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Assessment of Digital Battery Management and Maintenance Protocols for Maximizing 220Ah Tubular Battery Lifespan

Obiora Jeremiah Obiafudo[1], Godspower Onyekachukwu Ekwueme[2], Ugochukwu Richards Orji[3], Chibuzo Benjamin Nwanonobi[4]

[1]Department of Industrial and Production Engineering, Faculty of Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria, oj.obiafudo@unizik.edu.ng

[2]Department of Industrial and Production Engineering, Faculty of Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria, og.ekwueme@unizik.edu.ng

[3]Department of Industrial and Production Engineering, Faculty of Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria, ur.orji@unizik.edu.ng

[4]Department of Industrial and Production Engineering, Faculty of Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria, bc.nwanonobi@unizik.edu.ng

Corresponding Author: oj.obiafudo@unizik.edu.ng[1]

Abstract: Reliable energy storage is critical for sustainable power systems, particularly in academic environments where interruptions can disrupt teaching and research. Tubular lead-acid batteries, widely adopted for their affordability and robustness, often face reduced lifespan due to inadequate maintenance and poor monitoring practices. With the advent of digital technologies, battery management can now integrate real-time monitoring, predictive diagnostics, and automated alerts to improve efficiency and reliability. A three-phase framework—data collection and modeling, performance evaluation, and economic benchmarking—ensured coherence and reproducibility. Monocrystalline PV modules (220–330W, 18–20% efficiency) were mounted at a 7° tilt for optimal irradiance in Southern Nigeria, supported by passive cooling. A 60A MPPT charge controller and a 1kW pure sine wave inverter were modeled with high efficiency and protective features. Battery protocols were developed for both tubular lead-acid and $LiFePO_4$ types, balancing monitoring, maintenance, and cost quantification to maximize reliability, performance, and lifespan in academic settings. The results show clear differences between tubular lead-acid and $LiFePO_4$ batteries in maintenance, cost, and performance. Tubular systems demand weekly checks, monthly charging, and quarterly testing, totaling about 156 labor hours per year, compared to just 24 hours per year for $LiFePO_4$ with automated BMS monitoring. Results further indicate that incorporating digital monitoring reduces downtime, enhances predictive maintenance, and extends battery life. The study demonstrates that digital integration provides a cost-effective and sustainable framework for academic institutions, particularly in resource-constrained contexts.

Keyword: Digital battery management, Tubular lead-acid batteries, Maintenance protocols, Lifespan optimization, Energy storage systems

INTRODUCTION

In Nigeria and other regions with unreliable grids, 220Ah tubular lead–acid batteries play a central role in residential and small commercial backup power. Frequent deep discharges, irregular maintenance, high ambient temperatures, and improper charging routines shorten useful life and raise lifecycle costs (Senol et al., 2023). Efficient digital management and robust maintenance protocols promise to reduce premature ageing, but most literature focuses on li-ion systems; research describing how digital BMS features, predictive algorithms, and tailored maintenance regimes extend tubular lead–acid battery life remains fragmented. Battery management and maintenance protocols refer to the structured set of strategies, procedures, and technologies designed to monitor, regulate, and sustain the optimal performance and longevity of batteries (Krishna et al., 2022). They encompass activities such as charging control, electrolyte level checks, temperature regulation, cleaning, and periodic inspections to prevent premature failures.

These protocols are critical for ensuring energy efficiency, minimizing downtime, reducing operational costs, and extending overall battery service life. Role of battery-management systems (BMS) covers continuous monitoring (voltage, current, temperature), SOC/SOH estimation, cell/element equalization, charging control, thermal protection, and fault diagnosis all materially affect longevity (Gabbar et al., 2021; Krishna et al., 2022). Although most high-fidelity BMS literature targets lithium chemistries, the core principles helps to avoid overcharge/overdischarge, limit depth of discharge (DOD), control temperature, and maintain balanced cells/elements that can apply to lead–acid tubular banks as well (Gabbar et al., 2021). For 220Ah banks, practical BMS functions include float/absorption stage control, prevention of prolonged undercharge, and alarm/lockout on unsafe temperature or voltage excursions.

