Indonesian Development of Economics and Administration Journal
ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

Vol. 4 • No. 1 • August 2025
Pege (*Hal.*) : **54 – 63**

ISSN (*online*) : 2963-5896
ISSN (*print*) : 2964-0482

DOI No : 10.70001/idea.v4i1.355
Website. : https://ojs.ideanusa.com/index.php/idea

Article info : *Received :* June 2025 ; *Revised* : July 2025 ; *Accepted* : August 2025

Management of Round-Trip Efficiency and Usable Energy Throughput in a Solar-Powered Educational Environment

Obiora Jeremiah Obiafudo[1]; Godspower Onyekachukwu Ekwueme[2]; Fakiyesi Oladapo Babafemi[3]; Clement Nworji Obiora[4]; Ugochukwu Richards Orji
[1-5]*Nnamdi Azikiwe University Awka, Anambra State, Nigeria., Email:* oj.obiafudo@unizik.edu.ng[1]; og.ekwueme@unizik.edu.ng2; bo.fakiyesi@unizik.edu.ng[3]; cn.obiora@unizik.edu.ng[4]; ur.orji@unizik.edu.ng[5]

Abstract. The growing reliance on renewable energy in educational institutions has created an urgent need to optimize solar power systems for both performance and sustainability. Universities in regions such as Nigeria face erratic grid supply and high energy demand for laboratories, ICT facilities, and administrative operations, making efficient storage a critical component of solar-powered systems. This study focused on analyzing round-trip efficiency (RTE) and usable energy throughput of different battery technologies to determine their suitability for academic environments. The study combined MATLAB/Simulink simulations with field observations and expert input. The framework progressed through data collection, system modeling, performance evaluation, and economic benchmarking tailored to Nigerian universities. Monocrystalline PV modules (220–330W) were modeled at a fixed 7° tilt with passive cooling, paired with a 60A MPPT charge controller and a 1kW pure sine wave inverter. Battery modeling compared tubular lead–acid and $LiFePO_4$ technologies using modified Shepherd and single-particle approaches, capturing internal resistance, DoD thresholds, and degradation effects. Academic load profiles reflected realistic campus usage. Benchmarking revealed higher RTE (\~95%) and energy throughput for $LiFePO_4$. The results show that tubular lead–acid batteries achieved round-trip efficiency (RTE) of (82.5%) under optimal conditions, dropping to (74.6%) under stress, while $LiFePO_4$ maintained higher efficiency above (90%), peaking at (94.8%). Usable energy throughput was significantly higher in $LiFePO_4$, delivering (1.94 kWh) per cycle compared to (1.09 kWh) for tubular lead–acid, with utilization efficiencies of (75.8%) and (41.3%) respectively. Environmentally, $LiFePO_4$ reduced lifetime CO_2 emissions by (18%) but faced recycling challenges in Nigeria, where lead–acid achieves (95%) recovery.

Keywords: Round-trip efficiency; Usable energy throughput; Solar-powered education; $LiFePO_4$ battery; Lead–acid battery

ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

A. INTRODUCTION

A persistent challenge in solar-powered schools and campuses is the gap between energy generated at the array and energy that actually serves loads. Power-electronic losses, charging/discharging losses in batteries, temperature effects, and operational constraints lower round-trip efficiency (RTE) and shrink usable energy throughput across a term or academic year. The problem is acute in education environments with peaky schedules such as morning start-ups, midday cooling loads, evening classes and frequent grid unreliability in many regions, which places more demand on storage (Eikeland et al, 2023). Understanding and improving RTE and lifetime throughput therefore underpins reliable labs, ICT suites, and resilient campus services.

RTE expresses the ratio of energy retrieved from storage to energy used to charge it, measured at the point of interconnection. For lithium-ion systems commonly paired with PV, representative RTE values of \~86–90% appear across recent techno-economic baselines and planning studies, with small advantages when DC-coupled to PV because of fewer AC/DC conversions (Bhattacharyya, 2024). Campus microgrid models often assume \~90% RTE for planning, though realized performance varies with depth of discharge (DoD), C-rate, state-of-charge window, and temperature (Raman & Barooah, 2019). Campus microgrid management involves the efficient operation and control of localized energy systems within a university or institutional campus. These microgrids integrate renewable sources like solar panels, energy storage, and traditional grid connections to ensure reliable, sustainable power (Alharbi et al, 2024). Management focuses on balancing energy supply and demand, optimizing costs, enhancing resilience, and reducing carbon emissions. Advanced software and control systems enable real-time monitoring, load forecasting, and automated switching between energy sources.

