Digital Innovations & Contemporary Research in SCIENCE, ENGINEERING & TECHNOLOGY
Vol. 13. No. 4, 2025 Series

Article Citation Format
Oyeniran O.R., Oladosu J.A.& Olaniran N.O. (2025): Energy Sustainability Framework for Effective Transition and Community Development: A Case Study Of Esa-Oke Town, Osun State, Nigeria . Journal of Digital Innovations & Contemporary Research in Science, Engineering & Technology. Vol. 13, No. 4. Pp 11-22. www.isteams.net/digitaljournal dx.doi.org/10.22624/AIMS/DIGITAL/V13N2P2

Article Progress Time Stamps
Article Type: Research Article
Manuscript Received: 14th September, 2025
Review Type: Blind Peer
Final Acceptance: 28th November, 2025

Energy Sustainability Framework for Effective Transition and Community Development: A Case Study Of Esa-Oke Town, Osun State, Nigeria

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ABSTRACT

This paper reveals energy management activities and the transition strategies in a semi-urban area of Esa-Oke, Nigeria, where energy waste, inconsistent grid power supply, and overreliance on generators continue to affect the economy. The research uses a mixed-methods approach, combining household, business, and institutional surveys and qualitative interviews, enabling a more comprehensive evaluation of consumption trends, cost differences, and willingness to adopt renewable energy. The results indicate that high-wattage appliances are one of the most energy-demanding both in homes and institutions. Simultaneously, frequent power outages also mean that they have to rely on petrol and diesel generators, which also adds to significant variations in the cost per kWh across the groups. Energy consumption and spending exhibit right-skewed distributions, showing that a few large organizations control the total energy consumption, while low-income households bear a disproportionately high cost burden relative to income. More than three-quarters of the surveyed people indicate readiness to embrace solar energy, assuming that favorable financing systems are in place. The research project presents a synthesized energy transition model that considers the use of solar deployment, energy-efficient technologies, and behavioral change approaches. Projections indicate, with a 22 percent reduction in cumulative electricity and a 15 percent rise in the renewable energy share, there's a possibility of the same in ten years. In general, the study provides a viable, evidence-based model that can inform the process of sustainable energy transition planning in Esa-Oke and other semi-urban communities in Nigeria and in the emerging economies of the sub-Saharan region.

Keywords: Energy Management; Energy Policy; Renewable Energy; Smart Grid Technology; Supply

1. INTRODUCTION

Energy management is a critical part of national development, particularly in a resource-endowed country like Nigeria, where proper use of the energy resources can have a great impact on economic growth and societal well-being. Although these benefits are possible, Nigeria has significant energy-related problems that make it hard to attain sustainable development.

The energy sector is also characterized by poor infrastructure, high transmission losses, and overdependence on fossil fuels, and as a result, frequent power outages and limited access to clean energy options are experienced in the country (Augusta Heavens Ikevuje et al., 2024). Alarmingly, more than 55 percent of the Nigerian population is today without access to reliable electricity, so that economic inefficiencies are further fanned and the growth of industries suppressed. (Adebayo & Ainah, 2024).

To address these hurdles, various initiatives have been put in place by the Nigerian government, including the National Energy Policy, which tries to ensure the sustainability of energy. These efforts have, however, been sabotaged due to gaps in implementation, lack of monitoring, and sometimes inconsistent policies. (D.E. & B.I., 2025a). The recent research notes that the introduction of the data-driven approach to managing energy can maximize energy use, increase efficiency, and that the transition to sustainable energy solutions can be made in Nigeria much more easily. (Adewoyin et al., 2025). Moreover, it is critically important to introduce renewable energy sources (solar, hydro, biomass, etc.) into the national power grid to secure energy security over the long term. (Osuma & Yusuf, 2025). However, the rate at which renewable energy is being adopted is slow because of the lack of financial resources, technical skills, and opposition to the change of policies. (Chanchangi et al., 2023).

