Feasibility analysis of replacing lithium-ion battery with sodium ion battery

Fang Hu[1, *], Hanjie Lin[2] and Runliang Pan[3]

[1]Latter&Science, University of California, Davis, Davis, U.S.

[2]School of Artificial Intelligence, Wuchang University of Technology, Wuhan, China

[3]College of Chemical Engineering, Zhejiang University of Technology, Hangzhou, China

* Corresponding Author Email: fahu@ucdavis.edu

Abstract. Since the beginning of the 21st century, the global energy crisis has become a pressing issue, prompting researchers to explore more efficient ways of utilizing energy production and storage technologies in our daily lives. In recent years, there have been major improvements in lithium-ion batteries (LIBs) technology, considerably improving living conditions globally. LIBs are currently commonly employed in electric cars. However, the efficient distribution of renewable energy and smart grids raises concerns, along with the long-term availability of lithium resources. The scarcity and rising costs of lithium metal in recent years have been attributed to substantial price fluctuations. Thus, LIBs have made it difficult to meet the increasing demands of both small and medium to large energy storage applications. Due to the readily available properties of sodium metal, it has similar chemical properties to LIBs. To alleviate these challenges, sodium-ion batteries (SIBs) can be used as the finest candidates for power supply. In recent years, different materials such as metal oxides and phosphates have been introduced as positive electrode materials for SIBs. The use of selected carbonaceous materials, transition metal oxides, intermetallic compounds, and organic compounds as negative electrode materials for SIBs has also contributed to recent developments. SIB is a promising next-generation replacement, but there are still some challenges in the market acceptance of SIBs. In this research, we summarize and compare the market application status of SIB and lithium iron phosphate (LFP), and propose the future development trajectory of SIB and LFP according to their respective characteristics. This will provide a unique insight into practical application problems and market realities.

Keywords: sodium-ion batteries, lithium-ion batteries, comparison.

1. Introduction

The increasing global demand for energy and the environmental issues arising from traditional energy use underscore the urgency of developing new energy technologies. The extensive burning of traditional fuels not only exacerbates greenhouse gas emissions but also raises concerns over energy security and price volatility. These challenges have spurred the exploration of new energy technologies, particularly in the area of innovative electrical energy storage systems.

Lithium-ion batteries (LIBs), the mature electrochemical energy storage technology, continue to dominate the market, with lithium iron phosphate (LFP) batteries operating by inserting and removing lithium ions into anode and cathode materials. It is widely utilized in power and energy storage applications, accounting for approximately 70% of power batteries usage and up to 95% in energy storage batteries. LIBs are highly favored because of their exceptional energy ratio, long cycle life, and excellent energy efficiency. However, recent global events such as the COVID-19 pandemic, inflation, and challenges in lithium production have led to significant fluctuations in lithium prices. Consequently, there has been a focus on technological advancements and cost improvements in LFP technology. In parallel with LFPs, major corporations have also begun exploring sodium ion batteries (SIBs), which offer similar synthesis pathways as LFPs but serve as potential alternatives from a technological standpoint.

At the same time, as a complement to LIBs technology, SIBs have also garnered widespread attention. Furthermore, SIBs have very similar operating principles and structure as the LIBs, meanwhile, SIBs have many advantages that LIBs don’t have, for example, SIBs have outstanding performance in terms of power, circularity, recyclability and safety. These qualities making many people believe that sodium batteries will become a possible solution to the defects of LIBs [1]. However, SIBs also have non-negligible shortcomings, such as its low battery energy density, the number of cycles and service life is insufficient, which are the main factors restricting the development of SIBs [2].

In the backdrop of the thriving global energy storage sector, both LIBs and SIBs are emerging as significant players. SIBs, in particular, find extensive applications in storing renewable energy, ensuring power supply stability, and showcasing vast prospects across various domains. In contrast, LIBs enjoy a mature and widespread presence in electric vehicles and portable electronic devices. These two technologies play pivotal roles in their respective fields, offering diversified solutions for clean energy and portable electronic devices.

In this study, we conducted extensive literature research and market surveys to gain an in-depth understanding of the field under investigation. By reviewing a substantial amount of relevant literature and references, we obtained valuable insights into the latest technological trends and industry developments. Additionally, we conducted market surveys to collect data and insights regarding market size, competitive landscape, potential opportunities, and challenges. In our research, we specifically conducted a comparative analysis of SIBs and LIBs to assess their performance, advantages, and disadvantages in the field of energy storage.

2. Materials

As rechargeable secondary batteries, SIBs exhibit a high degree of similarity in their working principles to LIBs. Both operate by facilitating the movement of sodium and lithium metal ions between the cathode and anode, a process often referred to as the 'rocking-chair' mechanism. The earlier and more widespread adoption of lithium in secondary batteries can be attributed to its smaller ionic radius, higher standard potential, and significantly greater specific capacity. However, SIBs, due to their lower capacity and shorter lifespan resulting from sodium ions being three times heavier than lithium ions, remained overlooked for a long time. It wasn't until after 2010 that relevant research began to emerge.