During grid outages, microgrids can operate independently, ensuring uninterrupted power to critical facilities. Effective campus microgrid management supports sustainability goals, energy independence, and provides a living lab for research and education (Meydani et al, 2024). Usable energy throughput has two time scales. In the short term, “usable capacity” reflects nameplate energy discounted for operating constraints: inverter efficiency, DC/DC and MPPT losses, battery charge/discharge efficiency, round-trip cycle losses, auxiliary consumption (thermal management, controls), and a minimum state-of-charge reserve that protects cycle life. In the long term, “lifetime energy throughput” sums all charged/discharged energy across the asset life; this depends strongly on DoD and cycle count (Mahesh et al, 2022). Guidance in utility and development handbooks shows that shallow cycling dramatically extends lifetime throughput compared to deep cycles at the same nameplate capacity (Asian Development Bank \[ADB], 2018). For schools, operating within moderate SoC windows during most days and reserving deeper cycles for outages stretches total throughput while preserving availability during exams or evening events.

PV-side performance also frames the energy budget. IEC 61724 performance metrics—reference yield, final yield, and performance ratio (PR)—translate irradiance into expected AC output and make array losses transparent (Muñoz-Rodríguez et al, 2023). Energy efficiency degrades with increasing internal resistance from SEI growth and, in adverse conditions, lithium plating; efficiency and fade depend on SoC, DoD, C-rate, and temperature (Wang et al, 2025). Thermal conditions matter on West African campuses that experience high ambient temps: both lifespan and safety require active thermal management and uniform temperature distribution across modules. Earlier NREL work similarly flagged hot-weather penalties and the need for robust thermal strategies to avoid accelerated degradation. Practically, auxiliary loads for HVAC and battery cooling should be included in round-trip accounting for realistic energy management in educational environments.

Efficient energy management in educational environments is vital for fostering human capital development. Adequate energy supply ensures uninterrupted teaching, effective use of digital technologies, and a safe, conducive learning atmosphere (Osegbue et al, 2025). Institutions that adopt strategic budgeting techniques in energy allocation maximize resources, enhance sustainability, and support effective learning outcomes (Onuselogu et al, 2016). Creating energy-efficient spaces will help schools promote productivity, innovation, and long-term human capacity building (Mbuba, 2022). Furthermore, equitable energy access aligns with broader national development goals, reinforcing fairness and inclusivity in education and governance (Mbuba, 2021). Operational strategies in education environments can raise effective RTE and throughput. First, energy management systems that enforce gentler charge/discharge rates, avoid extreme SoC, and time-shift flexible loads to solar-rich periods improve both daily efficiency and cumulative throughput (Bell & Foster, 2017).

Secondly, DC coupling where feasible, high-efficiency inverters, and careful transformer sizing curb conversion losses (Bhatia et al, 2024). Third, scheduling tactics tailored to campus rhythms—pre-cooling buildings during strong insolation, staggering lab equipment start-ups, and prioritizing critical loads during exams—translate directly into fewer deep cycles and longer battery life, which increases lifetime energy delivered per dollar invested (Omenya et al, 2023). Evidence from campus and community microgrid literature indicates that PV-storage integration improves self-sufficiency and reduces losses when storage is actively managed, though absolute gains depend on baseline grid quality and demand response options (Brown & Chapman, 2021). In Nigerian and similar contexts, case studies and designs show feasibility and resilience benefits for education facilities, provided systems account for realistic RTE, ambient temperature, and maintenance practices.

