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Review of Research on Lithium-Ion and Sodium-Ion Energy Storage Batteries

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ABSTRACT
Energy storage batteries are a crucial part of the modern energy system. They can address the intermittent and fluctuating issues of renewable energy power generation, achieve the temporal and spatial transfer of electrical energy, and improve energy utilization efficiency. In the power grid, they can regulate peak and valley loads, enhancing the stability and reliability of the grid. They also play a key supporting role in distributed energy systems and the electric vehicle field, promoting energy transformation and sustainable development. Among them, sodium-ion batteries and lithium-ion batteries are also indispensable key components. Energy storage batteries have a high energy density and are widely used in the fields of electronic devices and electric vehicles. This article comprehensively provides an overview of sodium-ion and lithium-ion batteries.

KEYWORDS
Energy storage batteries; Sodium ions; Lithium ions

1 Introduction

With the advancement of industrialization and urbanization, the demand for and consumption of energy have been continuously increasing. The limited fossil fuel resources are gradually decreasing and may even be depleted in the future. At the same time, the consumption of fossil fuels has led to air pollution such as the greenhouse effect and smog, which seriously threatens the global ecology. Under the guidance of the carbon neutrality goal, promoting environmentally friendly and sustainable energy has become the key to energy transformation. Although clean energy sources such as solar energy, wind energy, and hydropower are more environmentally friendly, they are restricted by environmental conditions such as temperature, region, and season, and their stability is insufficient. Therefore, exploring efficient solutions for collecting renewable energy has always been an important research direction in the scientific community. The introduction of an energy storage system can store the excess electrical energy generated by renewable energy and release it as needed, effectively resolving the supply-demand imbalance problem of green energy power generation and ensuring a stable power supply. Among them, new energy batteries such as lithium-ion and sodium-ion batteries can be recharged. With the advantages of flexible response, high energy density, long service life, no pollution, high efficiency, and portability, they have received much attention in energy storage devices.

The technology of lithium-ion batteries is mature. Abroad, countries such as Japan and South Korea are leading in material research and development and process control. Domestic enterprises have carried out large-scale production, and companies like Contemporary Amperex Technology Co., Limited (CATL) have ranked among the top in the world. However, there is still a need to make breakthroughs in high-end materials. Sodium-ion batteries have abundant resources and low costs. Research on them is of great significance for large-scale energy storage and power supply in high-cold regions. Both of them promote energy transformation and sustainable development.

In terms of lithium-ion batteries, domestic CATL supplies many automobile enterprises and electronic enterprises, and BYD applies them in the fields of new energy and consumer electronics. Abroad, LG Energy Solution and Samsung SDI supply batteries for global electric vehicles and consumer electronics. Tesla's electric vehicles and energy storage products also use lithium-ion batteries. The research on sodium-ion batteries is in the development stage. Abroad, the focus is on the innovation of electrode materials and performance optimization, while in China, there is a close combination of industry, university, research, and application. Sodium-ion and lithium-ion batteries are widely used by domestic and foreign enterprises. Among domestic sodium-ion battery enterprises, HiNa Battery Technology Co., Ltd. applies them in energy storage and automobiles. CATL cooperates with Chery to develop related automobiles, and the battery cells of Great Power Energy Co., Ltd. are used in energy storage power stations.

2 Structural Composition of Energy Storage Batteries

2.1 Working Principle of Lithium-Ion Batteries

When a lithium-ion battery is charged, lithium ions are extracted from the inside of the positive electrode material, enter the electrolyte, pass through the separator, and are embedded in the negative electrode material. At the same time, the compensating charges of electrons in the external circuit reach the negative electrode from the positive electrode to ensure that the internal and external charges are in a balanced state. As the charging reaction continues, all the lithium ions inside the positive electrode material are extracted to the negative electrode, so the negative electrode reaches a lithium-rich state. The discharge process is the opposite. Lithium ions are extracted from the inside of the negative electrode material, enter the electrolyte, pass through the separator, and are embedded in the positive electrode material. At the same time, the compensating charges of electrons in the external circuit reach the positive electrode from the negative electrode. As the discharge reaction continues, the positive electrode material reaches a lithium-rich state. During the charging and discharging process, lithium ions are transferred back and forth between the positive and negative electrodes, which is similar to the left and right rocking of a rocking chair. Therefore, lithium-ion batteries are also known as "rocking chair batteries" [1].