Global lithium reserves are limited, with lithium content in the earth's crust being only 0.0065%. As the demand for batteries grows with the development of new energy vehicles, resource bottlenecks become apparent, and the significant cost associated with LIBs constrains their widespread adoption on a large scale. In contrast, sodium resources are plentiful, widely distributed, and easier to extract. They are widely distributed and easier to extract. LIBs are made from high-purity lithium carbonate, derived from spodumene, lepidolite, and salt lake brines. Recently, China has been actively developing salt lake lithium resources. However, the high magnesium content in these brines, which is difficult to separate from lithium, leads to the preference for lithium ore extraction. Lithium ores, mainly spodumene and lepidolite, are used, with spodumene being the primary source due to its simple elemental composition, high lithium grade, and abundant reserves. Its industrial development and utilization are somewhat limited due to the harsh mining conditions of cold and high altitudes, and the production process involves adding sulfuric acid for roasting, which poses significant environmental pressure and entails high investment and operational costs for gas treatment. Lepidolite has a complex chemical composition and lower lithium grade, with 5%-10% fluorine content leading to lithium loss during extraction, thus making its lithium extraction process complex and costly. Therefore, SIBs hold inherent advantages in production cost and output when compared to LIBs.

The structure and performance of cathode and anode materials determine the battery's sodium and lithium storage capabilities. For instance, in SIBs, a membrane is interposed between the cathode and anode to avert short-circuiting, while the electrodes are pervaded by the electrolyte to enable ion mobility, and the current collector assumes the role of gathering and transmitting electrons. and the current collector serving to collect and transmit electrons. During charging, Na^+ ions traverse from the cathode to the anode via the electrolyte, resulting in a high-potential sodium-depleted cathode and a low-potential sodium-rich anode. The discharge process is the reverse, with Na^+ ions moving from the anode back to the cathode, restoring the cathode to a sodium-rich state. To maintain charge balance, a corresponding number of electrons traverse the external circuit during both the charging and discharging phases, facilitating oxidation and reduction reactions at the electrodes.

The choice of anode materials, primarily providing the ion source, determines the battery's energy density. LIBs, categorized by their cathode materials, include various technology routes such as lithium cobalt oxide. In contrast, cathode materials for SIBs are still evolving, with over 100 different types currently under exploration. Cathode materials commonly used in SIBs include layered metal oxides, Prussian blue analogs, and polyanion compounds. Among these, the layered metal oxide pathway is widely adopted due to its high capacity and straightforward processing. However, owing to the disparity in atomic weight between sodium and lithium, SIBs inherently exhibit lower energy density. For cathode material, preferred are carbon-based materials due to their role in storing and releasing energy during charging and discharging. Sodium ions, having a different radius than lithium ions, cannot intercalate effectively into graphite, requiring a larger interlayer spacing than what ordinary graphite materials can provide, thus increasing the overall cost of SIBs.

In SIBs, aluminum foil is used for the current collector, significantly cheaper than that in LIBs. The current collector connects the powdery active material and collects and outputs the current generated, inputting the electrode current to the active material. In graphite-based lithium batteries, lithium reacts with aluminum to form an alloy, necessitating the use of copper foil as the current collector for the anode. In contrast, in SIBs, sodium and aluminum do not react to form an alloy, allowing both the positive and negative electrode current collectors to be made of aluminum foil, which is significantly more cost-effective than in LIBs.

In the short term, due to the relatively low level of industrialization in the SIBs sector, the cost advantages of SIBs materials have not been fully realized. It is anticipated that in the future, with modifications to the cathode materials, the performance of SIBs is expected to continue improving, and the maturity of cathode materials is expected to significantly increase. Additionally, through scale production, there is the potential for a substantial reduction in the cost of sodium-ion cathode materials.

3. Performance and security

3.1. Comparison of battery energy density

In terms of electrochemical performance, the LFP battery functions within a voltage range of 3.0-4.2 V, whereas SIBs operate at a lower voltage range of 2.8-3.5 V. The small molecular weight and high unit mass energy storage enable the SIBs to achieve a theoretical energy density of up to 200 Wh/kg. However, practical applications are limited to an energy density of approximately 90-160 Wh/kg due to sluggish diffusion rates in the electrode material leading to reduced reaction kinetics and low voltage output. This limitation is also influenced by process specifications and manufacturing costs during production lines. In contrast, LFP batteries exhibit higher energy densities ranging from 160~300 Wh/kg owing to their efficient lithium-ion diffusion within the electrode material and favorable reaction kinetics, coupled with operation at a higher voltage level that further enhances overall energy density.