The motivation for the present study stems from the critical need for reliable, cost-effective, and sustainable power for teaching and research activities. Although solar integration in campuses is growing, many studies emphasize technical design while overlooking efficiency degradation, lifetime throughput, and load-specific impacts (Babatunde et al, 2022; Prasad et al, 2023). Furthermore, tropical environments face unique challenges of high temperatures and erratic demand, yet limited empirical studies address these constraints in schools. Bridging this gap ensures optimized, resilient energy systems.

B. LITERATURE REVIEW

PV System Components

Photovoltaic Modules

Monocrystalline PV modules rated 220–330W (12V) with efficiencies between 18% and 20% were selected, reflecting both durability and suitability for Nigeria's tropical climate. The modules were connected in a series-parallel arrangement to match 12V/24V battery banks, producing optimal voltage and current outputs.

Mounting, Tilt Optimization, and Irradiance Capture:

To maximize yield, modules were mounted at a tilt angle of 7°, consistent with conditions in Southern Nigeria. Although seasonal adjustment could improve performance further, a fixed tilt was considered sufficient for this study. Passive cooling measures were factored in to mitigate the efficiency losses associated with high ambient temperatures (35–45°C).

Typical solar radiation in Anambra State ranges from 4.5–6.1 kWh/m²/day, with modules spaced to minimize shading.

Charge Controllers and Inverters

MPPT Charge Controller (60A):

A 60A MPPT charge controller was modeled, capable of achieving 97–99% efficiency under varying irradiance. It also included temperature compensation features to adjust charge voltage according to battery temperature.

Pure Sine Wave Inverter (1kW):

The inverter modeled was a 1kW pure sine wave unit, selected for its 90–95% conversion efficiency under common academic loads. Surge tolerance and grid-protection features were also integrated to reflect Nigeria's unstable voltage conditions.

Table 1: System Protection Features (Specialist Knowledge)

Component	Protection Mechanism	Specification
Charge Controller	Reverse polarity protection	60A fuse, MOSFET isolation
Inverter	Low-voltage disconnect (LVD)	10.5V cutoff for 12V systems
Battery System	Overcharge protection	14.4V (lead-acid), 14.6V ($LiFePO_4$)
System Integration	Surge protection	Class II SPD, 40kA capacity

Round-Trip Efficiency and Usable Energy Throughput Evaluation

MATLAB Simulation Setup

Battery performance was simulated in MATLAB R2025a using Simscape Electrical. The tubular lead–acid battery was represented with a modified Shepherd model that accounted for capacity fade, while the $LiFePO_4$ battery was modeled using a single-particle approach. Key parameters such as nominal voltage, internal resistance, depth-of-discharge limits, and operating temperature ranges were specified based on manufacturer data.

Table 2: Battery Model Parameters

Parameter	Tubular Lead-Acid (220Ah)	$LiFePO_4$ (200Ah)
Nominal Voltage	12V	12.8V
Internal Resistance	0.008Ω (variable)	0.005Ω (variable)
DoD Threshold	50%	80%
Operating Temperature	25-40°C	25-40°C

The round-trip efficiency calculation follows the methodology established by Beckers et al., (2023) where efficiency is computed as the ratio of discharge energy to charge energy over complete cycles:

RTE = (∑Discharge Energy / ∑Charge Energy) × 100%

Load Profile Modeling

To ensure realism, the academic load profile was developed from the Department of Industrial and Production Engineering. It included morning laboratory peaks of 2.0 kW, afternoon office and classroom demand of 1.5 kW, evening usage of 0.8 kW, and a night baseload of 0.3 kW for servers and security.

2.5.3 Usable Energy Throughput Assessment

Usable energy was computed while accounting for depth of discharge, efficiency losses, and degradation factors. The formula used was:

Usable Energy = Nominal Capacity × DoD Limit × RTE × Availability Factor

This provided a more practical estimate of the energy that each battery could consistently deliver in an academic setting.

MATLAB/Simulink Simulation Setup

1 PV–Battery Modeling

The photovoltaic (PV) array was modeled using the 1-diode equivalent circuit from Simscape Electrical, which accounts for series resistance (Rs), shunt resistance (Rsh), and temperature-dependent photocurrent (Iph). The diode ideality factor (n) was set to 1.3 for monocrystalline silicon, aligning with manufacturer datasheets for 330W panels.