Advances in digital twins, cloud logging, and machine-learning SOH prediction can convert routine measurements into actionable maintenance schedules and remaining-useful-life estimates (Krishna et al., 2022; NREL, 2025). Physics-aware ML models and dual-Kalman filters have been shown to improve SOC/SOH accuracy and to inform charge/discharge dispatch that reduces ageing (NREL, 2025). For tubular lead–acid banks, embedding inexpensive sensors (temperature, voltage across individual cells/blocks, and current) into an IoT stack enables early detection of stratification, thermal hotspots, and imbalanced elements covering issues that accelerate grid-cycle wear. Digital logging also creates audit trails that help operators correct harmful operating patterns (excessive DOD, prolonged float at high temperature).

Recent applied work on tubular battery monitoring demonstrates that IoT platforms and low-cost data acquisition units can track per-cell/block voltage and temperature in real time, enabling alarms and remote corrective actions (Haldar, 2024). Studies show that alerting users to recurrent deep discharges, electrolyte low-level, or unequal block voltages allows timely watering, rebalancing, or replacement of weak cells with steps that measurably increase cycle life of tubular banks in hot climates. Implementations that combine local edge processing for alarms with cloud analytics for trend detection are most practical where network connectivity is intermittent.

Empirical surveys and field studies in Nigeria highlight that lack of routine maintenance is a leading cause of premature PV/battery system failure: one study reported over 70% of installations received no regular maintenance, and respondents linked poor maintenance to short system lifetimes (Adetona et al., 2020). Standard maintenance tasks for tubular batteries which involves periodic distilled water top-up, terminal cleaning, electrolyte specific-gravity checks, and correct charging profile verification remain essential complements to digital monitoring. Critically, digital systems only deliver value if owners or appointed technicians act on alerts; capacity building, service contracts, and institutionalised maintenance schedules are therefore necessary.

Literature converges on a few high-impact protocols for lead–acid tubular banks: (1) maintain SOC in an optimal window (avoid chronic undercharge and deep cycling), (2) use multistage chargers (CC–CV or tailored MCC profiles) that reduce gassing and stratification, (3) limit high-temperature exposure and improve ventilation, and (4) use periodic equalization charges only when needed. Forecast-aware charging strategies and health-aware dispatch (which schedule charging during cooler hours or lower grid stress) show promise in other contexts for prolonging lifetime and could be adapted to tubular systems in high-temperature zones (Krishna et al., 2022; Gabbar et al., 2021).

This study is timely considering the growing reliance on batteries as critical energy storage systems for renewable energy and backup power. Tubular batteries, particularly the 220Ah type, are widely used in residential, industrial, and hybrid energy applications due to their durability and deep-cycle capabilities. However, poor maintenance practices, lack of real-time monitoring, and reliance on manual inspection significantly reduce their operational lifespan. In contrast, recent advances in digital battery management systems (BMS) promise automated monitoring of parameters such as state of charge, electrolyte levels, and temperature, thereby minimizing degradation and failures (Park et al., 2020).

In spite of these innovations, little empirical research has critically evaluated the effectiveness of digital maintenance protocols, relative to traditional protocols, in maximizing tube battery life. Moreover, the available literature has largely concentrated on lithium-ion technologies with a knowledge gap on lead-acid tubular batteries which are commonly utilized in developing economies. The aim of this research is thus informed by the necessity to fill this gap with factual information on the efficiency, sustainability, and cost-effectiveness of effective maintenance procedures in ensuring optimum battery life in tubular batteries.

METHOD

Research Design and Framework

The study was based on a mixed-method approach. The quantitative analysis was primarily performed using MATLAB/Simulink simulations, with qualitative information being collected through field observations and expert judgment. The framework was applied in three phases that include; initial data gathering and system modelling, performance testing and benchmarking, and economic and benchmarking testing. This stepwise model made sure that one objective was tackled at a time, maintaining the overall process in a consistent and repeatable form. Integrating both theoretical assumptions based on literature and applied realities within the Nigerian universities allowed the framework to deliver results that can be directly used to inform policy and practice.

