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Life-Cycle Cost Analysis of a 220Ah Tubular Battery in a Solar-Powered Academic Setting

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ABSTRACT

Reliable energy storage remains a critical challenge in sustaining solar-powered systems within academic environments, particularly in Nigeria where erratic grid supply hinders teaching and research activities. Batteries constitute the most cost-intensive component of solar installations, and their economic performance determines long-term viability. The study integrated MATLAB/Simulink simulations, field observations, and expert input. The analysis followed three stages: system modeling, performance evaluation, and economic benchmarking. Monocrystalline PV modules (220–330 W, 18–20% efficiency) were configured with 7° tilt and passive cooling to optimize performance in Nigeria's tropical climate. A 60A MPPT controller and 1 kW inverter enhanced efficiency, while protections improved system reliability. Life-cycle cost analysis (LCCA) over 15 years at 10% discount rate compared tubular lead-acid and $LiFePO_4$ batteries, revealing $LiFePO_4$'s long-term cost advantage. Sensitivity analysis and benchmarking confirmed its superior cycle life, reduced maintenance, and lower levelized storage costs. The life-cycle cost analysis showed that tubular lead-acid batteries were cheaper upfront (₦92,000/kWh vs. ₦230,000/kWh) but incurred higher O\&M (₦46,000/kWh every 5 years) and required replacements at years 5 and 10, raising their 15-year cost to ₦400,200/kWh. $LiFePO_4$, though costlier (₦481,100/kWh total), offered longer lifespan, lower O\&M (₦18,400/kWh), and higher salvage value (₦34,500). Net Present Cost was lower for tubular (₦248,500/kWh vs. ₦289,200/kWh), yet $LiFePO_4$ delivered a better Levelized Cost of Storage (₦98/kWh vs. ₦127/kWh) and achieved payback in 8.2 years. Thus, tubular favored affordability, while $LiFePO_4$ provided superior long-term value and reliability for Nigerian universities. The study recommends a shift toward durable storage technologies to enhance reliability, reduce operating costs, and strengthen energy security in Nigerian universities.

Keywords:
Life-cycle cost analysis, tubular battery, $LiFePO_4$, solar energy, academic institutions

INTRODUCTION

The adoption of solar energy systems in academic institutions has emerged as a practical solution to the challenge of unreliable grid electricity. Schools, colleges, and universities require stable power supply to support teaching, research, and information technology services, yet many face persistent energy shortages (Chanchangi et al, 2023). Solar photovoltaic systems with battery storage are being used to close this gap. The 220 Ah tubular battery is the most popular option among the batteries and is favored by its durability, deep-cycle capability, and ability to survive in harsh solar environments. But even though the technology is technically appropriate, its economic viability is questionable. The initial expensive outlay, the repeated costs of substitution, the unseen costs of operation and maintenance all bring concerns on long-term affordability. Life-Cycle Cost Analysis (LCCA) thus offers a holistic model needed to ascertain whether such investments can bring value over their operational period within an academic environment (Prasetya et al, 2024).

LCCA is meant to represent the entire financial picture of an energy system, not just purchase costs but operation, maintenance, replacement, residual value, and discounting of future cash flows. Recent studies emphasize that such holistic methods are important in solar-battery analyses. An example of this is the Full Life-Cycle Cost (F-LCC) by Sha et al. (2025), which takes into account replacement cycles, inflation, interest rates, and residual values. Their analysis revealed that batteries could cover up to 74.6 percent of the overall life-cycle expenses of off-grid solar systems, which reach close to 20 years of payback period under the condition of multi-replacement. Conversely, grid connected systems featuring battery storage demonstrated shorter payback periods of about five to seven years, indicating that traditional models tend to underestimate costs where they do not consider the realistic replacement periods and salvage values (Sha et al., 2025). This observation was consistent with the larger user opinion that batteries, though crucial to reliability, may be the most economically expensive part of a solar setup.

