Systematic Analysis on Power Battery Technology for New Energy Vehicles

Hengyan Ye *

College of Urban Rail Transit and Logistics, Beijing Union University, Beijing, 100020, China

* Corresponding Author Email: yehengyan@bjlhdxwmh.wecom.work

Abstract. With the global drive toward carbon neutrality and the rapid expansion of the new energy vehicle (NEV) industry, power batteries—as the core energy storage component of NEVs—directly dictate critical performance metrics such as driving range, safety, and cost, making them a pivotal focus of technological innovation. Currently, lithium-ion batteries are taking the market lead and ternary lithium batteries and lithium iron phosphate batteries stand out as two technical routes. However, in spite of the benefits they possess, including enhanced safety and higher energy density, there is still too much headway for solid-state batteries, such as low density and high raw material price. Future developments will prioritize enhanced fast-charging capacity, improved design of batteries, establishment of a sustainable closed-loop recycled-battery supply chain, and the acceleration of solid-state batteries going into practical use. In this paper, synthesize the current situation and major challenges of mainstream power battery technologies and predict some future research trends in order to serve as an aid for further related study and research and industrial application.

Keywords: NEVs; Power Battery Technology; Lithium-Ion Batteries.

1. Introduction

With global efforts toward carbon neutrality, the NEV industry saw tremendous expansion recently and became the main force of worldwide automotive industry transformation [1]. NEVs' performance, cost and safety are all limited greatly due to the power battery technology, which is essentially important. With higher demands of consumers on driving range, quick charging, low price and strict restrictions of laws and regulations, the high-performance power battery technology is a matter of urgency to break down the bottleneck of industrial development [2].

Power battery technology research has considerable significance in both practical and strategic values. Practically speaking, it helps to enhance NEVs performance, reduce NEVs' manufacturing and usage costs, promote NEVs penetration into the market, and speed up the substitution of traditional internal combustion engine vehicle applications. Strategically speaking, it can enable a country to have an edge over competitors in the NEVs and energy storage domains around the world, thereby driving long-term carbon emission reduction goals towards reality [3].

Regarding the state of domestic and foreign studies. Foreign institutions focus on solid-state battery and advanced battery material research, achieving significant advances in energy density and safety; domestically, substantial progress has been made with the industrialization of lithium-ion batteries such as LiFePO4 batteries and construction of battery recycling systems, however, challenges remain: unstable raw material supply and insufficient development in top-end battery materials requiring further study [4].

The article is written in an orderly style: Chapter 2 reviews main stream power battery technical routes and characteristics; Chapter 3 analyses important problems in current power battery technology, explores the development trend of power battery technology in the next generation of automobiles, summarizes the whole study in chapter 4, which gives a reference for related research work and industry practice.

2. Energy Supply Principle and Classification of Power Batteries

2.1. Electrochemical Principle of Power Batteries

The core function of power batteries relies on reversible electrochemical reactions to realize energy conversion and storage, with the reaction process centered on the migration and redox of active ions. Taking the widely used lithium-ion system as an example, the battery consists of a positive electrode (lithium-containing oxide, e.g., $LiFePO_4$), negative electrode (carbon-based material, e.g., graphite), electrolyte (lithium salt dissolved in organic solvent), and separator (porous insulating membrane). During charging, the external power source drives electrons to flow from the positive electrode to the negative electrode through the external circuit; simultaneously, lithium ions (Li^+) are deintercalated from the positive electrode material, dissolve into the electrolyte, and migrate through the separator's pores to the negative electrode, where they are intercalated into the graphite lattice and form a stable complex—this process converts electrical energy into chemical energy [5]. Schematic diagram of the electrochemical charging and discharging process of power batteries is shown in Fig. 1.

