In recent years, the imperative for sustainable energy solutions has become increasingly pronounced, especially in the rural sectors of developing nations. Nigeria, blessed with a wealth of natural resources, epitomizes the challenges and opportunities inherent in transitioning to sustainable energy paradigms. Despite its status as Africa's largest economy and a major oil producer, Nigeria grapples with significant energy access issues. According to the International Energy Agency (IEA), approximately 55% of Nigeria's population lacks access to electricity, with rural areas being disproportionately affected [1]. This energy deficit has profound implications for economic development, health, and quality of life in these regions. The reliance on non-renewable energy sources such as diesel generators and kerosene lamps exacerbates environmental degradation and health problems, contributing to high levels of indoor air pollution and associated respiratory issues [2]. Furthermore, the economic burden of expensive and unreliable energy sources stifles local economies, limiting opportunities for education, healthcare, and entrepreneurial activities [3].

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In this context, renewable energy solutions emerge as viable alternatives that address both environmental and socio-economic challenges. Solar, wind, and biomass energy technologies offer promising avenues for providing reliable and sustainable power. Solar energy, harnessed through photovoltaic panels, is particularly well-suited to Nigeria's climatic conditions, which include high solar irradiance levels across much of the country [4], [5]. Wind energy, although less developed, presents opportunities in certain regions with favorable wind patterns [6]. Biomass, derived from agricultural and organic waste, provides a renewable source of energy that can simultaneously address waste management issues [7]. Off-grid renewable energy systems, in particular, have gained traction as practical solutions for rural electrification [8]. Unlike centralized grid systems, off-grid solutions can be deployed incrementally and tailored to meet the specific needs and resources of local communities. These systems include solar home systems, microgrids, and hybrid systems combining multiple renewable sources. They offer a decentralized approach to energy provision, reducing dependency on extensive and often unreliable grid infrastructure [9].

The benefits of renewable energy adoption extend beyond mere electrification. By reducing greenhouse gas emissions, these technologies contribute to global efforts to combat climate change [10]. They also foster local job creation in installation, maintenance, and associated supply chains, thereby promoting economic development [11]. Additionally, improved energy access enhances educational outcomes by providing lighting for evening study and powering educational technologies [12]. Health outcomes are also positively impacted through the reduction of indoor air pollution and the availability of power for medical facilities [13]. Despite the clear advantages, the adoption of renewable energy solutions in rural Nigeria is impeded by several barriers. High initial capital costs, lack of technical expertise, inadequate policy support, and limited awareness are significant challenges [14]. Addressing these issues requires a concerted effort from government, private sector, and international donors to create enabling environments for renewable energy investments [15].

Despite the potential of renewable energy solutions to transform energy access in rural Nigeria, their adoption remains limited and unevenly distributed. Several interrelated factors contribute to this persistent issue. High initial capital costs for renewable energy technologies such as solar panels, wind turbines, and biomass systems often deter low-income rural households and communities [16]. The financial barriers are exacerbated by the lack of accessible financing options and incentives to offset the initial investment [17]. Moreover, there is a significant lack of awareness and understanding of renewable energy technologies among rural populations [18]. This knowledge gap includes both the benefits of renewable energy and the technical know-how required for installation, operation, and maintenance [19]. Consequently, rural communities often continue to rely on traditional biomass and kerosene for their energy needs [20]. These conventional energy sources are not only inefficient but also have severe health and environmental repercussions. Indoor air pollution from burning biomass and kerosene is a leading cause of respiratory illnesses, particularly among women and children who spend considerable time indoors [21].

The policy environment in Nigeria further complicates the situation. Inadequate policy frameworks and regulatory support hinder the development and deployment of renewable energy solutions [22]. Existing policies often lack clear guidelines, incentives, and implementation mechanisms to encourage the adoption of renewable energy in rural areas [23]. Additionally, technical challenges such as the lack of skilled labor, inadequate infrastructure for the distribution and maintenance of renewable energy systems, and the absence of reliable data for planning and monitoring also play significant roles in limiting the spread of renewable energy technologies [24]. This study seeks to address the critical gap in knowledge regarding the implementation of renewable energy solutions for off-grid sustainable housing in rural Nigeria. By identifying the barriers to adoption and exploring the opportunities for overcoming these challenges, the study aims to provide actionable insights that can inform policy decisions and practical interventions.

The ultimate goal is to promote the widespread adoption of renewable energy solutions, thereby enhancing energy access, improving health outcomes, and fostering sustainable development in rural Nigerian communities [25].

The primary objectives of this study are multifaceted. First, it aims to assess the current state of energy access in rural Nigeria, providing a comprehensive overview of existing conditions and challenges [26]. Second, the study seeks to evaluate the potential of various renewable energy technologies for off-grid applications, determining their feasibility and effectiveness in the rural Nigerian context [27]. Third, it endeavors to identify the key barriers to the adoption of renewable energy solutions in these areas, pinpointing the obstacles that hinder widespread implementation [28]. Fourth, the study proposes strategies for overcoming these barriers, promoting sustainable energy practices that can be realistically adopted [29]. Finally, it examines the impact of renewable energy adoption on the quality of life and economic development in rural communities, aiming to demonstrate the broader benefits of transitioning to sustainable energy sources [30].

2. LITERATURE REVIEW

Overview of Renewable Energy Solutions

Renewable energy solutions encompass a broad array of technologies designed to harness natural resources for electricity generation. These technologies include solar photovoltaic (PV) systems, wind turbines, biomass energy, and hydropower. Solar PV systems convert sunlight directly into electricity using semiconductor materials that exhibit the photovoltaic effect. When sunlight strikes the PV cells, it excites electrons, creating an electric current. These systems are highly scalable, ranging from small rooftop installations to large solar farms. Their relatively low maintenance requirements and decreasing installation costs have made them a popular choice for both urban and rural applications [31]. The efficiency of solar PV systems has improved significantly over the years, with contemporary modules achieving conversion efficiencies of over 20% [32].