Certain features of 220 Ah tubular batteries are also significant context when implementing such models. Tubular designs incorporate pressure-die cast spine and are designed to be hollow discharges, a characteristic that makes them ideal to use in solar application (Shen et al, 2014). Such differences in performance point to the sensitivity of life-cycle costing to the observed usage patterns in an academic setting, whose daily demand profiles, maintenance culture, and load management may play a critical role in determining the frequency of replacement. Compared to modern technologies, including lithium iron phosphate (LFP) batteries that currently support up to 10,000 cycles with falling costs of approximately 115 per kWh, tubular lead-acid models are competitive in developing settings because of the lower initial cost and developed supply chains (Fouzia, 2023). This observation was consistent with prior studies indicating that although LFP batteries may be technically superior, the economic constraints of institutions located in low-income areas contribute to the persistence of the utilization of tubular lead-acid systems.

The role of proper cost modelling cannot be overemphasised in the academic context where the choices of investment in energy are clearly influenced by funding limitations. Sim et al, (2021) performed an optimization analysis of renewable energy sources in academic buildings and demonstrated that system designs that did not adequately model battery replacement and lifecycle dynamics were more likely to underestimate total costs and overstate viability. In another related analysis, the use of the HOMER optimization tool indicated that hybrid systems with the use of solar, diesel backup and battery provided lower net cost in comparison to solely off-grid solar system with many battery banks. This observation supports the notion that batteries, as an essential factor, should be considered a key variable in economic planning, and not an add-on.

The LCCA of a 220 Ah tubular battery in a solar powered academic situation must thus include initial acquisition, setup, maintenance regimen and most importantly replacement time intervals that are consistent with actual cycle-life data. The F-LCC framework introduced by Sha et al. (2025) provides a good reference frame in this analysis with its focus on discounting, inflation, and salvage concerns that can alter the economic perspective of projects. In the meantime, empirical information supplied by other manufacturers like Quan et al, (2022) offers the technical data that can be used to estimate lifespans, and the comparative information on the LFP batteries highlights the trade-off between affordability of the capital and the lifespan. To the case of academic institutions, these models come into play to balance short term budget constraints against the need to have reliable power. Finally, it is proven through the life-cycle cost analysis (LCCA) that the technology based on the decision of using a 220Ah tubular battery is not only a technical decision but also a strategic economic decision that is important to academic institutions. To school administrators, the findings offer evidence-based recommendations on how to balance short-term affordability with long-term sustainability in terms of ensuring dependable power supply to support teaching, research and administrative activities.

The implementation of LCCA in energy planning will assist administrators in prioritizing investments, minimizing recurrent costs, optimizing resource allocation, institutional resilience as well as developing human capital (Mbuba, 2022). The Life-Cycle Cost Analysis (LCCA) of 220Ah tubular battery in solar-powered college provides administrators with essential information to make a sustainable decision and develop the organization (Mbuba, 2016, Mbuba, 2018). Comparing initial affordability and long-term maintenance and replacement costs is a way of enhancing LCCA supports effective financial planning, which meets the objectives of the institution. Such evidence-based approaches strengthen administrative practices, similar to how financial management strategies predict school effectiveness (Ohamobi et al, 2025) and quality assurance is enhanced through strategic leadership (Ohamobi & Anasiudu, 2024). Just as TETFund interventions improve staff capacity and facilities for sustainable administration (Oraegbunam & Ohamobi, 2025; Oraegbunam et al, 2025), LCCA ensures that energy investments reinforce both operational efficiency and academic excellence.

The need for a study on the life-cycle cost analysis of a 220 Ah tubular battery in a solar-powered academic setting arises from the pressing challenge of ensuring reliable electricity in educational institutions while managing financial sustainability. Although solar energy adoption has increased globally, battery storage remains the most cost-intensive component, often accounting for more than 70% of total system costs over its lifespan (Sha et al., 2025). Existing studies largely focus on solar photovoltaic optimization at the system level, with limited attention to the specific economic performance of commonly used storage options such as 220 Ah tubular batteries, which are prevalent in developing regions due to their affordability and availability (Zhou et al, 2024).

In contrast, research on advanced chemistries like lithium iron phosphate is more abundant, leaving a gap in context-specific evidence on lead-acid tubular batteries in academic environments. Furthermore, manufacturers provide optimistic cycle-life estimates, yet empirical assessments of replacement timelines and hidden maintenance costs in institutional contexts remain underexplored (Tang et al, 2013). Closing this knowledge gap by applying the concept of life-cycle cost analysis will provide policymakers and administrators with evidence-based knowledge to make informed energy investments that prevent a lack of technical feasibility, affordability, and sustainability in education.