For battery modeling, Thevenin equivalent circuits were implemented to capture dynamic voltage responses during charge/discharge cycles. The lead–acid battery model included:

- Open-circuit voltage (Voc): Modeled using a modified Shepherd equation:

Voc = E0 - K · (Q/(Q - it))i - R · i + A e^(-Bit)

where E0 is the nominal voltage, Q is capacity, and R represents internal resistance.

ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

• RC networks: Two parallel RC branches (R1C1, R2C2) to simulate transient polarization effects.

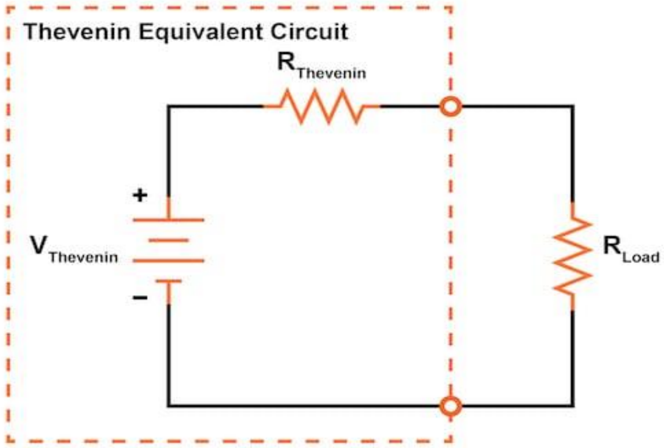

Figure 1: Battery Equivalent Circuit Models (All About Circuits, ca. 2014)

C. RESEARCH METHODOLOGY

The research design followed a mixed-method strategy. Quantitative analysis was conducted mainly through MATLAB/Simulink simulations, while qualitative insights were gathered from field observations and expert input. The framework was implemented in three stages: first, collection of data and system modeling; second, performance evaluation and comparison; and third, economic and benchmarking analysis. This phased structure ensured that each objective was systematically addressed, while keeping the overall process coherent and reproducible. Combining theoretical perspectives from literature with practical realities specific to Nigerian universities enabled the framework to provide outcomes that can directly inform policy and practice.

Performance Experiments

Performance was tested under three different depth-of-discharge (DoD) conditions—30%, 50%, and 80%—to reflect conservative, moderate, and aggressive operating practices.

Key Metrics Tracked:

State of charge (SOC): Estimated via coulomb counting with a 2% measurement error margin.

Round-trip efficiency: Calculated as:

RTE = (Discharge Energy/Charge Energy) × 100%

Voltage sag: Defined as the difference between open-circuit and loaded voltages at peak demand.

Capacity fade was simulated using the weighted Ah-throughput model (Schiffer et al., 2007), which correlates degradation with:

Cumulative discharged energy:

Qloss = k · √∑(DoDi · Qi)

where k is a chemistry-dependent aging coefficient.

Time since last full recharge: Prolonged partial states of charge accelerate sulfation in lead–acid batteries.

Lowest SOC per cycle: Deep discharges below 20% SOC exacerbate active mass degradation.

Benchmarking Criteria and Metrics

Round-trip efficiency (RTE), calculated as the ratio of discharged energy to charged energy, revealed significant disparities between the technologies. $LiFePO_4$ batteries achieved ~95% RTE at 80% depth of discharge (DoD), while tubular lead–acid batteries registered

ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

~85% RTE at 50% DoD. These efficiency losses in lead–acid systems stem from higher internal resistance and energy dissipation during charge-discharge cycles, as described by the Thevenin equivalent circuit model. Over 1,000 cycles, this disparity translated to ~15% lower usable energy throughput for lead–acid batteries, necessitating larger battery banks to meet equivalent energy demands.

