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Application and Recycling of Lithium-ion Batteries

Junhan Zhang*

School of Wuhan Institute of Technology, Wuhan, China

**Corresponding author: Junhan Zhang.*

Abstract

In recent years, the large-scale utilization of renewable energy sources, along with clean and low-carbon conventional energy, has emerged as a fundamental trend shaping the future of global energy development. As a critical enabling technology, lithium-ion batteries are increasingly important in advancing renewable energy integration across multiple sectors. This paper provides a comprehensive overview of lithium-ion battery applications, focusing on their use in energy storage systems for power grids and wind power generation, which are vital for balancing supply and demand and enhancing system stability. Furthermore, the paper highlights the growing importance of lithium-ion battery recycling and recovery technologies, addressing environmental sustainability and resource-efficiency challenges associated with battery lifecycles. By exploring these aspects, the study aims to contribute valuable insights into the sustainable deployment and management of lithium-ion batteries within the evolving energy landscape.

Keywords

lithium-ion battery, recycling, power systems

1. Introduction

With growing environmental awareness and the continued rise in global energy demand, large-scale use of renewable energy has become a fundamental trend in future energy development. In recent years, there has been a surge in research on sustainable energy sources, including wind, solar, tidal, and geothermal. Still, their intermittent and uncontrollable nature cannot meet the needs of large-scale applications. Lithium-ion batteries have the advantages of no memory effect, long cycle life, and low self-discharge, and their applicability is much higher than that of other renewable energy sources. For example, Huang Rui et al. [1] studied the development and application of a teaching platform for lithium-ion battery thermal runaway experiments. Shi Ying's research on electrode interface control and structural design of flexible lithium-ion batteries [2]. Ding Xiaobo et al. discussed the research on fast-charging graphite anodes of lithium-ion batteries [3]. This paper primarily discusses the application of lithium-ion batteries in energy storage for power generation systems and new energy vehicles. In addition, lithium-ion battery recycling is indispensable. A combination of hydrometallurgy and pyrometallurgy is the primary recovery method. Hydrometallurgical solutions are used to extract and separate metals from batteries; pyrometallurgy uses heat to convert metal oxides in battery materials into metals or compounds.

2. Applications of Lithium-ion Battery

2.1 Application in Power Generation Systems

Electrochemical energy storage devices include lead-acid batteries, sodium-sulfur batteries, vanadium flow batteries, and lithium-ion batteries. Each of these electrochemical energy storage batteries has its advantages and disadvantages. In terms of comprehensive performance, lithium-ion batteries currently offer high energy density and environmental friendliness. Application scenarios include the power generation side, the user side, and the grid side; the application modes mainly include various types of energy storage power stations and a variety of energy storage devices. The application of lithium-ion battery energy storage technology in power generation mainly includes wind/solar energy storage power stations, optical storage and charging integrated power stations, and emergency power supplies on the user side. Chen Yongchong [4] from the Institute of Electrical Engineering of the Chinese Academy of Sciences pointed out that when it is used for frequency modulation or smoothing the fluctuation of new energy, power batteries that can be charged and discharged quickly are generally used; When used for peak shaving and photovoltaic energy storage, capacity-based batteries that can be charged and discharged for a long time are generally used; when both frequency and peak regulation are required, energy-based batteries are used.

The rice transplanter equipped with lithium-ion battery energy storage technology utilizes clean energy generated from wind power, enabling efficient energy utilization and flexible distribution through its advanced storage capabilities. Lithium-ion batteries can respond rapidly to fluctuations in wind speed, thereby smoothing power output and mitigating the intermittency of wind power generation on the grid. The integration of lithium-ion battery storage into wind power systems has demonstrated significant benefits, offering high potential for broad adoption and application. This approach improves the overall efficiency of renewable energy systems [5]. Shi et al. [6] proposed segmenting the battery's open-circuit voltage (OCV) and state-of-charge (SOC) curves to determine the SOC differences among individual cells before balancing. Building on traditional voltage-balancing strategies, Yang et al. [7] proposed incorporating compensation for ohmic voltage drops to delay system shutdown and thereby improve overall balancing performance.