3.2. Battery life comparison

The limited cycle life of SIBs can be attributed to the sluggish diffusion rate of SIBs within the electrode material, resulting in diminished reaction kinetics. Moreover, the substantial volume fluctuations experienced during charge and discharge processes contribute to structural instability in the electrode material and cell bulging issues, ultimately leading to a shortened lifespan for the battery [3]. LFP exhibits a prolonged lifespan due to the rapid diffusion rate of lithium ions within the electrode material and favorable reaction kinetics [4]. The stability of LFP's electrode structure surpasses that of SIBs, facilitating the accommodation of more ions during stacking or winding processes, ultimately leading to an enhanced cycle life. LFP batteries in top products typically have a lifespan that is twice as long as SIBs. However, during the charging process of LIBs, Li^+ is extracted from the positive electrode and incorporated into the negative electrode [5]. In exceptional circumstances such as limited space for negative lithium insertion or excessive resistance hindering faster embedding of Li^+ into the negative electrode compared to its equal embedding from the positive electrode, anomalies arise where Li^+ fails to be embedded in the negative side. Instead, electrons accumulate on the surface of the negative electrode forming a silver-white metallic elemental lithium commonly known as "lithium out" [5]. The presence of lithium dendrites is a major factor affecting the lifespan of LFP batteries and also poses significant safety concerns. The deposition of lithium not only reduces battery performance and shortens its cycle life, but it also hampers fast charging capabilities. Moreover, there is a risk of puncturing the separator and losing control over the cells, which can lead to unforeseen consequences like battery combustion or explosion.

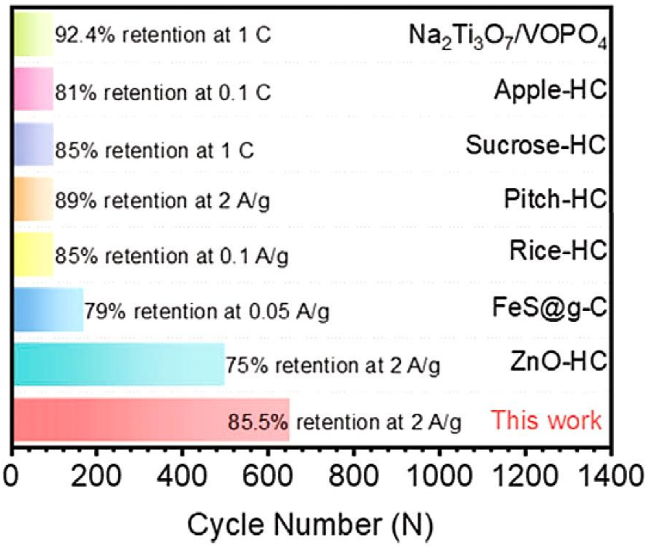

Fig. 1 Cycling stability of the prepared electrode compared with previously reported electrodes [6].

3.3. Charge and discharge performance

The charging and discharging performance of the SIBs is quite excellent. This procedure is reversed during discharge. The charge and discharge voltage and current curves of the SIBs are steady, the temperature variations are modest, and the battery has good charge and discharge performance. Lu et al. learned about the storage mechanism of hard carbon at different temperatures by synthesizing ZnN_4-containing hard carbon, a derivative of 2, 4-diaminophenol formaldehyde resin, thus verifying the possibility of hard carbon working at low temperatures and provided new strategies to achieve the purpose of regulating the complex interfacial electrochemistry and electrode chemistry of hard carbon-based materials [6]. As shown in Fig. 1, the prepared electrode has an excellent recyclability compared to other reported electrodes. The binding energy of Na^+ and PF6- is substantially less than that of Li^+ and PF6- and may be easily dissociated by carbonate molecules. Therefore, the ionic conductivity of SIBs electrolyte is higher than that of lithium, and the lower the temperature, the clearer the benefit of SIBs. At now, the practical application on the market has also been created to utilize SIBs in low-temperature environments, which is one of the reasons why SIBs may soon take the market.

The charge and discharge performance of LFP is also superior, and it also demonstrates an outstanding energy efficiency ratio in high-temperature environments. On the other hand, during the charging process, ions migrate from the positive electrode to the negative electrode, but electrons cannot travel from the positive electrode to the negative electrode [7]. This leads to the sluggish charging speed of LFP, which makes it easy to create high temperatures during fast charging, resulting in safety issues such as cell loss of control.