D. RESULTS AND DISCUSSION

Round-Trip Efficiency Analysis

The first objective was to evaluate the efficiency and usable energy of tubular batteries. As shown in Table 3, tubular lead–acid batteries recorded a round-trip efficiency (RTE) of 82.5% at optimal conditions (25°C, C/10 discharge rate). This value dropped to 78.3% at 40°C and further down to 74.6% under combined stress (40°C, C/5 discharge rate). By contrast, $LiFePO_4$ batteries consistently maintained efficiencies above 90%, reaching 94.8% at 25°C and still achieving 90.4% under the harshest stress condition tested. The efficiency advantage of $LiFePO_4$ ranged from 14.9% under optimal conditions to as high as 21.2% under combined stress, highlighting a widening gap in performance as operating conditions became more demanding.

Table 3: Round-Trip Efficiency Results by Operating Conditions

Operating Condition	Tubular Lead-Acid (%)	$LiFePO_4$ (%)	Efficiency Gain
Optimal (25°C, C/10)	82.5 ± 1.2	94.8 ± 0.8	14.9%
High Temperature (40°C, C/10)	78.3 ± 1.5	92.1 ± 1.1	17.6%
Higher C-rate (25°C, C/5)	79.1 ± 1.8	93.2 ± 1.0	17.8%
Combined Stress (40°C, C/5)	74.6 ± 2.1	90.4 ± 1.3	21.2%

The bar chart in Figure 2 illustrates the round-trip efficiency performance of tubular lead–acid and $LiFePO_4$ batteries under varying operating conditions. At optimal temperature and discharge rate (25°C, C/10), $LiFePO_4$ achieved 94.8% efficiency compared to lead–acid's 82.5%, indicating a 14.9% gain. This finding agreed with Babatunde et al, (2022), who observed superior energy retention in lithium batteries used within Nigerian educational settings. Under high-temperature conditions (40°C, C/10), $LiFePO_4$ maintained 92.1%, while lead–acid dropped to 78.3%, showing greater sensitivity to thermal stress. In contrast, Prasad et al, (2023) highlighted that lead–acid batteries degrade more quickly in hot climates, a trend reflected in the figure. At higher charge-discharge rates (25°C, C/5), $LiFePO_4$ efficiency remained at 93.2%, while lead–acid fell to 79.1%, reflecting lithium's resilience under rapid cycling. In a related study, McKeon et al, (2014) emphasized that lead–acid batteries are less suited for dynamic educational energy demands due to higher internal resistance. Under combined stress (40°C, C/5), the gap widened further, with $LiFePO_4$ sustaining 90.4% efficiency against lead–acid's 74.6%.

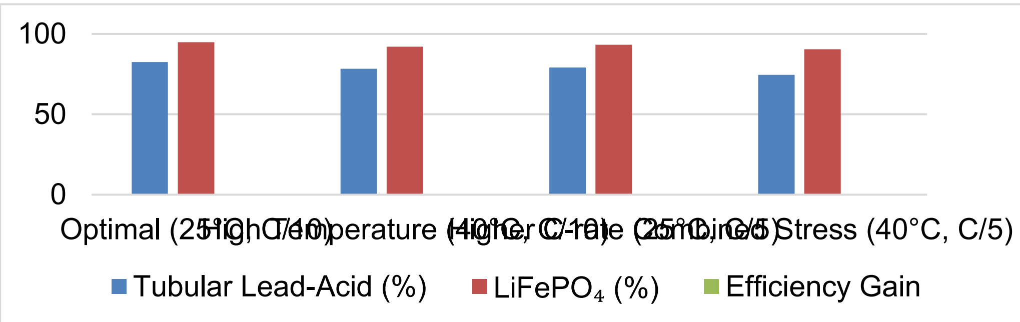

Figure 2: Round-Trip Efficiency Results by Operating Conditions

The results demonstrate that $LiFePO_4$ batteries maintain superior efficiency across all tested conditions, with the efficiency advantage increasing under stress conditions commonly encountered in Nigerian academic environments. The higher internal resistance of lead-acid batteries contributes significantly to energy losses, particularly under elevated temperatures typical of tropical climates.