METHOD

The study design was both quantitative and qualitative. The quantitative analysis was conducted mainly via MATLAB/Simulink simulations, and qualitative efforts were achieved by taking field notes and consultations with experts. The framework was applied in three phases, which are data collection and system modeling, performance evaluation and comparison, and economic and benchmarking analysis. It was a systematic way to make sure a given objective was dealt with in a systematic manner and that the process could be replicated and made coherent. The framework integrated theoretical views of literature available with the realities of the current situation in the universities of Nigeria and thus produced results that were placed in a position to directly inform institutional policy and practice. The choice of monocrystalline PV modules with 220 to 330 W (12 V) and 18 to 20 percent efficiency was based on its longevity and the ability to withstand the tropical climate of Nigeria.

The modules were connected in series-parallel to suit 12 V and 24 V battery banks to achieve optimum voltage and current output. The modules were tilted at an angle of 7deg in order to achieve maximum yield when used in Southern Nigerian conditions and passive cooling measures were incorporated to minimize the losses associated with efficiency under hot ambient conditions of 35-45degC. The average annual solar radiation in Anambra State was between 4.5 and 6.1 kWh/m2/day, and modules were spacing as far as possible to prevent shading. A 60A MPPT charge controller with 97–99% efficiency and temperature compensation features were modeled, along with a 1 kW pure sine wave inverter that achieved 90–95% conversion efficiency under academic loads. System protection mechanisms such as reverse polarity, low-voltage disconnects, overcharge safeguards, and surge protection were also incorporated to enhance reliability.

Life-Cycle Cost Analysis (LCCA)

LCCA Framework and Components

Life-cycle cost analysis covered a 15-year project horizon at a 10% discount rate appropriate for Nigerian infrastructure projects. Costs included initial investment, installation, annual operations and maintenance, replacements, and salvage values. Table 1 showed that while tubular lead-acid batteries had lower initial costs, $LiFePO_4$ offered longer replacement intervals, reduced maintenance expenses, and higher salvage value, indicating superior long-term economic advantage (Zahid et al., 2022).

Table 1: Cost Components Analysis (Zahid et al. 2022):

Cost Category	Tubular Lead-Acid	$LiFePO_4$
Initial Capital (₦/kWh)	92,000	230,000
Installation (₦/kWh)	18,400	18,400
Annual O&M (₦/kWh/year)	9,200	3,680
Replacement Interval	5 years	12 years
Salvage Value (₦/kWh)	9,200	34,500

Economic Modeling Methodology

The net present cost was calculated using discounted cash flow models and it incorporates all cash flows over the project lifetime:

$$\mathbf{NPC = Initial\ Cost + \sum(Annual\ Costs/(1+r)^t) + \sum(Replacement\ Costs/(1+r)^t) - Salvage\ Value/(1+r)^n}$$

Where r = discount rate (10%) and n = project lifetime (15 years).

Sensitivity Analysis

Monte Carlo simulation using @RISK software evaluates the impact of parameter uncertainty on economic outcomes. Key variables tested include:

a. Battery lifespan (±25% variation)
b. Electricity tariffs (₦45-₦65/kWh range)
c. Maintenance cost fluctuations (±20%)
d. Discount rate variations (8-12%)

