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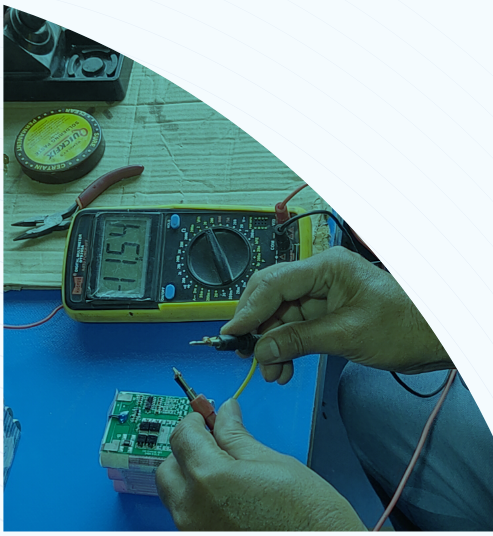

Unlocking Second-Life Value of Electric Vehicle Batteries for Low-Power Energy Storage Systems

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Credits

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Executive Summary

Electric Vehicle (EV) batteries that are retired after reaching reduced State-of-Health thresholds often retain substantial residual capacity that can be utilised in alternate applications. Existing research on second-life batteries has largely focused on grid-scale storage, with limited focus on low-power energy storage applications, which constitute a significant market. This study investigates the technical feasibility, economic rationale, and circular economy potential of refurbishing end-of-life (EoL) EV batteries.

The paper explores three central questions:

i. Whether refurbished EV batteries can reliably meet the operational requirements of low-power applications,

ii. How their performance compares with lead-acid batteries commonly used in such systems, and

iii. What methodological and ecosystem challenges influence large-scale refurbishment adoption.

Refurbished lithium-ion battery modules were experimentally tested against equivalent lead-acid batteries across four representative applications: a Direct Current (DC) lamp, DC fan, agriculture spray pump, and small uninterruptible power supply (UPS). Results show that refurbished lithium-ion batteries perform equal to or better than lead-acid systems across all tested applications, demonstrating longer discharge durations, stable current delivery, and safe thermal performance under low-power operating conditions. Policy support, standardised refurbishment protocols, and improved battery data accessibility are identified as key enablers for scaling second-life battery ecosystems.

Key Policy Recommendations

- Recognize battery refurbishment as a distinct pathway under the Battery Waste Management Rules 2022, alongside recycling, rather than treating EoL batteries only as recycling feedstock.
- Allow refurbishers to earn Extended Producer Responsibility (EPR) credits for batteries they process and redeploy, which would improve access to batteries and create a more efficient supply channel.
- Create design incentives for refurbishment-friendly batteries, so manufacturers are encouraged to develop packs that are easier and safer to repair, test, and reuse.
- Reduce GST on refurbished batteries, ideally to a lower slab such as 5%, to improve price competitiveness versus new batteries and make refurbishment more commercially viable.
- Develop dedicated refurbishment standards and guidelines, since existing frameworks such as UL 1974 may be too costly and burdensome to apply universally in this context.
- Mandate testing of critical battery components at National Accreditation Board for Testing and Calibration Laboratories (NABL)-accredited laboratories, including the Battery Management System (BMS), thermal separators, connectors, and other safety-critical parts, before refurbished batteries are sold in the market.
- Permit market access only to refurbishers whose components have been tested and validated, to ensure safety and build consumer confidence.
- Provide financial assistance and policy parity for refurbishers, placing them on the same footing as upstream manufacturers and recyclers under central and state EV policies.
- Create mechanisms for battery usage-data sharing, so refurbishers can assess state of health more accurately and make faster, better refurbishment decisions.

01

Introduction

Electric vehicles (EVs) are seen as one of the important solutions for decarbonising the road transport sector. Globally, the uptake of EVs is accelerating owing to favourable policies, increased product choices from Original Equipment Manufacturers (OEMs), rising public awareness of the cost and environmental benefits of EVs, and more. In particular, China has emerged as a market leader, with more than 60% of all electric cars sold worldwide.[1] India is also showing a strong year-on-year growth and has set ambitious targets. The total EV sales in FY 2025 were 1.5 times the EV sales in 2024[2]. Since 2015, over 9.1 million EVs have been deployed on Indian roads. The EV sales penetration in India in 2025 hovers around 8.25% of total vehicle sales. It appears that India is on track to meet its 2030 target of 30% EV sales penetration[3]. This uptick in EV deployment brings a parallel and urgent challenge: managing the end-of-life (EoL) of traction lithium-ion batteries at scale.

Lithium-ion chemistries dominate modern EVs because they deliver high gravimetric and volumetric energy density and long cycle life[4,5]. But those characteristics do not eliminate degradation: batteries in real vehicles experience a wide range of stresses (high cycle counts[6], variable charge/discharge rates, temperature swings[7], vibration, and partial-state-of-charge operation) that collectively drive capacity fade and resistance rise. Defining the precise moment a battery has reached EoL for traction is therefore non-trivial. One key benchmark, often referred to across the EV ecosystem to quantify the EoL of EVs, is the 80% State of Health (SoH), originally proposed by the United States Advanced Battery Consortium (USABC) in 1996[8]. However, with advancements in battery technology leading to increased energy density, this threshold has become irrelevant, and the vehicles will still have significant capacity for traction applications[9,10].

This paper considers that, though the EoL threshold will vary for EVs as this fact gets validated and accepted, the EVs that will retire will have batteries with significant usable in other non-traction applications. Rather than treating those packs as immediate waste, they can be diverted into “second life” through refurbishment. When refurbished to appropriate safety and performance standards, retired EV batteries can serve as low-cost energy storage for a wide range of uses[11,12]. And those unsuitable for refurbishment should be sent to recycling to recover critical materials and close the circular loop.

Refurbishment occupies a distinct place in the battery circular value chain. Whereas recycling focuses on material recovery (pyrometallurgical, hydrometallurgical, and emerging direct-recycling processes), refurbishment extends the functional life of cells and packs, thereby postponing the energy and material costs of producing new batteries, creating local value-chain jobs[13], and reducing dependency on critical imports. Given the relatively mature state of recycling technologies[14,15] and the policy attention that route receives across countries[16,17,18,19], this study narrows its scope to the refurbishment and second-life deployment of EoL EV batteries for low-power energy storage systems.

Battery manufacturing remains the dominant cost and carbon contributor in EV production. Extending battery utility via second life spreads both cost and embodied emissions across additional service years and applications. Where imported battery raw materials bring forth national energy security concerns due to mining and processing facilities situated in a select few countries, refurbishment provides a critical window of opportunity to reduce imports. Further, several studies and pilot projects have showcased that refurbished battery packs can deliver meaningful service life, often a decade or more, in stationary use cases, making refurbishment a critical aspect of battery circularity[20].

1.1 Challenges in Battery Waste and Resource Scarcity

As EV adoption rises, large volumes of EoL battery packs will start appearing in the short to medium term. In case these batteries are not properly refurbished or recycled, they will be directed to landfills, driving contamination due to their hazardous nature[21]. Moreover, global demand for battery-grade critical minerals (lithium, nickel, cobalt, graphite) creates supply-security and price-volatility risks for national manufacturing strategies[22], risks that refurbishment helps mitigate by lowering near-term raw-material demand.

1.2 Concept and Scope of Battery Refurbishment

“Battery refurbishment” in this paper refers to a set of processes that recover vehicular battery packs or cells, assess and sort them by electrical and physical condition, perform non-destructive conditioning and repair as appropriate, reconfigure cells into new modules or packs, integrate suitable battery management and safety systems, and qualify the resulting modules for designated second-life applications. Refurbishment pathways range from remanufacturing (rebuild to vehicle-grade packs) to repurposing (repackaging cells for stationary systems)[23] and direct reuse (minimal conversion for compatible deployments like integrating EoL batteries with EV chargers[24], mobile power banks[25] and telecommunication towers[26]) as seen in Figure 1. This study places emphasis on low-power, low-current applications like solar-coupled Direct Current (DC) appliances, small uninterruptible power supply (UPS) units, street lighting, and agriculture spray pump because these applications are particularly well matched to the remaining capacity and power capability typical of retired EV cells and because they represent large, underserved markets in many regions.

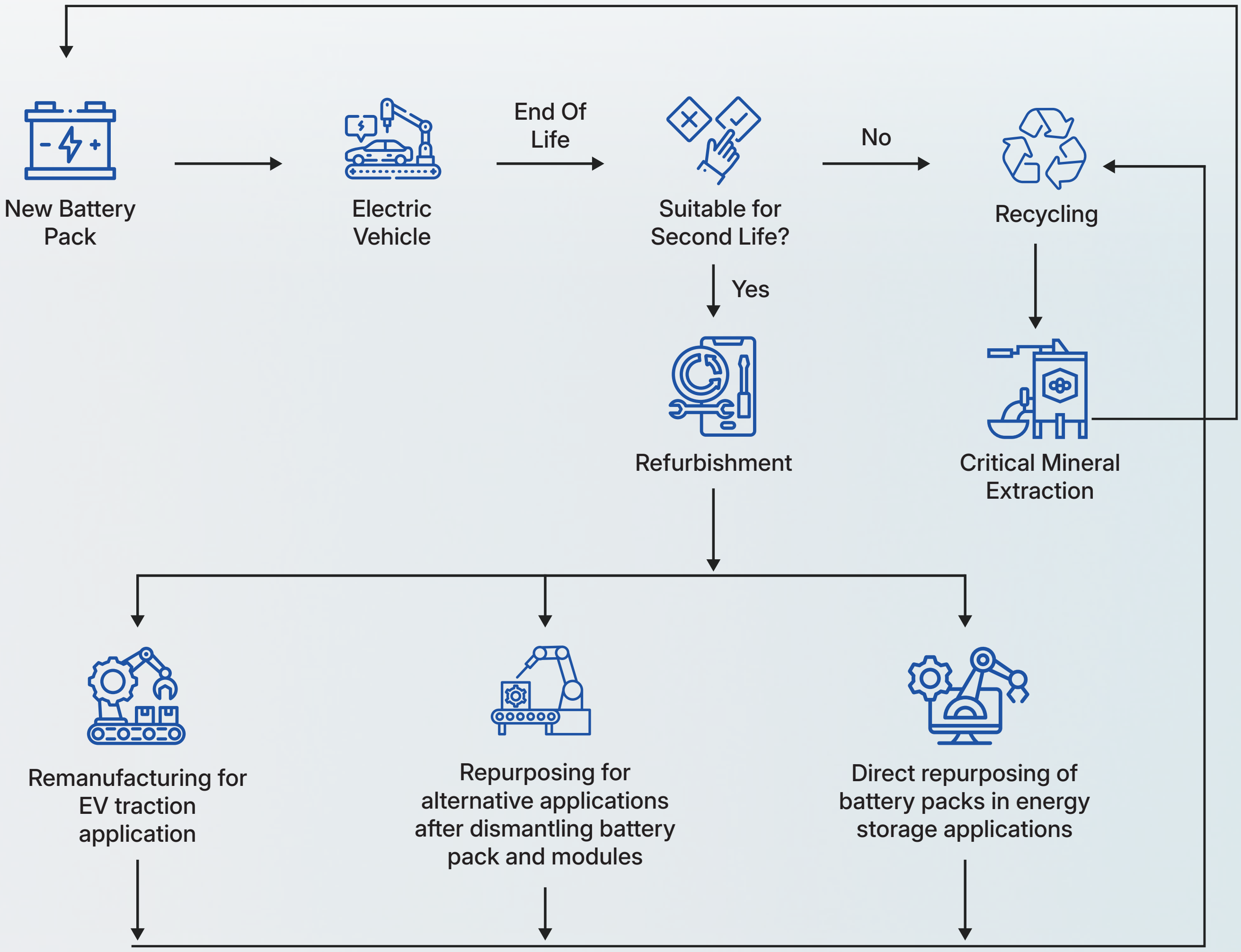


Figure 1: Lifecycle of a lithium-ion battery, highlighting production, primary use, second-life applications, and EoL recycling