PV System Components

a. Photovoltaic Modules

PV monocrystalline 220-330W (12V) with efficiencies ranging 18 to 20 percent (rated) was chosen, which is not only durable but also suited to the Nigerian tropical climate. The modules were linked in a series-parallel configuration to correspond to battery banks of 12 V/24 V generating optimum voltage and current output.

2.2.2 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.

b. 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

Battery Management and Maintenance Protocols

a. Protocol Development Methodology

Battery management protocols were formulated by integrating manufacturer guidelines, expert consultations, and field observations, while adapting to local operating conditions. For tubular lead-acid batteries, weekly monitoring of electrolyte levels and specific gravity is complemented by monthly equalization charging, quarterly capacity testing with terminal cleaning, and annual thermal imaging alongside torque verification. For $LiFePO_4$ batteries, continuous BMS monitoring with automated alerts ensures real-time oversight, supported by quarterly cell balance checks and firmware updates, semi-annual thermal management inspections, and annual capacity verification with performance trending. Together, these protocols enhance reliability, extend lifespan, and optimize performance of both battery types.

b. Maintenance Cost Quantification

Maintenance protocols are cost-quantified based on labor requirements, consumable materials, and downtime impacts. Each maintenance activity is assigned time requirements and resource costs to enable accurate LCCA integration.

RESULTS AND DISCUSSION

Results

Battery Management and Maintenance Protocol Assessment

1. Maintenance Requirements Comparison

The analysis of maintenance protocols reveals significant differences in complexity, frequency, and resource requirements between the two battery technologies. Table 2 shows the difference in maintenance complexity. Tubular batteries require weekly inspection, regular electrolyte management, monthly equalization charging, and quarterly capacity testing. $LiFePO_4$, on the other hand, requires only quarterly inspections, minimal manual intervention, and automated monitoring through its Battery Management System (BMS). In terms of labor, tubular systems demand about 156 hours per year, compared to just 24 hours for $LiFePO_4$. This gap has big implications in Nigerian universities, where technical staff are often limited. Maintaining tubular systems requires both training and constant attention, increasing the risk of premature failure if neglected. $LiFePO_4$'s minimal requirements make it more suitable in environments where skilled manpower is scarce.

Table 2: Maintenance Protocol Comparison

Maintenance Activity	Tubular Lead-Acid	$LiFePO_4$
Frequency of Inspection	Weekly	Quarterly
Electrolyte Management	Required (weekly)	Not required
Equalization Charging	Monthly	Not required
Terminal Cleaning	Monthly	Quarterly
Capacity Testing	Quarterly	Semi-annually
BMS Monitoring	Manual	Automated
Annual Labor Hours	156	24
Training Requirements	Extensive	Minimal

2. Maintenance Cost Quantification

Detailed analysis of maintenance costs incorporates labor, materials, and system downtime impacts. As seen in Table 3 and Figure 1, tubular batteries incur annual maintenance costs of about ₦1,950/kWh/year, compared to ₦360/kWh/year for $LiFePO_4$. This represents an 82% saving in favor of lithium. Most of tubular's costs come from labour (₦1,180) and downtime (₦450), while $LiFePO_4$ avoids these by eliminating electrolyte management and reducing inspection frequency. In Nigeria, downtime costs can be severe, especially in labs where interrupted power can spoil experiments or damage sensitive equipment. This makes $LiFePO_4$ particularly attractive for critical applications, while tubular remains better suited for simpler, less sensitive loads.

Table 3: Annual Maintenance Cost Breakdown (₦/kWh/year)

Cost Component	Tubular Lead-Acid	$LiFePO_4$
Labor (156h vs 24h @ ₦2,000/h)	1,180	188
Materials (electrolyte, terminals)	320	80
Downtime Cost (productivity loss)	450	92
Total Annual Maintenance	1,950	360

