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Comparative Performance and Optimization of Lead-Acid, Nickel-Metal Hydride, and $LiFePO_4$ Batteries for Renewable Energy Storage Applications

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Abstract

Battery selection for renewable energy storage is a technology-choice problem rather than a simple comparison of nominal capacity or purchase price. Here, we quantitatively compare lead-acid, a nickel-metal hydride cell, and $LiFePO_4$ using common-load discharge testing, $LiFePO_4$ load-resistance optimization, and linked lifecycle and sustainability interpretation. Under identical discharge conditions, $LiFePO_4$ retained the highest operating voltage and the longest discharge duration, whereas lead-acid showed the shortest useful discharge, and the nickel-metal hydride cell remained intermediate. The optimization dataset further showed that maximum measured $LiFePO_4$ power occurred at the lowest tested resistance, consistent with low internal resistance and favorable high-rate operation. When these results are interpreted together with replacement frequency, maintenance, recyclability, and environmental trade-offs, $LiFePO_4$ emerges as the most defensible option for repeated-use renewable energy storage applications, while lead-acid remains relevant where mature recycling infrastructure and low upfront cost dominate decision-making. The analysis, therefore, moves beyond a simple chemistry ranking and offers a technology-level framework for battery selection under the practical constraints of renewable energy deployment.

1. INTRODUCTION

Electrochemical batteries are indispensable to renewable-energy systems and electric vehicles because they store and deliver power on demand. Among the major rechargeable-battery families, lead-acid, nickel-based, and lithium-ion systems represent three technological generations with distinct trade-offs in energy density, durability, cost, safety, and recyclability. (Bhawna et al., 2025; Sutikno et al., 2025; Yi et al., 2024; Zelinsky et al., 2018)

Modern lithium-ion batteries offer a step change in performance. Lithium iron phosphate, abbreviated here as $LiFePO_4$, has become especially important for stationary storage and electric vehicles because it combines safety, long cycle life, and the absence of cobalt and nickel in the cathode. Recent reviews by Chen, Li, and Bae in 2024 and by Coccato and colleagues in 2025 likewise identify LFP chemistry as a leading option for grid-connected and distributed storage due to its durability, thermal stability, and strong system-level performance. (Chen et al., 2024; Sathishkumar et al., 2022; Sutikno et al., 2025)

Aside from performance, sustainable battery selection requires a holistic view of costs and environmental impacts. Lead-acid batteries remain inexpensive upfront and highly recyclable, whereas $LiFePO_4$ batteries often achieve lower lifetime cost in cycling-intensive applications because they last longer and operate more efficiently. A recent primary-data life-cycle assessment by Jasper et al in 2025 also shows that the environmental ranking between lead-acid and $LiFePO_4$ depends strongly on use case, especially on cycling frequency and service life. (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; Enexer Technologies, 2025; Jasper et al., 2025)

Given this background, a comprehensive evaluation is needed that benchmarks these battery chemistries under identical discharge conditions and then interprets the resulting technical, economic,

and environmental trade-offs at the technology level. This study addresses that need through controlled comparative testing, $LiFePO_4$ load optimization, lifecycle cost analysis, environmental interpretation, and recommendations for temperature-aware deployment and field validation. (Chen et al., 2024; Coccato et al., 2025; Jasper et al., 2025; Sutikno et al., 2025; Zelinsky et al., 2018)

2. MATERIALS AND METHODS

2.1 Study design

The study was conducted from March to May 2025 in the Engineering laboratories of [Institution withheld for blind review], Philippines. A two-phase experimental design was used to evaluate and then optimize battery performance. Phase I compared battery chemistries in a single-factor design. The factor was battery chemistry with three levels: lead-acid, nickel–metal hydride, and lithium iron phosphate.

Voltage at load (V_{load}) was measured near the start of discharge, after the response had stabilized under load. This response quantifies the voltage sag associated with internal resistance. Discharge time was the elapsed time from the start of discharge until the cutoff voltage was reached. It served as a proxy for delivered capacity under the test load. Peak temperature was the maximum battery-surface temperature recorded during discharge and was used as an indicator of heat generation from internal losses, including I^2R heating.

A one-way analysis of variance was used to determine whether battery chemistry significantly affected each response. Diagnostic checks based on normal Q-Q plots and residual-versus-fit plots were used to verify approximate normality and homogeneity of variance before interpreting the ANOVA results. (Zelinsky et al., 2018)

Phase II focused on $LiFePO_4$, which emerged as the strongest performer in Phase I. In this phase, load resistance in ohms was varied to identify the resistance that maximized power output, with power calculated as the product of voltage and current. (Coccato et al., 2025)

2.2 Battery samples and test setup

Representative commercial rechargeable cells of each chemistry were obtained and tested. The lead-acid unit was a sealed 2 V, 5 Ah cell. The nickel–metal hydride unit was a 1.2 V, 2 Ah cylindrical cell. The lithium iron phosphate unit was a 3.2 V, 1100 mAh cylindrical cell. All batteries were fully charged according to manufacturer recommendations before testing.