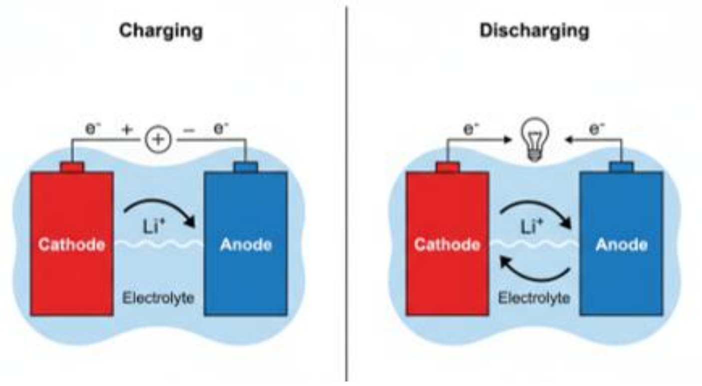

Fig. 1 Electrochemical charging and discharging process of power batteries [5]

During discharging, the reverse reaction occurs: Li^+ are deintercalated from the negative electrode, migrate back to the positive electrode, and electrons flow through the external circuit to the positive electrode to form a current, converting chemical energy into electrical energy. This cyclic "ion migration-redox reaction" is the fundamental electrochemical mechanism supporting power battery operation, and the reversibility and reaction rate of the process directly determine battery performance.

2.2. Main Classifications of Power Batteries

Currently popular power batteries are distinguished by different electrode materials and electrolyte forms, each having their own characteristics suitable for certain usage situations. Structural comparison of three mainstream power battery types: lithium-ion (liquid electrolyte), solid-state (all-solid components), and sodium-ion (Na^+ charge carriers) is shown in Fig. 2.

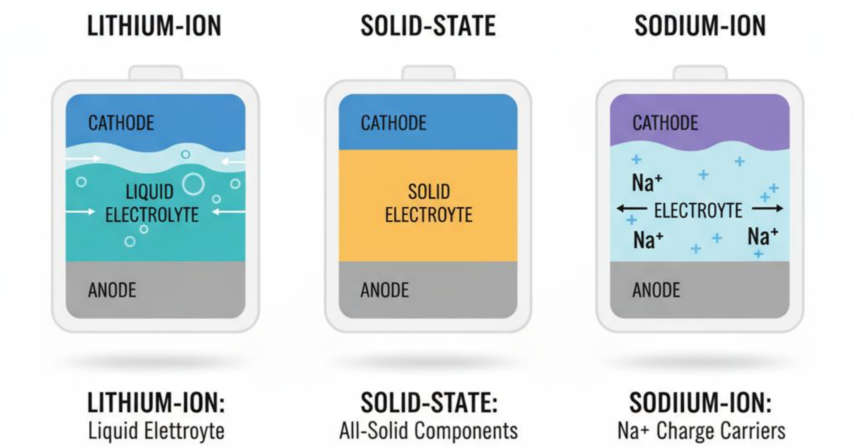

Fig. 2 Structural comparison of three mainstream power battery types [6].

The most mature and widely used is the lithium-ion battery: it has a balanced performance in energy density (150-300 Wh/kg), cycle life (1000-3000 cycles), and safety, with variants like lithium iron phosphate batteries (high safety, low cost, suitable for commercial vehicles) and ternary lithium batteries (high energy density, suitable for passenger vehicles); however, it relies on liquid electrolytes, which pose risks of leakage or thermal runaway under extreme conditions. Solid-state batteries, as a next-generation technology, replace liquid electrolytes with solid electrolytes (e.g., oxide, sulfide materials): they eliminate electrolyte leakage risks, improve thermal stability, and have a theoretical energy density exceeding 400 Wh/kg, but currently face challenges such as high preparation costs and low room-temperature ion conductivity. Sodium-ion batteries, which use sodium ions (Na^+) instead of Li^+ as charge carriers, have advantages in raw material availability (sodium is abundant in seawater and salt mines) and cost (30%-50% lower than lithium-ion batteries); their cycle life (800-2000 cycles) and low-temperature performance are comparable to lithium-ion batteries, but their energy density (100-180 Wh/kg) is relatively low, limiting their application in long-range vehicles [6].