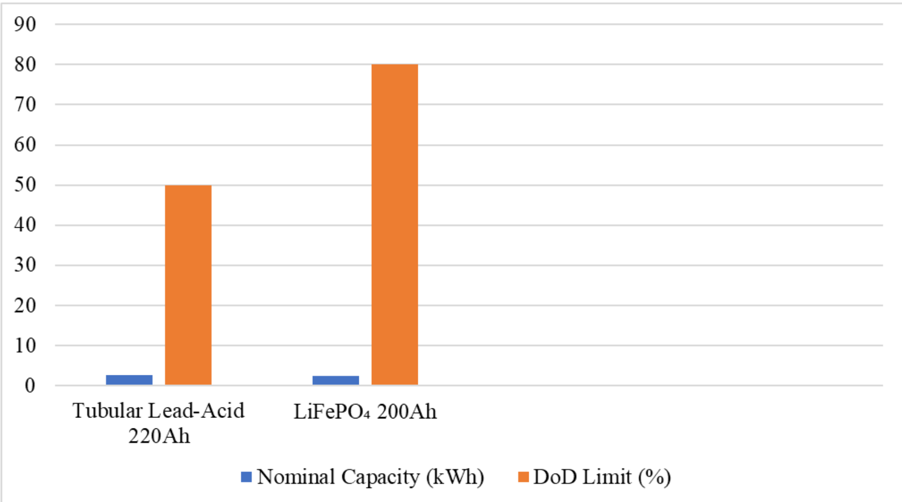

Figure 1: Annual Maintenance Cost Breakdown (₦/kWh/year)

Benchmarking Results for Campus Microgrid Applications

1. Multi-Criteria Performance Assessment

The comprehensive benchmarking analysis weights technical, economic, and operational criteria according to their importance for academic applications. The weighted performance scoring in Table 4 and Figure 2 shows $LiFePO_4$ scoring an overall 8.13, compared to 6.37 for tubular lead–acid. Lithium clearly outperforms in technical performance (efficiency, power density, cycle life) and operational factors (maintenance complexity, reliability). Tubular, however, scores better on capital cost (8.5 vs 4.0), reflecting its affordability advantage. This analysis shows that while tubular is attractive for cost-sensitive projects, $LiFePO_4$ is the better choice for reliability, long-term efficiency, and ease of maintenance. In a university setting where research and teaching are critical, these operational advantages are very important.

Table 4: Weighted Performance Scoring (Scale: 1-10, where 10 is best)

Criteria Category	Weight	Tubular Lead-Acid	$LiFePO_4$	Weighted Score Difference
Technical Performance	30%	6.2	8.7	+0.75
Energy Efficiency	10%	6.0	9.0	+0.30
Power Density	8%	5.5	8.5	+0.24
Cycle Life	12%	6.8	8.8	+0.24
Economic Factors	40%	7.1	6.8	-0.12
Capital Cost	15%	8.5	4.0	-0.68
Operating Cost	15%	5.2	8.8	+0.54
Total Cost of Ownership	10%	7.8	7.6	-0.02
Operational Factors	30%	5.8	8.9	+0.93
Maintenance Complexity	12%	4.5	9.2	+0.56
Reliability	10%	6.8	8.8	+0.20
Local Support	8%	7.0	8.5	+0.12
Total Weighted Score	100%	6.37	8.13	+1.56