4. Costs and future developments

4.1. Cost

In recent years, due to breakthroughs in related technologies, LIBs in various fields have ushered in a surge in popularity and widespread application, which has also led to a surge in demand for LIBs, the main raw material price of the battery, lithium carbonate, has also risen, and year by year [8], the trend is rising. Based on the similarities of the two batteries mentioned above, their cost structures are very similar, the cost of raw materials accounted for the total cost of nearly three-quarters of the total cost. However, the remaining costs, such as labour and depreciation, only accounted for a small portion of the total cost. The cost of raw materials is divided into cathode material cost, anode materials cost, diaphragm cost, electrolyte cost, fluid collector cost and other costs. Since there is not much difference between the two in many parts of the cost, we focus on discussing the parts that lead to the huge difference: cathode material, fluid collector material, and anode material cost.

Anode materials, as the major part of material costs, account for one-third to one-half of the raw material costs of batteries. $LiCoO_2$ and $LiFePO_4$ are mainly used in LIBs, while SIBs mainly use vanadium oxides, such as $Na_3V_2(PO_4)_3$, and manufacturers usually purchase lithium carbonate and sodium carbonate as raw materials. According to the data from network show (November 14, 2023), the current price of battery-grade lithium carbonate is maintained at 160,000 yuan per ton up and down, while in contrast, the price of high-quality sodium carbonate ($Na_2CO_3 \geq 99.2\%$) is only about 2,050 yuan per ton, the price of the sodium resource compared to lithium is much cheaper.

Collector materials are also a major factor in the cost difference. At present, the main use of copper foil and aluminium foil. According to the above, sodium-ion batteries mainly use cheaper aluminium foil for positive and negative collectors. In contrast, lithium-ion batteries use aluminium foil for the positive collector and copper foil for the negative collector. According to the data from network, the price of electrolytic copper is about 67,800 yuan per ton, while the price of aluminum is only about 18,900 yuan per ton. Sodium-ion batteries' cost of collectors is much lower than that of LIBs.

As mentioned above, SIBs have higher anode material costs compared to LIBs due to technical limitations. This is because they cannot use common graphite materials. However, the price difference is not significant enough to impact the overall price. The differences between the remaining components of these batteries are so minimal that they do not significantly impact cost, so that we will not talk about it more.

4.2. Future development

According to the current situation, the LIBs technology is very mature, in terms of energy density, operating voltage, cycle life, environmental protection and other aspects. It has outstanding advantages, mainly used in cell phones, notebook computers, digital cameras, power tools, and new energy vehicles and energy storage and other fields, in the future, LIBs will also be more used in aerospace, health care and other high-precision fields.

LIBs will dominate the use of batteries for a long period in the future, and it's difficult to discover a new battery technology to completely replace LIBs in a short period. However, due to limited lithium resources, coupled with the demand for lithium resources rising year by year, the scarcity of tense lithium resources will become more sought after, if you cannot find an effective alternative, is tantamount to fishing in troubled waters, resulting in the consequences of the LIBs prices, lithium resource shortages and other real problems, LIBs will also be difficult to reach the demand of the electric vehicles and large-scale storage industries' development. Thus, the need to develop a resource-rich and inexpensive new energy storage system. Against this background, thanks to the development of SIBs, its advantages, such as resource-rich, inexpensive, environmentally friendly nature and have similar properties to LIBs, makes it a new option for energy storage. Elemental sodium ranks sixth in the earth's crust, has a very high abundance, and is widely distributed. Sodium and lithium have similar physicochemical and electrochemical properties and reaction mechanisms, so SIBs are expected to have the similar electrochemical performance as the LIBs. SIBs's structure and principles and production lines and so on are the same as LIBs, there is the possibility of realizing the initial replacement. However, given the current research results, SIBs have many shortcomings which cannot be avoided, for example, low battery energy density, cycle times and service life and other defects that are limiting the future development of SIBs.

At present, the SIBs are still in its infancy, several domestic and foreign enterprises are in the research and development and trial production stage, and the more mature Ningde Times to Prussian blue compounds/hard carbon for the battery system has formed the basis of the industrial chain, the production of SIBs in the -20 ℃ such as extreme environments can also maintain excellent battery efficiency. According to the current development trend, SIBs shortly in portable appliances, part of the scene under the electric car can have good application prospects, if the future SIBs can overcome some of the shortcomings, will get better development [9, 10].

5. Conclusion

In summary, SIBs and LIBs have their own advantages and drawbacks. SIBs are better than LIBs in terms of resource abundance, mining feasibility, safety, recyclability, and performance in extreme conditions. However, they have lower battery energy density, fewer cycles, and shorter service life. A combination of the two batteries with complementary advantages and disadvantages can be the best solution. For example, in the low-temperature environment (-20 ℃), lithium batteries cannot be used normally, SIBs can maintain more than 90% of the charging and discharging efficiency. While SIBs have the potential to replace LIBs in many ways, their current technical limitations make it difficult for them to meet expectations. However, it is believed that once these difficulties are overcome, SIBs will have better prospects for practical applications.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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