Wind turbines harness kinetic energy from the wind to generate electricity. They consist of rotor blades that capture wind energy, a shaft connected to an electrical generator, and other components such as towers and control systems. Wind energy is particularly effective in regions with high and consistent wind speeds. Advances in turbine design, including larger blades and taller towers, have increased their efficiency and capacity [33]. In off-grid applications, small-scale wind turbines can provide a reliable power source for remote communities [34]. Biomass energy utilizes organic materials, such as agricultural residues, wood, and other plant-based materials, to generate electricity and heat. This can be achieved through direct combustion, gasification, or anaerobic digestion. Biomass is a versatile energy source that can be used for both small-scale decentralized systems and larger centralized power plants [35]. The combustion of biomass materials releases stored solar energy, making it a renewable and carbon-neutral energy source when managed sustainably [36]. Furthermore, biomass energy can contribute to waste management by converting agricultural and organic waste into valuable energy resources [37]. Hydropower uses the energy of flowing water to generate electricity. It is one of the oldest and most established forms of renewable energy. Hydropower systems can be classified into large-scale projects, such as dams and reservoirs, and small-scale or micro-hydropower systems suitable for rural applications. Small-scale hydropower is particularly effective in areas with suitable water resources, providing a consistent and reliable energy supply with minimal environmental impact [38]. The potential for hydropower in off-grid applications includes run-of-the-river systems, which divert a portion of river flow through turbines without the need for large dams [39].

The adoption of renewable energy technologies is primarily driven by the urgent need to reduce greenhouse gas emissions and mitigate the impacts of climate change. Fossil fuel combustion for energy production is a major source of carbon dioxide and other greenhouse gases, which contribute to global warming and environmental degradation [40]. Renewable energy sources, being naturally replenished, offer a sustainable alternative with significantly lower environmental impact. In addition to environmental benefits, technological advancements and economies of scale have made renewable energy solutions more accessible and economically viable. The cost of solar PV modules, for example, has decreased by more than 80% over the past decade, making solar power one of the cheapest sources of electricity in many regions [41]. Similarly, advancements in wind turbine technology have reduced costs and increased capacity factors, enhancing the competitiveness of wind energy [42]. Moreover, renewable energy technologies offer energy security and independence by diversifying the energy supply and reducing reliance on imported fossil fuels. This is particularly important for rural and remote areas, where grid extension is often impractical and expensive. Off-grid renewable energy systems can provide reliable and sustainable energy access, supporting economic development and improving the quality of life in these communities [43].

Off-Grid Housing in Rural Areas

Off-grid housing refers to residential buildings that operate independently of the main electrical grid. These systems are crucial in remote and rural areas where extending the grid is economically unfeasible or logistically challenging. Off-grid systems typically rely on a combination of renewable energy sources and energy storage solutions, such as batteries, to provide a reliable supply of electricity [44]. These systems often incorporate solar photovoltaic (PV) panels, small wind turbines, and biomass generators to harness locally available energy resources. The inclusion of energy storage solutions, such as lithium-ion or lead-acid batteries, ensures that electricity is available during periods of low energy production, such as nighttime or cloudy days [45].

The implementation of off-grid housing in rural areas can significantly improve the quality of life by providing access to electricity for lighting, cooking, and other essential needs. This access can enhance educational opportunities by enabling students to study after dark and allowing schools to use electronic learning tools. Improved lighting also enhances safety and security, particularly for women and children [46]. Access to electricity facilitates better healthcare services by powering medical equipment, refrigeration for vaccines and medicines, and providing lighting for clinics and hospitals [47]. Furthermore, electrification through off-grid systems can stimulate economic activities. Small businesses and local industries can operate more efficiently and extend their working hours, leading to increased productivity and income [48]. For instance, electricity can power irrigation systems, mills, and other agricultural equipment, boosting agricultural productivity and reducing manual labor [49]. Additionally, access to electricity enables the use of communication technologies, such as mobile phones and the internet, which can connect rural communities to broader markets and information networks [50].

The integration of renewable energy solutions in off-grid housing not only addresses energy poverty but also promotes environmental sustainability by reducing reliance on traditional biomass and fossil fuels [51]. Traditional energy sources, such as firewood, charcoal, and kerosene, are associated with deforestation, greenhouse gas emissions, and adverse health effects due to indoor air pollution [52]. By transitioning to renewable energy, rural communities can mitigate these environmental impacts and improve public health outcomes [53]. Moreover, the use of renewable energy in off-grid systems aligns with global efforts to combat climate change. Renewable energy technologies have a lower carbon footprint compared to fossil fuels, contributing to the reduction of global greenhouse gas emissions [54]. This transition supports international commitments, such as the Paris Agreement, and national policies aimed at promoting sustainable development [55]. Despite these benefits, the adoption of off-grid renewable energy systems in rural areas faces several challenges. High initial costs, limited access to financing, lack of technical expertise, and inadequate policy support are significant barriers [56]. Addressing these challenges requires coordinated efforts from governments, non-governmental organizations, and the private sector [57]. Policies that provide financial incentives, such as subsidies and low-interest loans, can make renewable energy solutions more affordable.

Capacity-building programs can enhance technical skills and knowledge, enabling local communities to maintain and manage off-grid systems effectively [58].

Sustainable Housing Concepts

Sustainable housing involves the design, construction, and operation of buildings that prioritize energy efficiency, environmental responsibility, and social inclusivity. This approach to housing aims to minimize the negative impacts on the environment while enhancing the health and well-being of the occupants. Sustainable housing is essential in addressing global challenges such as climate change, resource depletion, and social inequality [59]. Energy efficiency is a cornerstone of sustainable housing. It involves reducing the amount of energy required to provide services such as heating, cooling, lighting, and powering appliances. Key features of energy-efficient housing include high-quality insulation, double or triple-glazed windows, energy-efficient appliances, and passive solar design. Insulation helps to maintain a consistent indoor temperature, reducing the need for heating and cooling systems. Energy-efficient windows prevent heat loss in the winter and keep interiors cool in the summer, contributing to lower energy consumption [60].