1.3 Objectives and Contributions of this Paper

Although several studies and pilots have explored the second-life use of EV batteries, most of them focus on applications such as deploying retired batteries from cars, buses, and trucks in lower-power electric mobility solutions (e.g., electric cycles and two-wheelers) or in stationary energy storage systems. These include small-scale residential energy storage[27], energy storage systems integrated with EV charging infrastructure[28], and storage solutions supporting data centres[29]. However, the range of potential applications for refurbished batteries continues to expand, and there remains a limited body of research examining their suitability for low-power applications, particularly in comparison with conventional lead-acid batteries used for similar purposes.

Such low-power applications may include agriculture spray pump, solar street lighting systems, DC fans, DC lighting, and small UPS systems, among others. This paper aims to address this research gap by analysing the technical feasibility of refurbished batteries for the selected low-power energy storage applications and comparing them with lead-acid alternatives currently used extensively in these applications. Further, this paper also highlights the key challenges faced by the refurbishers and proposes solutions to address operational constraints. Moreover, a detailed process flow to carry out the refurbishment of EoL battery packs is presented and executed to guide the development of a viable second-life battery ecosystem.

1.4 Organisation of the Paper

The structure of the paper is as follows. Section 2 provides details on the need for the refurbishment of batteries in the Indian context by taking into account EV growth, battery circulation market size, and environmental and cost drivers. Section 3 highlights key applications examined for refurbishment in this paper. Section 4 examines market potential, costs, and adoption enablers and barriers for the selected applications. Section 5 provides a detailed refurbishment methodology focused on practicality and cost effectiveness for low-power energy storage applications. Section 6 describes the experimental setup and key tests performed between refurbished lithium-ion batteries and new lead acid batteries. Section 7 outlines key research areas to be looked at in the future, and Section 8 concludes with summary findings and policy implications.

02

Need for Battery Refurbishment

2.1 Growth of EVs and EoL Batteries

The global EV market has expanded significantly in recent years, leading to an inevitable increase in the number of batteries that will reach the end of their first life in vehicle applications. According to the Global EV Outlook 2025 by the International Energy Agency, global electric car sales crossed 17 million units in 2024, representing a substantial increase compared to previous years. This rapid growth is mirrored in emerging EV markets such as India, where electric mobility adoption has accelerated due to policy incentives, technological advancements, and expanding product offerings.

Within India, EV sales have shown consistent year-on-year growth. Electric two-wheelers contribute the largest share of total EV sales, followed by electric three-wheelers, while electric cars continue to gain traction, as shown in Figure 2. The market currently includes more than 66[30] manufacturers in the electric two-wheeler category and over 17[31] manufacturers in the electric passenger car segment. In terms of battery size, electric two-wheelers typically employ battery packs with an average capacity of approximately 2.66 kWh, whereas electric passenger cars utilise significantly larger battery packs averaging around 69.5 kWh[32].

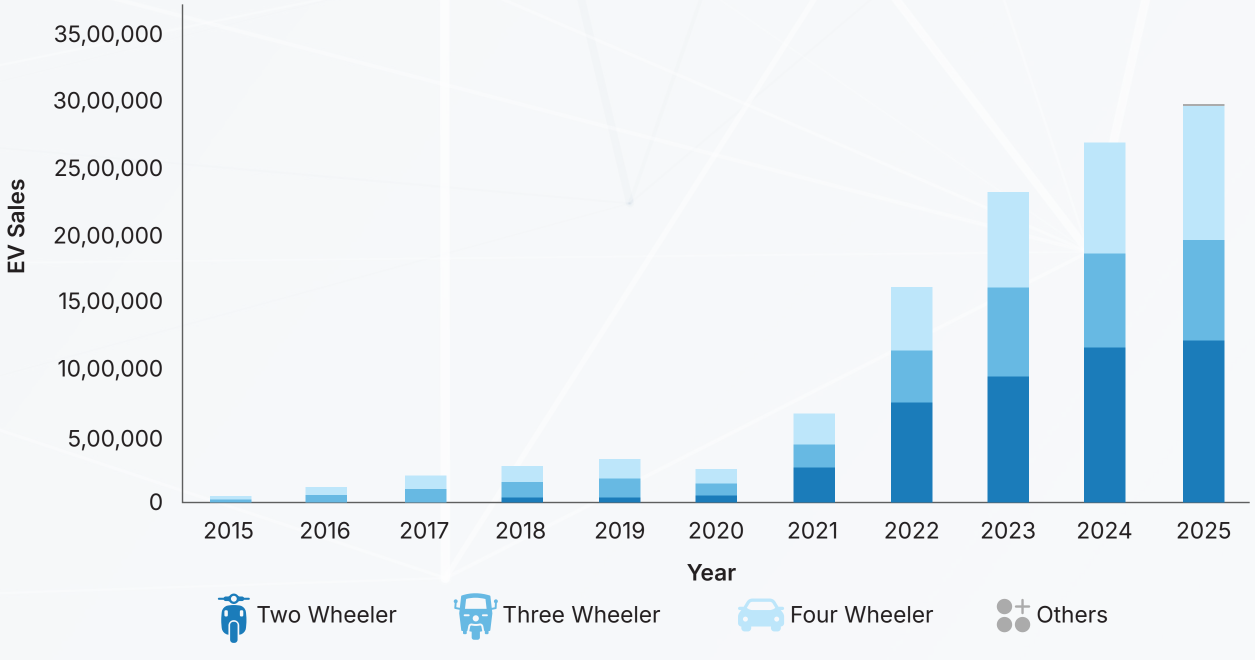


Figure 2: Year-on-year EV sales CY 2015-25

During their operational lifetime in vehicles, these lithium-ion batteries are subjected to varying climatic conditions, humidity levels, mechanical vibrations, and repeated charging and discharging cycles[33,34]. They also experience variations in charging rates, depth of discharge, and operating temperatures, all of which contribute to gradual performance degradation over time. As a result, battery capacity and power capability decline progressively, eventually reaching a state where the battery is no longer suitable for EV traction applications.

The increasing penetration of EVs, therefore, directly translates into a growing volume of EoL batteries entering the market. In India, EV battery demand is projected to reach approximately 1080 GWh by 2050, representing nearly 40 times the demand in 2025[35]. To support a robust circular battery ecosystem, the country is expected to require investments of around ₹15 lakh crore by 2050. This emerging stream of retired EV batteries represents both a challenge and a significant opportunity. While improper handling could result in environmental risks and material loss, these batteries still retain a considerable portion of their usable capacity and can potentially be redeployed in secondary applications through refurbishment.

Given that India continues to rely heavily on imports for lithium-ion batteries and critical raw materials[36], the effective reuse of retired EV batteries can contribute to resource efficiency, reduce import dependency, and support the development of a domestic circular battery economy.

2.2 Environmental and Sustainability Drivers

Battery refurbishment provides significant environmental advantages by extending the functional life of lithium-ion batteries and delaying their entry into the recycling or disposal stage[37,38]. The production of new lithium-ion batteries is resource-intensive, requiring substantial quantities of critical minerals such as lithium, cobalt, and nickel, along with energy-intensive manufacturing processes. Consequently, battery production constitutes one of the most emission-intensive stages in the EV value chain.

By enabling the reuse of EV batteries in secondary applications, refurbishment reduces the demand for newly manufactured batteries and therefore lowers the overall environmental footprint associated with raw material extraction, mineral processing, and battery manufacturing. In addition, refurbishment reduces the volume of battery waste generated and minimises the environmental risks associated with improper disposal or informal recycling practices.

Another important sustainability benefit lies in resource conservation[39]. The extension of battery life through second-life applications helps optimise the utilisation of embedded materials and energy that were already invested during the first life of the battery. Instead of recovering materials immediately through recycling, which itself requires energy and infrastructure, refurbishment allows the battery to deliver additional years of service before eventually entering the recycling stage.

From a circular economy perspective, battery refurbishment therefore serves as an intermediate step between first-life use and material recovery, maximising resource productivity while supporting sustainable energy transitions.

2.3 Economic Rationale and Cost Considerations

From an economic standpoint, battery refurbishment presents a compelling opportunity to extract additional value from EV batteries after their retirement from vehicle applications. Battery packs represent a significant proportion of the total cost of an EV, typically accounting for 30–40%[40] of the vehicle's overall value. Extending the operational life of these batteries through refurbishment allows this cost to be amortised over a longer service period and across multiple applications.

The cost structure of battery refurbishment generally includes four primary components. The first is the procurement cost associated with acquiring EoL batteries from vehicle owners, OEMs, or secondary markets. The second component involves logistics costs related to the safe collection, transportation, and storage of used battery packs. The third cost element includes testing and diagnostic procedures required to assess the condition of individual cells and modules, including visual, mechanical, and electrical testing. The final component involves repackaging and integration, where suitable cells are assembled into new battery modules or packs designed for specific second-life applications.

While the environmental rationale for refurbishment is clear, the economic feasibility of such operations remain dynamic[41]. The cost of manufacturing new lithium-ion batteries has declined dramatically over the past decade, falling by more than 85% since 2010 due to improvements in manufacturing scale, supply chain optimisation, and technological advancements[42]. As a result, refurbished battery systems must remain cost-competitive with newly manufactured batteries to ensure market viability.

In many cases, refurbishment can be economically advantageous when conducted by the original battery manufacturers or EV OEMs. These stakeholders have access to first-life operational data, BMS records, and proprietary knowledge regarding pack architecture and disassembly procedures. Such access allows them to perform quicker diagnostics and reduce refurbishment costs.

Conversely, third-party refurbishers face additional challenges[43]. Batteries arriving from different manufacturers may vary significantly in form factor, chemistry, degradation patterns, and historical usage conditions. The lack of standardised battery designs and limited access to operational data can increase the time and cost required for testing and sorting, potentially affecting the economic viability of refurbishment.