2.3. Performance Comparison

From the perspective of cost, sodium-ion batteries have the most obvious advantage due to abundant sodium resources and low-cost electrode materials (e.g., Prussian blue analogs), with a single-cell cost about 20%-40% lower than lithium-ion batteries; lithium-ion batteries benefit from large-scale production, with costs stable at \ (100-150/kWh; solid-state batteries are still in the R&D and small-batch trial stage, with costs as high as \)500-800/kWh due to expensive solid electrolyte materials and complex manufacturing processes. In terms of efficiency, solid-state batteries have the highest energy conversion efficiency (90%-95%) because solid electrolytes reduce ion migration resistance and avoid side reactions with liquid electrolytes; lithium-ion batteries have a mature efficiency level (85%-90%), while sodium-ion batteries are slightly lower (80%-85%) due to higher internal resistance. Performance comparison chart of mainstream power batteries including indicators: safety, energy density, fast-charging potential, and cost advantage is shown in Fig. 3.

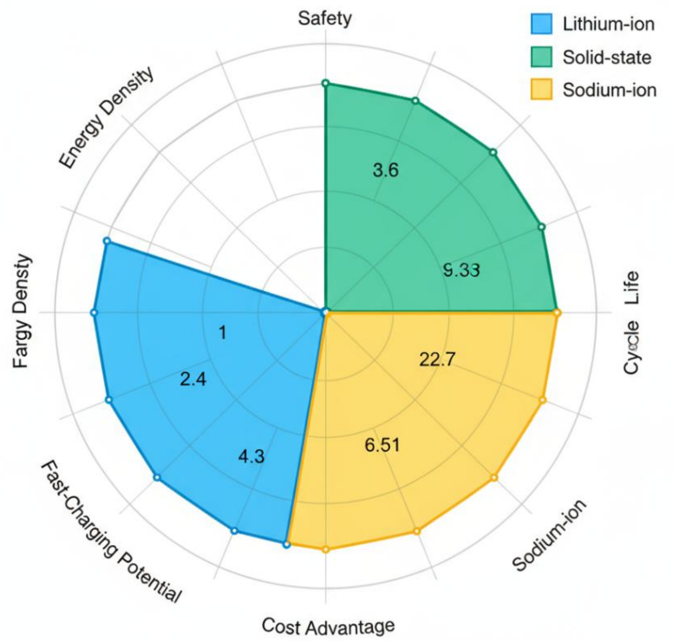

Fig.3 Performance comparison chart of mainstream power batteries [7]

Regarding charging speed (represented by the time to charge to 80% capacity), solid-state batteries have great potential, with a theoretical fast-charging time of 10-20 minutes due to high ion conductivity; lithium-ion batteries currently take 30-60 minutes under fast-charging conditions (limited by electrode material stability); sodium-ion batteries have a similar charging speed to lithium-ion batteries (35-70 minutes) but show better stability under high-current charging [7].

3. Basic Principles and Classification of Power Batteries

3.1. Basic Principles of Power Batteries

The core of power battery operation lies in reversible electrochemical reactions, which realize the conversion between electrical energy and chemical energy. Taking the mainstream lithium-ion battery as a typical example, its basic structure includes a positive electrode (usually lithium-based oxides), a negative electrode (mostly graphite), an electrolyte (for ion conduction), and a separator (preventing electrode short circuits while allowing ion passage). During charging, an external power source drives lithium ions (Li^+) to deintercalated from the positive electrode, migrate through the electrolyte and separator to the negative electrode, and embed in the graphite structure—this process stores electrical energy as chemical energy [8]. During discharging, Li^+ reversely migrate back to the positive electrode, and electrons flow through the external circuit to form a current, converting chemical energy into electrical energy to power the vehicle. This cyclic ion migration and electron transfer constitute the basic working principle of power batteries, and the stability of this process directly affects the battery's service life and safety [9].