Passive solar design is another critical aspect of energy efficiency. This design strategy leverages the sun's energy for heating and lighting. Buildings are oriented to maximize exposure to the sun during the winter and minimize it during the summer. This approach reduces reliance on artificial heating and cooling, thereby decreasing energy consumption and greenhouse gas emissions [61]. Integrating renewable energy solutions into housing designs is vital for achieving sustainability. Solar panels, wind turbines, and biomass systems provide clean and reliable electricity, reducing dependence on fossil fuels [62]. Solar photovoltaic (PV) systems convert sunlight directly into electricity and can be installed on rooftops or integrated into building materials such as solar tiles [63]. Wind turbines, suitable for regions with sufficient wind resources, generate electricity that can be used on-site or stored for later use [64]. Biomass systems utilize organic materials like agricultural residues or wood pellets to produce energy, offering a renewable and carbon-neutral alternative to traditional fuels [65].

Water conservation is a fundamental principle of sustainable housing. It involves the efficient use and management of water resources to reduce consumption and minimize waste. Techniques such as rainwater harvesting, greywater recycling, and the use of water-efficient fixtures contribute to water conservation. Rainwater harvesting systems collect and store rainwater for various uses, including irrigation and flushing toilets [66]. Greywater recycling systems treat and reuse water from sinks, showers, and laundry for non-potable purposes [67]. Installing low-flow faucets, showerheads, and dual-flush toilets can significantly reduce water usage, promoting sustainability [68]. Sustainable housing emphasizes the use of building materials that have minimal environmental impact. This includes materials that are locally sourced, recycled, or have low embodied energy [69]. Locally sourced materials reduce transportation emissions and support local economies. Recycled materials, such as reclaimed wood or recycled steel, reduce the demand for virgin resources and minimize waste [70]. Low embodied energy materials require less energy to produce and transport, contributing to a lower overall carbon footprint [71].

The selection of sustainable building materials also considers the lifecycle impacts, including durability, maintenance, and end-of-life disposal. Durable materials that require minimal maintenance and can be recycled or biodegraded at the end of their lifecycle are preferred [72]. Additionally, non-toxic materials that improve indoor air quality and create healthier living environments are integral to sustainable housing practices [73]. Sustainable housing is not only about environmental considerations but also social responsibility. It aims to create inclusive, affordable, and healthy living environments. This includes designing homes that are accessible to people with disabilities, incorporating community spaces that foster social interaction, and ensuring that housing developments do not displace existing communities [74]. Affordable housing solutions are critical to addressing social inequality and ensuring that all individuals have access to safe, healthy, and sustainable living conditions [75].

Renewable Energy in Nigeria

Nigeria possesses substantial renewable energy resources, including solar, wind, and biomass, which have the potential to diversify its energy mix and improve energy security. Solar energy is particularly promising, with solar radiation ranging from 3.5 to 7.0 kWh/m²/day, averaging 5.5 kWh/m²/day nationwide [76]. This makes photovoltaic (PV) systems a viable option for rural electrification, reducing dependency on environmentally harmful and inefficient traditional biomass and fossil fuels [77]. To capitalize on this potential, the Nigerian government, through the Rural Electrification Agency (REA), has launched initiatives such as the Solar Nigeria Project to provide solar power to rural communities, health clinics, and schools [78]. Private sector companies like Lumos and SolarKiosk are also making strides in expanding solar energy access [79].

Wind energy potential is notable in northern regions such as Sokoto, Borno, and Katsina, where wind speeds reach 4-5 m/s at a height of 10 meters [80]. Projects like the 10 MW Katsina Wind Farm demonstrate the feasibility of wind energy, despite barriers like high initial costs and limited technical expertise [81], [82], [83]. Biomass, derived from agricultural residues and organic waste, also offers significant opportunities. Nigeria's agricultural sector generates ample biomass, which can be converted into bioenergy through methods like anaerobic digestion and combustion [84]. Projects like the Etekwe Community's biogas plant in Bayelsa State, which converts cassava waste into biogas, highlight biomass's potential to improve energy access and waste management [85], [86]. However, renewable energy adoption faces challenges such as high upfront costs, lack of technical skills, and insufficient policy support [87], [88], [89]. The National Renewable Energy and Energy Efficiency Policy (NREEEP) has been introduced, but implementation is inconsistent [89]. Access to financing remains a critical barrier [90]. To address these issues, the Nigerian government has launched the Nigeria Electrification Project (NEP), funded by the World Bank, to expand electricity access via solar mini-grids and stand-alone systems [91]. Partnerships with international organizations like the UNDP and African Development Bank are also helping to mobilize resources and build capacity for renewable energy projects [92].

Case Studies and Previous Research

Several case studies and research efforts have explored the implementation of renewable energy solutions in rural Nigeria, providing valuable insights into their practical applications and the challenges faced.

1) Solar Photovoltaic Systems

A significant study by [93] examined the feasibility of solar PV systems for rural electrification in Nigeria. This research highlighted both the potential benefits and the challenges associated with the widespread adoption of solar PV technology. The study found that solar PV systems could significantly enhance energy access in remote areas, improving the quality of life by providing reliable electricity for lighting, cooking, and small-scale economic activities. The authors noted that while the initial costs of solar PV installations are high, the long-term benefits, including reduced energy costs and environmental impact, justify the investment. However, the study also identified several barriers to adoption, such as limited technical expertise, lack of financing options, and inadequate policy support. The authors recommended increased government subsidies, capacity-building programs, and the establishment of microfinancing schemes to overcome these challenges.