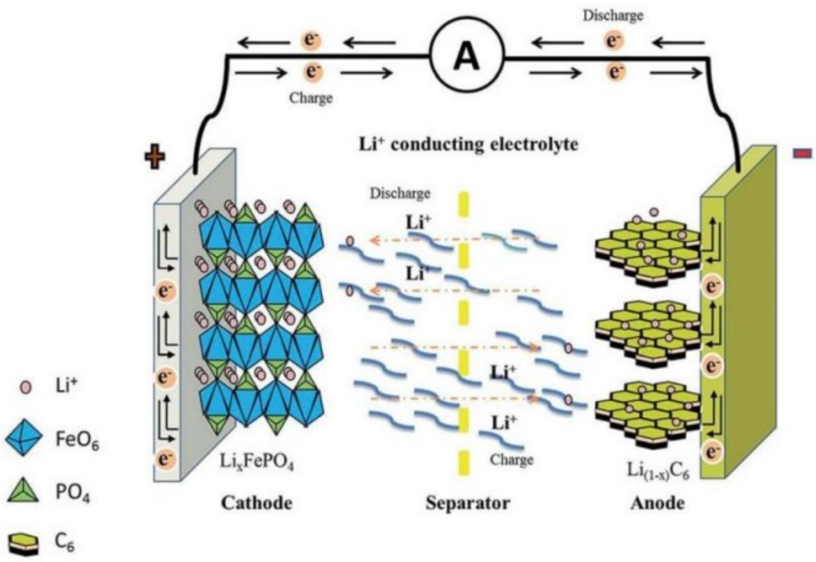

Figure 1-1 Working Principle Diagram of Charging and Discharging of Lithium-Ion Batteries [2]

Taking LiFePO4 as the positive electrode material and graphite as the negative electrode material as an example, the reaction mechanisms during the charging and discharging processes of the battery are as follows [3]:

Discharging Process

Positive electrode reaction: Li1-xFePO4 + xe- + $xLi^+ \rightarrow$ LiFePO4

Negative electrode reaction: LixC $\rightarrow$ C + xLi^+ + xe-

Overall reaction: Li1-xFePO4 + LixC $\rightarrow$ LiFePO4 + C

Charging Process

Positive electrode reaction: LiFePO4 $\rightarrow$ Li1-xFePO4 + xLi^+ + xe-

Negative electrode reaction: C + xLi^+ + xe- $\rightarrow$ LixC

Overall reaction: LiFePO4 + C $\rightarrow$ Li1-xFePO4 + LixC

2.2 Working Principle of Sodium-Ion Batteries

The charging and discharging process of a sodium-ion battery is essentially a dynamic process of energy conversion and "rocking chair-style" migration of ions and electrons. When charging, electrical energy is input into the sodium-ion battery. Inside the battery, an oxidation reaction occurs at the positive electrode, and sodium ions are extracted from the crystal lattice of the positive electrode material, enter the electrolyte, and migrate to the negative electrode. At the same time, electrons also leave the positive electrode and travel to the negative electrode through the external circuit. As the charging continues, the negative electrode accepts a large number of sodium ions and presents a sodium-rich state; while the positive electrode is in a sodium-deficient state due to the continuous loss of sodium ions. At this point, the electrical energy is successfully converted into chemical energy and stored in the sodium-ion battery.

During discharging, it is the "reverse process" of charging. At this time, the chemical energy inside the battery begins to play a role, and the migration directions of sodium ions and electrons are completely opposite to those during charging. Sodium ions start from the negative electrode, pass through the separator and electrolyte, and return to the positive electrode material; electrons flow in the opposite direction in the external circuit, and the directional movement of a large number of electrons forms an electric current. In simple terms, during charging, Na is extracted from the positive electrode material, and under the drive of the oxidation reaction, it diffuses to the negative electrode through the electrolyte and separator; during discharging, $Na^+$is extracted from the negative electrode material, and the electrons in the external circuit move synchronously to maintain charge balance, and finally are embedded in the positive electrode material through the electrolyte and separator.

