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Review

Recent advances in Sodium-ion battery research: Materials, performance, and commercialization prospects

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Abstract: Sodium-ion (Na-ion) batteries are becoming more popular as a budget-friendly and eco-friendly substitute for lithium-ion batteries, thanks to the plentiful supply of sodium and its reduced raw material expenses. Recent developments in sodium-ion battery research have concentrated on enhancing the performance of crucial elements such as cathodes, anodes, and electrolytes. Important advancements have been achieved in the creation of high-capacity cathodes, including layered transition metal oxides, Prussian blue analogs, and polyanionic compounds, as well as anode materials like hard carbon and alloy-based compounds. Research on electrolytes, including solid-state and ionic liquid options, aims to improve ionic conductivity, cycle stability, and prevent issues like dendrite formation. Although sodium-ion batteries generally have a lower energy density compared to lithium-based batteries, they exhibit significant potential for large-scale uses such as grid energy storage, where cost and cycle life are more important than energy density. This review highlights recent breakthroughs in Na-ion technology and discusses the growing prospects for its commercialization in the near future.

Keywords: Na-ion batteries; cathode materials; anode materials; solid-state electrolytes; cycling stability; dendrite formation

1. Introduction

The quest for improved energy storage technologies has accelerated in the past few years, fueled by the increasing need for incorporating renewable energy, electric vehicles (EVs), and portable electronic gadgets. While lithium-ion (Li-ion) batteries remain the dominant technology for energy storage, concerns over the high cost, limited availability, and environmental impact of lithium have prompted researchers to explore alternative battery chemistries. Sodium-ion (Na-ion) batteries have attracted significant interest because sodium is abundant, inexpensive, and environmentally friendly. These batteries present a viable option, especially for large-scale energy storage solutions like grid storage, where cost is more important than energy density [1–3]. This study aims to explore the recent advancements in sodium-ion (Na-ion) battery technology, examine the current limitations and drawbacks, and propose potential research directions to address these challenges. Na-ion batteries function in a manner akin to Li-ion batteries, utilizing sodium ions (Na^+) for the processes of charging and discharging, as illustrated in **Figure 1**.

Sodium ranks as the sixth most plentiful element in the Earth's crust and is found in widespread locations, making it a more viable and economical choice when compared to lithium. The process of extracting sodium has a comparatively lower environmental impact, positioning Na-ion technology as an appealing alternative to lithium-based battery systems. These benefits have generated interest in Na-ion batteries, especially for large-scale energy storage solutions, where high energy density matters less than cost, lifespan, and safety considerations [4–7].

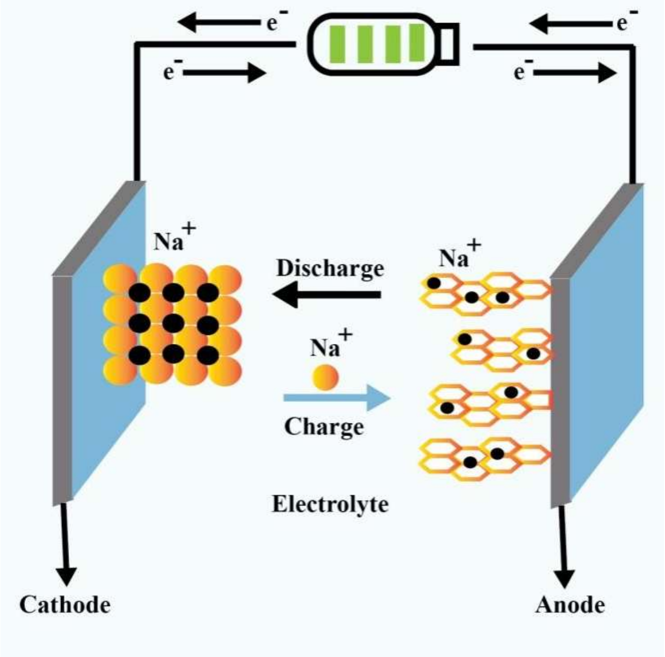

Figure 1. Schematic representation of sodium-ion battery cell.

Although Na-ion batteries offer several benefits, they encounter significant obstacles that impede their broader use. The main issue is their reduced energy density in comparison to Li-ion batteries. This is primarily attributed to the greater ionic radius and heavier atomic weight of sodium, which constrains the specific capacity of Na-ion electrodes and diminishes the total energy output of the battery [8–10]. In addition, the larger volume changes that occur during the insertion and extraction of sodium ions can cause mechanical stress and degradation in electrode materials over repeated cycling, leading to shorter battery life and poor cycling stability [11,12]. Furthermore, Na-ion batteries often perform poorly at low temperatures, making them less suitable for certain applications without further improvements in electrolyte and material chemistry [13,14].

