Enhancing Sodium-Ion Battery Performance: A Focus on Electrode Materials

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Abstract. As lithium-ion batteries (LIBs) near their performance limits, finding alternative energy storage solutions has become crucial for the future of electric vehicles. Sodium-ion batteries (SIBs) have emerged as a promising candidate due to their similar working mechanisms to LIBs, yet they hold the potential for more cost-effective and sustainable energy storage. However, the technology behind SIBs is still in its developmental stages, and achieving commercial viability remains a challenge. This review focuses on the importance of electrode materials in advancing high-performance SIBs. By analyzing several highly regarded studies, this article explores how different types of electrode materials, such as carbon-based anodes and layered oxide cathodes, can improve energy density, cycle life, charge/discharge rates, and overall efficiency. The review also addresses the current challenges these materials face and discusses possible strategies for overcoming them. Ultimately, this paper aims to provide a comprehensive understanding of the key role electrode materials play in driving the future of SIB technology and what advancements are needed to realize their full potential.

Keywords: Sodium-ion battery; electric vehicle; energy storage device; electrode material.

1. Introduction

In recent decades, the global shift towards green and sustainable development has gained widespread attention. Governments and automotive manufacturers are actively seeking alternatives to traditional internal combustion engine (ICE) vehicles, aiming to reduce carbon emissions and reliance on fossil fuels. Among the various approaches considered, electric vehicles (EVs) powered by batteries have emerged as one of the most promising solutions [1]. Batteries, serving as the primary energy storage systems for EVs, encompass a wide range of technologies, with LIBs being the most prominent at present.

LIBs offer several distinct advantages. Lithium, as an abundant element in the Earth's crust, provides a stable and accessible resource base for battery production. Furthermore, LIBs are relatively straightforward to manufacture and integrate into EV systems, and they exhibit a favorable safety profile compared to other battery technologies when used in everyday applications. Within the broader category of LIBs, two popular types have been widely adopted and studied: lithium cobalt oxide ($LiCoO_2$) batteries and lithium iron phosphate ($LiFePO_4$) batteries.

A comparison of the energy densities of these two battery types is illustrated in Fig. 1. $LiCoO_2$ batteries exhibit a higher energy density compared to $LiFePO_4$ batteries, making them suitable for applications requiring longer ranges and higher performance. However, this does not imply that $LiCoO_2$ batteries are without limitations. While they offer high energy density, trade-offs in cost, thermal stability, and environmental impact must be considered, especially when compared to the more stable and cost-effective $LiFePO_4$ chemistry.

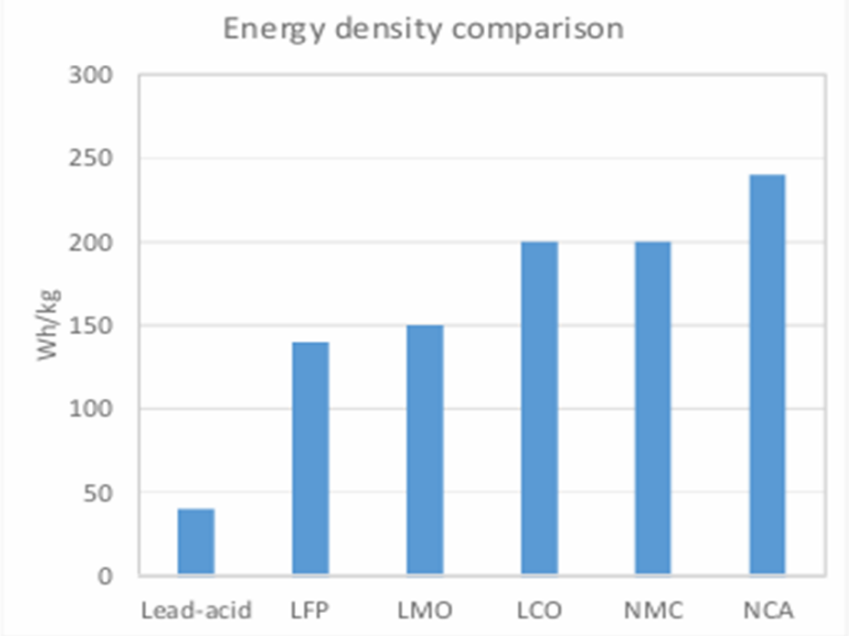


Fig. 1 Comparison of energy densities between several types of batteries [2]

$LiCoO_2$ batteries are highly regarded for their attractive advantages, particularly their high energy density, which significantly exceeds that of $LiFePO_4$ batteries. This makes $LiCoO_2$ a preferred choice for applications requiring maximum energy storage within a limited volume. However, despite these appealing features, $LiCoO_2$ batteries face critical challenges, the most significant being their high cost, primarily driven by the expense of cobalt as a precursor material. Additionally, $LiCoO_2$ exhibits poor thermal stability, which raises safety concerns, especially in high-temperature environments where it poses a potential hazard due to the risk of thermal runaway.