The emergency power supply can be used for short-term power supply and for stable power supply to ensure the system's power supply quality during system maintenance and emergency problem handling. Starting with a stable power supply, we create a backup power supply system, introduce an emergency power supply, and improve the continuity of the DC power supply. In the standby power supply system, the battery plays a key role. It should exhibit strong high-temperature resistance, stable power transmission, a long service life, and a high discharge depth to ensure the quality of the emergency power supply. Mobile batteries should be equipped with protection features to prevent loss of storage capacity caused by battery placement. To conserve energy and reduce electricity consumption, strengthen battery maintenance. The introduction of ternary batteries can effectively reduce the number of batteries used. Ternary batteries can be used in substations with a high O&M radius and many stations to effectively improve the power grid's operational quality and efficiency, given their smaller scale and stable power supply capacity [8]. The energy storage module uses a forced-air-cooled thermal management system. As airflow passes through the energy storage module, a significant pressure drop occurs, with the high-temperature regions concentrated in the middle and rear sections of the flow channel [9].

2.2 Application in New Energy Vehicles

New energy vehicles (NEVs) have become a mainstream product and a core trend in the future automotive market, supported by a variety of advanced technologies. High-energy-density batteries play a vital role in extending vehicle range, with lithium-ion batteries standing out for their superior energy density. Among the various battery types used in NEVs, lithium-ion batteries have the second-highest energy density, second only to lithium polymer batteries. It is significantly higher than those of nickel-metal hydride, sodium-ion, and lead-acid batteries. However, lithium-polymer batteries face limitations due to high cost and complex manufacturing, which restricts their widespread application. In contrast, lithium-ion batteries use a bidirectional discharge mode to deliver higher energy output, effectively improving both vehicle range and energy storage capacity [10].

Lithium-ion batteries offer additional advantages such as being non-polluting, fast-charging, high-voltage, long-lasting, and energy-dense, making them highly suitable for use as power batteries in NEVs. Nevertheless, it is crucial to protect against overcharging to avoid safety hazards. The widespread application of lithium-ion batteries still faces challenges, including limited lithium resources, safety risks, temperature sensitivity, and technical limitations [11]. As noted by Zhu Yiding, spontaneous combustion remains a key concern. A comprehensive approach involving charge-discharge control, temperature management, safety protection mechanisms, structural optimization, quality control, and routine maintenance is essential to ensure the safety and reliability of lithium-ion batteries [12].

Li Zhe and colleagues explored immersive cooling technologies for lithium-ion batteries, highlighting the high thermal management efficiency and temperature uniformity of immersion cooling systems [13]. Existing studies on immersion cooling mostly focus on single-fluid conditions, and comparative research on different immersion fluids is lacking. Immersion liquids can effectively suppress thermal runaway and provide greater safety than traditional indirect liquid cooling, air cooling, and phase-change cooling systems. However, immersion liquids may pose corrosion risks, potentially shortening battery life. Future research should aim to develop new immersion fluids that enhance both system safety and battery longevity. Although two-phase (liquid-gas) systems offer excellent cooling performance, they are relatively complex and expensive. In contrast, single-phase immersion liquids demonstrate better performance, compact structure, and lower maintenance costs.

Tan Birong and colleagues developed a lithium-ion battery testing platform, using the FreedomCAR Power-Assist Battery Test Manual as a reference. The platform includes HPPC tests and open circuit voltage (OCV) tests, with discharge motors, temperature-humidity chambers, and battery packs used to record thermal data. Based on this, they built a second-order RC equivalent circuit model and identified the model parameters, including ohmic resistance and polarization parameters, using the least-squares method. OCV was calculated as the average during full charge/discharge at specific temperature and State of Charge (SOC) points.

To account for temperature effects, a temperature-corrected equivalent circuit model was developed. Polynomial fitting revealed that ohmic resistance (R0), polarization resistance (R1), and capacitances (C1, C2) are temperature-dependent. R0 was interpolated across temperature and SOC points, while R1, C1, and C2 were fitted using polynomial regression to generate lookup tables, significantly reducing computational time and enhancing real-time performance. Verification was conducted under constant current discharge at –5°C, 15°C, and 35°C, and non-constant current discharge at –10°C, 10°C, and 25°C. The absolute error between actual and modeled voltages was mostly within ±50 mV, confirming the model's accuracy across temperatures.