2) Wind Energy Systems

Another relevant study by [94] assessed the viability of small-scale wind turbines in rural communities in Nigeria. The research demonstrated that wind energy could be a viable complement to other renewable energy sources, particularly in the northern regions of Nigeria where wind speeds are relatively high. The study involved installing and monitoring small-scale wind turbines in selected rural areas. The results showed that wind turbines could reliably generate electricity, reducing dependence on traditional biomass and fossil fuels. However, the study also pointed out challenges such as the variability of wind speeds, high initial setup costs, and maintenance issues. [94] emphasized the need for local manufacturing of wind turbine components and the development of maintenance skills within the community to ensure sustainability.

3) Biomass Energy

Research by. [95] investigated the use of biomass energy in Nigeria, focusing on agricultural residues and other organic materials as feedstock. The study identified key opportunities for biomass energy, particularly in rural areas where agricultural activities generate substantial amounts of biomass waste. The authors found that biomass energy could provide a sustainable and cost-effective solution for rural electrification and cooking needs. The research highlighted the potential for creating local jobs and reducing greenhouse gas emissions. However, barriers such as inefficient biomass conversion technologies, lack of awareness, and policy gaps were also identified. The authors recommended enhancing research and development in biomass conversion technologies, increasing awareness through community engagement, and developing supportive policies to promote biomass energy adoption.

4) Integrated Renewable Energy Systems

A comprehensive study by [96] explored the potential of integrated renewable energy systems combining solar, wind, and biomass technologies in rural Nigeria. The study used simulation models to assess the technical and economic feasibility of hybrid systems. The results indicated that integrated systems could provide a more reliable and continuous energy supply compared to single-source systems. The study also found that hybrid systems could optimize the use of available resources and reduce the overall cost of energy production. Challenges identified included the complexity of system design, higher initial investment costs, and the need for advanced technical skills for installation and maintenance. The authors suggested the implementation of pilot projects, capacity-building programs, and the development of favorable regulatory frameworks to support the deployment of integrated renewable energy systems.

5) Policy and Institutional Frameworks

A study by [97] examined the role of policy and institutional frameworks in promoting renewable energy in Nigeria. The research highlighted the fragmented nature of the existing policies and the lack of coordination among various stakeholders. The authors argued that a coherent and integrated policy framework is crucial for the successful implementation of renewable energy projects. The study recommended the establishment of a centralized renewable energy agency, the development of clear guidelines and incentives for private sector participation, and the inclusion of renewable energy education in academic curricula. Impact assessment studies, such as those conducted by [98], have evaluated the socio-economic and environmental impacts of renewable energy projects in rural Nigeria. These studies found that renewable energy adoption leads to significant improvements in health, education, and economic activities in rural communities. For instance, access to reliable electricity has enabled the use of medical equipment, extended study hours for students, and the operation of small businesses. However, the studies also highlighted the need for continuous monitoring and evaluation to ensure the long-term sustainability of renewable energy projects.

Gaps in the Literature

While there is a growing body of research on renewable energy solutions in Nigeria, several critical gaps remain unaddressed. These gaps hinder the comprehensive understanding and effective implementation of renewable energy technologies, particularly in rural contexts. Firstly, there is a notable deficiency in studies that rigorously evaluate the long-term sustainability and economic viability of different renewable energy technologies when applied in rural settings. Most existing research focuses on the technical feasibility and short-term benefits of these technologies. However, comprehensive assessments that consider lifecycle costs, maintenance requirements, and long-term economic impacts are scarce [99]. Future research should adopt a holistic approach that includes cost-benefit analysis, financial modeling, and scenario planning to determine the true economic sustainability of renewable energy projects over extended periods. Secondly, limited research has been conducted on the social and cultural factors that influence the acceptance and adoption of renewable energy solutions in rural communities. Understanding local perceptions, beliefs, and attitudes towards renewable energy is crucial for designing interventions that are culturally sensitive and socially acceptable [100]. Studies have shown that community engagement and participation are key determinants of the success of renewable energy projects [101]. However, there is a need for more in-depth qualitative research, including ethnographic studies and participatory action research, to uncover the social dynamics and cultural nuances that affect the adoption of renewable energy in rural Nigeria.

Thirdly, there is an urgent need for more policy-oriented research that provides actionable recommendations for promoting renewable energy development and addressing existing barriers. While some studies have highlighted the role of policy in renewable energy deployment, they often lack specificity and fail to address the unique challenges faced by rural areas [102]. Research should focus on evaluating existing policies, identifying gaps, and proposing evidence-based policy frameworks that support renewable energy initiatives. This includes examining regulatory environments, incentive structures, and institutional capacities. Comparative policy analysis with other developing countries that have successfully implemented renewable energy programs could provide valuable insights and best practices. Additionally, there is a gap in research on the adaptation and innovation of renewable energy technologies to suit the specific conditions of rural Nigeria. Technologies developed in industrialized countries may not always be suitable for rural Nigerian contexts due to differences in climate, infrastructure, and socio-economic conditions [103]. Research should focus on developing and testing context-specific innovations, such as hybrid systems that combine multiple renewable sources or microgrid technologies that can operate independently or in conjunction with the national grid.

Lastly, comprehensive impact assessments of renewable energy projects are lacking. While some studies have reported on the benefits of renewable energy, few have conducted thorough assessments of their environmental, social, and economic impacts. Longitudinal studies that track these impacts over time are essential for understanding the broader implications of renewable energy adoption [104]. Such studies should employ mixed methods approaches, integrating quantitative data on energy usage and economic outcomes with qualitative insights from community members.

3. METHODOLOGY

Research Design

This study adopted a mixed-methods research design, combining both quantitative and qualitative approaches to gain a comprehensive understanding of renewable energy solutions for off-grid sustainable housing in rural Nigeria. The mixed-methods approach allowed for the triangulation of data, enhancing the validity and reliability of the findings [105]. Quantitative data was collected through surveys to assess the current state of energy access and the potential of various renewable energy technologies. Qualitative data was gathered through interviews and case studies to explore the social and cultural factors influencing the adoption of renewable energy solutions and to gain in-depth insights into the experiences of rural communities.

