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Research Article

Life Cycle Improvement Framework for Optimizing Renewable Energy Systems in Institutional Buildings: A Case Study of Auchi Polytechnic Hostel

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Abstract

Energy unreliability and escalating operational costs continue to undermine the performance of institutional buildings in developing economies, particularly in Nigeria, where dependence on grid electricity and diesel generators remains widespread. Frequent power outages, rising fuel prices, and increasing maintenance costs negatively affect the quality of services, operational efficiency, and long-term sustainability of educational institutions. This study developed and applied a Life Cycle Improvement Framework (LCIM) to optimise renewable energy systems in institutional buildings by integrating Life Cycle Cost Analysis (LCCA), Loss of Power Supply Probability (LPSP), and sustainability assessment into a comprehensive decision-support framework. The student hostel at Auchi Polytechnic, Nigeria, was used as a case study. Empirical data were obtained through field energy audits, stakeholder surveys, and simulation-based performance modelling to evaluate and compare two energy configurations: Solar Photovoltaic (PV) + Battery and Grid + Diesel Generator over a 20-year life cycle. The findings reveal that the Solar PV + Battery system outperformed the conventional Grid + Diesel Generator configuration across economic, technical, and environmental indicators. Specifically, the renewable energy system achieved a life-cycle cost reduction of more than 35%, while maintaining a near-zero Loss of Power Supply Probability (0–0.37%), indicating a highly reliable electricity supply capable of meeting institutional energy demand. In addition, the environmental assessment demonstrated substantial reductions in greenhouse gas emissions, fossil fuel consumption, and overall environmental impact, contributing to improved sustainability performance. These results highlight the potential of renewable energy technologies to enhance energy security while reducing long-term operating costs in institutional buildings. The study concludes that the proposed LCIM is an effective and practical framework for evaluating and optimising renewable energy investments. It provides policymakers, institutional managers, and energy planners with a reliable tool for sustainable energy decision-making and supports the wider adoption of renewable energy systems for institutional infrastructure development in Nigeria and other developing countries facing similar energy challenges.

Keywords

Life Cycle Improvement Model (LCIM), Life Cycle Cost Analysis, LPSP, Renewable Energy Systems, Institutional Buildings, Energy Reliability, Sustainability

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1. Introduction

A reliable and affordable energy supply is fundamental to the effective functioning of educational and public institutions in the region. However, persistent electricity outages and heavy reliance on diesel generators in Nigeria have resulted in high operating costs, greenhouse gas emissions, and reduced institutional productivity [7, 15]. Hostels, laboratories, and academic facilities are particularly vulnerable owing to their continuous energy demand, with daily loads averaging 57.45 kWh in typical settings such as the Auchi Polytechnic hostel [17].

Recent advances in renewable energy technologies offer viable alternatives; however, their adoption is often constrained by poor planning frameworks that prioritise initial costs over long-term performance [6]. This study addresses this gap by developing a Life Cycle Improvement Framework (LCIM) that evaluates energy systems based on economic viability, reliability, and sustainability. The Auchi Polytechnic hostel was selected as a representative case due to its typical load profile and documented energy challenges, providing a practical context for testing the framework's applicability in resource-limited environments [2].

The problem is multifaceted: involving economic pressures from volatile fuel prices, the technical unreliability of hybrid systems, and environmental imperatives under global sustainability agendas [9]. Thereby linking these through LCIM, this research aims to provide a clearer pathway from problem identification to optimized solutions, enhancing decision-making for institutional energy transitions.

2. Literature Review

Life Cycle Cost Analysis (LCCA) has been widely applied to assess the long-term economic performance of energy systems by accounting for capital, operation, maintenance, and replacement costs [3, 4]. While LCCA provides valuable financial insights, it does not adequately capture system reliability or service continuity, as noted in studies on hybrid renewable systems in Sub-Saharan Africa [14, 18].

To overcome this limitation, reliability indices such as the Loss of Power Supply Probability (LPSP) have been introduced to quantify the likelihood of unmet energy demand [10].