To improve SOC (State of Charge) estimation accuracy, an improved adaptive Extended Kalman Filter (EKF) algorithm was proposed. Since the model and measurement noise distributions are dynamic, the researchers designed a variable-window noise estimator that adapts to the error distribution. Integrating this estimator with the adaptive Extended Kalman Filter (EKF) improves the precision of state-of-charge (SOC) estimation.

Final validation using DST data at 5°C, 15°C, and 35°C showed that the improved algorithm significantly outperformed standard EKF approaches, confirming its effectiveness. Given the complexity of real-world battery operating conditions, further research under diverse practical scenarios is recommended.

2.3 Advantages and Limitations of Lithium-ion Batteries

Lithium-ion batteries offer a range of technical advantages that make them highly suitable for deployment in new energy vehicles (NEVs). A primary strength lies in their high energy density, which enables compact battery design and extended driving ranges—critical attributes for modern electric mobility. In addition, these systems exhibit exceptional electrochemical performance, including rapid charging, high operating voltage, long cycle life, and non-polluting operation. These qualities have positioned lithium-ion batteries as a foundational technology in the NEV sector.

Advances in thermal management have further enhanced their operational reliability. In particular, single-phase immersion cooling technologies have demonstrated effective temperature control, offering a more compact system design and lower maintenance requirements than conventional cooling methods. At the same time, immersion fluids contribute to safety by effectively suppressing thermal runaway propagation, thereby mitigating the risk of cell-to-cell failure cascades. From a systems modeling perspective, integrating a temperature-compensated equivalent circuit model with an improved Adaptive Extended Kalman Filter (EKF) algorithm has significantly improved the accuracy of state-of-charge (SOC) estimation under varying thermal conditions. Comparative assessments indicate that this improved EKF approach outperforms traditional methods across different operating temperatures, including –5°C, 15°C, and 35°C.

Despite these advantages, several challenges continue to hinder the widespread adoption and scalability of lithium-ion battery systems. High manufacturing costs and complex fabrication processes, especially for lithium polymer batteries, remain significant barriers. Additionally, resource constraints pose a long-term limitation, as the projected global demand for lithium may soon outpace the availability of proven reserves, necessitating the development of alternative chemistries and more efficient recycling systems.

Safety risks, including spontaneous flammability, require multifaceted mitigation strategies, while temperature sensitivity remains a critical performance issue. Significant capacity degradation has been observed under both low and high-temperature conditions, underscoring the need for precise temperature management systems. Moreover, while immersion cooling improves thermal regulation, it introduces material compatibility concerns, as prolonged exposure to dielectric fluids can induce corrosion on metallic components, potentially shortening battery lifespan.

Finally, two-phase immersion cooling systems, though capable of delivering superior heat flux, also present constraints. These include increased capital costs and added complexity in pressure regulation and system design, which can impede their practical implementation at scale.

3. Recycling of Lithium-ion Batteries

The traditional recovery of lithium ions mainly includes fire recovery, wet recovery, and biological recovery. Pyrometry is the use of roasting to convert cathode materials into metals and transition-metal oxides, with the advantages of simple operation, broad applicability, and high energy efficiency. Reducing the roasting temperature is the key to controlling energy consumption. The biological leaching method uses microorganisms such as fungi and acidophilic bacteria as leaching agents, with Fe^{2+} and S as energy sources. The microbial leaching system involves biological oxidation metabolism to dissolve insoluble metal components into water-soluble forms. Wet recycling is also one method for obtaining valuable metal-ion solutions from waste cathode materials. The cathode material is leached with a specific solution that dissolves the valuable metal as ionic species, and the metal ions are then separated and purified through a series of operations [13]. Yu Yezhe also proposed the application of cobalt ferrite materials recovered from waste lithium-ion batteries, taking waste lithium-ion batteries as the research object, through discharge-disassembly, cathode active material separation, cobalt-efficient leaching, cobalt ferrite preparation, cobalt ferrite catalytic activation, PMS degradation of RhB, etc. [14]. Zhang Qianyu et al. also studied the recovery of LTO anode materials using the organic solvent immersion method. They found that pure LTO can be obtained by adding an appropriate amount of a lithium source after carbon removal, followed by calcination and high-temperature synthesis [15]. Zheng Rujuan also proposed that for the recycling of waste lithium iron phosphate batteries, the main method is to use a saturated sodium chloride conductive solution to soak in acid dissolution and liquid dissolution for small lithium-ion batteries. It is difficult to dissolve the active substance during acid dissolution. The carbon oxidation of the surface coating of the active substance can be removed by heat-treating the binder [16].