2.4 Refurbishment vs. Recycling

Although both refurbishment and recycling are essential components of a circular battery economy, they serve fundamentally different purposes within the battery lifecycle. Recycling focuses on recovering valuable materials such as lithium, cobalt, nickel, and copper from spent batteries so that these materials can be reintroduced into the battery manufacturing supply chain. Technologies such as pyrometallurgical, hydrometallurgical, and emerging direct-recycling processes have been developed to support efficient material recovery.

Refurbishment, on the other hand, focuses on extending the functional life of batteries before they reach the recycling stage. Refurbishment enables batteries with remaining usable capacity to continue delivering value, while postponing the need for energy-intensive recycling processes. From a sustainability standpoint, refurbishment often represents a higher value pathway than immediate recycling because it maximises the utility derived from the original battery while postponing material recovery to a later stage. Recycling remains essential once batteries can no longer meet the performance or safety requirements of second-life applications, ensuring that valuable materials are recovered and reintegrated into the production cycle.

Therefore, an optimal battery circular economy requires a balanced approach where refurbishment is prioritised whenever technically and economically feasible, followed by responsible recycling at the end of the battery's extended lifecycle.

03

Applications of Refurbished Batteries

Advancements in battery refurbishment have yielded significant economic and sustainable prospects for extending battery life. The advent of empirical models to determine the battery state-of-health (SoH), and progress in electrolyte extraction and subsequent refilling methods that can improve the battery SoH, have rendered benefits to realise second-life battery applications. Despite observed declines in battery costs, as of today, the cost of refurbishing batteries remains minimal compared to purchasing new batteries.

Typically, second-life battery pilots[44] have been conducted to serve as stationary storage for various on-grid and off-grid applications. Some of the prominent applications for second-life battery use are as follows-

- Ancillary Services to the Grid (Vehicle-to-Grid (V2G)): Use truck batteries for grid services during idle times, focusing on tasks that preserve battery health and minimise cycles, such as fast frequency response, reactive power compensation, and black start capability[45].
- Integration with Smaller Vehicles: Utilise EV batteries from larger vehicles to suit electric two-wheelers, three-wheelers, and cycles[46].
- Battery Energy Storage Systems (BESS): Develop modular BESS and integrate them with the electricity grid. Integration can occur at the transmission level, distribution level, or at renewable energy plant sites, with each location offering unique benefits to grid operators and distribution utilities[47].
- Home Energy Storage: Implement batteries for residential backup power systems[48].
- On-Site Power: Deploy batteries for logistics hubs and construction sites[49].
- Solar Cold Storage: Utilise batteries for solar-powered cold storage solutions[50].
- Mini and Microgrids: Support hinterland electrification through battery deployment in mini and microgrids[51].
- Mobile Tower Backup: Provide backup power for mobile communication towers[52].

Agricultural applications also present a promising opportunity for second-life battery deployment in agricultural equipment such as spray pumps and portable irrigation pumps. Agriculture spray pump operating at pressure levels of around 250 psi have a lucrative use case for second-life batteries.

Refurbished batteries also have significant use cases in the residential segment, with scope for scale, with DC – powered appliances, and residential electricity backup systems. In 2023, the DC power systems market in India was valued at over USD 205 million, and is projected to grow at a Compound Annual Growth Rate (CAGR) of 6.5% through 2029[53]. With this backdrop, the white paper has tested the utility of retired EV batteries to serve the following low-voltage applications-

- DC Lamp
- DC Fan
- Agriculture Spray Pump
- Residential UPS system

The technical specifications of the above appliances have been furnished under the experimental setup in Section 6.2.

04

Market Outlook for Refurbished Batteries

4.1 Market Size and Growth Trends

Emerging markets indicate strong potential for integrating refurbished EV batteries into low-power applications. DC fans represent a particularly promising segment due to their relatively low energy consumption and growing demand in regions experiencing high temperatures and limited access to grid electricity. The global DC-powered fan market was valued at approximately USD 420 million in 2023, with sales volumes reaching nearly 10.5 million units. The market is projected to grow at a CAGR of around 12.6% between 2025 and 2032, potentially reaching a value of approximately USD 1.2 billion[54].

On similar lines, the increasing reliance on electronic devices, communication infrastructure, and digital services has significantly raised the demand for UPS systems. The global UPS market was estimated at approximately USD 6.44 billion in 2023, with sales of around 17.1 million units. With an expected CAGR of approximately 6.4%, the market is projected to reach nearly USD 10.46 billion by 2030[55].

Agricultural equipment powered by rechargeable batteries represents another rapidly expanding market, particularly in developing economies. One such example is the agriculture spray pump market, which was estimated to be worth approximately USD 2.5 billion in 2022 with a sales volume of nearly 62.5 million units. This market is projected to grow to approximately USD 3.5 billion by 2027[56], representing a CAGR of roughly 6.8%.

DC light is another high-growth application segment that aligns well with the deployment of refurbished battery systems. The DC light market in India was estimated to be valued at approximately USD 1.07 billion in 2024 and is projected to expand significantly to around USD 3.54 billion by 2033. This growth corresponds to a CAGR of approximately 14.21%[57], driven by increasing investments in decentralised renewable infrastructure and government initiatives aimed at improving energy access.

Overall, these market trends indicate that low-power applications offer a substantial opportunity for the deployment of refurbished EV batteries, specifically in the early stages when the refurbishment market is still gaining momentum.

4.2 Adoption Barriers and Enablers

The successful deployment of refurbished battery systems depends not only on technological feasibility but also on the development of a supportive ecosystem involving supply chains, regulatory frameworks, data accessibility, and market acceptance. While second-life batteries present strong environmental and economic advantages, their widespread adoption is currently constrained by several technical, economic, and institutional challenges. At the same time, a number of emerging developments in policy, technology, and industry collaboration are acting as enablers that could accelerate the growth of this sector. Table 1 summarises the major barriers and corresponding enabling factors influencing the adoption of second-life battery systems.

Table 1: Major barriers and corresponding enabling factors for the adoption of second-life battery systems

Category	Barrier	Description	Potential Enabler	Impact of Enabler
Battery Identification	Lack of standardised battery identification and labelling[58]	Battery packs often lack uniform labelling and identification standards, making it difficult for refurbishers to quickly determine specifications such as chemistry, configuration, and capacity. This results in manual verification processes that are time- consuming and costly.	Implementation of digital battery tracking systems and battery passports	Digital tracking systems can store lifecycle data such as manufacturing details, usage history, and performance metrics, enabling quicker assessment and automated identification of batteries for second-life applications.
Data Availability	Limited access to first-life battery data[59]	BMS record valuable data regarding usage patterns, operating temperatures, charging behaviour, and degradation trends. However, this data is rarely shared with refurbishers due to commercial confidentiality and privacy concerns.	Data- sharing frameworks and lifecycle monitoring systems	Controlled data-sharing mechanisms and IoT-enabled monitoring platforms can allow refurbishers to access essential battery health data, enabling more accurate estimation of remaining useful life.
Economic Competitiveness	Competition with the declining cost of new batteries[60]	The cost of new lithium-ion batteries has declined significantly in the past decade due to advances in manufacturing and economies of scale. As a result, second-life batteries must offer a clear price advantage to remain competitive.	Improved refurbishment technologies and economies of scale	Automated testing, modular pack design, and larger refurbishment facilities can reduce processing costs and improve the price competitiveness of second-life batteries.
Market Perception	Consumer hesitation toward used battery systems[61]	Potential users may perceive second-life batteries as unreliable or unsafe due to their previous usage history, leading to reduced willingness to adopt such systems.	Certification standards and performance guarantees	Development of certification mechanisms and quality assurance standards for refurbished batteries can improve consumer confidence and support wider adoption.

Category	Barrier	Description	Potential Enabler	Impact of Enabler
Regulatory Environment	Policy and regulatory uncertainty[62]	Existing regulatory frameworks for energy storage systems were not originally designed with second-life batteries in mind. In some cases, policies restrict incentives or subsidies to new battery systems, excluding reused assets.	Supportive regulatory frameworks and incentives	Governments can introduce policies that explicitly recognise second-life batteries, including subsidies, tax incentives, and inclusion in energy storage incentive programs.
Collection and Logistics	Inadequate collection and reverse logistics infrastructure[63]	Without a structured system for collecting and transporting EoL batteries, many used batteries may enter informal waste streams rather than being recovered for refurbishment or recycling.	Establishment of formal collection networks	Organised battery collection systems and recycling centres can ensure proper recovery and channel batteries toward refurbishment pathways before recycling.
Supply Chain Coordination	Fragmented battery value chain[64, 65]	The battery lifecycle involves multiple stakeholders, including EV manufacturers, battery producers, recyclers, and refurbishers. Lack of coordination among these stakeholders limits efficient second-life deployment.	Value chain integration and industry collaboration	Better collaboration can facilitate battery designs that are easier to dismantle, test, and refurbish.
Technology and Diagnostics	Limited diagnostic and monitoring technologies[66]	Determining the remaining useful life of used batteries can be technically challenging without advanced diagnostic tools.	Advanced BMS and predictive analytics	Advanced BMS and predictive analytics replace limited diagnostic tools by continuously tracking operational data to accurately forecast cell health, remaining lifespan, and safety risks without manual testing.
Policy and Financial Support	High initial investment requirements	Establishing refurbishment facilities, testing infrastructure, and collection systems requires significant capital investment.	Government incentives and financial mechanisms	Policy instruments such as tax benefits, subsidies, and deposit-refund systems can encourage investment in refurbishment and recycling infrastructure.

05

Battery Refurbishment Methodology

At present, the refurbishment of EoL batteries is primarily guided by the standard UL 1974[67], which provides a detailed framework for evaluating the suitability of used batteries for second-life applications. While the standard outlines comprehensive testing procedures to ensure safety and performance reliability, implementing its full set of requirements can be challenging for refurbishers, particularly those operating at small or medium scales. The procedures prescribed under UL 1974 involve extensive diagnostic and validation steps that require specialised equipment, time, and technical expertise. As a result, conducting the entire testing process may not always be economically feasible for refurbishers working with batteries intended for relatively low-power applications. In fact, estimates suggest that the testing and qualification procedures recommended by UL 1974 could account for nearly 30% of the value of the used battery pack[68], thereby significantly affecting the commercial viability of refurbishment activities. Considering these constraints, there is a need for a more nuanced assessment methodology that preserves safety while reducing operational complexity and costs.

The methodology proposed in this white paper, therefore, focuses on simplified yet effective diagnostic procedures that enable refurbishers to evaluate EoL batteries for second-life deployment in low-power energy storage applications. Batteries reaching their end of life in EVs can be sourced through multiple channels, including secondary battery markets, manufacturers, service centres, or directly from vehicle owners. Prior to removal from the vehicle, the battery pack must be completely discharged to ensure safe handling and to reduce the risk of electrical hazards during dismantling and transportation[69]. Once the battery pack is obtained, an initial assessment is carried out to determine whether the pack may still be suitable for remanufacturing in its existing configuration. If remanufacturing is not feasible due to degradation or design limitations, the battery pack proceeds to the disassembly stage.