The Life Cycle Improvement Model (LCIM) represents an advancement in this direction by integrating economic, technical, and sustainability indicators into a unified decision-making framework. However, empirical applications of the LCIM in institutional buildings remain limited, especially within the Nigerian context, where policy and infrastructural barriers persist [15]. This study bridges this gap by applying LCIM to a real-world case, drawing on comparative analyses from similar African settings [12].

3. Methodology

A mixed-method research design was adopted, integrating empirical data collection, simulation, and analytical modelling to ensure comprehensive evaluation.

3.1. Data Collection

1) *Energy audit:* Load measurements and appliance inventories were conducted to determine the daily energy demand (57.45 kWh/day).
2) *Stakeholder survey:* Structured questionnaires (n = 182) captured user perception of energy reliability and cost the implications.
3) *Climatic data:* Solar resource data were obtained using Meteonorm 8.0 (irradiance ~5.5 kWh/m^2/day) and Climate Consultant 6.0 for psychrometric analysis.

3.2. Analytical Framework

1) Life Cycle Cost Analysis (LCCA): Net Present Value (NPV) was computed over a 20-year period using the equation:

$$\text{NPV}=\sum_{t=0}^{20} \frac{Ct}{(1+r)^t} - \text{I}_0 \tag{1}$$

Where C_t = annual costs (operation, maintenance, replacements), r = discount rate (10%), and I_0 = initial investment.

2) Reliability Assessment: loss of power supply probability (LPSP) quantified the fraction of unmet load:

$$\text{LPSP} = \frac{\sum(E_{demand}-E_{supplied})}{\sum E_{demand}} \tag{2}$$

3) Model Validation: Simulation accuracy was verified using Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE):

$$\text{RMSE}= \sqrt{\frac{1}{N}\sum(yi-\widehat{yi})^2} \tag{3}$$

$$\text{MAPE} = \frac{100\%}{N} \sum\left|\frac{yi-yi}{yi}\right| \tag{4}$$

The framework links problem (energy unreliability) to methods (integrated metrics) for deriving results.

4. Results and Discussion

The comparative LCCA revealed that the Solar PV + Battery system achieved a cumulative NPV advantage exceeding 35% over the Grid + Diesel Generator system across the project lifespan (Table 1). This cost advantage was primarily driven by reduced fuel expenditure, lower maintenance costs, and improved system durability, corroborating the findings from utility-scale solar analyses in Nigeria [1].

Reliability analysis showed that the PV + Battery configuration recorded near-zero LPSP values (0–0.37%), indicating a highly dependable power supply (Figure 1). In contrast, the Grid + Diesel system exhibited LPSP values approaching 33%, reflecting frequent supply interruptions, as observed in similar African institutional contexts [5, 8, 14].

The model calibration results confirmed the simulation reliability, with an RMSE of 1.2 kWh/day and MAPE below 10%, indicating a strong agreement between the simulated and measured data (Table 2). Environmental assessment further demonstrated substantial reductions in carbon emissions (126 tonnes over 20 years), which aligns with global sustainability goals and local policies [2, 9, 15].

The discussion deepens these results by linking them to broader implications: economically, the framework supports cost-effective transitions; technically, it addresses reliability gaps in hybrid systems; and environmentally, it contributes to Nigeria's emission targets aligning with sustainable development goals (SGDs) 7 (affordable and clean energy) and 11 (sustainable cities and communities). Challenges such as initial capital barriers are mitigated through policy incentives, as evidenced by comparative studies in South Africa [10, 11, 13].