For Phase I discharges, the same resistive load was applied to each battery type. A resistor of approximately 0.5 Ω drew a moderate-to-high current from the cells, accentuating differences in voltage drop, runtime, and temperature response. Cutoff voltages were set at 1.75 V for lead-acid, 1.0 V for Ni-MH, and 2.5 V for $LiFePO_4$.

In Phase II, the $LiFePO_4$ cell was connected to high-power resistors of 0.33, 0.5, 1.0, and 2.0 Ω, each rated at 50 W with ± 5% tolerance. These values span a practical operating range from heavy load to light load and enable direct assessment of the power-resistance relationship.

2.3 Data analysis

For Phase I, one-way ANOVA was performed on voltage at load, discharge time, and maximum temperature using JMP statistical software. When the omnibus test was significant, pairwise differences were interpreted using Tukey's multiple-comparison procedure. The analysis emphasized effect direction, statistical significance, and practical interpretation rather than test statistics alone.

For Phase II, a second-order polynomial model was considered first for the relationship between power and load resistance. Because the quadratic contribution proved negligible, the discussion ultimately centers on the simpler first-order trend and the physically meaningful interpretation of the low-resistance operating region.

3. RESULTS

3.1 Phase I comparative discharge performance

Battery chemistry had a highly significant effect on voltage under load, with ANOVA giving $p < 0.0001$ and $F \approx 1692$. As shown in Fig. 1a and summarized numerically in Table 1, $LiFePO_4$ sustained the highest voltage under the common 0.5 Ω load, followed by PbA and then the nickel-based cell. (Chen et al., 2024; Sathishkumar et al., 2022; Sutikno et al., 2025; Zelinsky et al., 2018)

Figure 1 shows the load-voltage curves for each battery chemistry, reported as mean ± SD (n = 3). $LiFePO_4$ sustained a significantly higher operating voltage under the 0.5 Ω load than PbA or the nickel-based cell. In addition, the discharge duration under the common test load. $LiFePO_4$ provided the longest runtime, the nickel-based cell showed intermediate endurance, and PbA reached the cutoff earliest. Maximum temperature did not differ significantly across chemistries (ANOVA, $p = 0.288$). Figure 1c shows that all three cells remained within a comparatively narrow thermal band under the single-cycle test conditions, even though their electrical behavior differed strongly.

In summary, Phase I established a clear performance ranking among the tested batteries: $LiFePO_4$ > Ni–MH > lead–acid, in terms of both sustaining voltage under load and delivering longer discharge time.

Figure 2 plots power versus load resistance for the $LiFePO_4$ cell, and Table 2 compiles the corresponding optimization outputs recovered from the project documentation. Power declined approximately linearly as load resistance increased from 0.33 to 2.0 Ω. The reported linear regression was significant ($p \approx 0.03$), indicating that lower load resistance was associated with higher deliverable power within the tested range. (Coccato et al., 2025)

Table 1
Summary statistics computed from the recovered Phase I dataset and used to support the comparative interpretation in Section 3.1.

Battery chemistry	Voltage at load / V	Time drain / min	Maximum temperature / °C
PbA	1.903 ± 0.085	2.31 ± 0.05	63.87 ± 0.71
Ni-MH	0.527 ± 0.003	12.95 ± 0.38	61.80 ± 2.50
$LiFePO_4$	2.941 ± 0.025	19.47 ± 0.35	63.66 ± 0.90

3.2 Statistical diagnostics and Phase I summary

The Q-Q plots for voltage, time drain, and maximum temperature residuals followed the reference line reasonably well, with only minor tail deviations attributed to the limited sample size. Taken together with the residual-versus-fit checks, these diagnostics support the ANOVA interpretation summarised in Fig. 1 and Table 1. (Zelinsky et al., 2018)

$LiFePO_4$ was the strongest performer in terms of voltage at load and time drain, whereas the chemistry effect on maximum temperature was not statistically significant under the present conditions. (Chen et al., 2024; Sathishkumar et al., 2022; Sutikno et al., 2025; Zelinsky et al., 2018)

3.3 Phase II optimization of $LiFePO_4$ power output

The practical optimum for the $LiFePO_4$ battery within the experimental range occurred at the lowest tested resistance, approximately 0.33–0.36 Ω through a regression analysis performed in JMP. At this load, the reported power output was about 23–24 W, which was the highest value observed from the dataset. (Coccato et al., 2025)

Overall, Phase II demonstrated that $LiFePO_4$ delivers maximum power at very low load resistance because of its low internal resistance. This outcome is physically consistent with the maximum-power-transfer principle and supports the use of $LiFePO_4$ in applications that require stable power delivery under demanding operating conditions.

4. DISCUSSION

The discussion is structured around a single technology-selection question: how should shared discharge data, load-dependent power behavior, lifecycle implications, and sustainability constraints be interpreted together when choosing among mature rechargeable-battery options for renewable-energy storage? These framing matters because the present dataset is not intended to prove that a single battery is universally best. Instead, it shows how laboratory-scale comparative results can be translated into system-level decisions that remain sensitive to duty cycle, infrastructure, maintenance capacity, and end-of-life pathways.