This paper will critically examine the existing energy management practices in Nigeria, evaluate the implications of the existing policies, and present a systematic and data-based framework towards optimizing the use of energy. Through the use of statistical and econometric methods, the study aims to offer empirical evidence that is likely to help Nigeria on the path to a more sustainable and efficient energy sector. By taking the case study of Esa-Oke, the research study will also examine the effects of the removal of fuel subsidy on both energy demand and the economic operations, therefore aiding the understanding of the dynamics involved in the energy environment within Nigeria. Through this, the research will produce locally relevant evidence-based solutions to the existing unique issues affecting rural people in Nigeria that would eventually enhance a sustainable energy future.

2. LITERATURE REVIEW

Energy management is now being considered as a critical component towards promoting economic development and industrialization, especially in developing countries like Nigeria. Although the county is rich in natural energy sources, there are several difficulties in the energy industry, such as the lack of infrastructure, ineffectiveness, and high-frequency dependence on fossil fuels. (Mayer, 2022). In this literature review, the authors examine the energy management situation in Nigeria, including the shift to renewable energy, the implementation of the smart grid, and the obstacles preventing successful energy management.

Overview of Energy Management Challenges in Nigeria

Nigeria has critical energy issues, with more than 50 percent of the population having no access to constant electricity. (Somoye, 2023). The high frequency outages of the power and the high energy losses are the symptoms of the systemic inefficiencies in the energy sector. (Bukkarayasamudram et al., 2025). (EMEK et al., 2025) Underline the fact that the shortage of energy facilities not only influences the productivity of industries but also results in an increase in socio-economic inequalities.

Renewable Energy and Energy Transition

To address these challenges, the Nigerian government has embarked on a policy to encourage the use of renewable energy sources such as solar, wind, and biomass (D.E. & B.I., 2025b). National Renewable Energy and Energy Efficiency Policy (NREEEP) was set up to increase the sustainability of energy, but a lot of gaps in its implementation still exist (Dinneya-Onuoha, 2025). According to (Olanrewaju et al. (2025) highlight that financial constraints and policy (Ossai, 2017), a more sustainable energy ecosystem.

Smart Grid Technology and Energy Efficiency

The adoption of smart grid technology has been proposed to minimize energy wastage, increase the efficiency of the transmission, and permit real-time monitoring of energy usage (Augusta Heavens Ikevuje et al., 2024). Smart grids hold considerable potential to solve issues like grid failures and improve electricity reliability (David et al., 2025). Nevertheless, literature shows that high initial costs and technical challenges serve as major obstacles to the broader adoption of smart grid solutions in Nigeria (Unegbu et al., 2025).

The energy management landscape in Nigeria is fraught with barriers, including inconsistent policy frameworks, inadequate infrastructure, and persistent financial constraints (Shao et al., 2025). The lack of effective maintenance practices in power generation facilities further exacerbates these inefficiencies (Ossai, 2017). Public resistance to renewable energy technology adoption has also been identified as a crucial factor hindering the country's transition towards cleaner energy practices (Abubakar et al., 2024).

Economic and Environmental Impacts of Energy Management

In different studies, both economic development and environmental sustainability have been attributed to the existence of efficient energy management practices. (Omisore, 2018) Point out that inappropriate energy planning may lead to more carbon emissions and environmental degradation, which goes against the objectives of sustainable development. On the other hand, effective energy management structures can help reduce the effect on the environment and help Nigeria in its quest to have a green economy. (Emezue et al., 2024).

Data-Driven Approaches to Energy Management

Emerging trends in information-driven approaches have been identified as contributing to the improvement of energy management. Energy forecasting and analysis of consumption can be enhanced using approaches founded on statistical and econometric models (Patel & Shah, 2021). Furthermore, the application of Artificial Intelligence (AI) and Machine Learning (ML) to the development of the energy management system became a prospective direction in terms of energy distribution optimization and predictability (Javed et al., 2025).