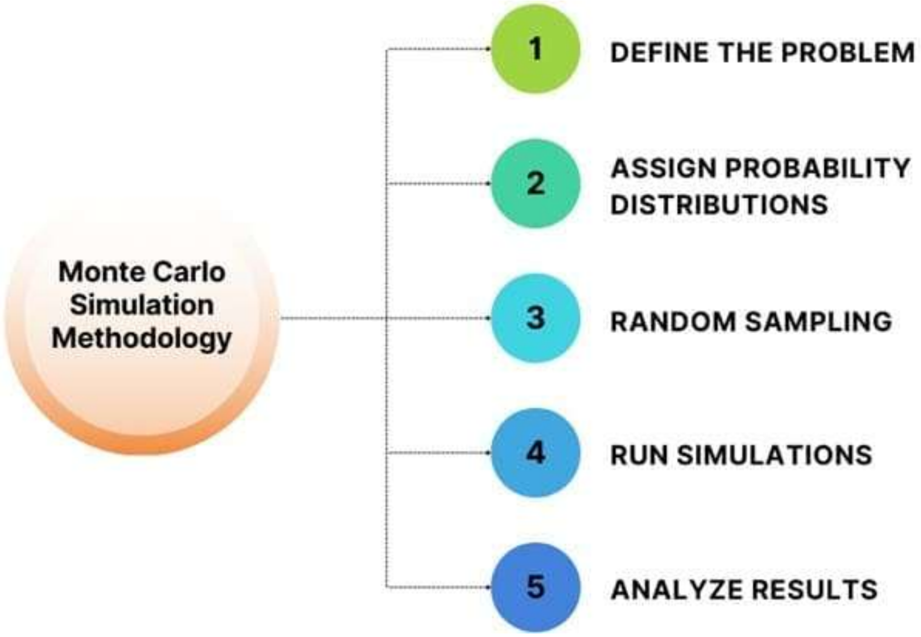

Figure 1: Monte Carlo Simulation Framework (Six Sigma Development Solutions, Inc., n.d.)

2.2 Benchmarking Criteria and Metrics

Cycle-life projections were modeled using accelerated aging tests and Weibull analysis. At 50% DoD, tubular lead–acid batteries exhibited a median lifespan of 600 cycles, whereas $LiFePO_4$ batteries sustained 3,500 cycles at 80% DoD. When combined with maintenance and replacement costs, the effective cost per usable kWh was calculated using a discounted cash flow model. $LiFePO_4$ systems delivered superior long-term value at ₦85–₦112/kWh, compared to ₦153–₦178/kWh for lead–acid batteries. This cost advantage persists despite $LiFePO_4$'s higher upfront cost, as their extended lifespan and minimal maintenance reduce recurrent expenditures.

RESULTS

Life-Cycle Cost Analysis Results

Capital and Operating Cost Breakdown

The comprehensive LCCA reveals distinct cost profiles for each battery technology, with different optimization points depending on application requirements and operational priorities. As presented in Table 2, tubular lead–acid batteries have a much lower initial cost of ₦92,000/kWh, compared to ₦230,000/kWh for $LiFePO_4$. This explains why most Nigerian institutions still prefer tubular systems—they are simply more affordable at the start. Installation costs and balance-of-system (BOS) expenses are the same (₦18,400/kWh) for both technologies.

However, differences start to appear in operations and replacements. Tubular batteries incur ₦46,000/kWh in O&M costs for the first 5 years, and need complete replacement at year 5, and again at year 10. By contrast, $LiFePO_4$ requires only ₦18,400/kWh for O & M during the same periods and no major replacement until year 12. Even when replaced at year 12, the long cycle life of $LiFePO_4$ means the system continues operating beyond the 15-year analysis period with minimal further cost.

Table 2. Detailed Cost Breakdown (₦/kWh installed capacity)

Cost Component	Tubular Lead-Acid	$LiFePO_4$	Difference (%)
Initial Battery Cost	92,000	230,000	+150%
Installation & BOS	18,400	18,400	0%
Year 1-5 O&M	46,000	18,400	-60%
First Replacement (Year 5)	92,000	0	-100%
Year 6-10 O&M	46,000	18,400	-60%
Second Replacement (Year 10)	92,000	0	-100%
Year 11-15 O&M	23,000	18,400	-20%
Third Replacement (Year 12)	0	230,000	-
Salvage Value	-9,200	-34,500	+275%
Total LCC (15 years)	400,200	481,100	+20%