4.1 Performance interpretation

The comparative results place $LiFePO_4$ clearly ahead of the other tested chemistries for voltage stability, runtime, and power capability under the shared load condition. This ranking is consistent with the more recent battery literature, which continues to position LFP chemistry as a strong option for renewable-energy storage because of its durability, thermal stability, and systems-level robustness. (Chen et al., 2024; Sathishkumar et al., 2022; Sutikno et al., 2025; Zelinsky et al., 2018)

The present findings align with recent literature published between 2024 and 2025. Chen, Li, and Bae reviewed recent advances in LFP battery technology and highlighted the chemistry's combination of safety, long cycle life, and broad applicability to renewable-energy integration. Coccato and colleagues likewise reported that lithium-ion systems, particularly LFP chemistry, outperform many competing chemistries in longevity, thermal stability, and deployment suitability in energy-storage optimization studies. These newer sources reinforce the interpretation drawn from the present dataset rather than replacing it. (Chen et al., 2024; Jasper et al., 2025)

The main effect of load resistance on power output was significant ($F = 4.346$, $p = 0.0286$), whereas the coded curvature term was not significant. This pattern supports the simpler interpretation that the dominant behavior over the tested interval was monotonic power reduction as resistance increased. The key optimization outputs are collated in Table 2, which should be read together with Fig. 2. (Coccato et al., 2025)

Using the JMP prediction profiler, an optimal resistance near 0.36 Ω and a predicted power output of approximately 23–24 W were obtained. These values complement the Phase I findings by showing that the same chemistry that retained voltage and runtime most effectively also maintained a strong power response under low-resistance loading.

Table 2
Reported optimization outcomes for Phase II $LiFePO_4$ power output.

Metric	Reported value	Interpretation
Main effect of load resistance	$F = 4.346$; $p = 0.0286$	Load resistance significantly affects power output
Interaction / coded term	$p = 0.6809$	No meaningful curvature detected
Lack of fit	$F = 7.726$; $p = 0.091$	Model adequacy acceptable
Profiler optimum	0.36–0.37 Ω	Optimum near the lower boundary of the tested region
Predicted optimum power	23.35–23.73 W	Model-based optimum from the project document

In summary, the direct comparison validates the expected technology hierarchy: lead-acid showed the weakest performance, the nickel-based cell occupied an intermediate position, and $LiFePO_4$ delivered the best overall balance of discharge stability and power output under the tested conditions.

4.2 Lifecycle cost analysis

When evaluating batteries for sustainable engineering projects such as off-grid solar or grid stabilisation, lifecycle cost is as important as technical performance. A battery with a low purchase price can still be the less sustainable option if frequent replacement, lower efficiency, and maintenance burdens drive up the total cost of ownership (Coccato et al., 2025; Enexer Technologies, 2025).

Lead-acid batteries have the lowest upfront cost per kilowatt-hour of storage. In the mid-2020s, deep-cycle lead-acid products commonly occupied the lower end of the cost range, whereas $LiFePO_4$ systems remained more expensive at purchase but continued to decline in price as production scaled up (Enexer Technologies, 2025; Sutikno et al., 2025).

Maintenance is another important cost driver. Flooded lead-acid systems require periodic electrolyte checks, watering, and terminal maintenance, whereas Ni-MH and $LiFePO_4$ systems are functionally maintenance-light in normal service (Enexer Technologies, 2025; PLC Enterprises, 2013).

Cycle life and replacement frequency are the most important differentiators. Table 2 should therefore be read not only as an optimization summary for $LiFePO_4$ power output but also alongside the lifecycle discussion in this section, because the electrical behavior that favors $LiFePO_4$ under load also contributes to lower long-term ownership cost in high-cycling applications.

Accounting for replacements and maintenance, $LiFePO_4$ remains the most cost-effective option in frequent-cycling applications despite its higher upfront cost. For systems that cycle daily, the extended lifetime and higher efficiency of $LiFePO_4$ often offset the initial price premium (Enexer Technologies, 2025).

It is important to note that these cost calculations can change depending on usage patterns. If a battery is used only for backup with a few cycles per year, lead–acid's calendar life (~ 5–7 years) might be the limiting factor rather than cycle life. The cost advantage of $LiFePO_4$ is less pronounced since all chemistries might last ~ 5 years, the upfront cost dominates. But in high-utilization scenarios (daily deep cycling), $LiFePO_4$ provides the lowest levelized cost of energy storage among the three. This is echoed by industry analyses and the rapidly growing $LiFePO_4$ market share in home and grid storage. The only caveat is the higher initial investment and the need for a proper BMS and charger for Li-ion batteries. In contrast, lead–acid systems are simpler to configure, but then one has to invest in replacements later. (Enexer Technologies, 2025)

From a cost-benefit perspective, lead-acid remains attractive for low-budget or infrequently cycled applications, while $LiFePO_4$ dominates when long service life, efficiency, and reduced replacement frequency are prioritised. Nickel-based systems occupy a narrower niche in applications where environmental conditions or legacy infrastructure still favor them (Coccato et al., 2025; Enexer Technologies, 2025).