Governance and Policy Recommendations

To achieve a sustainable energy management system, Nigeria should emphasize enhanced governance systems and regular policy drafts, and put substantial investments in renewable energy initiatives (Gungah et al., 2019). The role of the private sector in addressing the challenge of the quick introduction of innovative energy solutions is vital, and the encouragement of a public-private partnership (PPP) is significant (Idu et al., 2023).

Conceptual/Theoretical Framework

Some of the hypothetical frameworks on which energy management studies in Nigeria are based are the Energy Management Systems (EMS) Model, which suggests systematic monitoring and control measures as the means to optimize the use of energy (Ofori et al., 2023). Resource-Based View (RBV) Theory is a theory that advises that competitive advantages in managing the energy industry are based on the prudent utilization of natural resources. (Liu, 2025). Also, the Renewable Energy Transition Theory emphasizes the need to shift to renewable energy, and it outlines the inconsistencies in policy that make this process challenging (Mollik Babu et al., 2025). Also, the Renewable Energy Transition Theory points to the fact that the change from fossil fuels to renewables is necessary, and the current policy contradictions make this process more difficult. (Chanchangi et al., 2023).

Though Nigeria has great potential in promoting better energy management by adopting renewable energy and introducing smart technologies to be used, the process is hindered by complex challenges. These challenges need to be addressed by strong governance systems, new policy formulations, and sustainability in energy use practices. The future research needs to proceed with finding data-based solutions and implications for the socio-economics of energy management in Nigeria.

3. METHODOLOGY

The qualitative and quantitative research methodologies are combined in this study to support the investigation of energy consumption level and management practice in Esa-Oke. The research design framework allows the development of a thorough knowledge of the energy processes in the region, as it combines the knowledge of stakeholder interviews and policy consultations with quantitative information obtained in the form of structured field surveys. This two-pronged approach allows addressing the topic of energy consumption, the management process, and the socioeconomic context of these relationships, which gives a more holistic vision of the multidimensionality of the problem of energy consumption in society.

The techniques used to collect data in this study are a combination of intertwined techniques that are used to measure different dimensions of energy consumption in households, businesses, and institutions. Quantitative information regarding the energy consumption patterns, billing practices, the use of generators, and interest in adopting renewable energy, and qualitative information was collected based on structured surveys conducted with the stakeholders in the form of interviews with policymakers, community leaders, and the energy providers. These interviews add to the quantitative data by elucidating the communal perceptions and circumstances, especially in the context of the implications of the recent changes in energy policy, like the elimination of fuel subsidies. Moreover, it is possible to complement primary survey results with the analysis of secondary statistical data, which will help in identifying trends and correlations with different socioeconomic factors in the past and, therefore, contribute to the overall image of energy consumption in Esa-Oke.

The analytical model of the present paper utilizes the different statistical and econometric methods in the evaluation of energy patterns of consumption and correlations of different variables. The energy utilization is summarized using descriptive and inferential statistics, and the effects of energy transition strategies are quantified using econometric modeling. The geospatial analysis is employed to visualize the energy access and where intervention is required.

Preprocessing of the data using Python-based libraries, including Pandas and NumPy, ensures data integrity, and the calculated metrics give a more profound understanding of the economic impacts of energy consumption. The paper can reveal substantial connections in the data using a careful use of correlation analysis and principal component analysis (PCA) to provide practical information on sustainable energy use and policy design in rural settings such as Esa-Oke. With this holistic approach, the research is expected to provide practical findings on how the energy management practices and policies in rural communities can be improved to achieve a sustainable energy transition.

4. RESULTS AND DISCUSSION

This part provides the leading findings of the analysis with the help of statistical summaries and figures. Both visualizations bring out important findings concerning the cost and reliability of energy, its efficiency, and the behavioural grouping of the Esa-Oke people. Through this analysis, the energy use characteristics, reliability effects, and adoption preparedness of the renewable alternatives like solar are to be quantified.

Business Sector Energy Consumption and Efficiency Analysis.