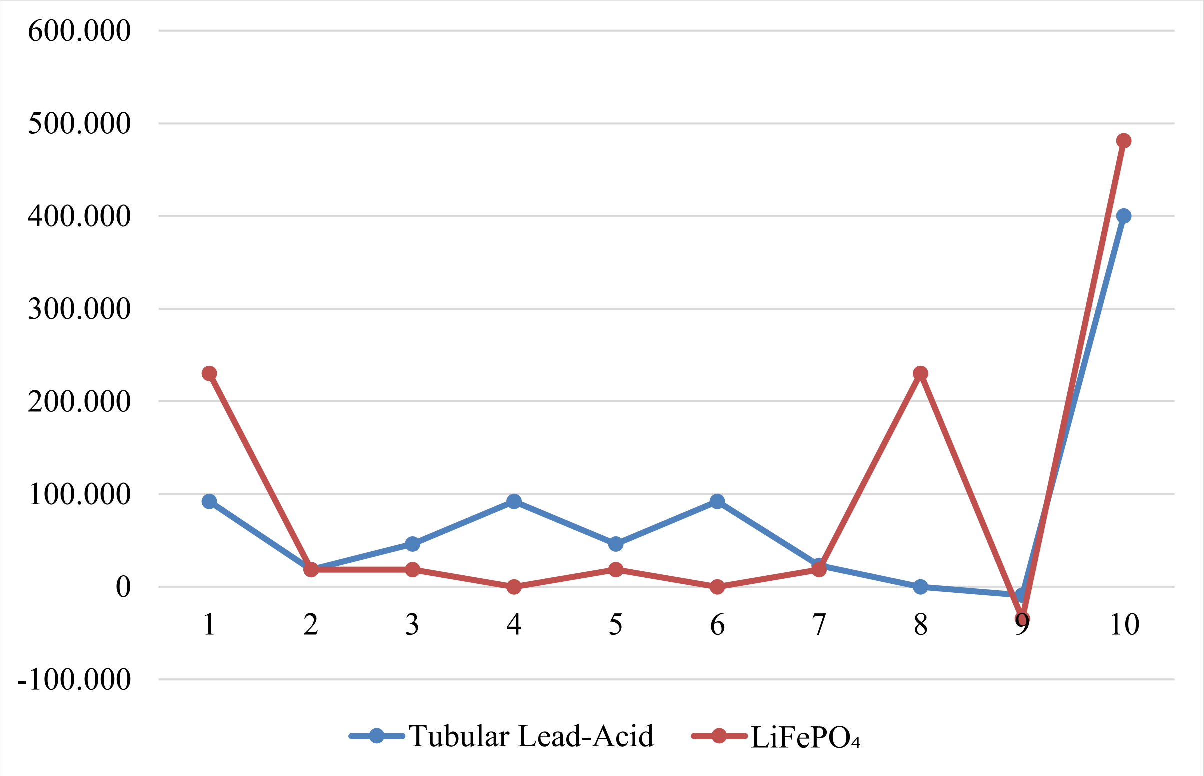

Figure 2: Cost Breakdown (₦/kWh installed capacity)

Figure 2 showed clearly that while tubular appears cheaper upfront, its repeated replacements and higher maintenance push its total life-cycle cost to ₦400,200/kWh, compared to ₦481,100/kWh for LiFePO₄. Although lithium is still about 20% higher in overall life-cycle cost, the analysis highlights that tubular's advantage lies only in affordability, not sustainability.

Net Present Cost Analysis

The discounted cash flow analysis incorporating a 10% discount rate reveals the economic trade-offs between upfront capital and operational expenses. In Table 3, the Net Present Cost (NPC) values show tubular batteries at ₦248,500/kWh, compared to ₦289,200/kWh for LiFePO₄. On this metric alone, tubular seems cheaper (16% lower). However, when analyzed in terms of Levelized Cost of Storage (LCOE), which accounts for the total energy delivered over the system's life, LiFePO₄ is superior—₦98/kWh compared to ₦127/kWh for tubular (a 23% advantage).

This difference occurs because LiFePO₄ delivers far more usable energy across its longer lifespan. The payback period also highlights this contrast: while tubular systems do not achieve meaningful payback within their life, LiFePO₄ systems recover their cost in about 8.2 years. This reinforces findings by IRENA (2020), which concluded that although lithium technologies are more capital-intensive, they deliver better long-term value when life-cycle performance is considered. For Nigerian universities, this presents a dilemma: tubular is cheaper to start with, which is attractive under budget constraints, but lithium offers better long-term savings and stability. In practice, institutions often go for tubular because of short-term financial realities, even if the long-term economics favors LiFePO₄.

Table 3: Net Present Cost Analysis Results

Economic Metric	Tubular Lead-Acid	LiFePO₄	Advantage
Net Present Cost (₦/kWh)	248,500	289,200	Lead-Acid: 16%
Levelized Cost of Storage (₦/kWh)	127	98	LiFePO₄: 23%
Payback Period (years)	N/A	8.2	-

Figure 4 compared the net present cost of storage technologies, showing tubular lead-acid at about ₦250,000/kWh and LiFePO₄ at roughly ₦290,000/kWh. Although LiFePO₄ incurred higher upfront costs, its longer lifespan and reduced maintenance suggest lower levelized storage costs, making it more economically viable in the long term compared to tubular lead-acid batteries.