Finally, one must consider end-of-life costs: lead–acid batteries typically have a trade-in value or rebate because of their recyclable lead content, which can offset some of the replacement cost, as retailers often take old batteries for $5–$10 each to recycle. Ni–Cd batteries may incur disposal costs because cadmium is hazardous waste (though recycling can recover nickel and cadmium for reuse, often at a net cost). Ni–MH and $LiFePO_4$ currently have low scrap value (nickel in Ni–MH can be recovered, while lithium/iron/phosphate in $LiFePO_4$ has low market value). As lithium battery recycling technologies improve, we might see the end-of-life value of $LiFePO_4$ rise or at least the recycling cost decrease. At present, from a purely economic standpoint, $LiFePO_4$ offers the best life-cycle value for intensive use, followed by Ni–Cd, with lead–acid being the cheapest upfront but costly in the long term for daily deep-cycle scenarios.

4.3 Environmental impact analysis

Beyond cost, sustainability requires examining each battery chemistry across raw-material extraction, manufacturing, use, and end-of-life. Figure 1 and Table 1 establish the performance differences among the tested batteries, while the present section interprets those differences from an environmental perspective (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; Jasper et al., 2025).

Lead–acid batteries are composed mainly of lead, sulfuric acid, and plastics. Their environmental profile is strongly shaped by the maturity of the lead-battery recycling industry, which allows recycled lead to supply a large share of production feedstock and reduces the burden associated with primary extraction (Battery Council International & International Lead Association, 2023; Jasper et al., 2025). This gives lead–acid an important circular-economy advantage over many newer chemistries. At the same time, lead mining and smelting remain environmentally damaging when primary lead is required, and the toxicity of lead means that poor handling, informal recycling, or landfill disposal can create serious risks to soil, water, wildlife, and human health. Thus, lead–acid combines a favorable recycling profile with potentially severe consequences when end-of-life management fails.

Battery systems do not emit greenhouse gases during use, but production and end-of-life treatment contribute substantially to the overall carbon footprint. Recent primary-data work by Jasper and colleagues in 2025 showed that lead–acid can outperform $LiFePO_4$ in several environmental categories during production and end-of-life processing, largely because of the established closed-loop lead-recycling system (Battery Council International & International Lead Association, 2023; Jasper et al., 2025). However, that ranking can shift when the use phase is considered, since the longer service life and higher cycle capability of $LiFePO_4$ reduce the need for replacement under repeated cycling. In other words, lead–acid may be environmentally preferable on a per-battery basis, whereas $LiFePO_4$ may become preferable when impacts are normalized over the long service life and delivered energy.

Nickel-based chemistries occupy an intermediate position. Ni–Cd batteries have a long service life and can operate reliably under demanding conditions, reducing the frequency of replacement and manufacturing. They can also be recycled through cadmium and nickel recovery. However, cadmium is

highly toxic and is classified as a persistent environmental contaminant, so production, disposal, and recycling require strict control. If Ni–Cd batteries are landfilled or processed informally, cadmium can leach into soil and groundwater, creating substantial ecological and health risks. Ni–MH batteries avoid cadmium and are therefore less problematic from a toxicity perspective, but they contain nickel and rare earth elements whose extraction can carry ecological burdens. Nickel can be harmful to groundwater at elevated concentrations, while rare-earth mining can generate toxic residues if poorly managed. In addition, rare earth recycling remains limited, so some of the resource value embodied in Ni–MH batteries is still not well recovered at end of life (Almemark et al., 2024; Jasper et al., 2025).

$LiFePO_4$ has a different environmental profile. On one hand, it avoids lead and cadmium, contains no cobalt, and is widely regarded as one of the safest lithium-ion chemistries both operationally and environmentally (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; PLC Enterprises, 2013). If a $LiFePO_4$ cell ruptures, it generally does not release highly toxic heavy metals; its main environmental concerns arise from residual electrolyte salts, potential fire risk from short-circuiting in waste streams, and the broader upstream impacts of lithium, phosphate, graphite, and copper supply chains. On the other hand, $LiFePO_4$ recycling remains less mature than lead–acid recycling. Only a small share of lithium batteries is currently recycled globally, and $LiFePO_4$ is often less attractive economically to recyclers than cobalt-containing lithium-ion systems because it lacks high-value metals such as cobalt and nickel (Battery Council International & International Lead Association, 2023; PLC Enterprises, 2013). This means that, despite its lower toxicity, $LiFePO_4$ still faces important end-of-life challenges, especially as retired EV and stationary-storage packs accumulate.