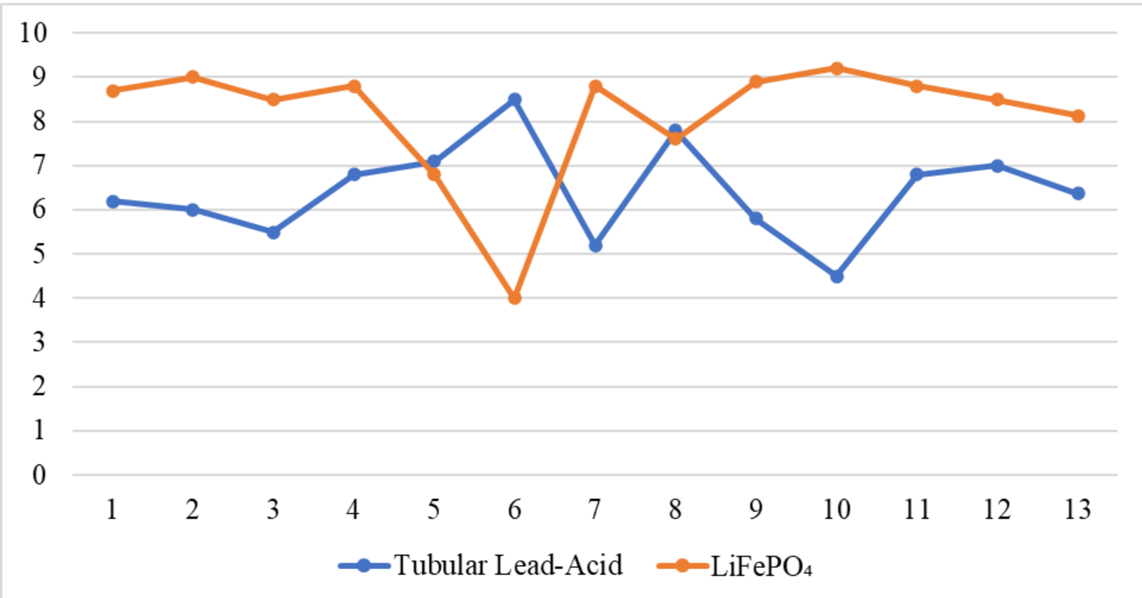

Figure 2: Weighted Performance Scoring (Scale: 1-10, where 10 is best)

Discussion

These findings indicate the existence of significant differences in how tubular lead-acid and LiFePO4 batteries are handled and maintained, and that the findings are relevant to the management of academic institutions in Nigeria. Tubular batteries require a great deal of manual preparation, such as weekly electrolyte balancing, monthly equalization charging, and quarterly capacity testing, or approximately 156 man-hours of labor time per year. Conversely, LiFePO4 only needs quarterly check-ups, semi-annual testing, and the automated monitoring of the battery is enabled by its Battery Management System (BMS), with only 24 hours of labor needed every year. The observation was consistent with Wang et al., (2022) which showed that automation of lithium systems reduces human error and maintenance burden in institutional micro-grids.

The relative cost analysis also highlights the economic superiority of lithium. Tubular systems are estimated to cost N1,950/kWh/year in maintenance (largely attributed to labor N1,180) and downtimes (N450). LiFePO4, however, is priced at only N360/kWh/year, which is 82 percent less. Similarly, Yudhistira et al., (2022) demonstrated also that lithium systems incurred lifecycle maintenance costs that were over 75% less than lead-acid in remote energy applications. Conversely, but, according to Enache et al., (2020), the higher initial capital requirement of LiFePO4 still is a scourge to universities with limited budgets, which clarifies why tubular is still an option in cost-conscious projects despite its greater costs to maintain.

The benchmarking analysis indicates that lithium has a total weighted score of 8.13, whereas tubular batteries have 6.37. Lithium compares much better concerning technical criteria like efficiency, power density, and cycle life. This result concurred with Rostami et al., (2024) who showed that LiFePO4 systems had the potential to provide effective depth of discharge relative to tubular lead-acid in comparable conditions. Conversely, tubular batteries ranked more favorably in capital cost (8.5 vs. 4.0), which supports their short-term financial benefit. This is in line with Jan et al., (2020) who opined that affordability still supports demand of lead-acid system in most economies in the developing world even though they have relatively lesser long-term value.

Operational concerns also contribute to the argument in favor of the use of lithium. The findings indicate that LiFePO4 had an operational factors score of 8.9 in aspects like maintenance complexities and reliability, versus 5.8 in the tubular. Similar research conducted by Madani et al., (2025) noted that the integration of digitalised BMS in lithium systems facilitates predictive maintenance and optimization of performance, thus limiting the chances of power outage in sensitive settings such as research laboratories. This is unlike in the case of tubular systems in which failure to undertake routine electrolyte maintenance most times results in an early death, as witnessed in Nigerian colleges with the few competent technical staff.

The results show that although tubular batteries are cheaper in the short term, they require high maintenance, are vulnerable to downtime, and have lower technical capabilities compared to other battery types, and thus are not as well-suited to harsh academic use. LiFePO4 is more expensive initially, but has better reliability, lower maintenance, and long term efficiency benefits. This synthesis validates the position of Graham et al., (2021), who concluded that lithium systems are a more sustainable option in institutions of higher education that need continuous energy supply and less operational risk.