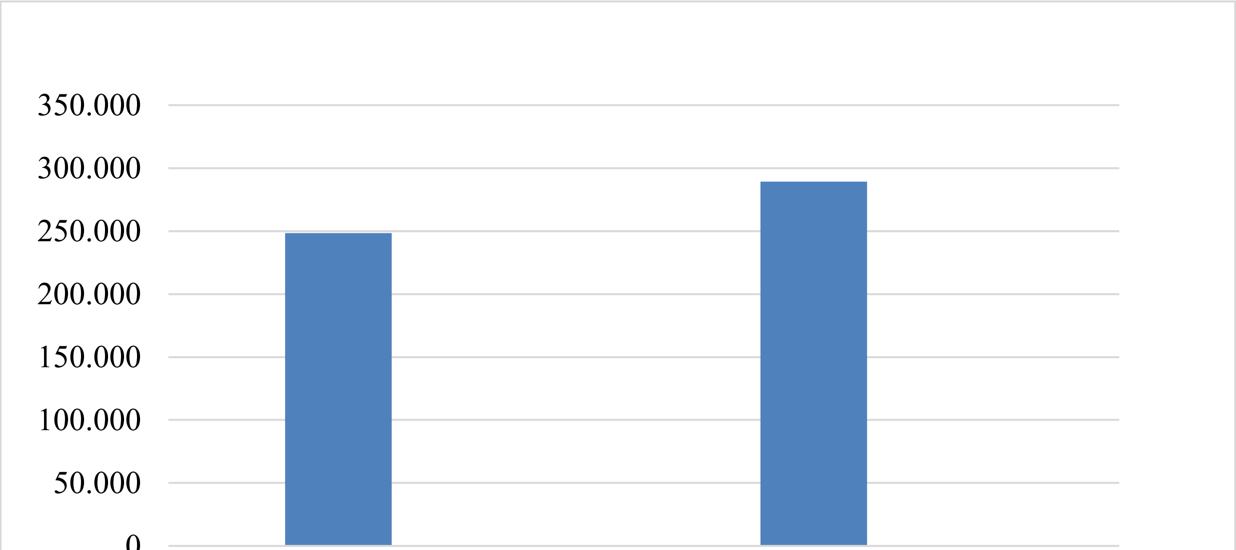

Figure 3: Net Present Cost Analysis Results

The above finding shows that while lithium is more economical on paper, tubular remains the “practical” choice for institutions operating under constrained budgets.

Discussion

The life-cycle cost analysis (LCCA) revealed that tubular lead–acid batteries appeared financially attractive due to their lower initial capital of ₦92,000/kWh compared to ₦230,000/kWh for LiFePO_4. This finding explained why many Nigerian institutions continue to adopt tubular batteries, as affordability remains the primary concern under budget constraints. In contrast, the results highlighted that while installation costs were identical at ₦18,400/kWh, tubular systems attracted far higher operations and maintenance (O\&M) costs of ₦46,000/kWh in the first five years, requiring replacements at years 5 and 10. This finding agreed with Fouzia (2023), who argued that lead–acid technologies often become less cost-effective due to recurring maintenance burdens.

The higher resilience of LiFePO4 that did not need to be replaced until year 12 and had minimal O&M at N18400/kWh made it the more sustainable choice, despite the higher initial cost. In a related experiment, Ciez and Whitacre (2016) have shown that compared to other types of batteries, lithium batteries were expensive initially but yielded lower effective storage costs over their life cycle because of a longer cycle life. In a similar vein, the net present cost (NPC) analysis indicated tubular batteries at N248,500/kWh versus N289,200/kWh at lithium, which was apparently cheaper at face value. Nevertheless, LiFePO4 was preferred to N127/kWh with a 23% lower levelized cost of storage (LCOE), compared to N98/kWh. This supported Mallapragada et al, (2020) who observed that lithium systems have a stronger alignment with long-term value creation when the energy provided per unit cost is taken into account.