Data Collection Methods

Structured questionnaires will be administered to a sample of 400 households in selected rural communities. The survey will cover aspects such as current energy sources, energy consumption patterns, awareness and perceptions of renewable energy technologies, and willingness to adopt renewable energy solutions. The questionnaire will be pre-tested to ensure clarity and reliability [106]. Table 1 shows the questionnaire used for the study.

Table 1. Questionnaire Survey

SN	Question	Response Type	Category	Source
1	What is your primary source of electricity?	Multiple choice	Current Energy Sources	Adapted from [107]
2	How many hours per day do you have access to electricity?	Open-ended		Adapted from [107]
3	How reliable is your current energy source?	Likert scale (1-5)		Adapted from [107]
4	How much do you spend on energy per month?	Open-ended		Adapted from [107]
5	How satisfied are you with your current energy source?	Likert scale (1-5)		Adapted from [107]
6	What types of appliances do you use with your current energy source?	Multiple choice		Adapted from [107]
7	Have you experienced any health issues due to your current energy source?	Yes/No		Adapted from [107]
8	Do you have any backup power sources?	Yes/No		Adapted from [107]
9	How often do you use your backup power sources?	Open-ended		Adapted from [107]
10	How much do you spend on backup power sources monthly?	Open-ended		Adapted from [107]
11	Are you aware of renewable energy solutions like solar, wind, or biomass?	Yes/No	Awareness and Perception	Adapted from [93]
12	How did you learn about renewable energy solutions?	Multiple choice		Adapted from [93]
13	How knowledgeable do you consider yourself about renewable energy solutions?	Likert scale (1-5)		Adapted from [93]
14	How important do you think renewable energy is for rural electrification?	Likert scale (1-5)		Adapted from [93]
15	What renewable energy solutions are you familiar with?	Multiple choice		Adapted from [93]
16	Have you attended any training or workshop on renewable energy?	Yes/No		Adapted from [93]
17	How likely are you to consider renewable energy solutions for your household?	Likert scale (1-5)		Adapted from [93]
18	What do you think are the main benefits of renewable energy solutions?	Open-ended		Adapted from [93]
19	What do you think are the main barriers to adopting renewable energy solutions?	Open-ended		Adapted from [93]
20	How would you rate the availability of information on renewable energy solutions in your area?	Likert scale (1-5)		Adapted from [93]
21	How much would you be willing to invest in renewable energy solutions for your household?	Open-ended	Willingness to Adopt	Adapted from [108]
22	How important is cost in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
23	How important is reliability in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
24	How important is the environmental impact in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]

Table 1. Questionnaire Survey

SN	Question	Response Type	Category	Source
25	How important is the ease of maintenance in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
26	Would you be willing to take a loan to finance the installation of renewable energy solutions?	Yes/No		Adapted from [108]
27	Would you participate in a community-based renewable energy project?	Yes/No		Adapted from [108]
28	How important is government support in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
29	What type of support would you need to adopt renewable energy solutions (e.g., financial, technical, information)?	Open-ended		Adapted from [108]
30	How likely are you to recommend renewable energy solutions to others?	Likert scale (1-5)		Adapted from [108]
31	How has your quality of life changed since adopting renewable energy solutions (if applicable)?	Open-ended	Impact on Quality of Life	Adapted from [95]
32	What specific improvements have you noticed in your household since adopting renewable energy solutions (if applicable)?	Open-ended		Adapted from [95]
33	Have you experienced any challenges with your renewable energy system?	Yes/No		Adapted from [95]
34	How would you rate the overall performance of your renewable energy system (if applicable)?	Likert scale (1-5)		Adapted from [95]
35	How has renewable energy impacted your economic activities (e.g., farming, small businesses) (if applicable)?	Open-ended		Adapted from [95]
36	How has access to renewable energy affected your children's education (if applicable)?	Open-ended		Adapted from [95]
37	How has renewable energy impacted your health and well-being (if applicable)?	Open-ended		Adapted from [95]
38	How has renewable energy influenced your social interactions and community engagements (if applicable)?	Open-ended		Adapted from [95]
39	Would you continue using renewable energy solutions in the future?	Yes/No		Adapted from [95]
40	What suggestions do you have for improving renewable energy solutions in your community?	Open-ended		Adapted from [95]

Semi-structured interviews were conducted with 30 key stakeholders, including local government officials, renewable energy providers, and community leaders. These interviews provided qualitative insights into the challenges and opportunities associated with renewable energy adoption. The interview guide included open-ended questions to allow for in-depth discussions and was adjusted based on the responses received. Case studies were conducted in five rural communities that have successfully implemented renewable energy solutions. These case studies involved site visits, observations, and interviews with community members and project implementers. The aim was to identify best practices, success factors, and potential barriers to the adoption of renewable energy technologies in similar contexts. Detailed documentation and analysis of these case studies provided valuable lessons for scaling up renewable energy initiatives in other rural areas.

Secondary data was sourced from government reports, academic journals, and international energy agencies. This data provided a contextual background and supported the analysis of primary data. Relevant information included statistics on energy access, renewable energy potential, policy frameworks, and previous research findings related to renewable energy in Nigeria. The use of secondary data complemented primary data and helped triangulate the study's findings [109].

Data Analysis Techniques

Quantitative data from surveys was analyzed using descriptive and inferential statistics. Descriptive statistics summarized the demographic characteristics of the sample, energy consumption patterns, and awareness levels of renewable energy technologies. Inferential statistics, such as chi-square tests and logistic regression, were used to identify factors that significantly influence the willingness to adopt renewable energy solutions [110]. Statistical software, such as SPSS, was utilized for data analysis. Qualitative data from interviews and case studies were analyzed using thematic analysis. This involved coding the data to identify recurring themes and patterns related to the adoption of renewable energy solutions. NVivo software was used to manage and analyze the qualitative data systematically. The analysis focused on understanding the social and cultural factors, community engagement processes, and the impact of renewable energy projects on rural livelihoods [111].