This will offer a breakdown of the energy consumption trend in businesses in different sectors. The study analyzes the relationship between the cost of electricity, reliance on generators, and the frequency of outages on operational efficiency using descriptive, inferential, and clustering methods.

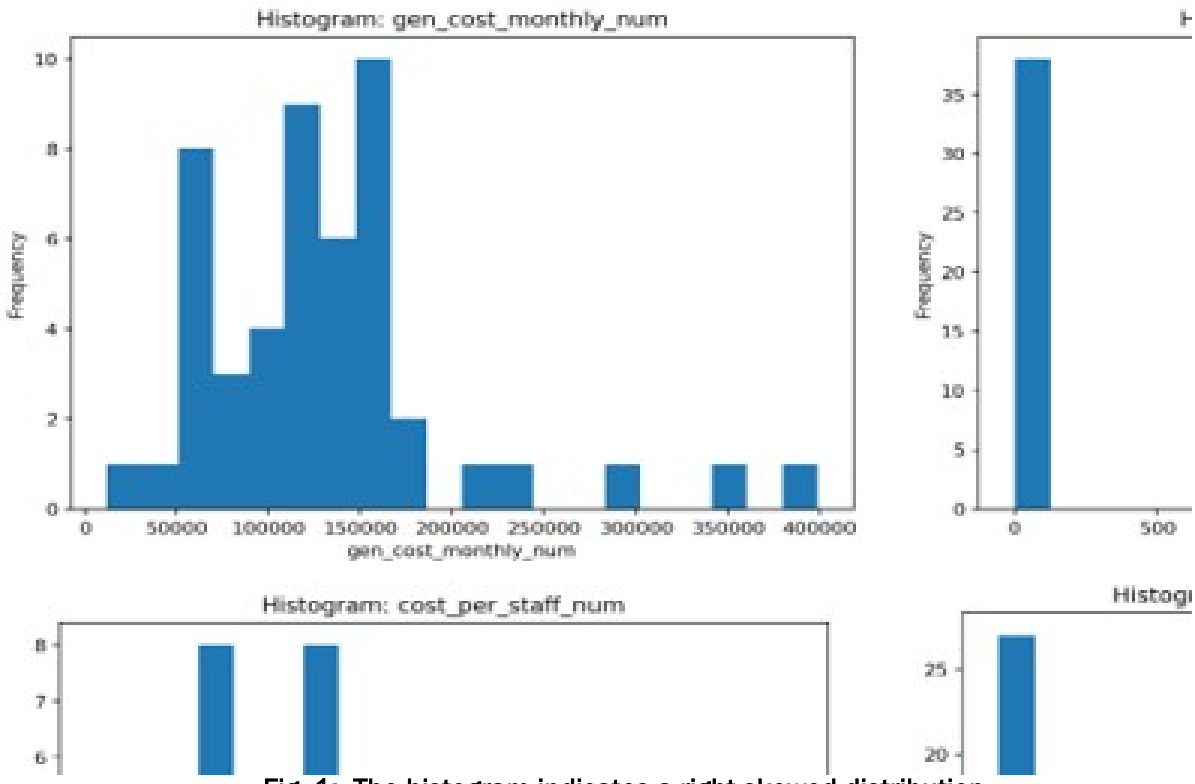

Fig. 1: The histogram indicates a right-skewed distribution

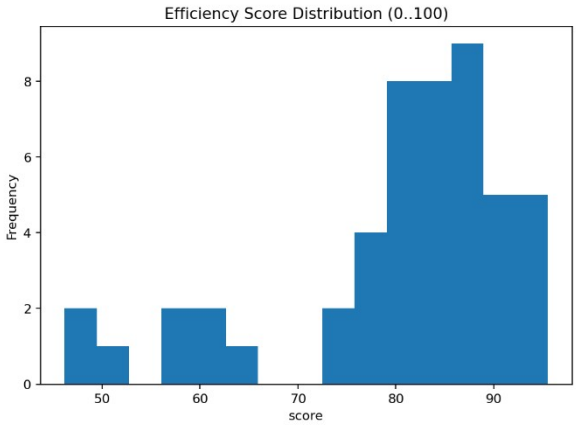

Fig. 2: Histogram distribution

Descriptive analysis showed that the businesses are incurring very high monthly energy bills, with the fuel cost of a generator being a large proportion of total energy expenditure. The histogram (Fig. 1) shows a right-skewed distribution with most of the SMEs with moderate energy expenses and a few of the large enterprises with very high expenses. Sectoral comparison indicates that the manufacturing and hospitality industries experience the greatest energy costs since they are required to operate at all times.