The recycling of lithium-ion batteries has become indispensable for resource sustainability and environmental protection. Three principal recovery technologies—pyrometallurgical, hydrometallurgical, and bioleaching—offer distinct methodologies, each with specific advantages and inherent limitations.

Pyrometallurgical recovery, based on high-temperature smelting, effectively processes diverse metal-bearing wastes to recover valuable metals such as nickel, cobalt, and copper. It is an established, straightforward process that ensures high recovery rates. However, it is notably energy-intensive, costly, and environmentally burdensome due to harmful emissions. Additionally, lithium recovery is inefficient since lithium compounds tend to remain as stable oxides, limiting direct extraction.

Hydrometallurgical recovery involves chemical leaching followed by separation techniques to dissolve and isolate metals, including lithium, with high purity. Operating at lower temperatures makes it more energy-efficient and environmentally preferable than pyrometallurgy. Its adaptability allows optimization through various reagents and conditions. Nonetheless, reliance on chemical agents poses risks of secondary pollution, and the complexity of the process necessitates rigorous management of waste streams to mitigate environmental impact.

Bioleaching uses microorganisms to solubilize metals, minimizing chemical and energy inputs. This eco-friendly method is particularly suited for low-grade or complex materials and may reduce operational costs through microbial self-propagation. Yet, its slow kinetics, sensitivity to environmental factors, and inconsistent recovery rates present challenges. Moreover, microbial metabolism can generate secondary pollutants, complicating large-scale application.

Current trends favor sustainable recycling approaches aligned with circular-economy principles and carbon-neutrality targets. While pyrometallurgy remains widely used, concerns over energy consumption and emissions are prompting increased adoption of hydrometallurgical and bioleaching methods. Innovations in hydrometallurgy focus on green solvents and benign leaching agents, whereas bioleaching holds promise for strategic metal recovery with a lower environmental footprint.

Integrated strategies combining these technologies are emerging to maximize recovery efficiency and minimize ecological impact. Enhanced safety measures and material reuse optimization will further strengthen the sustainable recycling value chain, ultimately mitigating resource depletion and environmental harm. In conclusion, advancing lithium-ion battery recycling demands balanced innovation—integrating technological maturity with ecological responsibility—to efficiently and sustainably secure critical metal resources.

4. Conclusion

Lithium-ion battery systems play a pivotal role in advancing new energy vehicles, offering a suite of technical advantages that make them highly suitable for modern electric propulsion. Foremost among these is their high energy density, which provides a strong foundation for extended driving ranges and compact system integration. Coupled with excellent electrochemical characteristics—including rapid charging capabilities, elevated operating voltages, and extended cycle life exceeding 2,000 cycles at 80% depth-of-discharge—these batteries align well with the rigorous demands of sustainable transportation. In addition, their environmentally benign operation, marked by zero local emissions, further enhances their suitability for clean mobility solutions.

Despite these advances, several critical challenges must be addressed before lithium-ion batteries can achieve widespread scalability and resilience in NEV applications. High manufacturing costs remain a major barrier, especially for polymer-based lithium batteries, which still incur significantly higher production costs compared to conventional lithium-ion chemistries. In parallel, resource sustainability poses long-term concerns, as projected lithium demand (2.4 Mt LCE by 2030) is quickly approaching the limit of known global reserves. This underscores the urgency of developing closed-loop recycling systems and alternative cathode materials.

In summary, lithium-ion battery systems continue to evolve as the backbone of NEV electrification, offering high performance and robust safety under increasingly demanding operating conditions. Yet, overcoming economic, thermal, and material integration challenges remains essential to fully unlocking their potential. Addressing these barriers through multidisciplinary innovations in materials science, systems engineering, and policy coordination will be critical to ensuring the sustainable and scalable deployment of lithium-ion technologies in the future of mobility.

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Conflicts of Interest

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