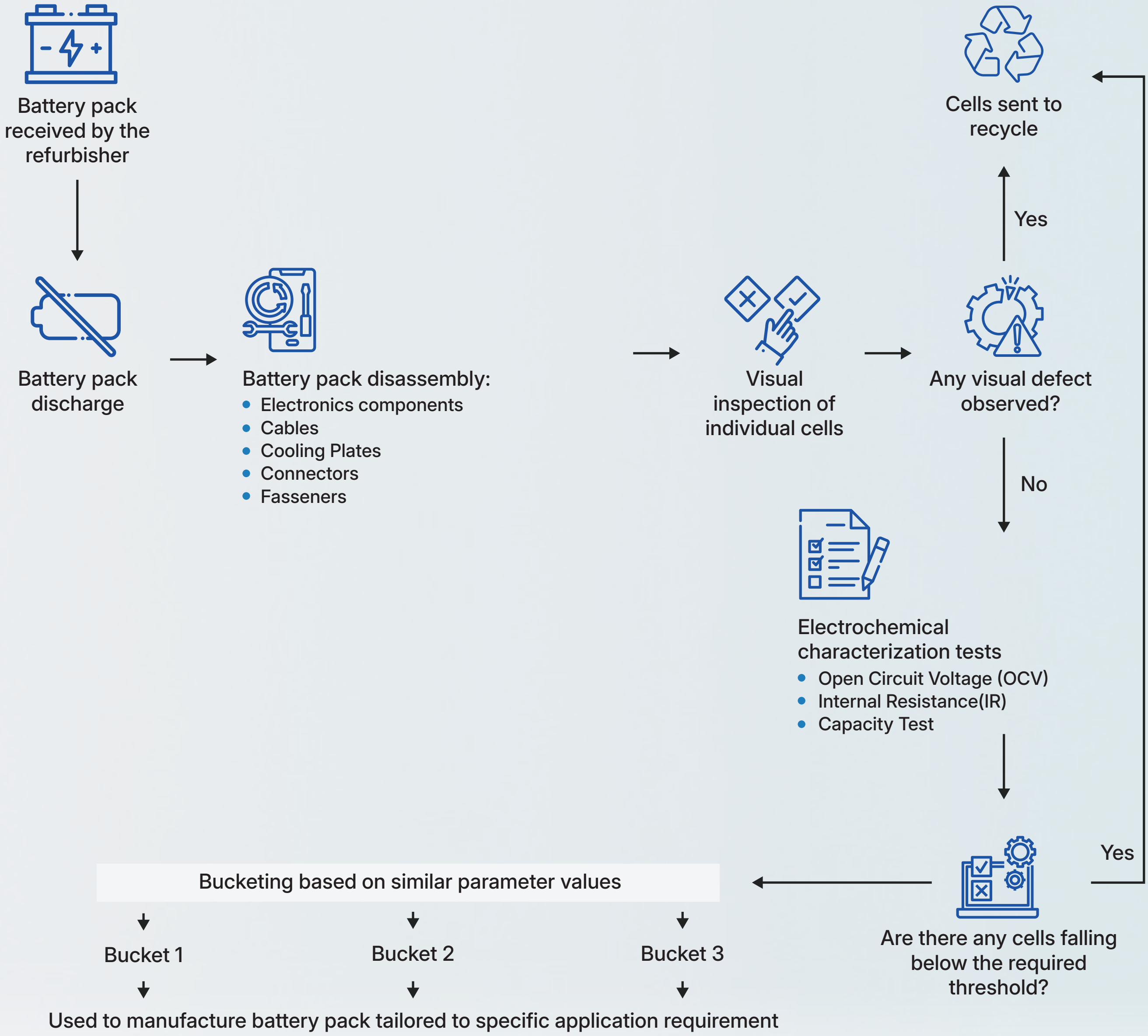


Figure 3: Methodology illustrating the refurbishment process of battery packs, including inspection, cell selection, reassembly, and testing

The disassembly process involves carefully removing external and internal components of the battery pack in order to access individual cells. This process typically includes the removal of cables and connectors, electronic components, enclosures, cooling plates, fasteners, and other structural elements. The distilling process may cause damage to the cells[70]. Once the individual battery cells are extracted from the pack, they undergo a visual inspection stage that serves as the first level of screening. During this inspection, cells are examined for physical defects such as corrosion, electrolyte leakage, water ingress, damaged terminals, or bulging and deformation of the cell structure. The presence of any of these defects can compromise the operational safety of the battery and may lead to premature failure during second-life use[71,72]. In more severe cases, damaged lithium-ion cells may pose risks of thermal runaway or other catastrophic failure events. Therefore, cells exhibiting any visible signs of structural or chemical damage are immediately rejected from the refurbishment pathway and diverted to recycling streams.

Cells that successfully pass the visual inspection stage are subjected to a set of rapid electrochemical tests designed to evaluate their electrical characteristics. These tests are intentionally designed to be conducted within relatively short timeframes so that the refurbishment process remains economically viable while still providing meaningful indicators of cell health. Commonly performed measurements include Open Circuit Voltage (OCV), internal resistance (IR), and remaining capacity expressed in ampere-hours (Ah) . The OCV is the voltage measured across the terminals of a cell under no-load conditions. This measurement must be taken after the cell is fully charged, followed by a resting period that allows transient relaxation in the terminal voltage caused by concentration gradients, surface polarisation, and other electrochemical effects. OCV measurements help identify issues related to capacity loss or internal short circuits within the cells[75].

IR measurement reflects the degree of ageing and degradation within the cell[76]. Capacity testing, on the other hand, provides an estimate of the amount of energy the cell can still store and deliver during operation. Cells that exhibit values below the manufacturer's specified thresholds, obtained from the cell datasheet or from lithium-ion chemistry–specific industry-accepted limits, must be rejected to ensure safety in second-life applications.

Based on the results obtained from these electrical tests, the cells are categorised into groups or "buckets" according to their electrical characteristics[77,78,79]. Cells with similar values of voltage, internal resistance, and capacity are grouped together to form matched sets that can later be assembled into new battery modules or packs. This cell-matching process is essential because large variations between cells within a battery pack can lead to imbalanced charging and discharging behaviour, which in turn accelerates degradation and reduces the overall lifespan of the system. By grouping cells with closely aligned performance characteristics, the refurbisher can minimise cell-to-cell variation and thereby improve the reliability and operational stability of the second-life battery pack.

It is also reasonable to assume that in low-power applications, where the current demand and discharge rates are relatively modest compared to EV traction systems, the degradation behaviour of refurbished cells may follow a more gradual and approximately linear trend[80]. This operational characteristic further supports the feasibility of deploying second-life batteries in such applications, as the performance demands placed on the cells are significantly lower than those experienced during their first life in EVs.

An important consideration in the refurbishment process is that second-life batteries cannot realistically be subjected to destructive safety tests[81]. Such tests would involve intentionally damaging or stressing the cells to determine their failure limits, which would defeat the purpose of refurbishment by destroying potentially usable cells. Additionally, the batteries handled by refurbishers often originate from multiple manufacturers and vary widely in terms of chemistry, form factor, and usage history. Conducting destructive safety testing for each batch of cells would therefore be impractical and economically prohibitive. Instead, the methodology relies on rigorous screening, visual inspection, and non-destructive electrical diagnostics to ensure that only cells meeting acceptable performance and safety thresholds are selected for second-life use.

Given the relatively modest power requirements of the target applications considered in this study, the assessment of SoH can also be simplified compared to the detailed diagnostics typically required for automotive applications[82]. In many cases, simplified capacity and resistance measurements may provide sufficient information to determine the suitability of a cell for low-power deployment. Consequently, the SoH assessment procedures for such applications can be less demanding, and in some cases may even be bypassed if other diagnostic indicators demonstrate acceptable performance characteristics. This adapted methodology therefore provides a practical pathway for refurbishers to evaluate and repurpose EV batteries efficiently while maintaining the fundamental safety and reliability requirements necessary for second-life deployment.

06

Experimental Setup and Comparative Performance Evaluation

6.1 Manufacturing Refurbished Battery Packs

For the purpose of this study, an EoL lithium-ion battery pack obtained from an electric two-wheeler was selected for refurbishment. The battery pack had a rated voltage of approximately 48 V and a capacity of 38 Ah, with a total weight of about 12.25 kg. Before dismantling, the battery pack was completely discharged to ensure safe handling and to minimise the risk of electrical hazards during the disassembly process. After safe discharge, the pack was dismantled to recover the individual battery cells and internal components. The key specifications of the EoL battery pack and its sub-components are summarised in Table 2.

Battery Pack Details
Battery ID: M10369572140127D
Model Name: Battery Module V4 – 48V
Nominal Voltage: 50.4 V
Capacity (Typical / Minimum): 38 Ah/36 Ah
Charge Current: 15 A
Discharge Current (Typical / Maximum): 19 A/38 A
Cell Chemistry: Nickel Manganese Cobalt (NMC)
Enclosure: Metallic
Total Weight: 12.25 kg
Cell Weight: 7.85 kg
Battery Configuration:
2 Battery Banks (24 V + 24 V ≈ 48 V)
Cell Configuration:
Each Bank: 84 cells
Configuration per Bank: 7 Series × 12 Parallel (7S12P)
Total Cells: 168

According to the manufacturer's datasheet, each individual cell had a rated capacity of 3000 mAh when discharged at a current of 0.61 A at an ambient temperature of 20°C. The recommended charging voltage for each cell was approximately 4.2 V. The detailed cell specifications are provided in Annexure 1.

Following the dismantling process, all extracted cells were subjected to an initial visual inspection to identify any physical defects that could compromise safety or performance. The cells that passed the visual inspection stage were cleaned at both the positive and negative terminals to remove any metallic outgrowths or welding remnants that may have remained from the dismantling process. The cleaned cells were then subjected to an electrochemical grading process using a battery grading machine. The specifications of the grading equipment are provided in Annexure 2. The grading procedure consisted of a sequence of seven controlled steps designed to evaluate the capacity and operational stability of each cell.

The process began with a constant current charging stage lasting 5 minutes, during which a current of 600 mA was applied to the cells. This was followed by a second constant current charging stage lasting approximately 220 minutes at a current of 900 mA, with a charging voltage limit of 4200 mV. In the third stage, the cells were subjected to constant voltage charging for 45 minutes at 4,200 mV with a cut-off current of 200 mA. After this stage, the cells were allowed to rest for a period of 60 minutes to stabilise the electrochemical processes and eliminate measurement deviations caused by temperature rise or transient effects.

The fifth stage consisted of a constant current discharge cycle lasting 300 minutes, with a discharge current of 610 mA and a lower voltage limit of 2,500 mV. This discharge step enabled the accurate determination of the remaining capacity of each cell. Subsequently, a second rest period of 60 minutes was provided to allow the cells to return to their equilibrium state. Finally, the seventh stage involved a constant current charging process for 120 minutes at 1,200 mA with a charging voltage limit of 3,800 mV.