Correlation analysis showed that there exist strong relationships among durations of outage, cost of generators, and total monthly energy cost. The scatterplot also indicates that the frequency of outages has a direct proportional effect on the energy loss and cost impact. Cluster analysis was used to identify two clusters, namely the high-consumption, high-cost segment and the low-cost, low-reliability segment. Efficiency scores (Fig. 2) are highly dispersed, which means that there was a high potential for cost optimization by energy audit and renewable adoption. The analysis of the text brings out the prevailing themes of feedback, including: generator maintenance, fuel price, supply reliability, and solar installation. Sentiment polarity reveals that the majority of them were negative or neutral, which is in accordance with the frustration with the high energy costs and frequent blackouts.

Household Energy Consumption and Efficiency Analysis in Selected Communities

This part will contain descriptive and inferential analysis based on the data. Pictures are used to demonstrate distributions, correlations, and cluster patterns to aid in interpretation. The Statistical analysis is presented (Fig. 3). The histograms indicate that income and energy costs are skewed to the right, and therefore, this implies that households are concentrated at low prices. The availability of outages is too high, and it indicates a low reliability of the supply. The correlation heatmap depicts close positive correlations between appliances, meaning that appliance ownership is a direct cause of the energy demand. PCA demonstrates more than 80 percent cumulative variance accounted for by four factors. The K-Means clustering (Fig. 4) recognizes two groups: high-cost and low-cost households, which suggests that there is behavioral and income-based stratification of energy consumption.