Recent strides are being made to tackle the issues associated with Na-ion battery technology. Scientists are diligently working on innovative cathode and anode materials to enhance the energy density, longevity, and cycle life of Na-ion batteries. For instance, progress in layered transition metal oxide cathodes, Prussian blue analogues, and polyanionic compounds has demonstrated encouraging results concerning both capacity and structural integrity [15,16]. In a similar vein, the advancement of hard carbon anodes and materials based on alloys is enhancing the performance of Na-ion batteries by tackling problems like low capacity and inadequate cycling stability [17,18]. Another major area of progress is the development of advanced electrolytes. Innovations in liquid, solid-state, and ionic liquid electrolytes are improving the overall performance of Na-ion cells by enhancing ionic conductivity, thermal stability, and cycling efficiency. Solid-state electrolytes, in particular, hold the potential to significantly improve safety, mitigate dendrite growth, and increase energy density, which could be crucial for enabling Na-ion batteries to compete with Li-ion batteries in a wider range of applications [19,20].

The affordability and availability of sodium make Na-ion batteries particularly ideal for large-scale uses such as grid energy storage, where cost efficiency, long lifespan, and scalability are more important than achieving the highest energy density. In grid storage systems, Na-ion batteries could offer an economical and sustainable means of storing fluctuating renewable energy, like solar and wind power, while also aiding grid stability by holding surplus energy for future use. This paper presents a summary of the latest developments in Na-ion battery technology, highlighting significant progress in materials, electrolytes, and battery construction. It also addresses the persistent issues that Na-ion batteries encounter and their potential for commercial use, especially in large-scale energy storage scenarios. As research advances, Na-ion batteries are set to become increasingly significant in the upcoming generation of sustainable energy storage solutions, providing a cost-effective and eco-friendly option compared to lithium-ion batteries.

2. Recent progress in Sodium-ion battery technology

Sodium-ion (Na-ion) batteries are increasingly being recognized as a viable substitute for lithium-ion (Li-ion) batteries, particularly in large-scale energy storage applications, owing to sodium’s abundant availability and lower cost. Recent developments have significantly improved the performance of Na-ion batteries by enhancing materials, electrolytes, and design. These innovations are progressively tackling the issues of energy density, stability, and cycling efficiency, thereby making Na-ion batteries more competitive with conventional Li-ion systems. In the following section, we will examine the crucial advancements that are influencing the future of Na-ion technology.

3. Advancements in cathode materials

The cathode material in Na-ion batteries significantly influences their energy density, voltage, and cycle life as illustrated. Research in this area has focused on optimizing existing materials and discovering new compounds that can enhance battery performance [21,22]. J. Wang et al. pointed out that $Na_4MnCr(PO_4)_3$ stands out as an effective cathode material for sodium-ion batteries, exhibiting a high specific capacity of 130 mAh g^{-1} during discharge. This capability is achieved through high-voltage redox transitions involving Mn^{2+}/Mn^{3+} (3.5 V), Mn^{3+}/Mn^{4+} (4.0 V), and Cr^{3+}/Cr^{4+} (4.35 V) transition metals. Additionally, $Na_4MnCr(PO_4)_3$ demonstrates exceptional rate capability (97 mAh g^{-1} at 5 °C) and outstanding performance across a wide temperature range [23]. Moreover, as cathodic materials in Na-ion batteries, the galvanostatic cycling of Ni1/3Fe1/3Co1/3O2 displays excellent performance within the voltage window of 2.0 to 4.2 V, resulting in about 165 mAh/g of reversible capacity at 20 °C. This material also exhibits remarkable rate capability, being able to de-intercalate 80 mAh/g even at a temperature of 30 °C [24].

3.1. Multilayer transition metal oxides

Transition metal oxides like sodium nickel manganese cobalt oxide (NCM) [25] and sodium cobalt oxide ($NaCoO_2$) [26] are widely used as cathode materials because of their impressive theoretical capacity and voltage. Recent research has concentrated on enhancing their stability and performance by employing doping or coating techniques. For instance, doping with elements like magnesium (Mg) or titanium (Ti) can enhance both capacity and cycling stability, making these materials more reliable for long-term use [27–29]. A. Kanwade et al. pointed out that the different phases of layered transition metal oxides ($NaxMO_2$, where TM denotes Co, Mn, Ti, Ni, Fe, Cr, Al, V, or any combinations of these metals) display impressive cycling performance, structural integrity, and Na^+ ion conductivity, making them strong candidates for cathode materials in sodium-ion batteries (SIBs) [30].