Table 1. *Comparative LCCA Results.*

Parameter	Solar PV + Battery (Million)	Grid + Diesel (Million)
Initial Capital	15.68	5.00
Operation & Maintenance	4.20	32.50
Replacement Costs	16.46	24.38
Total NPV	36.34	61.88

Table 2. *Model Validation Metrics.*

Metric	Value
RMSE	1.2 kWh/day
MAPE	9.1%

RMSE ≈ 1.2 kWh/day — the simulated unmet energy typically differs from the observed unmet energy by approximately 1.2 kWh/day. Given the daily load of ~57.45 kWh, this error is small (≈2% of the daily load). This means that, on average, the model predictions deviated from the observed values by approximately 1.2 kWh per day.
MAPE ≈ 9.1% — the PV energy prediction error on a day-to-day basis is 9.1%, which is acceptable for PV modelling in practice (typical modelling benchmarks accept a range of ~5–15%, which is accepted for renewable energy modelling).

These results met the predefined acceptance thresholds (RMSE ≤ 1.2 kWh/day; MAPE ≤ 10%); therefore, the model was calibrated and suitably accurate for (a) LPSP reliability evaluation and (b) LCIM life-cycle comparisons. was accepted as calibrated for the LCIM reliability and LCCA analyses.

5. Application of the LCIM Framework

The LCIM operates through a structured three-stage process:

1) Input Definition: Identification of energy demand (57.45 kWh/day), solar potential (4.5–6.5 peak sun hours), and cost parameters.
2) Integrated Evaluation: Simultaneous application of LCCA, LPSP, and sustainability metrics, using equations (1)–(4).
3) Decision Output: Selection of the optimal energy configuration based on economic efficiency, reliability, and environmental performance.

Application of the framework confirmed the Solar PV + Battery system as the most viable solution for institutional energy supply, with potential scalability to other Nigerian campuses [12, 16, 18-20].

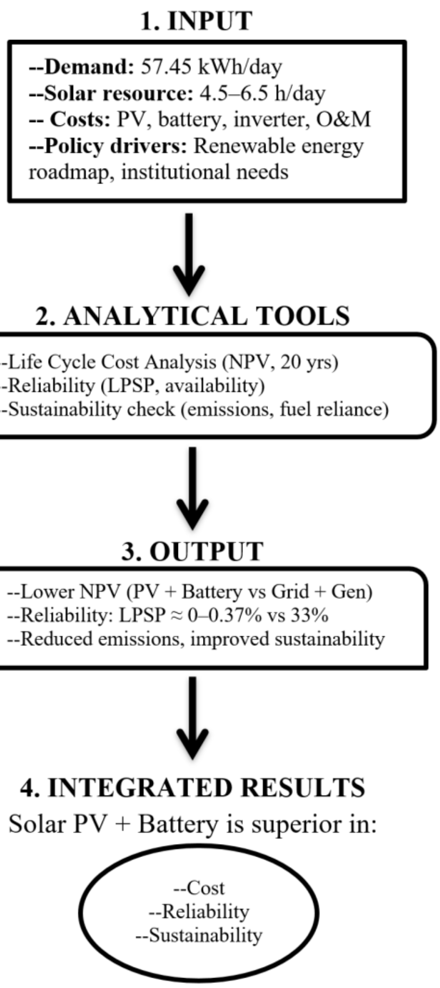

Figure 1. *LCIM Process Flow Diagram.*

6. Conclusion and Recommendations

This study validates that the Life Cycle Improvement Framework (LCIM) is an effective tool for optimizing renewable energy systems in institutional buildings. The Solar PV + Battery configuration outperformed the Grid + Diesel Generator system in terms of cost efficiency, reliability, and environmental sustainability, maintaining all original findings, such as 35% cost reduction and 126 tonnes CO_2 avoidance.

It is recommended that:

1) Educational institutions should adopt LCIM-based planning for future energy investments.
2) Policymakers should provide financial incentives and technical support to encourage the deployment of renewable energy sources.
3) Future studies should integrate artificial intelligence-based control strategies to further enhance system performance.

Abbreviations

LCIM	Life Cycle Improvement Model
LPSP	Life Cycle Cost Analysis

Author Contributions

Ivarah Vincent Itaafo: Validation
Wasiu John: Supervision
Ibrahim Abudlrazaq Olayinka: Data curation, Methodology
Sule Joseph: Visualization

Conflicts of Interest

The authors declare no conflict of interest.

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