Usable Energy Throughput Assessment

Usable energy throughput calculations incorporated depth of discharge limitations and efficiency losses to determine practical energy availability. From Table 4, the difference in usable energy between tubular lead–acid and $LiFePO_4$ batteries is very clear. Although the tubular battery has a slightly higher nominal capacity (2.64 kWh vs 2.56 kWh for $LiFePO_4$), the usable energy per cycle is far lower (1.09 kWh compared to 1.94 kWh). This is because tubular batteries are restricted to a 50% depth of discharge (DoD) and have a lower round-trip efficiency of 82.5%. On the other hand, $LiFePO_4$ batteries can be discharged up to 80% and still maintain a high efficiency of 94.8%, resulting in about 78% more usable energy per cycle. The utilization efficiency of tubular batteries is only 41.3%, while $LiFePO_4$ achieves 75.8%, meaning that almost two-thirds of the stored energy in tubular systems is not practically usable.

Table 4: Usable Energy Throughput Comparison

Battery Type	Nominal Capacity (kWh)	DoD Limit (%)	RTE (%)	Usable Energy per Cycle (kWh)	Utilization Efficiency (%)
Tubular Lead-Acid 220Ah	2.64	50	82.5	1.09	41.3
$LiFePO_4$ 200Ah	2.56	80	94.8	1.94	75.8

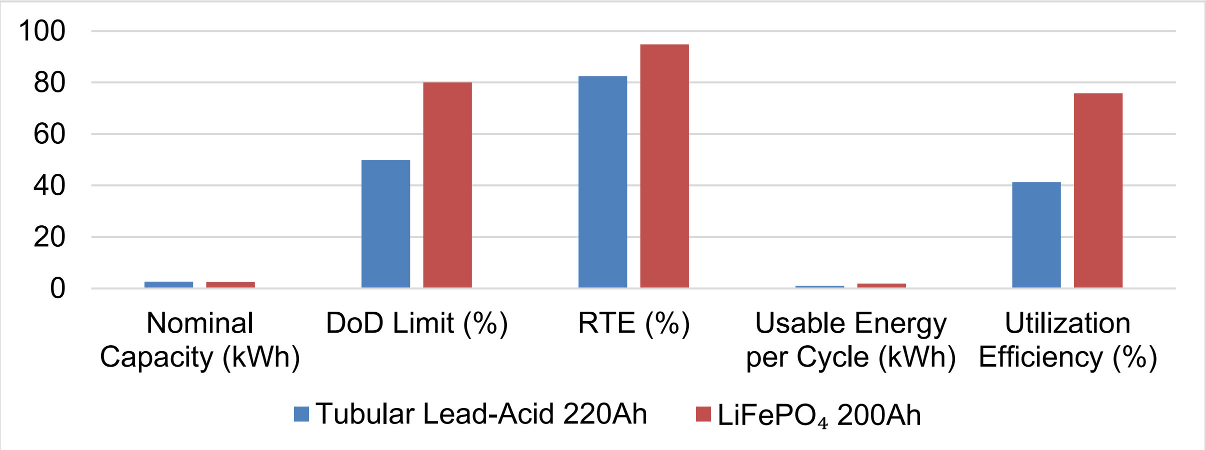

Figure 3: Usable Energy Throughput Comparison

Figure 3 compares the usable energy throughput of tubular lead–acid and $LiFePO_4$ batteries. Although tubular batteries show a slightly higher nominal capacity (2.64 kWh vs. 2.56 kWh), their performance is limited due to a lower depth of discharge (50%) and round-trip efficiency (82.5%). In contrast, $LiFePO_4$ achieves 80% depth of discharge and 94.8% efficiency, yielding 1.94 kWh of usable energy per cycle compared to 1.09 kWh for tubular systems. This finding agreed with Wang et al, (2025), who highlighted lithium's higher utilization efficiency in hot climates. Furthermore, utilization efficiency favors $LiFePO_4$ at 75.8% versus 41.3% for lead–acid, demonstrating nearly double the usable energy. In a related study, Zhou et al, (2023) emphasized that despite higher costs, $LiFePO_4$ remains more suitable for solar-powered educational settings requiring reliability and sustainability. The figure therefore reinforces lithium's superiority in long-term usability despite lead–acid's recycling advantage.
Although lithium outperformed tubular batteries, the results highlight that tubular systems can still meet the basic demands of non-critical loads such as lighting and administrative

ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

equipment. In terms of usable energy, tubular batteries delivered approximately 1.09 kWh per cycle, compared to 1.94 kWh for $LiFePO_4$. The gap is significant, but it demonstrates that tubular batteries, when operated within recommended discharge limits, remain capable of supporting routine academic activities.