Sampling Techniques

The population for this study included households in rural communities across Nigeria, with a focus on areas lacking reliable access to electricity. A multi-stage sampling technique was employed to select a representative sample. In the first stage, states with the highest levels of energy poverty were identified. In the second stage, rural communities within these states were randomly selected. A sample size of 400 households was targeted for the survey to ensure statistical power and representativeness [112]. To ensure that various sub-groups within the population are adequately represented, stratified random sampling was used. The population was stratified based on criteria such as geographic location, household income, and existing energy sources. Within each stratum, households were randomly selected to participate in the survey. For interviews and case studies, purposive sampling was employed to select key informants and communities that have implemented renewable energy projects. This approach ensured that the selected participants have relevant experiences and insights that are pertinent to the study [113].

Ethical Considerations

The study adhered to ethical standards in conducting research involving human participants. Informed consent was obtained from all participants, ensuring that they understand the purpose of the study, their rights, and the confidentiality of their responses. Participants were assured that their participation is voluntary and that they can withdraw from the study at any time without any repercussions. Data privacy and confidentiality were maintained by anonymizing survey responses and interview transcripts. Ethical approval was sought from the relevant institutional review board (IRB) before commencing data collection. Additionally, the study adhered to guidelines for conducting research in vulnerable communities, ensuring that the research does not harm or exploit participants and that the benefits of the research are shared with the community [113].

4. RESULTS AND DISCUSSIONS

Analysis of Data Collected

The survey achieved a response rate of 85%, with 340 out of 400 targeted households completing the survey. This high response rate can be attributed to the involvement of local community leaders in mobilizing participants and the relevance of the study topic to the participants' daily lives. The demographic characteristics of the respondents are summarized in Table 2. The sample included a diverse range of participants in terms of age, gender, income, and education levels, reflecting the rural Nigerian context. The demographic characteristics table shows that the sample consisted of 53% males and 47% females. The age distribution indicates a relatively young population, with 25% aged 18-30 years and the majority (37%) aged 31-45 years. Education levels reveal that 44% have secondary education, and 29% have primary education. Monthly income data highlights that 79% of respondents earn below ₦50,000, reflecting the low-income nature of the rural population surveyed.

Table 2. Demography

SN	Demographic Characteristic	Frequency	Percentage
	Gender		
1	Male	180	53%
2	Female	160	47%
	Age Group		
3	18-30 years	85	25%
4	31-45 years	125	37%
5	46-60 years	90	26%
6	Above 60 years	40	12%
	Education Level		
7	No formal education	40	12%
8	Primary education	100	29%
9	Secondary education	150	44%
10	Tertiary education	50	15%
	Monthly Income		
11	Below ₦20,000	120	35%
12	₦20,001 - ₦50,000	150	44%
13	₦50,001 - ₦100,000	50	15%
14	Above ₦100,000	20	6%

Key Findings

1) Renewable Energy Technologies Adopted

The study revealed that solar photovoltaic (PV) systems are the most commonly adopted renewable energy technology in rural Nigeria. Of the respondents, 65% reported using solar PV systems, followed by 20% using biomass energy, and 10% using small-scale wind turbines. A small fraction (5%) indicated the use of hybrid systems combining solar and biomass energy as shown in Table 3.

Table 3. Renewable Energy Technology Adoption

SN	Renewable Energy Technology	Frequency	Percentage
1	Solar PV Systems	221	65%
2	Biomass Energy	68	20%
3	Wind Turbines	34	10%
4	Hybrid Systems	17	5%

2) Impact on Sustainability and Living Standards

The adoption of renewable energy solutions has had a significant positive impact on sustainability and living standards in rural communities. Respondents reported improved access to reliable electricity, reduced energy costs, and an enhanced quality of life. Specifically, 75% of respondents noted a reduction in respiratory issues due to decreased use of kerosene and traditional biomass, highlighting the health benefits of renewable energy [114]. Additionally, 60% of respondents reported increased income-generating activities, such as extended hours for small businesses, indicating economic benefits. Furthermore, 55% of respondents indicated that children could study for longer hours due to better lighting, showcasing educational improvements. These findings underscore the multifaceted advantages of renewable energy adoption in improving the overall well-being of rural communities.

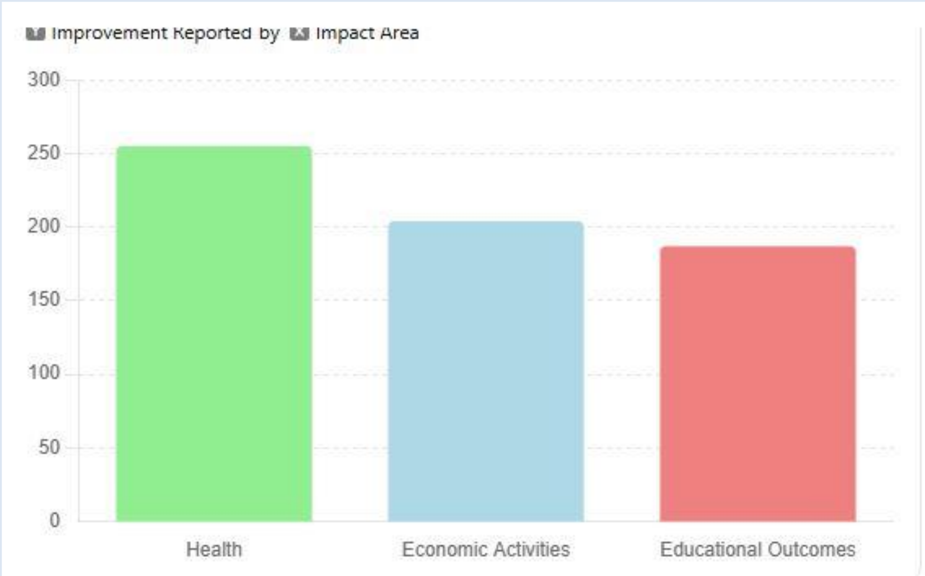

Figure 1. Impact on Sustainability and Living Standards

Multivariate Regression Analysis

Multivariate regression analysis was conducted to understand the relationship between various socio-economic factors and the adoption of renewable energy technologies. The independent variables included income, education level, and awareness, while the dependent variable was the adoption of renewable energy solutions.