3.2. Polyanionic compounds

Sodium-based polyanionic cathodes, such as $Na_3V_2(PO_4)_2F_3$ and $NaFePO_4$, are being developed for their excellent structural stability, high voltage, and safety characteristics [31,32]. Although their energy density is generally lower compared to transition metal oxides, polyanionic compounds offer advantages in terms of thermal stability and longer cycle life, which are crucial for safety in large-scale applications. Conversely, polyanionic compounds such as $(PO_4)^{3-}$, $(SiO_4)^{4-}$, $(SO_4)^{2-}$, and $(BO_3)^{3-}$ have gained increased attention lately due to their ability to stabilize structures, alter redox couples, and provide migration routes for “guest” ions. As a result, this contributes to electrode materials that exhibit extended cycling, higher energy density, and outstanding rate performance [33,34]. Besides this, Z. Zou et al. improved $Na_3V_2(PO_4)_3$ as a sodium-ion battery cathode by designing a biphasic heterostructure with $Na_{3.5}V_{1.5}Fe_{0.5}(PO_4)_3$ (NVFP) and V_2O_3 (NVFP–VO) in a porous carbon framework. Fe doping reduced the bandgap, boosting conductivity and capacity, while the V_2O_3 phase stabilized the structure and enhanced ion transport. The cathode achieved over 130 mAh g^{-1} at 0.1C, 72.6% capacity retention after 100,000 cycles at 100C, and pouch cells showed 153.4 Wh kg^{-1} energy density and over 500 cycles, marking the longest cycle life for polyanion-based cathodes [35]. The polyanionic crystal nanomaterials discussed in **Figure 2** for the recent development of sodium-ion battery electrodes.

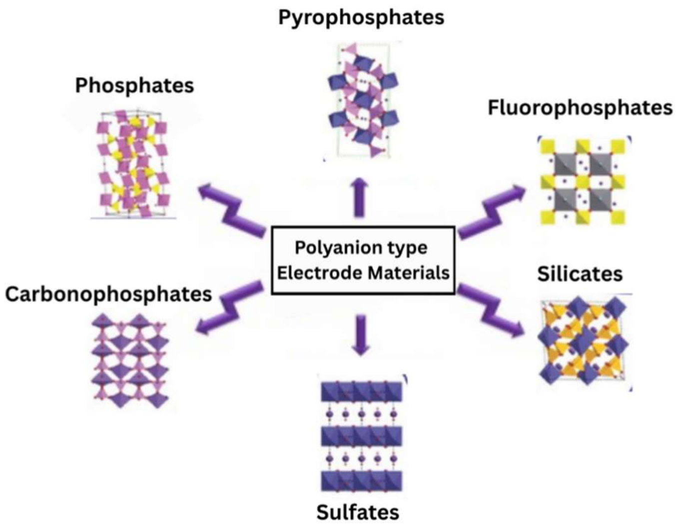

Figure 2. Polyanionic crystal nanomaterials for development of Na-ion battery.

3.3. Prussian blue analogues (PBAs)

PBAs are a low-cost alternative to more complex cathode materials. These compounds feature a porous framework that allows for efficient sodium-ion diffusion, making them ideal for fast charging and high-rate applications [36–38]. While PBAs have a lower energy density compared to certain other cathodes, their affordability and eco-friendliness render them a compelling choice for large-scale storage applications.

4. Developments in anode materials

The anode is essential in influencing the energy storage ability and lifespan of Na-ion batteries. The greater ionic radius of sodium relative to lithium poses difficulties for the anode material, especially concerning volume variations during charging and discharging cycles. Recent studies have concentrated on overcoming these obstacles through innovative material design.

4.1. Hard carbon

Hard carbon continues to be the predominant anode material for Na-ion batteries because it effectively accommodates sodium ions within its disordered and porous structure. Recent studies have aimed at enhancing the porosity and surface characteristics of hard carbon to boost its sodium storage potential, rate capability, and cycling durability, as illustrated in **Figure 3**. Altering the surface of the material has been demonstrated to minimize side reactions and improve the reliability of the solid-electrolyte interphase (SEI) layer, which is essential for extended cycle life [39–41]. In 2018, Li et al. [42] created a highly defective form of hard carbon through a microwave treatment method, produced from cellulose pyrolysis at 650 °C. Following just 6 s of microwave irradiation, the reversible capacity of this hard carbon rose from 204 to 308 mAh/g, greatly exceeding the capacity of hard carbon that had been annealed at 1100 °C for 7 h, which was 274 mAh/g [42].