In contrast, $LiFePO_4$ batteries, while having a lower energy density, as shown in Fig. 1, offer considerable advantages in other areas. $LiFePO_4$ is notably superior in terms of thermal stability compared to $LiCoO_2$, reducing the risk of overheating and making it a safer option for a wide range of applications. Furthermore, $LiFePO_4$ batteries are more cost-effective, primarily due to the lower material costs, and they boast an impressive cycle life [3]. According to Omar et al. (2014), $LiFePO_4$ batteries can achieve approximately 3221 charge-discharge cycles at an 80% depth of discharge (DOD), whereas $LiCoO_2$ batteries typically endure only a few hundred cycles [4]. These attributes—long cycle life and lower cost—align well with consumer expectations for both reliability and affordability.

However, $LiFePO_4$ does have its drawbacks. The electrochemical performance of $LiFePO_4$ batteries is notably poor at low temperatures, which can affect their efficiency in colder environments. Nevertheless, this limitation is not unique to $LiFePO_4$, as most LIB chemistries experience performance degradation at lower temperatures, making it a manageable challenge rather than a fundamental flaw.

While LIBs have reached a level of maturity that allows for widespread application, researchers are increasingly seeking alternatives to improve vehicle battery performance. The extensive research and development conducted on LIBs have laid a strong foundation for the advancement of next-generation battery technologies, among which SIBs have emerged as a promising candidate. Some experts argue that LIBs have already reached or are approaching their theoretical performance limits, particularly in terms of energy density and resource sustainability. As a result, SIB technology has been proposed as a viable alternative.

SIBs are electrochemical energy storage devices that operate by utilizing sodium ions as charge carriers, akin to the mechanisms found in LIBs. These batteries consist of an anode, a cathode, and

an electrolyte, with sodium ions shuttling between the electrodes during charging and discharging cycles. The primary advantages of SIBs include the abundance and lower cost of sodium resources compared to lithium, which could make them a more sustainable and economically viable option for large-scale energy storage applications, particularly in the context of EVs.

2. The Working Mechanism of SIBs

2.1. Charging Process

During the charging process, sodium ions are extracted from the cathode and migrate through the electrolyte toward the anode. Simultaneously, electrons flow through the external circuit, facilitating the reduction of sodium ions at the anode. This electrochemical reaction results in the intercalation of sodium ions into the anode material, typically composed of carbon-based or other sodium-hosting compounds. The efficiency of this process largely depends on the ionic conductivity of the electrolyte and the structural compatibility of the anode material in hosting sodium ions without significant volumetric changes.

2.2. Discharging Process

In the discharging phase, the sodium ions are released from the anode and travel back through the electrolyte to the cathode, where they are re-intercalated. Concurrently, electrons flow from the anode to the cathode via the external circuit, generating electrical energy that can be used to power external devices. The reversibility and stability of these ion migrations between the electrodes, as well as the electrochemical performance of the materials involved, are critical for achieving optimal energy output and cycle life in SIBs.

3. Feasibility and Application Principles of SIB Technology

From a resource availability standpoint, SIBs present a compelling alternative to LIBs due to the significantly higher abundance of sodium in the Earth's crust. Sodium is widely distributed globally, making it a more readily available and potentially cost-effective material compared to lithium. Technologically, sodium and lithium share similar chemical properties, as both are alkali metals positioned in Group 1 of the periodic table. This similarity suggests that SIBs can operate under similar conditions, including comparable operating temperatures, and may exhibit similar electrochemical behavior. Furthermore, the theoretical cost of SIBs is expected to be lower than that of LIBs, primarily due to the abundance and widespread availability of sodium. This economic advantage, combined with the technological feasibility, indicates that SIBs have a strong potential to replace LIBs in various applications.

However, despite these advantages, SIBs are not without their challenges. While they are theoretically feasible and hold promise from both a cost and availability perspective, significant hurdles remain before they can be adopted on a large scale. These challenges must be addressed to fully realize the potential of SIB in the future energy storage landscape.