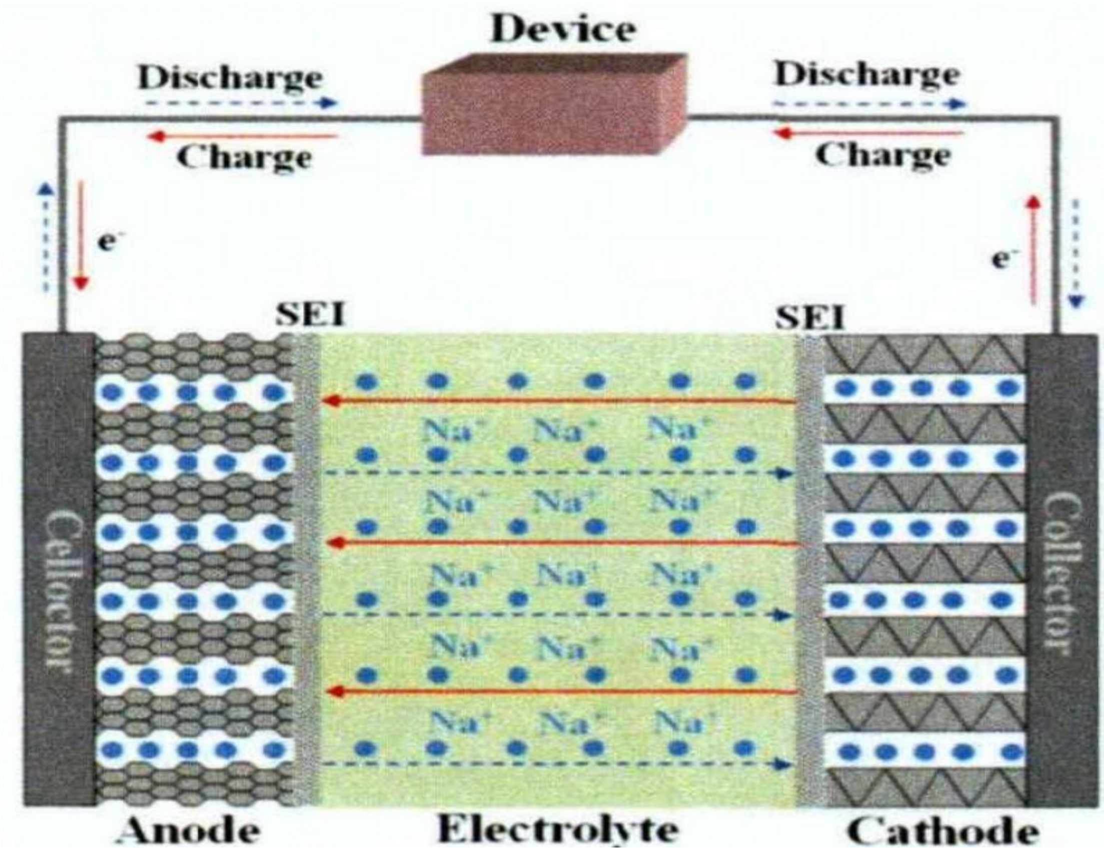

Figure 1-2 Working Principle Diagram of Charging and Discharging of Sodium-Ion Batteries [4]

Taking $NaMnO_2$ as the positive electrode material and graphite as the negative electrode material as an example, the reaction mechanisms during the charging and discharging processes of the battery are as follows [5]:

Discharging Process

Positive electrode reaction: $Na_{1-x}MnO_2 + xNa^+ + xe^- \rightarrow NaMnO_2$

Negative electrode reaction: $Na_xC \rightarrow C + xNa^+ + xe^-$

Overall reaction: $Na_{1-x}MnO_2 + Na_xC \rightarrow NaMnO_2 + C$

Charging Process

Positive electrode reaction: $NaMnO_2 \rightarrow Na_{1-x}MnO_2 + xNa^+ + xe^-$

Negative electrode reaction: $C + xNa^+ + xe^- \rightarrow Na_{1-x}MnO_2^+ Na_xC$

Overall reaction: $C + NaMnO_2 \rightarrow Na_{1-x}MnO_2 + Na_xC$

3 Application Advantages and Current Situation of Energy Storage Batteries

3.1 Application Advantages and Current Situation of Lithium-Ion Batteries

3.1.1 Application Advantages of Lithium-Ion Batteries

Lithium-ion batteries are still the absolute main force in the energy storage field. In 2024, the total output of lithium batteries in China reached 1170 GWh, and the output of energy storage lithium batteries was 260 GWh, accounting for 97% of new energy storage projects. Its high technical maturity and significant energy density advantage make it occupy a core position especially in power batteries and high-end energy storage scenarios. Lithium-ion batteries have great development potential. In the field of new energy vehicles, with the continuous innovation of technology, the driving range of lithium-ion batteries is expected to be further increased, and the charging speed will also be accelerated, thus strongly promoting the popularization of electric vehicles. In the field of consumer electronics, emerging products such as wearable devices and foldable mobile phones are constantly emerging. While putting forward higher requirements for the miniaturization and high performance of lithium-ion batteries, they also provide a broad market space for their development.