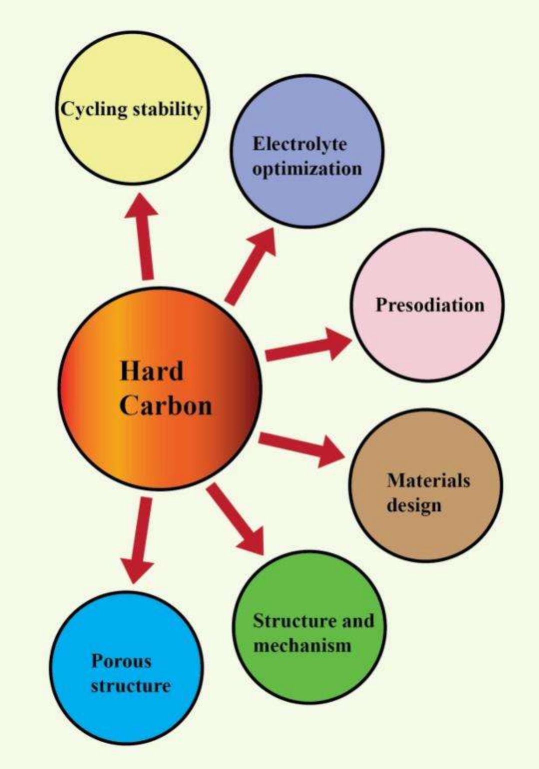

Figure 3. Factors affecting hard carbon anode performance in Na-ion batteries.

4.2. Alloy-based anodes

Materials like tin (Sn), antimony (Sb), and phosphorus (P) can alloy with sodium to form compounds with high theoretical capacities. However, these materials suffer from large volume changes during cycling, which can cause mechanical degradation and lower the battery's cycle life in **Figure 4** [43–45]. Recent advancements in nano-structuring and composite materials aim to mitigate these effects by providing structural support and enhancing conductivity. For example, combining these alloying materials with carbon-based nanostructures has shown promise in improving both capacity and stability [46,47]. Wang et al. [48] investigated the impact of cobalt (Co) content on the sodium storage performance of $Sn_{1-x}Co_x$ alloys (with x ranging from 0.2 to 0.5). The reduction in capacity observed with increased Co content was due not only to Co's lack of reactivity with sodium but also to its limited Na+ diffusion rate, which hindered access to tin (Sn) in the alloys. The sample Sn0.7Co0.3 exhibited the best performance, demonstrating a relatively high reversible capacity and strong cycle stability, yielding about 200 mAh/g over 80 cycles at room temperature and around 300 mAh/g over 60 cycles at 40 °C [48].