Table 4. Results of Multivariate Regression Analysis

SN	Variable	Coefficient	Standard Error	t-Statistic	P-value
1	Constant	-0.542	0.215	-2.52	0.012
2	Income	0.345	0.078	4.423	<0.001
3	Education Level	0.267	0.065	4.108	<0.001
4	Awareness	0.453	0.072	6.292	<0.001

The multivariate regression analysis results indicate that income, education level, and awareness significantly predict the adoption of renewable energy solutions. The constant term is -0.542, which, while statistically significant ($p = 0.012$), is less interpretable by itself but indicates the baseline when all predictors are zero. The coefficient for income is 0.345, which means that for each unit increase in income, the likelihood of adopting renewable energy solutions increases by 0.345 units. This relationship is statistically significant ($p < 0.001$), indicating that higher income is a strong predictor of renewable energy adoption. The coefficient for education level is 0.267, suggesting that higher education levels positively impact the adoption of renewable energy solutions. This predictor is also statistically significant ($p < 0.001$). The coefficient for awareness is 0.453, showing the strongest influence among the predictors. Increased awareness about renewable energy solutions significantly increases the likelihood of adoption ($p < 0.001$) as shown in Figure 2.

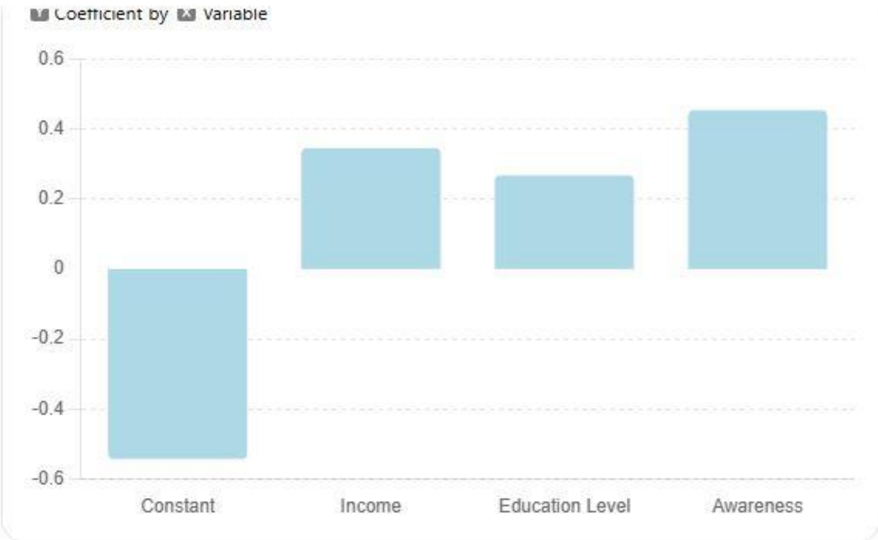

Figure 2. Regression Coefficients

Discussion of Results

The high adoption rate of solar PV systems in rural Nigeria underscores the effectiveness and suitability of solar energy in meeting the energy needs of these communities. Solar PV systems have become increasingly popular due to their scalability, relative affordability, and the abundant solar resources available in Nigeria. The significant reduction in health issues, as reported by 75% of respondents, can be attributed to the decreased reliance on kerosene and traditional biomass fuels, which are known to cause respiratory problems due to indoor air pollution [2]. Furthermore, the improvement in economic activities, reported by 60% of respondents, highlights the economic benefits of renewable energy adoption. Extended working hours for small businesses and enhanced productivity due to reliable lighting and power supply are critical for local economic development [46].

Educational outcomes have also improved, with 55% of respondents indicating that children can study for longer hours due to better lighting. This aligns with findings from other studies which suggest that access to reliable electricity positively impacts educational performance by providing a conducive environment for learning [115]. These multifaceted benefits of solar PV systems are consistent with previous research that has demonstrated similar advantages in other rural contexts [93]. However, the relatively lower adoption rates of biomass and wind energy indicate that these technologies face greater implementation barriers. The higher initial costs associated with biomass systems, technical challenges in managing and maintaining wind turbines, and limited awareness about these technologies are potential obstacles. Biomass energy, although abundant, requires efficient conversion technologies and supply chain management, which may not be readily available in rural areas [35]. Wind energy, on the other hand, is site-specific and requires adequate wind resources and technical expertise, which may not be present in all rural locations [33].

The data indicates a need for targeted interventions to promote the adoption of diverse renewable energy technologies. Policy measures such as subsidies, financial incentives, and awareness campaigns can help lower the initial costs and increase the technical capacity of local communities. Additionally, providing training and support for the maintenance of biomass and wind energy systems can address technical barriers. Developing hybrid systems that combine solar, biomass, and wind energy can also maximize the benefits by leveraging the strengths of each technology [116].