3.2. Main Classification of Power Batteries

Power batteries are mainly classified by electrode materials and electrolyte forms, with three mainstream types dominating current research and application. Lithium-ion batteries are the most mature: they have balanced performance in safety, cycle life, and energy density, and are widely used in passenger and commercial vehicles, though they rely on liquid electrolytes that carry minor leakage risks. Solid-state batteries, as a next-generation technology, use solid electrolytes instead of liquids—they have higher safety and theoretical energy density but are still in the small-batch trial stage due to high costs. Sodium-ion batteries use sodium ions (Na^+) as charge carriers: they benefit from abundant sodium resources (e.g., seawater) and lower costs, but have slightly lower energy density, making them suitable for low-to-medium range vehicles. These three types complement each other, adapting to different application scenarios in the new energy vehicle industry.

4. Application Research and Analysis of Power Batteries

The practical application of power batteries is the key link connecting technological R&D and industrialization, and the exploration of enterprises and research institutions in application scenarios, technical adaptation, and performance optimization directly promotes the development of the new energy vehicle (NEV) industry. This chapter selects 4 representative cases to analyze their application strategies and effects, reflecting the current development status of power battery application research.

4.1. Contemporary Amperex Technology Co., Ltd. (CATL) – Lithium-Ion Battery Industrialization Application

As the world's leading power battery enterprise, CATL focuses on the industrialization of high-performance lithium-ion batteries, and its core application strategy is to develop integrated battery technologies and deepen cooperation with automakers. It launched the Cell to Pack (CTP) 3.0 technology, which omits the battery module structure, directly integrates cells into the battery pack, and matches it with high-nickel ternary positive electrode materials (NCM811) and silicon-carbon negative electrodes. This technology is applied to NEVs of brands such as NIO and XPeng: for example, the XPeng G9 equipped with CATL's CTP 3.0 battery has a battery energy density of 210 Wh/kg, a CLTC driving range of 702 km, and the battery pack production cost is reduced by 15% compared with traditional module-based designs. In 2024, CATL's lithium-ion battery installation volume accounted for 35% of the global market, verifying the feasibility of its industrialization application.

4.2. Toyota Motor Corporation – Solid-State Battery Prototype Application

Toyota, which has long been committed to solid-state battery R&D, adopted a "cooperative R&D + prototype verification" application path. It jointly developed sulfide-based solid electrolytes with Panasonic, solved the problem of poor interface compatibility between solid electrolytes and electrodes by coating the electrode surface with a lithium ion-conducting layer, and applied this technology to a prototype EV in 2024. The prototype is equipped with a 110-kWh solid-state battery pack, with a maximum driving range of 1,000 km under WLTC conditions and can be charged from 10% to 80% in 10 minutes. Toyota plans to conduct small-scale road tests in 2025 and promote mass production in 2027, which provides a practical reference for the application of next-generation power batteries.

4.3. Build Your Dreams (BYD) – Sodium-Ion Battery Scenario-Specific Application

BYD targeted the low-to-medium range NEV and energy storage markets and promoted the scenario-specific application of sodium-ion batteries. It used Prussian blue analogs (PBA) as the positive electrode material and hard carbon as the negative electrode to develop a sodium-ion battery with an energy density of 160 Wh/kg and first applied it to the BYD Seagull (a compact EV priced at around $15,000) in 2024. Compared with lithium iron phosphate batteries, the sodium-ion battery in the Seagull reduces the battery cost by 30% and has a cycle life of 3,000 times (remaining capacity ≥80%), meeting the daily travel needs of urban users (CLTC range of 305 km). In addition, BYD also applied this battery to distributed energy storage systems, with a cumulative application scale of 500 MWh by the end of 2024, verifying its multi-scenario adaptation capabilities [10].