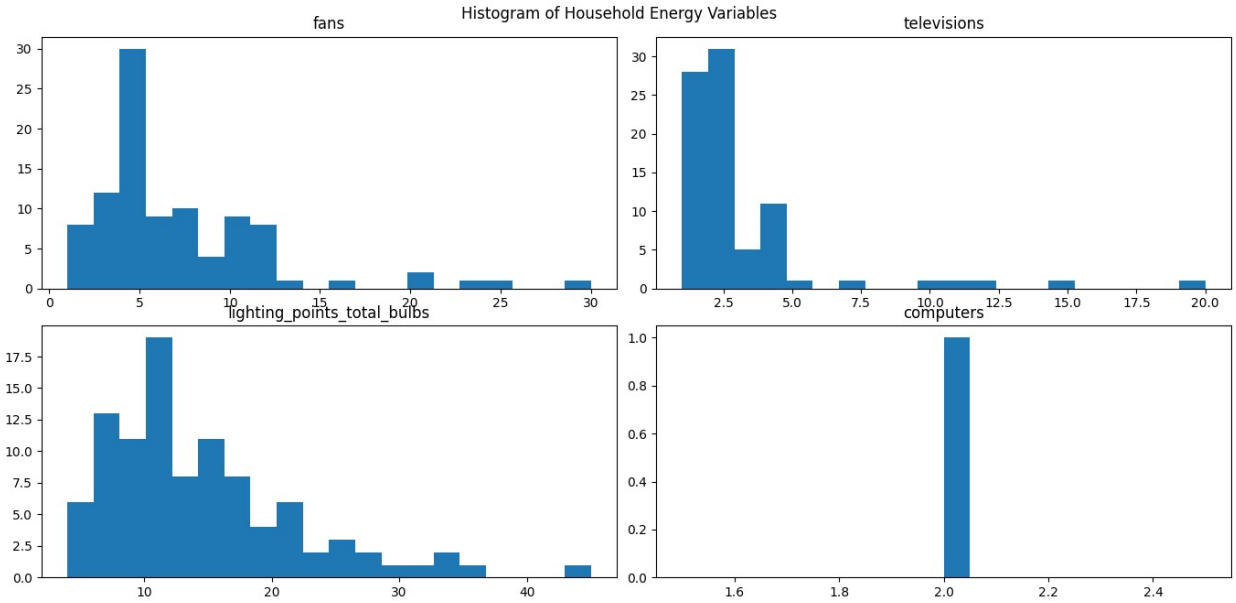

Fig 3: Household energy variables

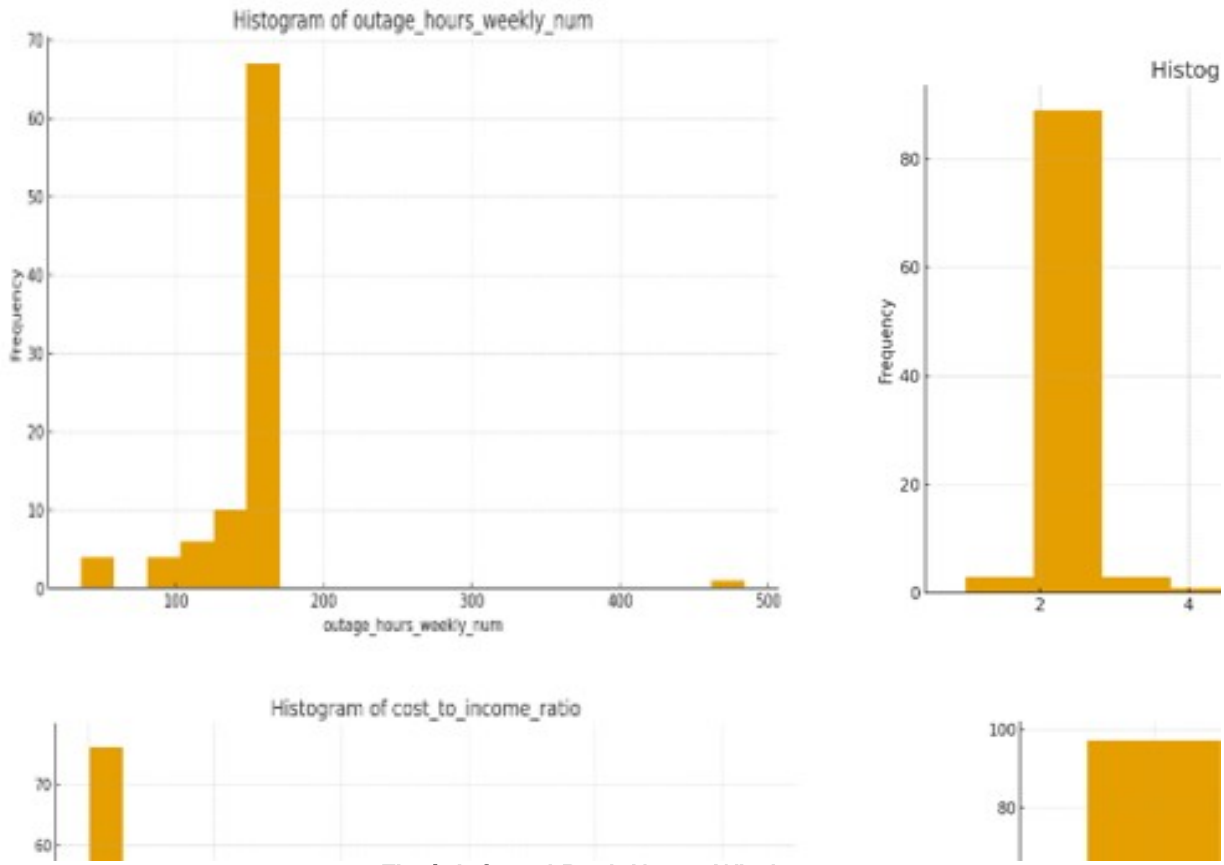

Fig 4: Inferred Peak Usage Window

Institutional Sector Energy Consumption and Efficiency Analysis

The paper will examine statistical distributions and correlation between the main energy indicators, with particular emphasis on the total energy cost, consumption, cost per kilowatt-hour (kWh), and outage periods by the institutions.