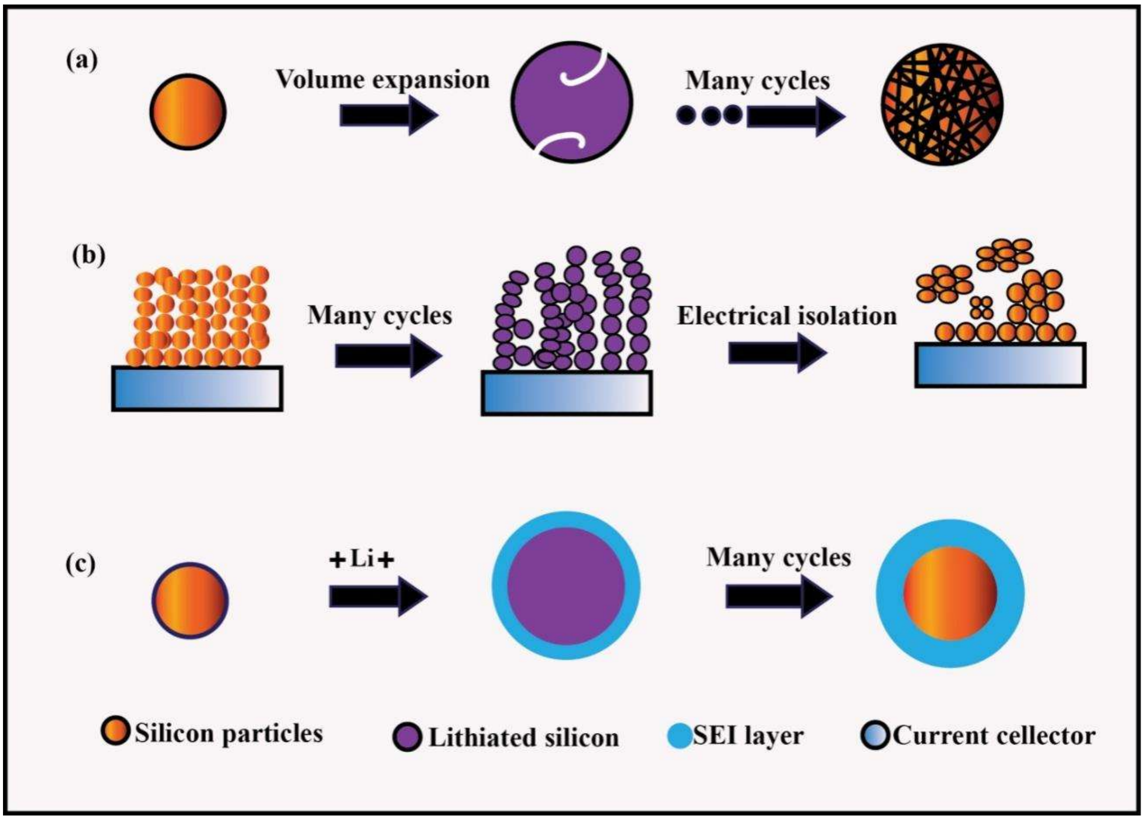

Figure 4. Degradation mechanisms of Si-based electrodes: **(a)** pulverization; **(b)** delamination; **(c)** unstable SEI layer.

In addition to this, Anatase TiO_2 has gained attention as an anode material for sodium-ion batteries because of its slight volume fluctuations and robust safety characteristics; nonetheless, its restricted capacity and insufficient rate performance hinder its practical use. To overcome these challenges, a bi-solvent enhanced pressure technique has been developed to produce N-doped TiO_2/C nanocomposites. This technique generates oxygen vacancies, minimizes particle size, and enhances electrical conductivity by employing ethanol and dimethylformamide as solvents. The resultant defects create additional ion storage sites, lower the bandgap, and improve ion diffusion. The N-doped TiO_2 preserves a stable crystal structure with slight alterations after sodiation, leading to high capacity, excellent rate performance, and extended cycling life. This approach offers fresh insights into the development of high-capacity, rapid-charging anode materials utilizing TiO_2 [49]. In 2024, M. Han and colleagues discovered that FeS/C yolk-shell nanosheets achieve an impressive reversible capacity of 664.9 mAh g^{-1} at a rate of 0.1 A g^{-1}, and after 10,000 cycles at a current of 10 A g^{-1}, they maintain 300.4 mAh g^{-1}, resulting in a capacity retention of 81.1% [50].

4.3. Graphene and carbon composites

Graphene-based materials are being explored for their excellent conductivity, mechanical strength, and flexibility. When combined with other materials such as tin or antimony, graphene can enhance the overall performance of the anode by improving conductivity and accommodating the volume changes associated with sodium-ion insertion. These composites are a promising direction for future Na-ion anodes, particularly for applications requiring high power and stability [51–56]. A schematic structure of graphene and its derivatives is shown in **Figure 5**. Recently, composites containing different amounts of multi-walled carbon nanotubes (MWNTs) were created by mechanically mixing MWNTs with an SHC precursor to manipulate nanopore density and enhance reversible sodium insertion/desorption at low charge/discharge (C/D) voltages. The incorporation of well-dispersed MWNTs into the SHC matrix decreased the crystallite size of SHC and increased the densities of meso-to-macropores in the composites. These modifications contributed to improved reversible capacity and better cyclability of the composite. With an optimal MWNT concentration of 5%, the composite achieved a reversible capacity of 300 mAh·g^{-1} at 20 mA·g^{-1}, surpassing the 221 mAh·g^{-1} recorded for pure SHC. This performance remained consistent after 50 C/D cycles, with the composite maintaining a strong capacity of 280 mAh·g^{-1}, while SHC showed 220 mAh·g^{-1} [57].

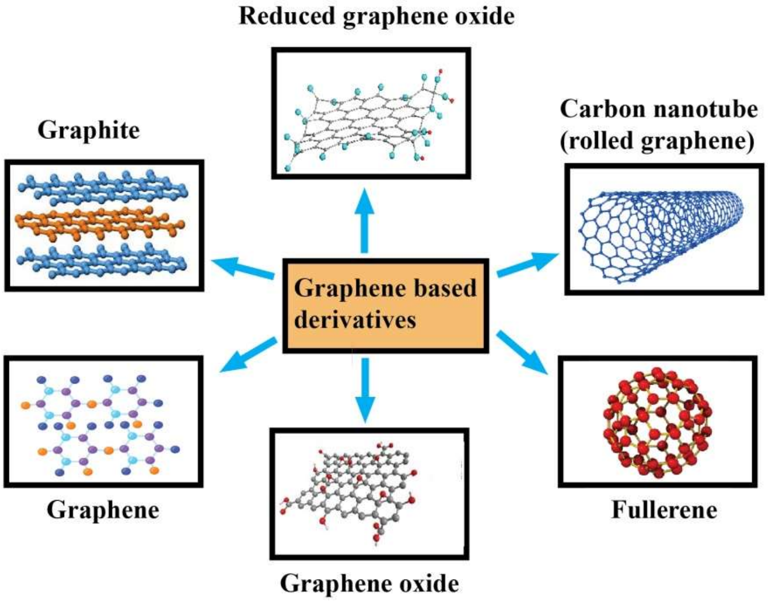

Figure 5. Schematic illustration of structures of graphene and its derivatives.