The results obtained from the grading process indicated that the majority of cells exhibited a remaining capacity in the range of 2,600–2,700 mAh, as seen in Figure 4. The grading analysis indicated that approximately 89 cells exhibited a capacity range of 2,700–2,750 mAh, while around 74 cells showed capacities between 2,750– 2,800 mAh. Two cells fell outside the expected range, with measured capacities of approximately 1400–1450 mAh and 2650–2700 mAh, respectively, and were therefore excluded from the refurbishment process.

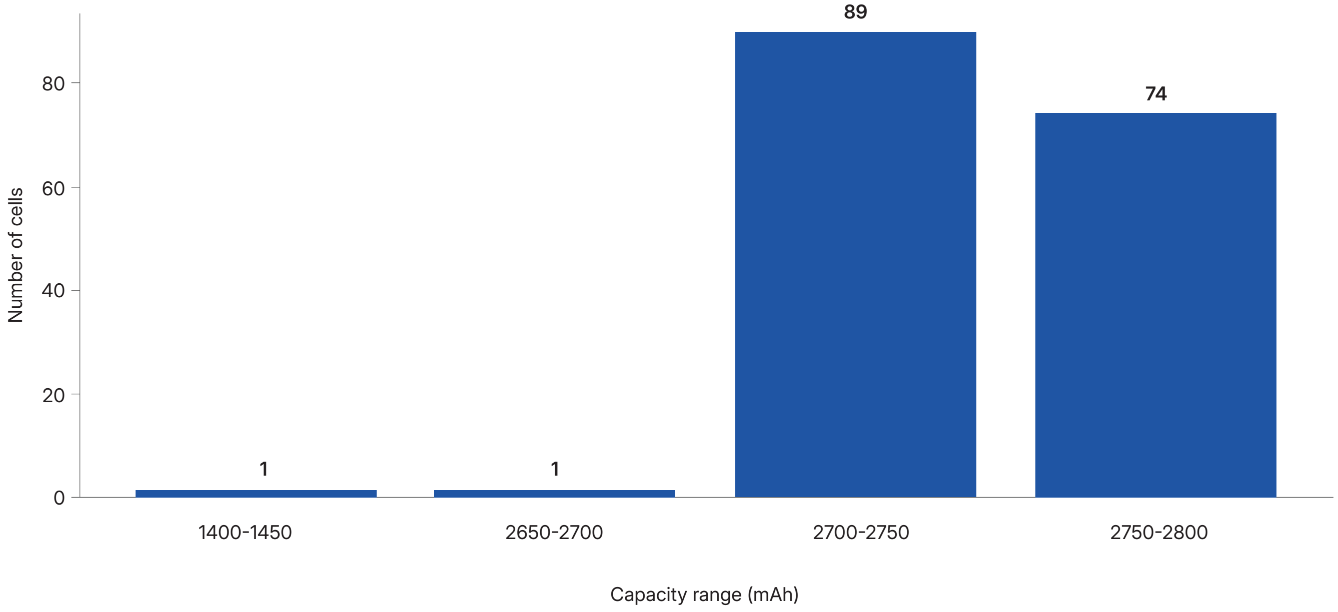


Figure 4: .Cell Capacity Distribution (50 mAh Bins- Non-Empty Only)

Note: 3 out of the 168 cells were physically damaged and could not be a part of the refurbishment process.

Following the grading process, the cells were further categorised based on their internal resistance and voltage characteristics using an automatic cell sorting machine. The sorting equipment operated within a voltage measurement range of 2.9 V to 3.9 V and an internal resistance range of 0–50 mΩ. The detailed specifications of the sorting machine are provided in Annexure 3. The sorting results revealed that 82 cells were categorised under channel 5 with an internal resistance range of 26–28 mΩ, while 77 cells were grouped under channel 6 with an internal resistance range of 28–30 mΩ.

After the sorting and classification stage, cells belonging to the same capacity and internal resistance bucket were selected for assembling refurbished battery packs. The new battery packs were designed using manual spot-welding techniques, as shown in Figure 5. For the intended low-power applications considered in this study, battery packs with a nominal voltage of 12 V and a capacity of approximately 7.5 Ah were constructed.

Figure 5: Spot welding of selected cells

Each battery pack consisted of nine cells arranged in a configuration of three cells in series and three cells in parallel (3S3P). The cells were interconnected using nickel strips through a spot-welding process to ensure reliable electrical connections while minimising thermal stress on the cells during assembly.

Figure 6: Refurbished battery pack

To ensure safe operation and proper charge management, a 12 V BMS was integrated into each refurbished battery pack. The BMS provides several essential protection functions, including overcharge protection, deep-discharge protection, overcurrent protection, and cell balancing during operation. The technical specifications of the BMS used in the study are provided in Annexure 4.

Finally, the assembled battery packs were enclosed in insulated plastic casings to provide electrical insulation, structural support, and mechanical protection. These enclosures also help improve the overall durability and safety of the refurbished battery packs during practical operation. The final assembled battery packs used in the experimental evaluation are illustrated in Figure 6.

6.2 Experimental Setups

6.2.1 Battery Systems and Test Setup

To experimentally evaluate the performance of refurbished lithium-ion battery packs in practical applications, a controlled test setup was developed to compare their performance against conventional lead-acid battery systems of equivalent specifications. The objective of this setup was to simulate real-world operating conditions and examine how the refurbished battery packs perform across a range of low- and moderate-power loads that are commonly powered by small energy storage systems.

The refurbished lithium-ion battery packs manufactured in the previous section were configured with a nominal rating of 12 V and approximately 7.5 Ah. For a fair comparison, commercially available sealed lead-acid (SLA) batteries with similar electrical specifications (12 V and 7.2–7.5 Ah capacity) were selected as the baseline reference system. Matching the voltage and capacity ensured that both battery chemistries operated under comparable electrical conditions during the experiments.

Each refurbished lithium-ion battery pack was paired with a lead-acid battery of similar rating and connected to identical electrical loads. The two battery types were tested simultaneously and independently, ensuring that each battery experienced the same load conditions. The experiments were conducted until the batteries reached their respective cutoff voltage limits, representing a full discharge cycle from a fully charged state. This approach enabled a direct comparison of discharge behaviour, energy delivery, and thermal response between the two battery technologies.

Four representative applications were selected for the testing phase: a DC lamp, a DC fan, an agriculture spray pump, and a small UPS. These applications were chosen because they represent common low-power energy consumption scenarios in residential, agricultural, and decentralised energy systems.

The first experimental load consisted of a 12 V, 50 W DC filament lamp, which served as a constant resistive load for evaluating discharge stability and energy delivery over time. The lamp provided a steady electrical demand that enabled observation of discharge behaviour under relatively stable load conditions. The test configuration for the DC lamp is illustrated in Figure 7.

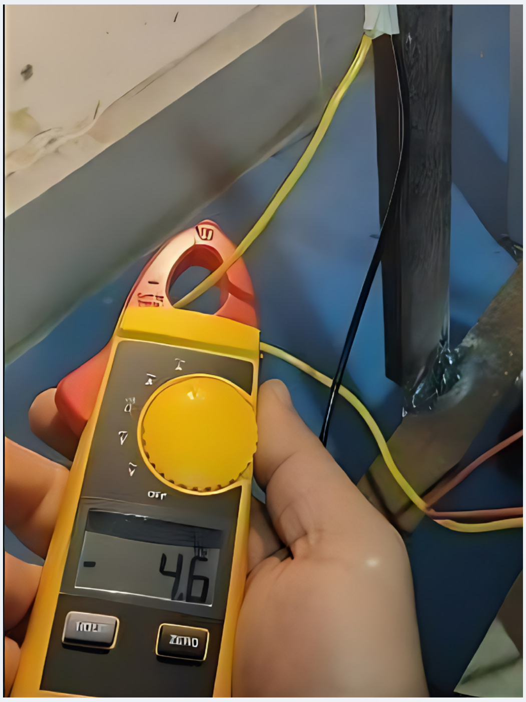


Figure 7: Experimental setup for performance testing using a 12 V, 50 W DC filament lamp connected to refurbished lithium-ion and lead-acid battery systems

The second load was a 12 V DC fan with a rated airflow capacity of approximately 240 m^3/min and an operating speed of around 375 RPM. Unlike the resistive lamp load, the fan represents a dynamic electromechanical load where current draw may vary during operation due to motor characteristics. This configuration allowed assessment of battery performance under a small motor-driven appliance. The experimental setup for the DC fan is shown in Figure 8.

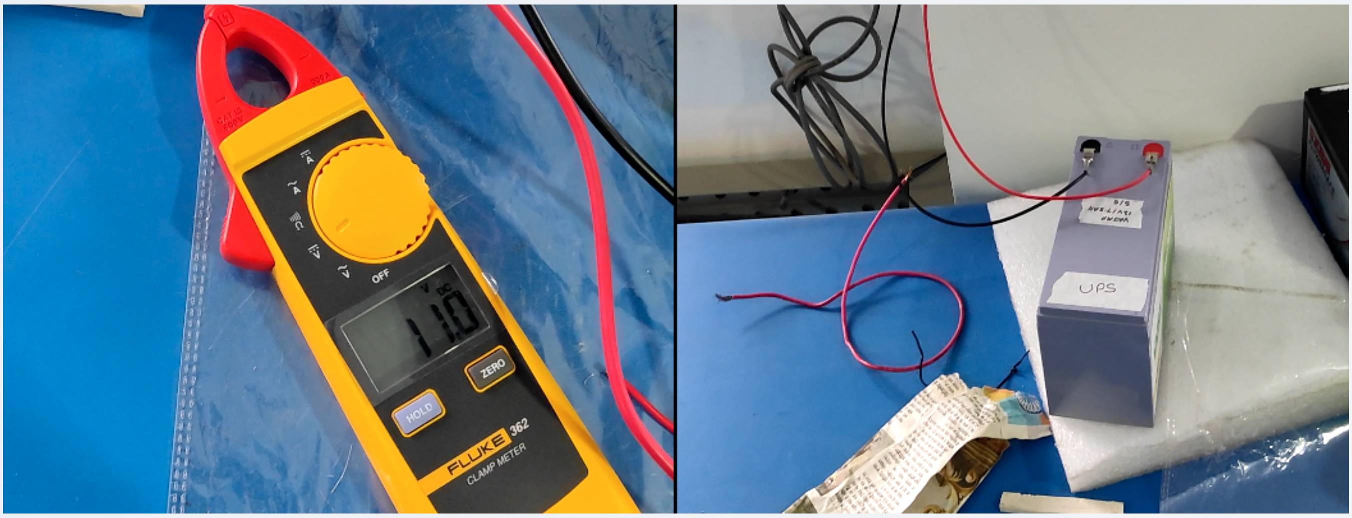


Figure 8: Test configuration for evaluating battery performance using a 12 V DC fan load, representing a small electromechanical appliance

The third application involved an agriculture spray pump - a device commonly used in small-scale farming operations. The pump operates at 12 V DC, produces a pressure of approximately 250 PSI, and typically draws a current in the range of 6–8 A during operation. This configuration represents a relatively higher load compared to the other devices and was included to evaluate the battery performance under moderate current demand. The setup used for the spray pump experiment is presented in Figure 9.