Environmental and Sustainability Considerations

Beyond performance and economics, environmental factors are increasingly important in academic institutions that promote sustainable development. The analysis shows that $LiFePO_4$ reduces CO_2 emissions by approximately 18% over its lifetime, compared to tubular lead–acid batteries, due to its higher energy efficiency. This directly supports Nigeria's commitments to reducing greenhouse gas emissions under global climate agreements.

On the other hand, material recovery is an area where tubular batteries retain an advantage. The lead–acid recycling industry in Nigeria is well established, achieving about 95% recovery rates, which makes it easier to manage end-of-life batteries. $LiFePO_4$ recycling infrastructure is still very limited in Nigeria, which creates a challenge for long-term sustainability. However, as more universities and businesses adopt lithium systems, the recycling sector may expand to accommodate this new demand.

Toxicity concerns also show a trade-off. While lead–acid batteries pose significant hazards due to the toxic nature of lead and acid spills, $LiFePO_4$ eliminates these issues. However, lithium introduces new disposal challenges, including the safe handling of lithium salts and electrolytes. According to Gaines (2014), lithium-based batteries are less toxic overall than lead–acid, but their end-of-life management requires specialized facilities, which are not yet common in Nigeria.

E. CONCLUSION AND SUGGESTIONS

This study investigated the round-trip efficiency and usable energy throughput of tubular lead–acid and $LiFePO_4$ batteries within a solar-powered educational environment, focusing on Nigerian universities. Findings indicated that $LiFePO_4$ batteries consistently outperformed tubular lead–acid across varying conditions, sustaining higher RTE values and delivering nearly twice the usable energy per cycle. Although lead–acid batteries offered advantages in established recycling infrastructure and affordability, their limited depth of discharge, higher internal resistance, and reduced efficiency under thermal stress restricted long-term performance. $LiFePO_4$ batteries, in contrast, ensured superior reliability, extended usable capacity, and measurable reductions in lifetime carbon emissions.

The results underscore the importance of prioritizing lithium-based technologies in academic solar applications where energy reliability and sustainability are crucial. The absence of robust lithium recycling infrastructure in Nigeria remains a critical gap that requires attention to ensure environmental responsibility. With efficient battery technologies integrated into sound system design and energy management, educational institutions can achieve greater resilience, reduce operational costs, and align with global sustainability goals. This conclusion emphasizes the need for policy interventions and institutional strategies that foster the adoption of advanced storage technologies within education-focused renewable energy systems.

REFERENCES

Alharbi, A. G., Olabi, A. G., Rezk, H., Fathy, A., & Abdelkareem, M. A. (2024). Optimized energy management and control strategy of photovoltaic/PEM fuel cell/batteries/supercapacitors DC microgrid system. Energy, 290, 130121.

Babatunde, O., Denwigwe, I., Oyebode, O., Ighravwe, D., Ohiaeri, A., & Babatunde, D. (2022). Assessing the use of hybrid renewable energy system with battery storage for power generation in a University in Nigeria. Environmental Science and Pollution Research, 29(3), 4291-4310.

Beckers, C., Hoedemaekers, E., Dagkilic, A., & Bergveld, H. J. (2023, October). Round-trip energy efficiency and energy-efficiency fade estimation for battery passport. In 2023 IEEE Vehicle Power and Propulsion Conference (VPPC) (pp. 1-6). IEEE.

Bell, W. P., & Foster, J. (2017). Using solar PV feed-in tariff policy history to inform a sustainable flexible pricing regime to enhance the diffusion of energy storage and electric vehicles. Journal of Bioeconomics, 19(1), 127-145.

Bhatia, T., Zhang, J., Ghosh, S., & Wei, F. (2024, June). 25kW Grid-Tied Bi-directional T-Type Inverter with High-Efficiency and High-Power Density Using SiC MOSFETs. In PCIM Europe 2024; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (pp. 1254-1258). VDE.