4. Challenges Faced by the Development of SIB Technology

One of the most significant challenges impeding the development of SIBs is their relatively low energy density compared to LIBs. This disparity arises from the larger ionic radius of sodium compared to lithium, which limits the amount of energy that can be stored per unit mass. Since the ionic size of sodium is a fixed characteristic and cannot be altered, other approaches must be explored to address this issue. A promising solution lies in optimizing the electrode materials used in SIBs. Specifically, identifying cathode materials that offer both high energy density and enhanced functionality is critical for improving the overall performance of SIBs.

Another pressing challenge is the structural stability of SIBs during practical operation, particularly with respect to the volumetric changes that occur during cycling. Large volume fluctuations in the electrode materials can lead to mechanical degradation and reduced battery lifespan. This issue can potentially be mitigated by developing anode materials that exhibit minimal volume change during charge and discharge cycles, thereby enhancing the structural stability of the battery. Towards these key challenges identified, the next section will detail specific strategies to overcome them, focusing on advancements in both cathode and anode materials.

5. Cathode Materials

For SIBs, the selection of cathode materials with high energy density and functional stability is critical to enhancing overall battery performance. This section explores several promising cathode materials that hold significant potential for SIBs.

5.1. Layered Metal Oxides

Layered metal oxides, such as $NaMnO_2$, represent a class of cathode materials with considerable promise. According to Xiang et al. (2015), $NaMnO_2$ serves as a representative example due to its layered structure, which facilitates efficient sodium ion intercalation and deintercalation during the charge and discharge cycles [5]. Fig. 2 illustrates the schematic operation principle and charge and discharge mechanism of SIBs, utilizing $NaMnO_2$ as the cathode material and hard carbon as the anode. This layered configuration has been shown to support stable cycling and moderate energy density, making it a candidate for further optimization in future battery designs.

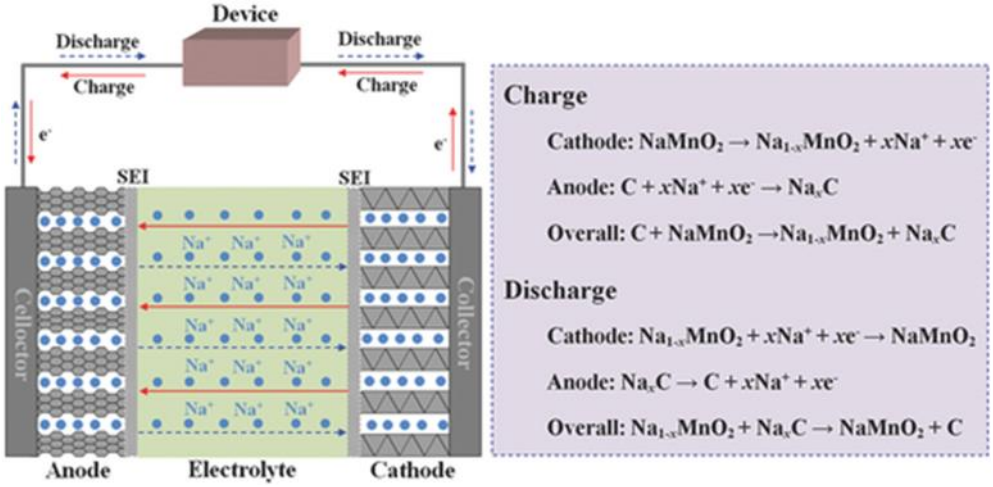


Fig. 2 Schematic operation principle and charge and discharge mechanism of SIBs, in which the cathode materials and anode materials are represented by layered $NaMnO_2$ and hard carbon, respectively [5]

5.2. Polyanionic Oxides

Currently, available polyanionic oxides mainly contain phosphates ($NaFePO_4$ and $Na_3V_2(PO_4)_3$), pyrophosphates ($Na_2MP_2O_7$ and $Na_4M_3(PO_4)_2P_2O_7$), fluorophosphates (Na_2MPO_4F, $Na_3(VO_x)_2(PO_4)_2F_{3-2x}$) (M stands for Fe, Co, Mn), and sulfates ($Na_2Fe_2(SO_4)_3$, $Na_2Fe(SO_4)_2{\cdot}2H_2O$) [5]. According to Yao et al., a symmetric SIB that has phosphate $Na_3V_2(PO_4)_3$ as a cathode and $Na_4V_2(PO_4)_3$ as an anode can reach a high energy density and lead to a stabilized electrochemical performance, which is higher than 3000 cycles [6].