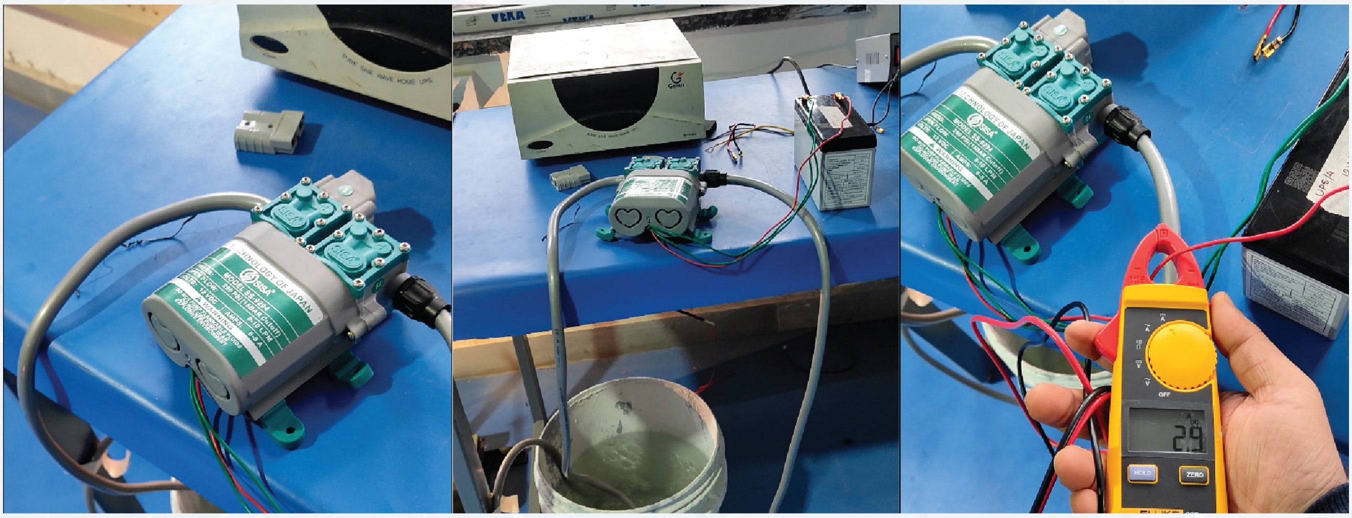


Figure 9: Experimental setup for testing battery discharge characteristics using a 12 V agricultural spray pump operating at approximately 250 PSI and 6–8 A current draw.

Finally, the fourth application involved a 650 VA UPS system that operates using a 12 V, 7 Ah battery configuration. The UPS normally functions within an input voltage range of 140–300 V AC at a frequency of 50 Hz and switches to battery backup during power outages. Testing the refurbished batteries within a UPS system provided insight into their ability to support short-duration but relatively higher power backup applications. The UPS test configuration is illustrated in Figure 10.

Figure 10: Test configuration of the 650 VA UPS used to assess the performance of refurbished lithium-ion batteries under backup power conditions.

During the experiments, both the lead-acid batteries and refurbished lithium-ion battery packs were connected to their respective loads and allowed to operate continuously until the battery reached its cutoff voltage. Key performance parameters, including discharge current, discharge duration, and temperature variation, were recorded throughout the testing process.

The primary purpose of this experimental setup was to subject the refurbished batteries to sustained operational loads and evaluate their performance relative to new lead-acid batteries under realistic conditions. Such stress testing provides valuable insights into the practical viability of second-life lithium-ion batteries for low-power energy storage applications.

6.2.2 Performance Testing and Comparison for Select Applications

The objective of this experimental analysis was to examine the operational behaviour of the refurbished battery packs under realistic load conditions and to determine their suitability for selected applications that commonly rely on small-scale energy storage.

The comparison between the refurbished lithium-ion battery pack and the lead- acid battery pack was carried out across three primary performance indicators:

- Discharge current profile during operation
- Discharge duration from full charge to complete discharge
- Thermal behaviour of the battery systems during operation.

These parameters were selected because they collectively provide insight into the electrical performance, energy delivery capability, and safety characteristics of the battery systems under practical operating conditions. All tests were conducted without the use of additional active or passive cooling mechanisms so that the intrinsic thermal behaviour of the battery systems could be observed.

6.2.2.1 Discharge Current Profile Across Applications

The discharge current drawn from the battery during operation was monitored for both battery chemistries across all selected applications. The results indicate that the discharge current profiles for the refurbished lithium-ion battery and the lead-acid battery were broadly similar across all applications. This observation is expected because the current demand is primarily governed by the electrical characteristics and power requirements of the connected load rather than the battery chemistry itself.

For each device, the load determined the current drawn from the battery system, resulting in comparable current curves for both battery types. This similarity in current profiles confirms that the refurbished lithium-ion battery packs are capable of delivering current levels required by these applications without exhibiting abnormal behaviour or instability.

The comparative discharge current profiles for both battery systems across the tested applications are illustrated in Figure 11.

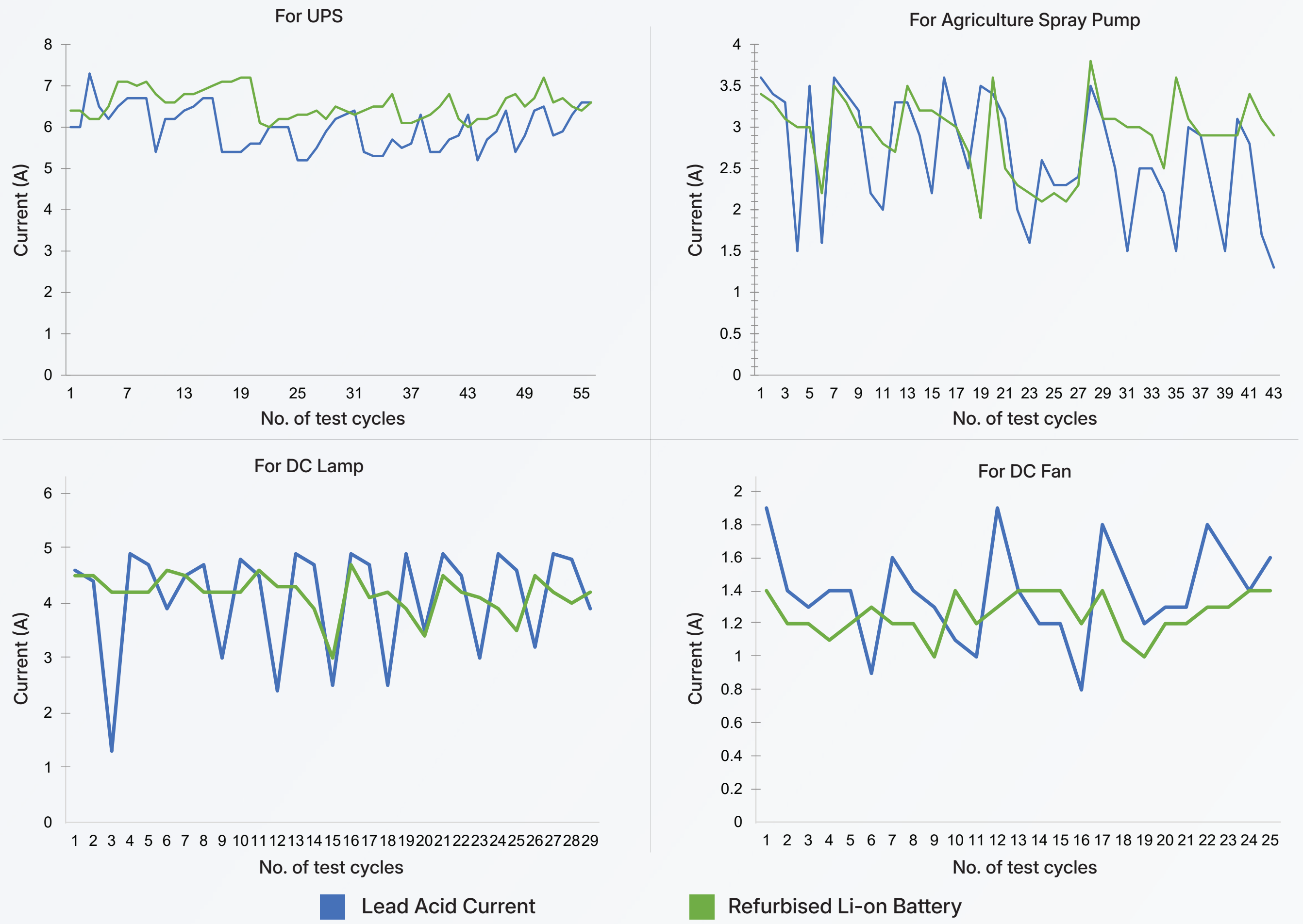


Figure 11: Comparison of discharge current profiles for lead-acid and refurbished lithium-ion battery packs across the selected applications

6.2.2.2 Discharge Duration Comparison

A key parameter in evaluating the suitability of refurbished batteries for second-life applications is the duration for which the battery can sustain the load before reaching its lower discharge limit. Therefore, a comparative analysis of discharge time was conducted for both battery types under identical load conditions.

The results demonstrate that in low-current, low-power applications such as the DC lamp, DC fan, and agriculture spray pump, the refurbished lithium-ion battery packs exhibited significantly longer discharge durations compared to the lead-acid batteries. This behaviour can be attributed to the higher usable energy density and improved discharge efficiency of lithium-ion chemistry, particularly under low-rate discharge conditions[83]. In contrast, lead-acid batteries often experience higher internal losses and reduced effective capacity when subjected to continuous discharge cycles.

For moderate-load conditions such as the UPS application, the difference between the two battery systems was less pronounced[84]; however, the refurbished lithium-ion battery still maintained a longer discharge duration across most of the cycles observed. This suggests that even under moderately demanding load conditions, refurbished lithium-ion batteries can provide performance that is at least comparable, and often superior, to conventional lead-acid systems. The comparative discharge duration results for the different applications are presented in Figure 12.