5. Electrolyte innovations

The electrolyte is a key component of Na-ion batteries, affecting ionic conductivity, stability, and safety. Recent innovations in electrolyte chemistry focus on improving performance, reducing degradation, and preventing issues like dendrite formation.

5.1. Solid-state electrolytes

Solid-state electrolytes (SSEs) represent a significant breakthrough for sodium-ion batteries. These materials offer advantages such as non-flammability and increased thermal stability, and they may improve the energy density of sodium-ion cells. Among the most promising options are sodium-conducting ceramics and sulfide-based electrolytes. Nevertheless, challenges persist in achieving high ionic conductivity and ensuring compatibility with the electrode materials. Researchers are also working on enhancing the interface between solid electrolytes and electrodes to reduce resistance and improve performance [58–60]. An all-solid-state battery utilizing solid-state electrolytes is depicted in **Figure 6**. Recent research has investigated yttrium halide-based compounds (Na3YX6, where X = Cl or Br) that contain inherent cation vacancies, acting as diffusion carriers for solid electrolytes in sodium-ion batteries (ASIBs). These compounds provide an excellent combination of electrochemical stability and ionic conductivity, effectively overcoming the shortcomings of sulfide- and oxide-based solid-state electrolytes. Specifically, Na3YCl6 and Na3YBr6 demonstrate Na+ conductivities of 0.77 and 0.44 mS cm–1 at 300 K, respectively, along with extensive electrochemical windows of 0.51–3.75 V and 0.57–3.36 V. Furthermore, they exhibit robust interfacial stability with sodium metal anodes and high-voltage polyanion (fluoro) phosphate cathode materials [61].

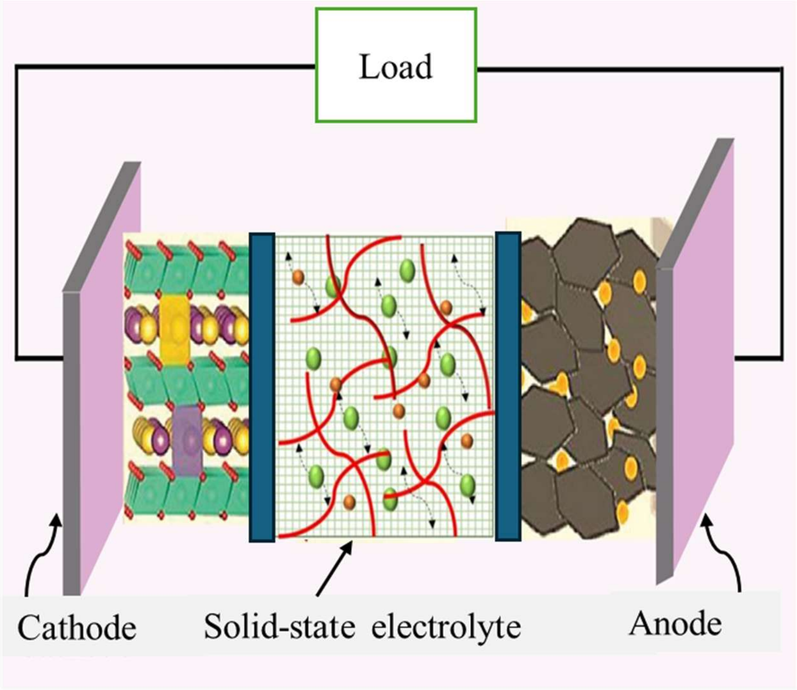

Figure 6. All solid-state battery with the solid-state electrolyte.

5.2. Ionic liquids

Ionic liquids (ILs), which are salts that remain in a liquid state at room temperature, are being investigated for use in Na-ion batteries due to their wide electrochemical stability window and high ionic conductivity. ILs can offer improved safety by reducing the volatility of traditional organic solvents. They are also less prone to forming undesirable by-products during cycling, making them a safer and more stable alternative to conventional electrolytes [62–64]. In a research conducted by F. Wu et al., innovative ionic liquid (IL) electrolytes were created through the combination of 1-ethyl-3-methylimidazolium bis-tetrafluoroborate (EMIBF4) and varying amounts of sodium salt (NaBF4). These IL electrolytes displayed an extensive electrochemical window of about 4 V (spanning from 1 to 5 V), which corresponded well with theoretical predictions from quantum chemical calculations. The IL electrolyte with a concentration of 0.1 M NaBF4 showed remarkable ionic conductivity measuring 9.833×10^{-3} S cm^{-1} at 20 °C [65].