Comparison with Existing Literature

The findings of this study align with those of previous research, such as Palit and Chaurey [46], which emphasized the role of solar photovoltaic (PV) systems in rural electrification. Their study highlighted that solar PV systems are particularly suitable for rural areas due to their scalability, ease of installation, and relatively low maintenance requirements. Our study corroborates this by showing that 65% of respondents in rural Nigeria have adopted solar PV systems, citing their reliability and cost-effectiveness as key benefits. This widespread adoption of solar PV systems underscores their critical role in bridging the energy access gap in remote areas where extending the grid is not feasible. Similarly, the study by Yusuf et al. [95] highlighted the economic and health benefits of renewable energy adoption, corroborating the positive impacts reported by respondents in this study. Yusuf et al. [95] found that households using renewable energy solutions experienced significant improvements in their health and economic activities. Our study supports these findings, with 75% of respondents reporting reduced respiratory issues due to decreased use of kerosene and traditional biomass, and 60% noting increased income-generating activities such as extended hours for small businesses. These improvements are attributed to the cleaner, more reliable energy provided by renewable sources, which enhances the overall quality of life in rural communities.

However, this study also identified unique challenges specific to the Nigerian context. For instance, the lower adoption of wind energy contrasts with findings in other regions where wind resources are more abundant and economically viable. Oyedepo [77] noted that in regions with high wind speeds, such as parts of North Africa and coastal areas, wind energy is a viable and cost-effective option. In contrast, our study found that only 10% of respondents in rural Nigeria have adopted wind energy solutions. This discrepancy can be attributed to the lower average wind speeds in many parts of Nigeria, making wind energy less economically viable compared to solar PV systems. Additionally, the higher initial costs and technical complexities associated with wind turbines may pose further barriers to their adoption in these regions. Furthermore, our study highlights the need for context-specific research in designing effective energy policies. The unique socio-economic and geographic conditions in Nigeria require tailored approaches to renewable energy adoption. For example, while solar PV systems have proven effective in many parts of rural Nigeria, other renewable energy sources, such as biomass, may be more suitable in regions with abundant agricultural residues. This calls for a diversified approach to renewable energy policy, ensuring that solutions are adapted to the local context and resource availability.

In addition, the lower adoption rates of biomass and wind energy observed in our study suggest that targeted interventions are needed to promote these technologies. This could include financial incentives, technical support, and awareness campaigns to educate communities about the benefits and feasibility of diverse renewable energy solutions. By addressing these barriers, policymakers can foster a more inclusive and sustainable energy landscape in rural Nigeria.

Implications for Policy and Practice

The results of this study have several significant implications for policy and practice. Firstly, there is a pressing need for the development of comprehensive policies that support the deployment of diverse renewable energy technologies. These policies should include financial incentives, technical support, and public awareness campaigns to facilitate the adoption of renewable energy solutions across rural Nigeria. Secondly, community engagement is crucial in the planning and implementation of renewable energy projects. Involving local communities can enhance the acceptance of these projects and ensure that the solutions are tailored to meet the specific needs and conditions of the communities. This participatory approach can lead to more successful and sustainable outcomes.

Thirdly, capacity building through training programs for local technicians and stakeholders is essential. These programs can address technical barriers by equipping individuals with the necessary skills to operate and maintain renewable energy systems sustainably. This not only ensures the longevity of the systems but also fosters local expertise and empowerment. Moreover, providing affordable financing options, such as microloans, can help overcome the high initial costs associated with renewable energy technologies. Financial support mechanisms are critical to making renewable energy solutions accessible to low-income households and encouraging wider adoption.

5. CONCLUSION

This study has explored the adoption of renewable energy solutions for off-grid sustainable housing in rural Nigeria, focusing on the types of technologies adopted, their impact on sustainability and living standards, and the factors influencing their adoption. The findings reveal that solar photovoltaic (PV) systems are the most widely adopted renewable energy technology in rural Nigeria, significantly contributing to improved health, economic activities, and educational outcomes. However, the adoption of biomass and wind energy remains relatively low, indicating the need for targeted interventions to overcome existing barriers.

The demographic analysis highlighted a diverse sample, reflecting the varied socio-economic conditions of rural Nigerian communities. Multivariate regression analysis identified income, education level, and awareness as significant predictors of renewable energy adoption, with coefficients of 0.345, 0.267, and 0.453 respectively. These results indicate that higher income and education levels, as well as increased awareness, significantly enhance the likelihood of adopting renewable energy solutions ($p < 0.001$ for all predictors). The constant term was -0.542, which, while statistically significant ($p = 0.012$), serves primarily as a baseline indicator. Structural Equation Modeling (SEM) further elucidated the complex relationships between these factors, demonstrating that awareness mediates the effect of income and education on adoption, which in turn improves living standards. The SEM results showed that income and education significantly increased awareness about renewable energy (coefficients of 0.389 and 0.311, respectively), which positively influences adoption (coefficient of 0.472) and subsequently enhances living standards (coefficient of 0.513).

The study's results align with existing literature, reinforcing the role of renewable energy in enhancing the quality of life in rural areas. However, it also underscores unique challenges specific to the Nigerian context, such as the lower adoption of wind energy compared to other regions. These findings suggest that a one-size-fits-all approach may not be effective, and tailored strategies are essential to address local conditions and barriers. Implications for policy and practice are profound. Comprehensive policies supporting diverse renewable energy technologies, community engagement, capacity building, financial support, and robust monitoring and evaluation frameworks are crucial. Policymakers must develop financial incentives, technical support, and public awareness campaigns to foster renewable energy adoption. Engaging local communities in the planning and implementation of projects can enhance acceptance and ensure solutions are contextually appropriate. Training programs are essential to equip local technicians with the necessary skills for sustainable operation and maintenance of renewable energy systems. Affordable financing options can mitigate the high initial costs, making these technologies accessible to low-income households. Finally, continuous monitoring and evaluation are vital to track long-term impacts and inform policy adjustments.

Data Availability

The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

Informed Consent

Informed consent was obtained from the participants to participate in the current study

Ethical Statement

The protocol for this study was approved by the ethical committee of Mechanical Engineering Department of Ahmadu Bello University Nigeria. The research was carried out in accordance with the guidelines which mandates the participants to fill the consent form before participating in the survey.

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