From a resource-sustainability standpoint, each chemistry presents a different trade-off. Lead is toxic but highly recyclable, which allows the lead–acid industry to operate with strong closed-loop characteristics. Cadmium in Ni–Cd is also hazardous, though it is available as a byproduct of zinc production and can be recovered if formal recycling systems are in place. Ni–MH avoids cadmium but depends partly on rare earth elements, which are associated with supply risk and environmentally intensive extraction. $LiFePO_4$ draws on lithium, phosphate, graphite, and copper, broadening its material base while avoiding cobalt and nickel; nevertheless, lithium extraction can consume large amounts of water, and phosphate mining can contribute to habitat disruption and resource pressure (Almemark et al., 2024; Jasper et al., 2025). Thus, $LiFePO_4$ reduces some critical-material concerns while introducing others related to lithium and phosphorus supply chains.

End-of-life management remains one of the clearest points of differentiation. Lead–acid batteries are the most recycled battery technology globally, with recovery rates approaching 99% in North America and Europe. This greatly reduces the life-cycle burden of production because recycled lead requires much less energy than primary lead. Ni–Cd recycling is also established, particularly in jurisdictions with strict hazardous-waste regulation, though collection volumes are lower than for lead–acid because the market is smaller and more specialized. Ni–MH recycling is still developing and tends to focus on recovering nickel, with only partial recovery of rare earths in many cases. $LiFePO_4$ and lithium-ion recycling are now active areas of technological and regulatory development, especially given the expected volume of

retired EV packs. Current processes include shredding and hydrometallurgical recovery, and future policy frameworks such as the EU Battery Regulation are likely to increase recovery rates and material targets (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; Jasper et al., 2025). At present, however, lead–acid remains the most effectively recycled chemistry, Ni–Cd is highly regulated and relatively well-managed where formal systems exist, Ni–MH is moderate, and $LiFePO_4$ is improving but still comparatively weak in recycling penetration.

Environmental safety also differs markedly if the batteries are improperly discarded. Lead–acid and Ni–Cd pose the highest hazards because lead can poison humans and wildlife, while cadmium is a carcinogenic and persistent toxin. Ni–MH presents a lower to moderate risk because it contains no cadmium, although nickel and alkaline electrolyte can still create localized environmental problems. $LiFePO_4$ has the lowest toxicity risk among the chemistries considered because it contains no toxic heavy metals, though fire risk and electrolyte-related effects remain concerns if disposal is mishandled (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; PLC Enterprises, 2013).

These distinctions are summarized in Table 3.

Table 3
Environmental advantages and limitations of lead–acid, nickel–metal hydride, and $LiFePO_4$ battery chemistries considered for renewable-energy storage applications.

Battery chemistry	Positive aspects	Negative aspects
Lead–Acid	Very high recyclability; established recycling infrastructure; low production energy when recycled lead is used	Lead mining and smelting are polluting when primary lead is needed; lead is toxic, so leakage or informal recycling can create serious health risks; heavier batteries can increase transport-related emissions per kWh
Ni–Cd	Long service life reduces manufacturing frequency; can operate under extreme conditions, which may reduce redundancy requirements; recyclable through cadmium and nickel recovery	Cadmium is highly toxic; production and disposal require strict control; recycling rates are only moderate in practice; nickel mining contributes to greenhouse gas emissions
Ni–MH	Contains no cadmium; reasonably long life compared with lead–acid; nickel and other components can be recycled; generally, less toxic overall	Contains rare earth metals whose mining has ecological impacts; rare earth recycling remains limited, leading to possible resource loss; manufacturing energy demand is relatively high
$LiFePO_4$	High energy efficiency and long cycle life spread environmental burden over more delivered kWh; contains no cobalt or cadmium; relatively safe to handle; second-life use and recycling prospects are improving, including reuse of retired EV LFP packs for stationary storage	Current recycling rate is still low; production has a notable carbon footprint; lithium supply chains raise resource-security concerns; end-of-life can contribute to e-waste if cells are not properly recycled

A key point from the recent literature is that the environmental ranking depends strongly on the functional unit used. A 2023 study found that, when recycling is included, lead–acid may show a lower total global warming potential than $LiFePO_4$ in a baseline automotive scenario, highlighting the importance of mature recycling systems (Battery Council International & International Lead Association, 2023; Jasper et al., 2025). However, if the comparison is based on energy delivered over many years, $LiFePO_4$ can become more favorable because fewer replacements are required. This distinction is particularly important in renewable-energy storage, where repeated cycling is often more relevant than one-time manufacturing impact.

Overall, lead–acid is environmentally attractive because of its strong recyclability and relatively low production burden when recycled lead is used, but it remains highly toxic if mishandled. Ni–Cd is the most problematic from a toxicity standpoint, although formal recycling can reduce that risk. Ni–MH avoids cadmium and is generally less hazardous, but it still faces material and recycling challenges. $LiFePO_4$ is comparatively safer in use and offers strong lifetime efficiency advantages, but its recycling infrastructure remains underdeveloped. For sustainable energy storage, improving lithium-battery recycling, especially for $LiFePO_4$, will be essential, while continued formal take-back and recycling

systems remain equally important for lead–acid and nickel-based batteries (Almemark et al., 2024; Battery Council International & International Lead Association, 2023; Jasper et al., 2025).