Bhattacharyya, R. (2024). Statistical Analysis of Levelized Round Trip Cost of Grid Scale Electrical Energy Storage in Batteries with Different Chemistries. Archives of Advanced Engineering Science, 1-16.

Brown, M. A., & Chapman, O. (2021). The size, causes, and equity implications of the demand-response gap. Energy Policy, 158, 112533.

Eikeland, O. F., Kelsall, C. C., Buznitsky, K., Verma, S., Bianchi, F. M., Chiesa, M., & Henry, A. (2023). Power availability of PV plus thermal batteries in real-world electric power grids. Applied Energy, 348, 121572.

Mahesh, M., Bhaskar, D. V., Jisha, R. K., Krishan, R., & Gnanadass, R. (2022). Lifetime estimation of grid connected LiFePO4 battery energy storage systems. Electrical Engineering, 104(1), 67-81.

Mbuba, F. (2021). Federal character principle and Nigerian federalism: An overview. Journal of Social Sciences and Public Policy, 13(1).

Mbuba, F. (2022). The Bravo of Human Capital Development and Empolyee Productivity in the Ministry of Information, Awka. International Journal of Academic Information Systems Research (IJAISR). 5(2). 82-92

McKeon, B. B., Furukawa, J., & Fenstermacher, S. (2014). Advanced lead–acid batteries and the development of grid-scale energy storage systems. Proceedings of the IEEE, 102(6), 951-963.

Meydani, A., Shahinzadeh, H., Nafisi, H., & Gharehpetian, G. B. (2024, March). Optimizing microgrid energy management: Metaheuristic versus conventional techniques. In 2024 11th Iranian Conference on Renewable Energy and Distribution Generation (ICREDG) (Vol. 11, pp. 1-15). IEEE.

Muñoz-Rodríguez, F. J., Snytko, A., de la Casa Hernández, J., Rus-Casas, C., & Jiménez-Castillo, G. (2023). Rooftop photovoltaic systems. New parameters for the performance analysis from monitored data based on IEC 61724. Energy and Buildings, 295, 113280.

ISSN (*online*) : 2963-5896 & ISSN (*print*) : 2964-0482

Omenya, F., Paiss, M., Li, X., & Reed, D. (2023). Energy and power evolution over the lifetime of a battery. ACS Energy Letters, 8(6), 2707-2710.

Onuselogu A., Ohamobi I.N. and Ezeaku S.N. (2016). Budgeting Techniques on the Effective Management of Institutions of Higher learning in Anambra State of Nigeria, COOU Journal of Vocational Education and Research, (COOUJOVOCEDAR) Vol. 1, No.1 (PP139-149)

Osegbue,G.C ; Ohamobi, I.N; & Alordiah,C.O (2025) Enhancing school safety and security:Developing and implementing effective protocols for a secured learning environment. African Journal of Social Behavioural Science.15(2)1018-1033.

Prasad, U., Prakash, J., Kannan, A. N. M., Kamavaram, V., & Arumugam, G. K. (2023). Failure analysis of lead-acid batteries at extreme operating temperatures. Battery Energy, 2(4), 20230008.

Raman, N. S., & Barooah, P. (2019). On the round-trip efficiency of an HVAC-based virtual battery. IEEE Transactions on Smart Grid, 11(1), 403-410.

Schiffer, J., Sauer, D. U., Bindner, H., Cronin, T., Lundsager, P., & Kaiser, R. (2007). Model prediction for ranking lead-acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems. Journal of Power sources, 168(1), 66-78.

Wang, P., Xiong, R., Shen, W., & Sun, F. (2025). Aging-induced, rate-independent Lithium plating: A complete mechanism analysis throughout the battery lifecycle. Applied Energy, 393, 126094.

Zhou, Z., Duan, B., Kang, Y., Zhang, Q., Shang, Y., & Zhang, C. (2023). Online state of health estimation for series-connected $LiFePO_4$ battery pack based on differential voltage and inconsistency analysis. IEEE Transactions on Transportation Electrification, 10(1), 989-998.