5.3. Amorphous Materials

Amorphous $NaFePO_4$ is another material that shows great promise for SIBs, particularly due to its cost-effectiveness, abundance, and safety. As Liao et al. (2024) pointed out, $NaFePO_4$ is an ideal positive electrode material owing to its ability to deliver stable performance at a relatively low cost

[7]. The amorphous structure provides a greater degree of flexibility, which can enhance the cycle stability and safety of SIBs.

6. Anode Materials

The main principle of choosing an anode material is to focus on its ability to restrict the volume change of electrodes so that the structure of an SIB is stable enough for the cycles. One another factor in selecting anode materials to consider is the formation of a solid electrolyte interface (SEI) [8]. SEI is formed during the cycle of a SIB, which helps maintain the stability and safety inside the battery.

6.1. Embedded Negative Electrode Materials

Graphite, along with other carbon-based materials, remains a popular choice as an anode material due to its ability to host sodium ions through intercalation. Graphite's amphoteric redox behavior makes it versatile, though the relatively weak interlayer bonding between graphene sheets presents challenges in mitigating volume changes during cycling. Despite this, the porous structure of graphite facilitates sodium ion storage, making it a valuable anode material, albeit with certain limitations in long-term stability.

6.2. Alloy Negative Electrode Materials

Alloy materials, such as fully lithiated silicon ($Li_{15}Si_4$) or tin ($Li_{15}Sn_4$), have demonstrated potential in controlling volume expansion during cycling. These materials provide greater mechanical stability, which helps maintain the structural integrity of the SIB and extends its cycle life. Alloys offer a promising avenue for improving anode performance in SIBs by addressing volumetric fluctuations during repeated charge and discharge cycles (ibid) [8].

7. Conclusion

In comparison to LIBs, SIBs present several advantages, including resource abundance and lower costs, making them attractive for industries and consumers alike. SIBs have demonstrated feasibility as a promising alternative for energy storage, particularly due to their efficient storage performance. However, the technology is still facing significant challenges, with the most critical being their relatively lower energy density. Current research has outlined potential solutions to these limitations, and it is anticipated that ongoing advancements will address these issues in the near future.

A key area for development lies in the search for cathode materials that offer high energy and functional densities, as well as anode materials that exhibit minimal volume change during charge/discharge cycles. This study underscores the essential role electrode materials play in enhancing the performance of SIBs, laying a solid foundation for future research. Continued exploration of novel electrode materials is expected to push the boundaries of SIB technology, bringing it closer to widespread commercial application and enabling high-performance SIBs to fulfill their potential in various energy storage systems.

References

[1] Poorshakoor Ehsan and Darab Mahdi. Advancements in the development of nanomaterials for lithium ion batteries: A scientometric review. Journal of Energy Storage, 2024, 75: 109638.

[2] Efore, Comparison of lithium-ion batteries. December 9, 2020. Retrieved on September 8, 2024. Retrieved from: https://www.efore.com/content/uploads/2020/12/Comparison_of_lithium_batteries_20201209.pdf

[3] Zhang Baoquan, Wang Shuzhong, Li Yanhui, et al. Review: phase transition mechanism and supercritical hydrothermal synthesis of nano lithium iron phosphate. Ceramics International, 2020, 46(18): 27922-27939.

[4] Omar Noshin, Monem Mohamed Abdel, Firouz Yousef, et al. Lithium iron phosphate-based battery – Assessment of the aging parameters and development of cycle life model. Applied Energy, 2014, 113: 1575-1585.

[5] Xiang Xingde, Zhang Kai and Chen Jun. Recent advances and prospects of cathode materials for sodium ion batteries. Advanced Materials, 2015, 27(36): 5343-5364.

[6] Yao Xuhui, Zhu Zixuan, Li Qi, et al. 3.0 V High energy density symmetric sodium-ion battery: Na4V2(PO4)3∥Na3V2(PO4)3. ACS Applied Materials & Interfaces, 2018, 10(12): 10022-10028.

[7] Liao Huanyi, Zhang Zhi, Zheng Yifan, et al. NaFePO4 for sodium-ion batteries: Mechanism, synthesis and optimization strategies toward commercialization. Energy Storage Materials, 2024, 65: 103157.

[8] Nayak Prasant Kumar, Yang Liangtao, Brehm Wolfgang, et al. From lithium-ion to sodium-ion batteries: advantages, challenges, and surprises. Angewandte Chemie International Edition, 2018, 57(1): 102-120.