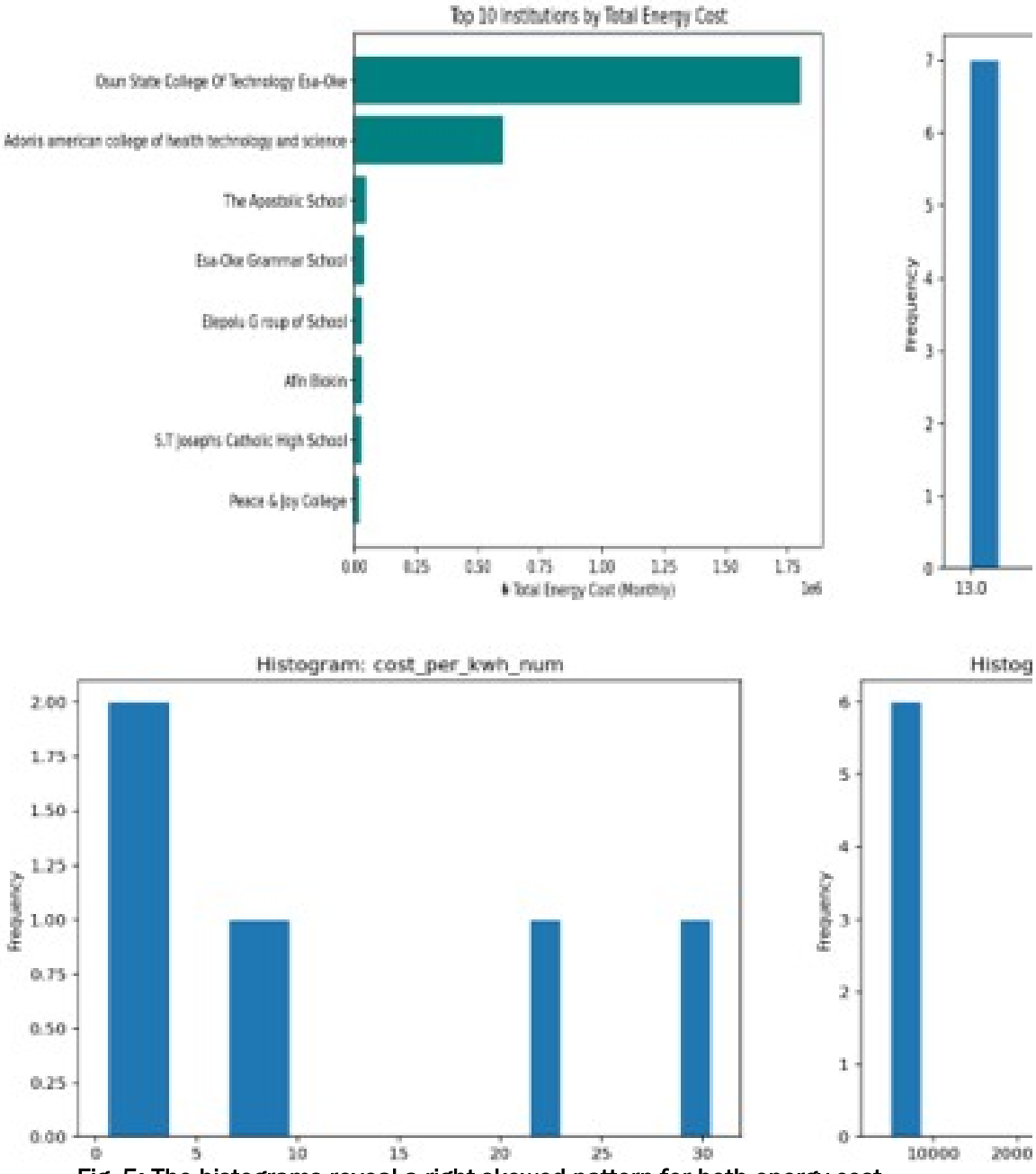

Fig. 5: The histograms reveal a right-skewed pattern for both energy cost

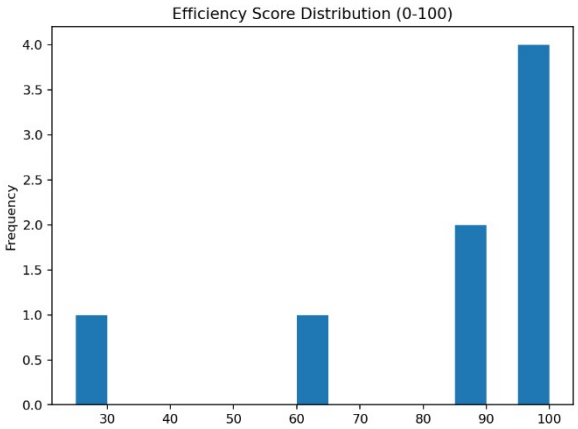

Fig. 6: Efficiency score analysis

Statistics show that there is a skewed distribution of energy cost and consumption, with a few large institutions accounting for the total usage. Any variation in cost per kWh indicates the variability in the tariff structure, whereas the outage time indicates that supply reliability is not regular. The high positive correlation between outage period, total energy cost, and consumption is an indicator of reliability as a major cost driver. An analysis of the efficiency scores indicates that only a small part of institutions have optimal cost-to-output ratios, which is an indicator of significant potential improvement. These data highlight the necessity of performance benchmarking and prescribe greater monitoring, efficient cost management, and the use of renewable energy in institutions.

5. CONCLUSION

This research is a detailed evaluation of energy management activities, usage behaviors, as well as switching opportunities in the semi-urban society of Esa-Oke, Nigeria. Although national policies have been implemented to help people have better access to energy and be more efficient, it is found that the community still experiences severe issues, such as unreliable grid supply, a high reliance on generators, and numerous high-wattage appliances that contribute immensely to the energy demand. The skewed nature of energy consumption and spending to the right is bringing out the imbalanced distribution of the burden of energy usage and spending to households and small businesses, with a small number of large institutions consuming a large proportion of the total energy. The large change in the cost per kWh is also an indicator of the dependency on unstable tariffs and electricity produced by generators. Notably, the study exhibits a high level of openness to renewable energy technologies in the community, where more than three-quarters of the sample population indicate their readiness to consider the use of solar systems, provided affordable financing options are in place.

To address these facts, this paper suggests a realistic transition model that incorporates solar implementation, energy-efficient technologies, and gradual grid modernization. It is estimated that, based on the model, these measures will result in a cumulative energy reduction of about 22 percent and will see the renewable energy percentage rise by about 15 percent in the next ten years. Such results are not only an emphasis on the practicality of an energy transition that is sustainable in Esa-Oke, but also a demonstration of the generalizability of this framework to other less-developed semi-urban settings in Africa at risk of similar infrastructural and economic limitations.

As the analysis is based on empirical findings and insights, the given research provides a feasible roadmap that policymakers, energy planners, and local stakeholders can follow to ensure higher energy reliability, lower costs, and improve long-term sustainability.

Acknowledgement

This research received funding from the Tertiary Education Trust Fund (TETFund) through the Institution-Based Research (IBR) grant, administered by the Directorate of Research, Publication, and Innovation at Osun State College of Technology, Esa-Oke, Nigeria. The authors express their sincere appreciation for this financial and institutional support, which was crucial to the successful completion of the study. We also extend our gratitude to the households, business owners, institutional representatives, and IBEDC office in Esa-Oke who generously participated in the surveys and interviews, providing valuable insights that enhanced the quality of this work.

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