5.3. Gel and hybrid electrolytes

Gel electrolytes, which combine the properties of liquid and solid-state electrolytes, are being explored as a way to improve both conductivity and safety. Gel electrolytes can reduce leakage risks while maintaining high ionic conductivity, and they can potentially offer better cycling performance compared to traditional liquid electrolytes. Hybrid electrolytes, which incorporate both solid and liquid components, are also being investigated for their potential to improve performance in Na-ion batteries [66–68]. A hybrid solid-state electrolyte (HybSSE) was created using halloysite clay-derived Na_2ZnSiO_4 ceramic combined with an ionic liquid through high-throughput techniques. This method led to the production of more than 700 ceramics to refine the synthesis and evaluate 22 distinct substituents at eight different levels of substitution. The resulting HybSSE exhibited remarkable ionic conductivities of up to 0.453 mS cm^{-1} at ambient temperature and 2.27 mS cm^{-1} at 48 °C [69].

5.4. Electrolyte additives

Additives in the electrolyte can play a significant role in improving the solid-electrolyte interphase (SEI), which governs the stability and longevity of Na-ion batteries. Additives such as fluoroethylene carbonate (FEC) [70,71] and vinylene carbonate (VC) [72,73] have been shown to enhance SEI formation, reduce dendrite growth, and improve cycling stability.

6. Battery Design and Architecture Innovations

To maximize the performance of Na-ion batteries, innovations in battery design are essential. These advancements aim to improve efficiency, scalability, and the longevity of Na-ion batteries in real-world applications.

6.1. Advanced Separators

The separator in a Na-ion battery must prevent short circuits while allowing efficient ion flow. Recent research has focused on developing high-performance separators with enhanced thermal stability and mechanical strength. Nanostructured separators and those with conductive coatings are being explored to improve the ionic conductivity and safety of the battery [74,75]. X. Casas et al. assessed an innovative membrane separator for use in $Na_3V_2(PO_4)_3$/Na half-cells. After completing 10 cycles at a rate of C/10, the cellulosic separator exhibited a capacity of 74 $mA \cdot h \cdot g^{-1}$ with a Coulombic efficiency of 100%, surpassing the performance of the commercially available Whatman GF/D separator, which provided 61 $mA \cdot h \cdot g^{-1}$ and 96% efficiency [76].

6.2. Electrode coatings and nano-structuring

Electrode coatings improve Na-ion battery performance by enhancing conductivity, protecting electrodes from degradation, and increasing stability. Common coatings include carbon-based materials (e.g., graphene) and conductive polymers (e.g., polyaniline), which boost electrode conductivity and shield against side reactions. Nanostructuring involves designing materials at the nanoscale to improve capacity, ion diffusion, and structural stability. Nanostructures, such as nanoparticles, nanotubes, and porous materials, increase surface area, reduce volume changes, and enable faster ion movement, enhancing the battery's rate performance and lifespan. Together, coatings and nanostructuring address key challenges in Na-ion battery technology, improving efficiency, longevity, and stability [77–79]. Previous studies have shown that carbon-coated $Na_3V_2(PO_4)_3$ cathodes benefit from different nitrogen species (pyridinic N, pyrrolic N, and quaternary N). Pyridinic and pyrrolic nitrogen species enhance electronic conductivity, create active sites, and increase defects, while quaternary nitrogen only boosts conductivity. The $Na_3V_2(PO_4)_3/C+N$ composite, characterized by a low presence of quaternary nitrogen and a higher number of extrinsic defects, exhibited superior electrochemical performance, especially in terms of rate capability and cycling stability. At a discharge rate of 5 C, it achieved a capacity retention of 83%, and retained 93% capacity after 100 cycles at the same rate of 5 C [80].

6.3. Modular battery designs

For extensive applications, particularly in grid storage, Na-ion batteries need to be both scalable and economically viable. Research efforts are focusing on modular designs that can be easily scaled to address the energy storage requirements of different applications. The objective of these designs is to enhance energy density, optimize thermal management, and lower costs, thereby making Na-ion batteries more appropriate for large-scale utilization. [81,82].

7. Outlook on Sodium-ion batteries (Na-ion)

Sodium-ion (Na-ion) batteries are becoming increasingly recognized as a viable substitute for lithium-ion (Li-ion) batteries, especially in large-scale energy storage contexts. Although Na-ion batteries present significant benefits, including the availability and cost-effectiveness of raw materials (with sodium being much more plentiful than lithium), there are various obstacles that must be overcome for them to achieve widespread commercialization. These challenges affect their performance, scalability, and competitiveness with more established battery technologies is shown in **Figure 7**. Below, we explore the ongoing hurdles facing Na-ion batteries and their potential for widespread adoption, especially in grid-scale energy storage.