Payback period also came out as a divergence since the tubular systems failed to generate meaningful payoffs, but LiFePO4 took about 8.2 years to recoup expenses. This conclusion was in line with Sauer et al, (2017), who reiterated that lithium technologies better fit institutional purposes that require reliability and economic retribution. Conversely, tubular was more school-friendly because schools with limited financial means needed a solution that is affordable in the short run, which is consistent with the finding of Oyedepo (2014) that Nigerian institutions tend to focus on short-term affordability rather than sustainability.

Additionally, the difference in salvage values N9,200/kWh tubular, N34,500/kWh LiFePO4 further supported the idea that the lithium-based technologies retained a stronger asset value, which was also determined by Barbosa et al, (2025). Together, the results indicated that whereas tubular lead-acid batteries are adequate to address the short-term affordability requirements, LiFePO4 offers better long-term savings, sustainability and institutional stability. This duality indicates that there is a trade-off between immediate accessibility and long-term efficiency of Nigerian universities, which highlights the need to harmonize financial reality with sustainable energy planning.

Application-Specific Recommendations

Depending on the overall analysis, particular recommendations are made concerning various campus microgrid cases that are prevalent in Nigerian universities. These are the recommendations in Table 4. LiFePO4 is preferable to high-usage labs and critical infrastructure due to its better cycle life and reliability. Tubular is more feasible in price-sensitive projects or when the project is remote and a local support team and affordability is important. Systems and research applications that are expansion-ready are better served by LiFePO4, thanks to its modularity and constant performance. In universities of Nigeria, it is possible that a hybrid solution is the most realistic one: tubular batteries in offices and classrooms where price is the key consideration, and LiFePO4 in laboratories and ICT centres where quality cannot be compromised. The approach strikes a balance between cost and sustainability in the long run.

Table 4: Application-Specific Battery Recommendations

Application Scenario	Recommended Technology	Primary Justification
High-Usage Labs (>8h/day)	$LiFePO_4$	Superior cycle life and efficiency
Critical Infrastructure	$LiFePO_4$	Higher reliability and availability
Budget-Constrained Projects	Tubular Lead-Acid	Lower capital requirements
Remote Locations	Tubular Lead-Acid	Better local support availability
Expansion-Ready Systems	$LiFePO_4$	Modularity and space efficiency
Research Applications	$LiFePO_4$	Consistent performance and data quality

Implications for Nigerian Academic Institutions

There are significant implications of the comparative results to the Nigerian universities aiming to enhance power supply to support teaching, research and administration. Strategic planning has to strike a balance between short-term affordability and long-term sustainability. Tubular batteries still offer the short-term option of those institutions with budgetary constraints. They are cheaper to install initially, and campus technicians are already familiar with their installation and maintenance. This renders them less difficult to implement in the short-term, particularly in small universities or faculties with low funding. But looking at 4.4 results reveal that LiFePO4 systems are a smarter choice when the university looks at it long-term, as it produces more energy at a lower cost in a span of 15 years.

Another determinant is technical capacity. Universities that have good engineering or renewable energy departments can have the skills to handle LiFePO4 systems, thus breaking the skills wall. Tubular systems can be easier to use in smaller institutions that lack such capacity and have locally available manpower to maintain them. In the case of research uses, the argument in favor of LiFePO4 is even more pronounced. Laboratories with sensitive equipment such as spectrometers, incubators, or computing servers need consistent power quality, which may not be maintained by the tubular batteries.

CONCLUSION

Life-cycle cost analysis of a 220Ah tubular battery in a solar-powered academic installation demonstrated economic and technical trade-offs involved in the search to sustainable energy solutions by the Nigerian universities. Although tubular lead-acid batteries seem cheaper initially, capital cost is N92,000/kWh, the short cycle of replacement and high maintenance costs added long-term cost of N153-N178/kWh of usable energy. However, lithium iron phosphate (LiFePO4) batteries with an initial price of N230,000/kWh, but showing better battery life of N20,000/kWh, reduced operational needs, and a levelized price of N85-N112/kWh showed advantage in the 15-year perspective. The results indicated that the tubular batteries were affordable in the short-term, at the expense of sustainability, and the LiFePO4 systems would guarantee superior economic and performance metrics. In the case of the Nigerian universities, the implication is evident; LiFePO4 batteries offer a higher value (in terms of long-term value, reliability, and energy security) even in the critical cases of academic and research use, although in many cases, budget constraints provide a more compelling reason to go with tubular batteries in the short term.

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