4.4. Tesla Inc. – Power Battery Recycling Application

Tesla focused on the full-life cycle application of power batteries and built a closed-loop recycling system. Its Nevada Gigafactory uses mechanical disassembly + hydrometallurgical technology: first, the spent battery packs are disassembled into cells, the shell is removed, and then the electrode materials are leached with acid solution to recover lithium, cobalt, nickel and other metals. The recovered lithium is purified to produce lithium carbonate, which is reused in the production of 4680 battery cells. In 2024, Tesla's battery recycling plant achieved a lithium recovery rate of 95%, a cobalt and nickel recovery rate of 99%, and the cost of recovered materials was 20% lower than that of raw materials. The 4680 batteries made from recycled materials have the same energy density and cycle life as those made from raw materials, realizing the "resource reuse" of power batteries [11].

In short, all above cases involve practical application of both mature Li-ion batteries and emerging solid-state batteries and Na-ion batteries, reflecting multi-directional development trend for power batteries, and also achieve applicable results through matching technology with market demand and scene characteristics by enterprises and research institutes, which is worthy to be used as effective reference for further enhancing power battery application [12].

5. Conclusion

The most recent studies suggest that lithium-ion batteries reign on the market, where CATL's CTP 3.0 technology generates an energy density of 210Wh/kg at an additional cost reduction of 15%, and holds onto 35% of the world market. Novel emerging technologies include Toyota's newly created solid-state battery prototype that can charge up to 10 minutes and travel 1,000 km distance, as well as BYD's sodium-ion battery that drops the price of EVs by around 30% in the low range. The progress in recycling is reflected when Tesla could recover 95% lithium of its used batteries which can reach the same efficiency as raw materials.

However, there are still significant problems such as: Solid-state batteries have interfacial resistance, high production costs, sodium-ion batteries lag behind lithium-ion batteries in energy density (160Wh/kg), recycling requires considerable energy and has few standards, and industry collaborations need to be strengthened in order to promote closed-loop development.

Future work can be extended in the following directions: (1) Accelerate solid-state electrolyte interface improvement and further reduce cost. (2) Develop high energy density sodium materials such as NaVOPO4, NaFePO4, etc. (3) Promote the adoption of direct recycling and automatic disassembly, as well as industrialization of upstream materials processing capabilities. (4) Establish recycling consortia across industries as well as systematized standards and materials database.

References

[1] Tackett R. Proterra battery technology to power ENC next-generation electric transit buses. Bus Ride, 2022, 58(6).

[2] Lu M, Zhang X, Ji J, et al. Research progress on power battery cooling technology for electric vehicles. Journal of Energy Storage, 2020, 27: 101155.1-101155.16.

[3] Zhu L, Zhang L, Gao R, et al. Prediction of available capacity of power battery based on autoregressive integrated moving average model. Proceedings of SPIE, 2024, 13071: 0007.

[4] Wang J, Liwen Z, Song L, et al. Analysis of power battery technology R&D strategies under the supply chain competitive environment in post-subsidy era. Technological Forecasting and Social Change, 2025, 215.

[5] Liu G G. Research on power battery testing technology of new energy vehicles. Friend of Humanities, 2020, (20): 67.

[6] Ablikemu Y, Golden T. Research on key technologies of new energy vehicle power batteries. China High-Tech, 2022(14).

[7] Chi X. Research on performance testing technology of new energy vehicle power batteries. Volkswagen, 2024(7): 107-109.

[8] Fan Z C, Zhong S J. Research on the application of new energy vehicle power battery technology — Using lithium-ion batteries as a case study. Automotive Test Report, 2024(2): 49-51.

[9] He Y. Research review on power battery cooling technology for new energy vehicles. Automotive Digest, 2024(10): 9-13.

[10] Wang D, Wang C, Chen C. Recent progress on Prussian Blue analogue cathode materials for sodium-ion batteries. Advanced Materials, 2023, 35(50): 2305333.

[11] Famprikis T, Kudu Ö, Clark A J, He X, de Leeuw N H. Designing solid–solid interfaces for all-solid-state batteries. Nature Reviews Materials, 2024, 9(1): 59-78.

[12] Li J, Wang G, Xu Z. Direct recycling of lithium-ion batteries: recent advances and perspectives. Green Chemistry, 2023, 25(14): 5459-5484.