4.4 Thermal property considerations

Battery performance and service life are strongly affected by temperature. Although the present experiments were conducted near 25°C, practical renewable-energy deployments often operate across seasonal conditions spanning roughly 15 to 40°C, so the laboratory results must be interpreted with temperature effects in mind (Chen et al., 2024; PLC Enterprises, 2013; Sathishkumar et al., 2022; Sutikno et al., 2025). At lower temperatures, internal resistance rises and electrochemical kinetics slow, reducing both available capacity and power delivery. Lead–acid batteries are especially vulnerable to cold-weather losses, whereas nickel-based systems generally retain better low-temperature performance. At higher temperatures, batteries may show improved short-term power capability because internal resistance decreases, but sustained heat accelerates ageing and shortens service life, particularly for lead–acid and lithium-ion systems (Chen et al., 2024; Sathishkumar et al., 2022; Sutikno et al., 2025).

These temperature-dependent shifts mean that the same battery can show markedly different voltage sag, discharge duration, and energy delivery under otherwise identical loading conditions. Controlled testing at 15, 25, and 40°C would therefore provide a practical basis for validating the trends proposed here by capturing discharge time, voltage profile, internal resistance, and self-discharge behavior at each temperature (Coccato et al., 2025). Such data would support temperature-aware battery models based on empirical resistance trends and simplified degradation relationships, enabling the chemistry rankings observed in this study to be translated into climate-specific design guidance. Extending the analysis to include temperature, load, and possibly state of charge in a multi-factor framework would further strengthen the predictive value of the present work.

For systems expected to experience ambient swings across 15–40°C, thermal management should be considered at the design stage. Cooling, ventilation, and enclosure spacing can help limit heat accumulation and preserve battery life at elevated temperatures, while low-temperature conditioning or preheating may be necessary for critical operation in colder environments (Chen et al., 2024; PLC Enterprises, 2013; Sathishkumar et al., 2022; Sutikno et al., 2025). Storage conditions also matter: discharged lead–acid batteries may freeze in cold conditions, nickel-based batteries can self-discharge more rapidly at high temperatures, and $LiFePO_4$ ages faster when stored in heat. Overall, temperature-aware testing and design are essential if laboratory-based battery rankings are to be confidently translated into field-deployment decisions, and extending the present dataset with temperature-dependent experiments would provide stronger, application-specific guidance for battery selection (Chen et al., 2024; Coccato et al., 2025; Sathishkumar et al., 2022; Sutikno et al., 2025).

4.5 Field deployment pathways and pilot studies

To translate these findings into practice, field trials should be designed to test not only discharge performance but also operational resilience, maintenance demand, and lifecycle value under realistic

renewable-energy duty cycles. (Coccato et al., 2025; Enexer Technologies, 2025; Sathishkumar et al., 2022)

A practical next step is a small solar-plus-battery pilot in which PbA, nickel-based, and LiFePO,ÇÑ systems are operated under comparable charge-discharge schedules. Such a setup would validate whether the ranking observed in Fig. 1 persists under real cycling, charge control, and environmental exposure. (Coccato et al., 2025; Enexer Technologies, 2025; Sathishkumar et al., 2022)

A second pathway is a grid-connected peak-shaving or time-shifting trial. In that context, battery efficiency, replacement rate, and operating constraints can be measured directly against an application in which daily cycling and load-following matter. (Coccato et al., 2025; Enexer Technologies, 2025)

Although the present study is not an electric-vehicle paper, the same comparative logic is relevant to mobility. LiFePO,ÇÑ is widely recognized for safe, stable high-cycle operation, whereas nickel-based chemistries retain historical importance in hybrid systems and lead-acid remains limited mainly to auxiliary roles. (Chen et al., 2024; Sutikno et al., 2025)

Any pilot study must also include chemistry-specific safety procedures. Nickel-based and lead-acid systems require appropriate ventilation and maintenance protocols, whereas LiFePO4 systems require robust battery management controls and abuse-prevention measures. (Chen et al., 2024; PLC Enterprises, 2013; Sathishkumar et al., 2022; Sutikno et al., 2025)

Field datasets should include cycle count, retained capacity, downtime, maintenance events, thermal behavior, and replacement history so that laboratory observations can be connected to technology-level decision metrics. (Coccato et al., 2025) Those field results would feed directly into design rules for renewable-energy storage, particularly with respect to usable depth of discharge, maintenance schedules, enclosure design, and the real cost of capacity fade. (Coccato et al., 2025; Enexer Technologies, 2025)

In summary, pilot deployments should confirm the laboratory ranking and refine the conditions under which each chemistry is technically and economically justified.