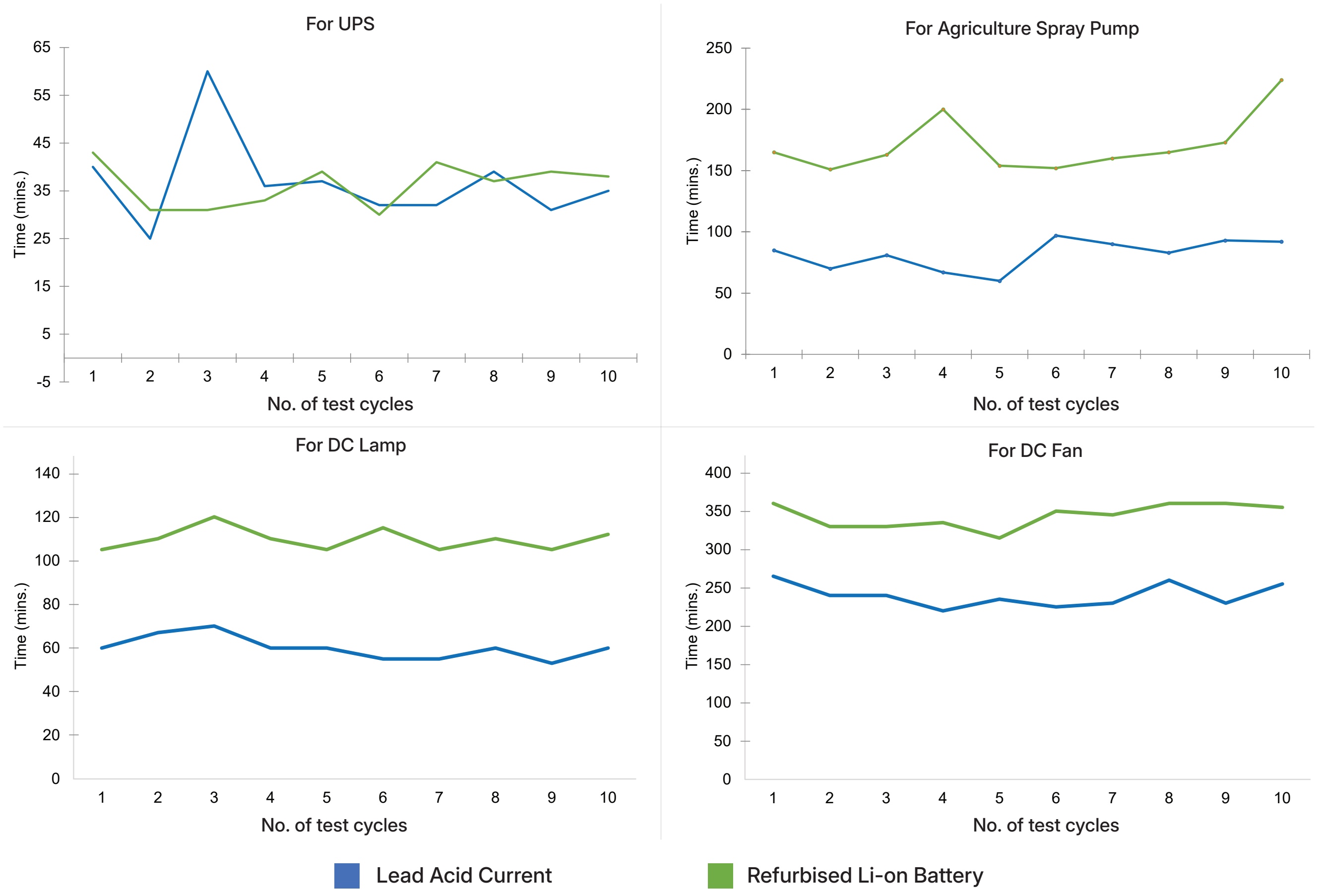


Figure 12: Comparative analysis of discharge duration between lead-acid and refurbished lithium-ion battery packs across the tested applications.

6.2.2.3 Temperature Profile and Thermal Behaviour

Thermal performance is an important factor in assessing the safety and reliability of battery systems. During the testing phase, the temperature of both battery systems was continuously monitored to evaluate thermal behaviour under operational loads.

The experimental observations indicate that the temperature rise was more pronounced for moderate current applications, particularly in the UPS configuration. In this case, the temperature of the refurbished lithium-ion battery pack reached approximately 44°C during operation. Although this temperature remains within the acceptable operating limits specified in the cell manufacturer's datasheet, sustained operation at elevated temperatures may influence long-term battery degradation and potentially impact operational life[61].

Consequently, it is important to ensure that appropriate safety mechanisms are incorporated into the battery system to prevent overheating. The inclusion of a BMS with thermal monitoring and protective cutoff functions is therefore essential to ensure safe operation in practical deployments.

For low current applications such as the DC lamp, fan, and agriculture spray pump, the temperature variation between the lead-acid and refurbished lithium-ion batteries was minimal. The thermal behaviour observed in these applications indicates that refurbished lithium-ion battery packs operate within safe temperature ranges when used in low-power systems. The comparative temperature profile and thermal behaviour for the different applications are presented in Figure 13.

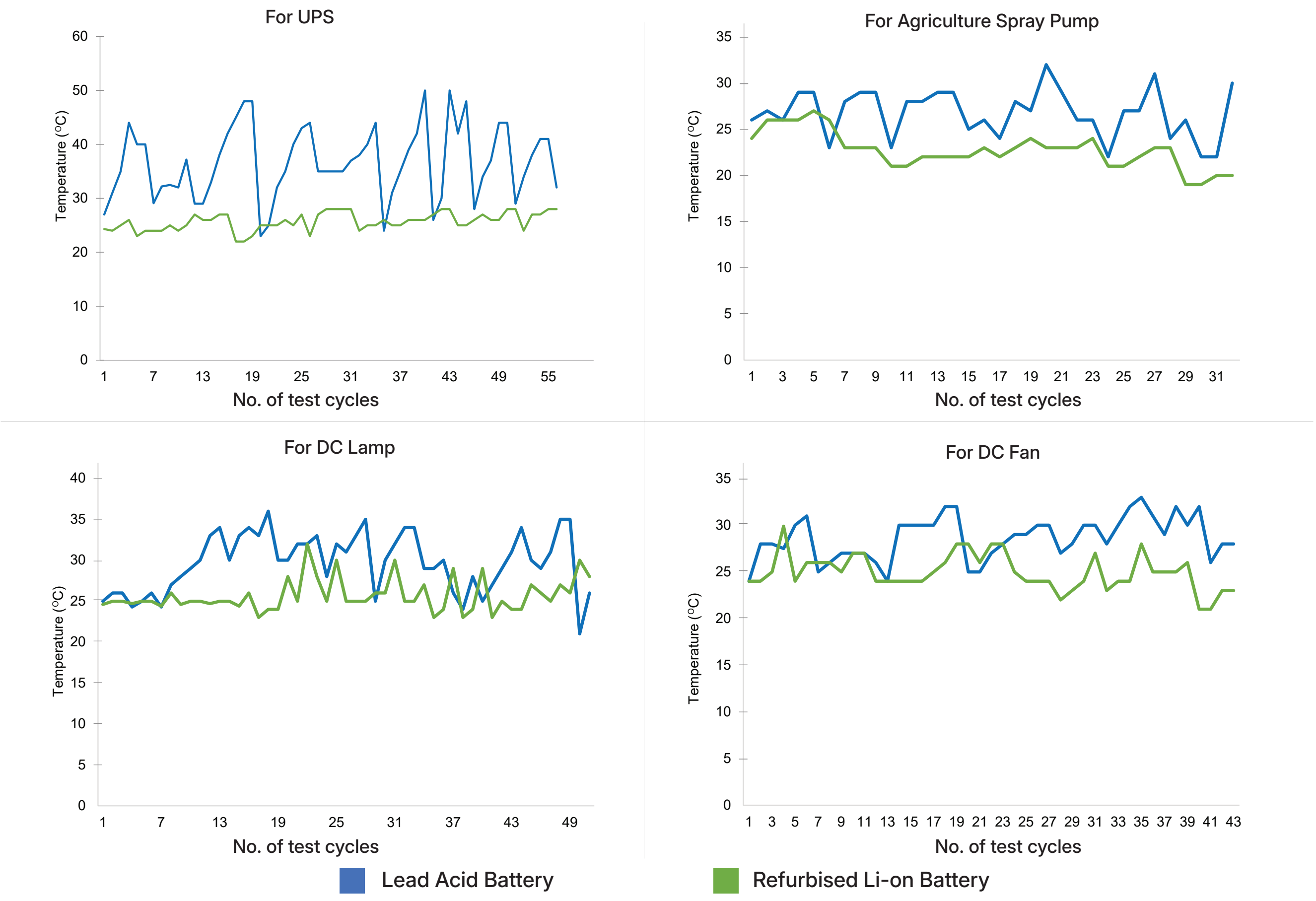
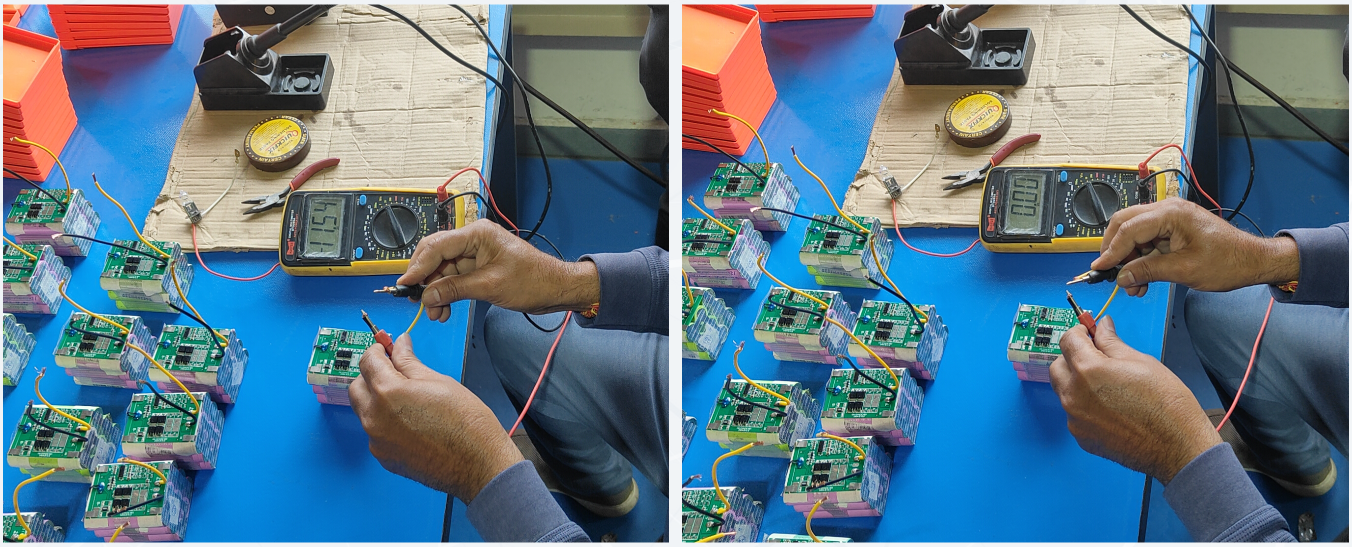


Figure 13: Analysis of the comparison of temperature between lead acid battery and refurbished lithium-ion battery.