CONCLUSION

The evaluation of digital battery management and maintenance procedures of 220Ah tubular lead-acid batteries shows that systematic and technology-oriented solutions substantially enhance reliability, downtime and working life. Digital monitoring tools need to be integrated with traditional maintenance protocols, like electrolyte checks, equalization charging, and thermal images, as this minimizes human error and still provides interventions in a timely fashion.

The results validate that digital management improves predictive maintenance and reduces long-term operational expenses, and it is a sustainable solution in resource-constrained institutions. Though tubular batteries are not very expensive and are easy to find, their life cycle requires regular maintenance, which can be facilitated by digital tools. The paper emphasizes the importance of integrating the traditional methods with the contemporary systems of monitoring and this provides a useful guideline to universities and other educational institutions to have the optimum performance of batteries and stable energy to all important academic operations.

REFERENCE

Adetona, Z. A., Ogunyemi, J., & Bitrus, I. (2020). Maintenance management regime for off-grid solar PV renewable energy system in Nigeria. *European Journal of Engineering and Technology Research*, *5*(11), 1376-1382.

Enache, B. A., Seritan, G. C., Grigorescu, S. D., Cepisca, C., Adochiei, F. C., Argatu, V. V., & Voicila, T. I. (2020, October). A battery screening system for second life $LiFePO_4$ batteries. In *2020 International Conference and Exposition on Electrical And Power Engineering (EPE)* (pp. 298-301). IEEE.

Gabbar, H. A., Othman, A. M., & Abdussami, M. R. (2021). Review of battery management systems (BMS) development and industrial standards. *Technologies*, *9*(2), 28.

Graham, J. D., Rupp, J. A., & Brungard, E. (2021). Lithium in the green energy transition: The quest for both sustainability and security. *Sustainability*, *13*(20), 11274.

Haldar, S., Gol, S., Mondal, A., & Banerjee, R. (2024). IoT-enabled advanced monitoring system for tubular batteries: Enhancing efficiency and reliability. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*, *9*, 100709.

Jan, K. U., Dubois, A. M., Diallo, D., Uddin, W., Nasir, M., & Khan, I. (2020, September). Reuse Legacy to Repower the Microgrids–An Affordable Solution for Test and Restoration of Repurposed Lead Acid Batteries. In *2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES)* (pp. 463-468). IEEE.

Krishna, G., Singh, R., Gehlot, A., Akram, S. V., Priyadarshi, N., & Twala, B. (2022). Digital technology implementation in battery-management systems for sustainable energy storage: review, challenges, and recommendations. *Electronics*, *11*(17), 2695.

Madani, S.S., Shabeer, Y., Fowler, M., Panchal, S., Chaoui, H., Mekhilef, S., Dou, S.X. and See, K., 2025. Artificial Intelligence and Digital Twin Technologies for Intelligent Lithium-Ion Battery Management Systems: A Comprehensive Review of State Estimation, Lifecycle Optimization, and Cloud-Edge Integration. *Batteries*, *11*(8), p.298.

National Renewable Energy Laboratory (NREL). (2025). Battery lifespan. U.S. Department of Energy. Retrieved 06/09/25 from https://www.nrel.gov/transportation/battery-lifespan

Park, S., Ahn, J., Kang, T., Park, S., Kim, Y., Cho, I., & Kim, J. (2020). Review of state-of-the-art battery state estimation technologies for battery management systems of stationary energy storage systems. *Journal of Power Electronics*, *20*(6), 1526-1540.

Rostami, H., Valio, J., Tynjälä, P., Lassi, U., & Suominen, P. (2024). Life cycle of LiFePO4 batteries: production, recycling, and market trends. *ChemPhysChem*, *25*(24), e202400459.

Senol, M., Bayram, I. S., Naderi, Y., & Galloway, S. (2023). Electric vehicles under low temperatures: A review on battery performance, charging needs, and power grid impacts. *Ieee Access*, *11*, 39879-39912.

Wang, J., Wang, Z., Ni, J., & Li, L. (2022). Electrospun materials for batteries moving beyond lithium-ion technologies. *Electrochemical Energy Reviews*, *5*(2), 211-241.

Yudhistira, R., Khatiwada, D., & Sanchez, F. (2022). A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. *Journal of Cleaner Production*, *358*, 131999.