For $LiFePO_4$, the central objective is to confirm high efficiency and long service life while optimizing battery management settings for safe, stable operation. For lead-acid, the priority is to mitigate sulfation, thermal stress, and maintenance burden through conservative depth-of-discharge limits, charge-control strategies, and oversizing where necessary. For nickel-based systems, pilot work should test whether their reputed resilience in harsh conditions outweighs their environmental and cost disadvantages in the specific application. For Ni-MH specifically, any pilot would need to pay close attention to self-discharge, thermal management, and charge acceptance under repeated cycling.

The end goal of these field trials is to develop best-practice guidance for sustainable energy projects that select battery chemistry based on measured duty cycle, environment, maintenance capacity, and lifetime value rather than on upfront cost alone. (Coccato et al., 2025; Enexer Technologies, 2025)

Field deployment studies should be designed to confirm whether the comparative laboratory ranking observed here is maintained under realistic cycling, maintenance, and environmental conditions.

For $LiFePO_4$, the primary field objective is to verify long service life, high efficiency, and stable power delivery under practical battery management conditions. For lead-acid, the priority is to determine whether lower initial cost can offset shorter life and higher maintenance demand under actual operating conditions. For nickel-metal hydride, the key question is whether intermediate electrochemical performance is balanced by acceptable lifecycle cost and operating tolerance.

The end goal of field validation is to develop application-specific guidance for battery selection in sustainable energy projects based on measured duty cycle, environmental exposure, maintenance capacity, and end-of-life management. Such guidelines, backed by both our lab data and field experience, would be invaluable to engineers and decision-makers when choosing a battery technology for sustainable installations.

5. CONCLUSIONS

This study compared the discharge behavior of lead-acid, nickel–metal hydride, and $LiFePO_4$ batteries under a common load and then optimized the power output of $LiFePO_4$ under varying resistance. Across the tested conditions, $LiFePO_4$ showed the highest operating voltage, the longest discharge duration, and the strongest overall technical performance. The nickel–metal hydride cell showed intermediate behavior, whereas the lead-acid battery exhibited the shortest useful discharge.

The optimization phase showed that the highest measured $LiFePO_4$ power occurred at the lowest tested resistance, indicating favorable high-rate behavior within the experimental range. When these results were combined with lifecycle costs, recyclability, and environmental considerations, $LiFePO_4$ emerged as the most suitable option for repeated-use renewable-energy storage under the conditions examined.

Lead-acid batteries may remain practical where low initial cost and established recycling infrastructure are the dominant considerations. In contrast, nickel–metal hydride systems may remain relevant in applications that value intermediate cost and operating tolerance. Battery selection for renewable-energy storage should therefore be based on technical performance, replacement frequency, environmental trade-offs, and the requirements of the intended application.

Future work should include broader temperature testing, expanded replicate trials, and field validation under actual renewable-energy operating conditions to strengthen the application of these findings.

Declarations

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS STATEMENT

This study did not involve human participants, animal subjects, or confidential personal data. The data reported here were gathered, analyzed, and presented honestly and without fabrication, falsification, or inappropriate manipulation. All relevant prior work has been cited.

STATEMENT ON THE USE OF GENERATIVE AI

Generative AI-assisted language support was used during manuscript drafting and editing. The authors reviewed, verified, and accepted full responsibility for the accuracy, interpretation, and final content of the manuscript.

AUTHOR CONTRIBUTIONS

-XXXX-, -XXXX-, -XXXX-, -XXXX-, and -XXXX- contributed to the conceptualization, experimentation, and analysis of the study. -XXXX-, -XXXX-, and -XXXX-contributed to supervision, manuscript revision, and final approval of the submitted version. All authors reviewed and approved the final manuscript and agree to be accountable for its content.