6.2.3 Refurbished Battery Pack Safety Test

As part of the non-destructive testing process of refurbished batteries, the following procedures were conducted:

- Short circuit test: The objective of this test was to evaluate the stability and protective response of the circuit under short-circuit conditions. A voltmeter reading of 11.54 V was observed (see Figure 14) across the battery terminals at the start of the test. Subsequently, the two terminals were brought in contact via a copper wire to intentionally create a short circuit. At the moment of contact, the voltmeter reading immediately dropped to 0 V, as shown in Figure 14 (right). This instantaneous voltage collapse confirms that the BMS successfully interrupted the current flow after detecting the short circuit, thereby validating the effectiveness of the short-circuit protection mechanism.



Initial reading

Test reading

Figure 14: Short circuit test demonstration showcasing successful BMS cutoff.

- Voltage cutoff test: In this test, the refurbished battery was connected to the load (DC bulb) for discharging and the voltage was constantly monitored. As observed in Figure 15, upon reaching the minimum cutoff voltage (8.78 V), the BMS cuts the current flow, as evidenced by the minor residual voltage and load shut off. This prevents the battery from entering a deep discharge state.

Instance of Reaching minimum voltage

BMS Cutoff Successful - Load disconnected

Figure 15: Minimum voltage cutoff demonstration showcasing successful BMS cutoff.

6.2.4 Summary of Experimental Results

The experimental evaluation carried out provides important insights into the operational performance and feasibility of deploying refurbished lithium-ion battery packs in low-power applications. The refurbished lithium-ion battery packs consistently performed equal to or better than the lead-acid battery systems across the selected applications. One of the key observations from the testing was that the discharge current profiles for both battery chemistries were largely similar across the tested loads. The refurbished lithium-ion batteries were able to reliably meet the current requirements of all tested loads without any operational instability.

A more significant difference was observed in the discharge duration of the batteries. In low-power applications such as the DC lamp, DC fan, and agriculture spray pump, the refurbished lithium-ion battery packs demonstrated longer discharge times compared to the lead-acid batteries. This improved performance can be attributed to the higher usable energy density and superior discharge efficiency of lithium-ion cells, particularly under low-rate discharge conditions. Even in the moderately demanding UPS application, the refurbished battery packs provided comparable or slightly improved operational duration relative to the lead-acid systems.

Thermal performance analysis also revealed that the refurbished lithium-ion batteries operated within safe temperature limits during the testing phase. Although a moderate temperature rise was observed in the UPS application due to moderately higher current demand, the recorded temperatures remained within the acceptable operational limits specified by the cell manufacturer. In low current applications such as lighting, fan operation, and the spray pump, the temperature profiles of the lithium-ion and lead-acid batteries were largely comparable, indicating stable and safe operation under such load conditions.

Taken together, these findings suggest that refurbished lithium-ion batteries derived from EoL EV battery packs can effectively replace lead-acid batteries in a wide range of low-power applications. From a broader perspective, the successful demonstration of refurbished battery performance in these applications highlights the emergence of a significant secondary market opportunity. Many low-power devices currently rely heavily on lead-acid batteries due to their low upfront cost and widespread availability. However, lead-acid battery manufacturing and disposal processes are associated with considerable environmental impacts, including lead contamination risks and energy-intensive production processes[85]. By contrast, repurposing lithium-ion batteries that have already completed their first life in EVs can extend the useful life of these materials and reduce the need for additional battery manufacturing.

Therefore, the deployment of refurbished lithium-ion batteries in low-power applications presents a dual advantage. On one hand, it provides a technically viable alternative to conventional lead-acid batteries. On the other hand, it supports circular economy principles by maximising resource utilisation and reducing the environmental footprint associated with new battery production and disposal.

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Future Research Directions

Although this study has underscored the rationale for refurbishing EoL EV batteries and has demonstrated the approach for low-power energy storage applications, there are still several aspects that require detailed examination to establish its viability and scalability. First, there is a need to conduct an economic comparison among refurbished batteries, new lithium-ion batteries, and lead-acid batteries with nearly similar energy capacity for these low-power applications. The cost of refurbished batteries should account for all key components such as the cost of procuring EoL batteries, logistics, dismantling, testing, reassembly, and more. The results of this techno-economic analysis will provide clarity on the market competitiveness of the refurbished battery packs.

Second, there is a need to explore the technical feasibility of incorporating different lithium-ion cells varying in chemistry, energy capacity, and form factors in refurbished battery packs. As time progresses, refurbishers will face an increasingly varied supply of EoL batteries, and there is a need to explore the usage of these in refurbished battery packs to ensure economic prudence while simultaneously ensuring the safety and longevity of the battery packs. Third, there is a need to develop mechanisms to quantify the Remaining Useful Life (RUL) of the refurbished battery packs. Although the current study demonstrated the immediate performance of refurbished battery packs in terms of discharge duration, current delivery, and thermal behaviour, there is a need to gauge their long-term performance in order to ensure market acceptability. These studies should be able to identify the RUL for refurbished batteries, with or without life cycle usage data in place, and at a fast pace for acceptance by the refurbishers. The RUL assessment is also important from an economic standpoint. If the RUL of refurbished battery packs is an order of magnitude higher than that of lead-acid batteries, then even a slightly higher price of refurbished battery packs will be justified. This is due to the fact that frequent replacements with lead-acid batteries will be avoided, ensuring that the total cost of ownership is significantly cheaper for the end users.

Finally, building on the RUL quantification, there is a need to ensure that this assessment is carried out while taking into account the real-life usage of the refurbished batteries. This is important as there has been a stark contrast seen in the laboratory testing of EV batteries, where they are forced with continuous charge-discharge cycles, and the real-life usage, which involves short discharge periods followed by extended rest intervals that allow batteries to recuperate, thereby optimising battery life[86]. Addressing these areas will be critical in developing a robust technical, economic, and regulatory framework for second-life lithium-ion batteries.

08

Conclusion

This paper aimed to explore the potential of refurbishing EoL EV batteries in low-power energy storage applications. An electric two-wheeler EoL battery was used to demonstrate the refurbishment methodology encompassing visual inspection, dismantling, electrochemical testing, grading, and repackaging of viable cells into battery packs. Further, a detailed operational comparison was carried out between refurbished battery packs and lead acid batteries with nearly the same form factor and energy capacity across multiple applications. These include a DC fan, a DC lamp, an agriculture spray pump and a small UPS system.

It was observed that the refurbished lithium-ion battery packs performed better than the lead acid counterpart across all applications. These refurbished battery packs showcased more usable energy capacity, leading to extended discharge duration while being within acceptable thermal limits. Clearly, the refurbished batteries present themselves as a superior alternative to lead acid batteries across low-power energy storage applications. Add to this, the refurbished batteries offer several environmental benefits ranging from extending the life of lithium-ion batteries before recycling, avoiding the mining of new minerals to manufacture batteries for low-power energy storage applications, while creating an opportunity to steer away from conventional lead-acid systems and their associated harmful impacts.

Still, for battery refurbishment to be mainstreamed, there is an urgent need to create a conducive ecosystem that acknowledges its benefits in the first place. Currently, as the EV batteries reach their EoL, a large part of these batteries is considered for recycling. This highlights the importance of increasing accountability at the recycler's end, necessitating justification for recycling instead of refurbishment. Similarly, the Extended Producer Responsibility (EPR) framework should equally focus on refurbishment along with recycling pathways. This, in turn, will lead to manufacturers exploring battery designs suitable for refurbishment.

Another key challenge highlighted in the paper revolves around the lack of standards and guidelines for the refurbishment of EoL battery packs. Apart from UL 1974, there is no standard in place to provide guidance, creating ambiguity in this evolving sector. And for refurbishers to comply with UL 1974 is cost and labor-intensive, requiring more nuanced standards to be put in place, keeping safety and cost efficiency at the center. Finally, the lack of availability of usage data of EoL batteries for refurbishers is another major constraint. This lack of data inhibits the refurbishers in assessing the SoH of the EoL battery packs, which can assist them in making quick decisions around refurbishment. A few emerging initiatives, such as the European Union's battery passport and India's Draft Battery Pack Aadhar guidelines, are a right step in this direction. Once these critical aspects are addressed, battery refurbishment can become an important pillar of the circular battery economy in India.

09

Annexures

Annexure 1

Product Name: Lithium Ion Battery NCR18650BD

Item	Specification	Notes
Rated Capacity	3000 mAh	0.61 A discharge at 20°C
Capacity (Minimum)	3080 mAh	0.61 A discharge at 25°C
Capacity (Typical)	3180 mAh	Reference only, 0.61 A discharge at 25°C
Nominal Voltage	3.60 V	0.61 A discharge at 25°C
Discharging End Voltage	2.5 V	—
Charging Current (Std.)	0.9 A	Max. 1.5 A
Charging Voltage	4.20 ± 0.03 V	—
Charging Time (Std.)	8.0 hours	—
Continuous Discharging Current (Max.)	10:00 AM	0 ~ +40°C
Internal Resistance	< 35 mΩ	AC impedance 1 kHz
Weight	< 49 g	—
Operating Temperature (Charge)	10 ~ +45°C	—
Operating Temperature (Discharge)	−20 ~ +60°C	—
Storage Conditions (< 1 month)	−20 ~ +50°C	Percentage of recoverable capacity
Storage Conditions (< 3 months)	−20 ~ +40°C	—
Storage Conditions (< 1 year)	−20 ~ +20°C	80% recoverable capacity

Annexure 2

Product Name: DNA Cell grading machine 5V 6A 512Ch

Parameter	Specification
Channel quantity	Up to 512 channels
Communication method	RS485
Input power	Three-phase four-wire system AC390V±3%, 50Hz
Max. output power	< 27KW
COMPATIBLE CELL SIZES:	18650, 21700, 26650, 32700, 33140 & 34189
Continuous cycle range	1-999 times
Sleep time setting range	1-720 minutes
Time measurement resolution	1S
Type	Linear

Annexure 3

Product Name: BT-1810 cell sorting machine

Parameter	Specification
Power	AC220V 50/60HZ 1.6KW
Air pressure	0.4-0.8 Mpa, no water, no impurities
Battery cell range	14430/14500/18500/18650/21700/26650/26700/32650/32700
Standard IR test	HK3560
Optional tester	HIOKI3561/HIOKI2562/HK3561
Efficiency	About 5000pcs/h
Control device	PLC Touch screen control
Run power	Stepper motor
Voltage setting	0.00000V-6.0000V
Internal resistance	000.00mΩ-999.99mΩ
Channel	8-16 OK,1NG
Test data	U disk storage, can be copied to the computer
Communication interface	RS485
Test method	4-wire system
Test pin	DZ100-214A30G
Dimensions	L1100*W930*H1390MM/ L2260*W930*H1390MM
Weight	About 110/160KG
Usage	Coin Cell Test
Warranty	2 Years

Endnotes

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Notes

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