3.1.2 Current Application Situation of Lithium-Ion Batteries

The technology of lithium-ion batteries is mature, and they will still be the key power source in many fields in the future. In the field of consumer electronics, devices such as smartphones, tablets, and laptops mainly use lithium-ion batteries as power sources; in the transportation field, lithium-ion batteries are not only the mainstream power source for new energy vehicles but also widely used in electric bicycles, electric scooters, drones, etc.; in the energy storage field, lithium-ion batteries assist in grid energy storage, distributed energy storage, and household energy storage, effectively improving the utilization efficiency of renewable energy. Lithium-ion batteries have a high energy density, which can provide longer battery life for devices; they have a long cycle life and can be charged and discharged multiple times, thus reducing the use cost; and their technology is mature, and a complete industrial chain has been formed from research and development to production, and the product quality and performance are reliably guaranteed. Currently, lithium-ion batteries have the problems of lithium resource shortage (the crustal abundance is only 0.0065%) and the intensified supply chain risk caused by price fluctuations. In 2024, the average price of lithium carbonate dropped to 90,000 yuan per ton, but the long-term resource bottleneck still exists. In addition, the structural overcapacity of production capacity (the production capacity utilization rate of energy storage batteries in 2024 was 65%) and environmental protection pressure further squeeze the profit space.

3.2 Application Advantages and Current Situation of Sodium-Ion Batteries

3.2.1 Application Advantages of Sodium-Ion Batteries

Sodium elements are abundant in reserves and widely distributed on the earth, making sodium-ion batteries based on sodium elements have resource advantages and low costs. Compared with the limited lithium resources, the cost advantage of sodium-ion batteries is particularly obvious. At the same time, sodium-ion batteries also have many excellent performances. They have high safety and are not prone to dangerous situations such as thermal runaway; they have excellent low-temperature performance and can still maintain good charging and discharging performance in cold environments to ensure the normal operation of devices.

With the characteristics of low cost, abundant resources, and good low-temperature performance, sodium-ion batteries are gradually emerging. In the future, they have great development potential in the field of large-scale energy storage and can provide efficient and stable energy storage solutions for the grid connection of renewable energy, helping to realize the transformation of the energy structure. In addition, in application scenarios with relatively low requirements for energy density, such as low-speed electric vehicles and start-stop batteries, sodium-ion batteries are also expected to achieve large-scale promotion and application by virtue of their cost advantages.

3.2.2 Current Application Situation of Sodium-Ion Batteries

Energy Storage Field：In large-scale energy storage power stations, for example, in May 2024, China's first 10-megawatt-hour sodium-ion battery energy storage power station in the new energy storage field was officially put into operation in Nanning, Guangxi, effectively improving the power system's ability to absorb new energy and being able to participate in power peak regulation intelligently. In the distributed energy storage scenario, the world's first 1 MWh sodium-ion battery photovoltaic-storage-charging intelligent microgrid system jointly launched by the Institute of Physics of the Chinese Academy of Sciences and HiNa Battery Technology Co., Ltd. takes sodium-ion batteries as the energy storage main body, combines with utility power, photovoltaic, and charging facilities to form a microgrid system. It can interact intelligently with the public power grid according to demand, store electricity during low-power consumption periods, and discharge electricity during peak periods, achieving "using valley electricity during peak periods".

Transportation Field：In the electric two-wheeler market, Yadea launched the Jina S9 equipped with the "Jina 1" sodium-ion battery, achieving a range of more than 100 kilometers, and it can be charged to 80% in 10 minutes; Tailing cooperated with Chaona New Energy to establish a sodium battery joint laboratory, and its super sodium battery vehicle is designed with an IPX7-level whole-pack waterproof function. In terms of electric vehicles, CATL has achieved the mass production of the first-generation sodium-ion battery on Chery models, and "Jianghuai Yiwei" has delivered the world's first mass-produced vehicle equipped with a sodium-ion battery. However, currently, it is mainly applied to low-range small and micro vehicles. In addition, in some low-speed four-wheeled vehicles with low requirements for energy density and large space, such as golf carts and tourist sightseeing vehicles, as well as in medium and large commercial vehicles, such as logistics vehicles and buses, sodium-ion batteries have also begun to be explored for application.

Other Fields：In communication base stations, sodium-ion batteries can be used as backup power sources to provide a stable energy supply and deal with sudden power outages. In places such as data centers and hospitals, sodium-ion batteries can serve as uninterruptible power supplies (UPS) to ensure the continuity of power supply and meet their high requirements for power supply reliability. At the same time, in the field of low-speed engineering vehicles such as electric forklifts and electric stackers, sodium-ion batteries are gradually being applied by virtue of their characteristics such as high discharge rate.

4 Conclusion and Prospect of Energy Storage Batteries

Lithium-ion batteries will still dominate the energy storage market in the short term, but the industrial breakthrough of sodium-ion batteries will reshape the industry pattern. The two are not in a substitution relationship but form a complementary relationship based on scenario requirements and technical advantages. 2025 may become the "true first year" of large-scale application of sodium batteries, and lithium batteries will continue their competitiveness through solid-state and integrated technologies. In the future, the coordinated development of multiple technical routes in the energy storage industry will be the key path to achieving the carbon neutrality goal.

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