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Figures

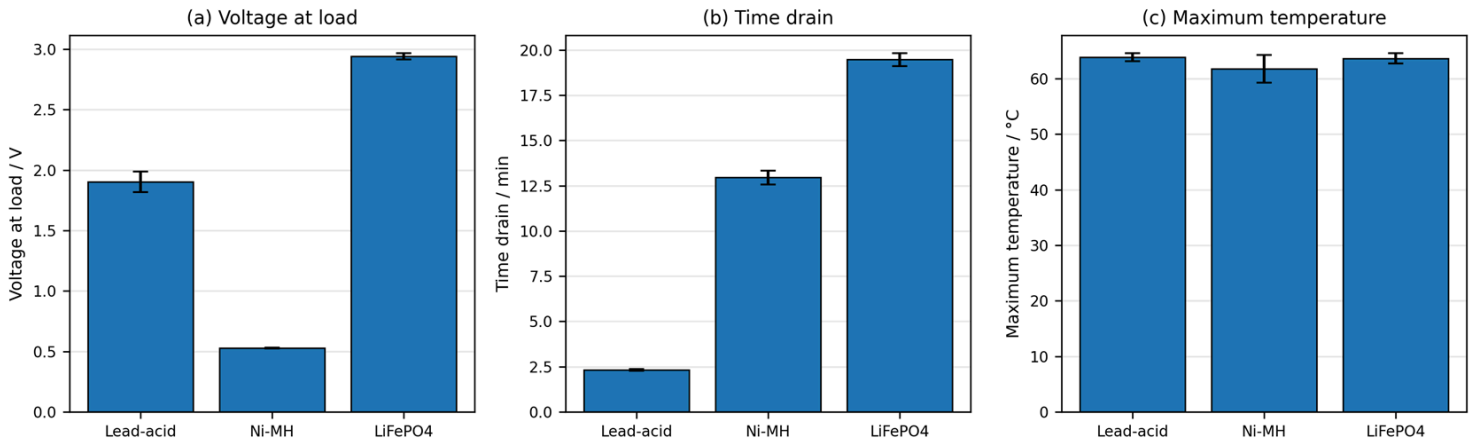


Figure 1

Comparative performance of lead-acid, nickel–metal hydride, and $LiFePO_4$ using the Phase I dataset, with n = 3 per chemistry: voltage at load, discharge time, and maximum temperature. Error bars denote one standard deviation.

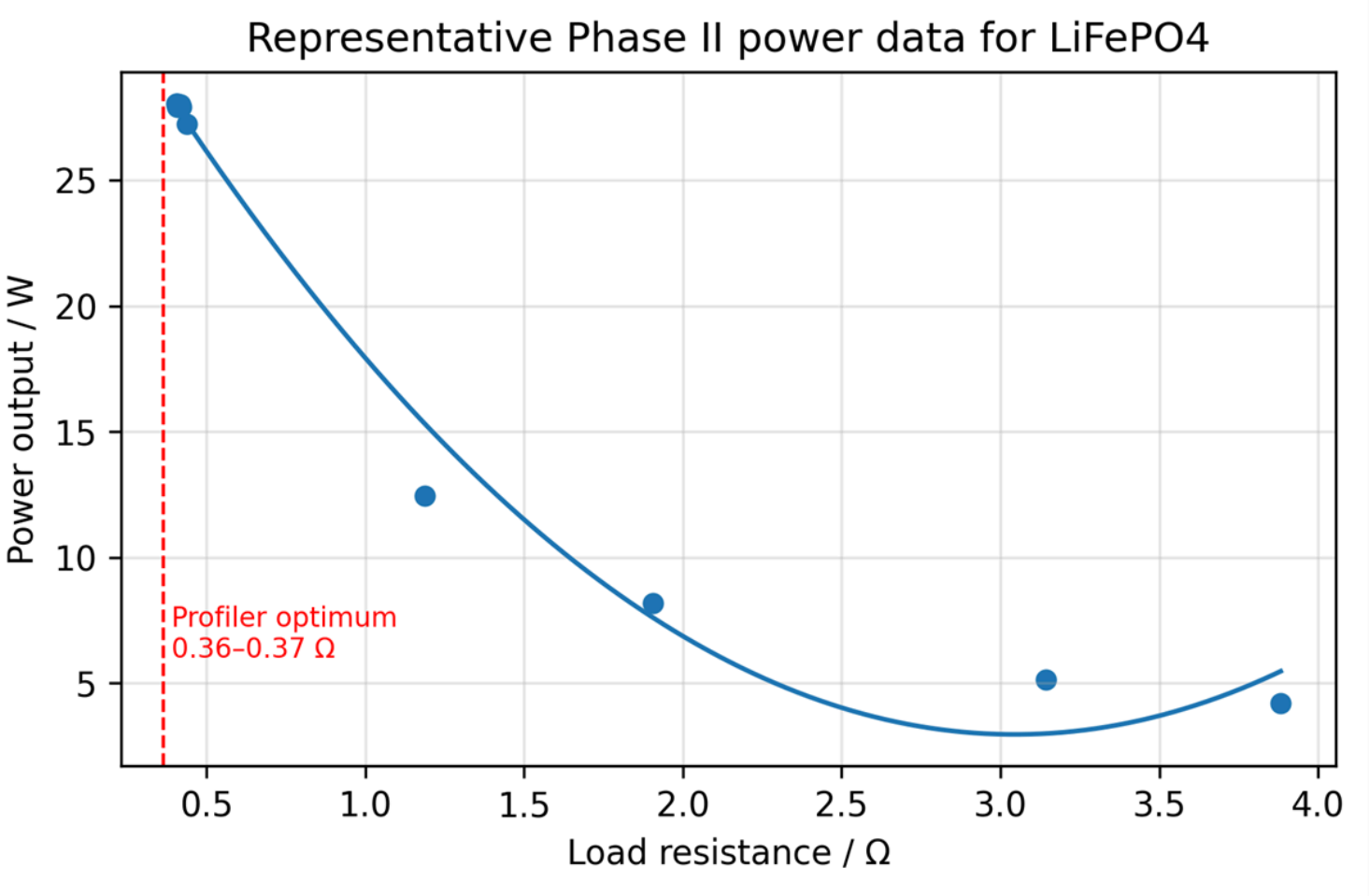


Figure 2

Representative Phase II $LiFePO_4$ power data. The dashed vertical line marks the profiler optimum (0.36–0.37 Ω) reported in the analysis.