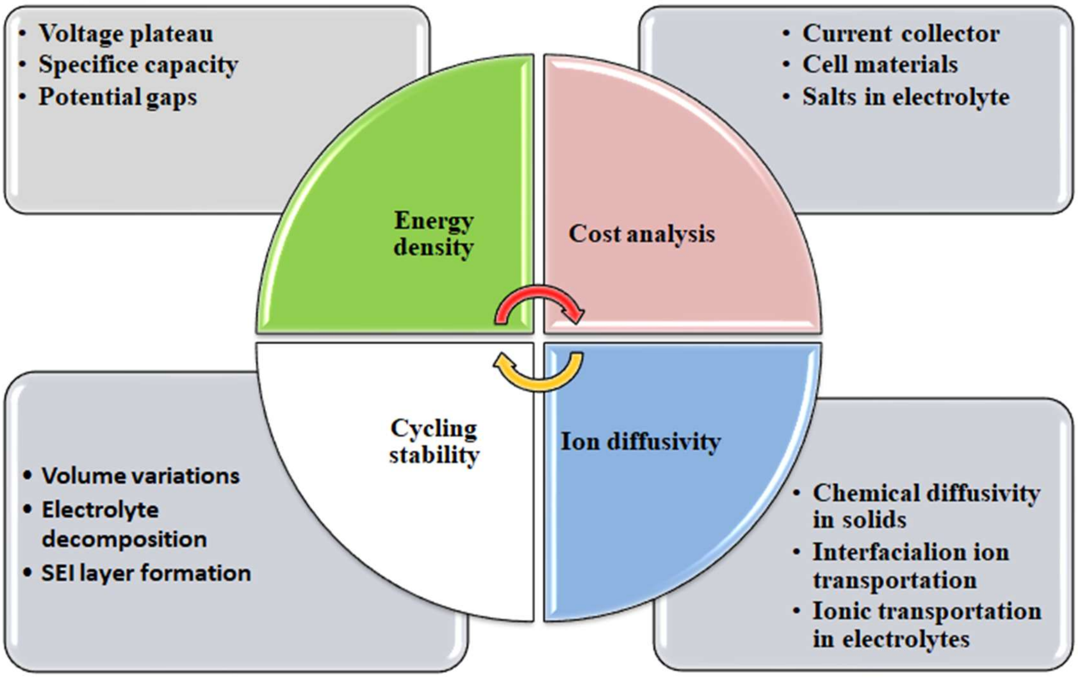

Figure 7. Four important parameters and issues with scalable energy storage systems.

7.1. Lower energy density

One of the primary drawbacks of Na-ion batteries is their reduced energy density when compared to Li-ion batteries. Sodium ions are bulkier and heavier than lithium ions, which limits the energy that can be stored within the same physical volume or weight of the battery. Consequently, Na-ion batteries provide less energy per charge, rendering them less ideal for uses where weight and space are crucial, such as in electric vehicles (EVs) or portable devices. While this lower energy density poses a significant challenge for mobile applications, it becomes a lesser issue for stationary energy storage, where dimensions and weight are not as pressing. In grid storage scenarios, where cost-effectiveness and long-term reliability take precedence over energy density, Na-ion batteries present a viable alternative. Considerable research is underway to enhance the energy density of Na-ion batteries by creating higher-capacity cathode materials (including high-voltage layered oxides, polyanionic compounds, and Prussian blue analogues) and improving the performance of anodes. Through the optimization of electrode materials, it is possible to achieve better energy storage densities, making Na-ion batteries more competitive for larger-scale applications.

7.2. Low-temperature performance

Sodium-ion (Na-ion) batteries generally exhibit inferior low-temperature performance compared to lithium-ion (Li-ion) batteries. This is primarily due to the larger ionic radius of sodium (Na^+) compared to lithium (Li^+), which results in slower ion diffusion and lower conductivity at low temperatures. Additionally, the solid electrolyte interphase (SEI) layer in Na-ion batteries tends to form less effectively in cold conditions, further hindering performance. However, under optimized conditions—such as using hard carbon as the anode and low-temperature electrolytes—Na-ion batteries can show improved low-temperature performance. These optimizations enhance ionic conductivity and stability at lower temperatures, allowing Na-ion batteries to perform better in such environments compared to standard configurations. To address low-temperature performance, researchers are developing novel electrolytes and additives that maintain high ionic conductivity even in colder environments. The use of solid-state electrolytes and ionic liquids, which tend to perform better in low temperatures, could help mitigate this issue. Additionally, improving battery pack designs with better thermal management could also help enhance performance in cold climates.

7.3. Cycle life and stability challenges

One of the ongoing challenges for Na-ion batteries is their cycling stability. The repeated insertion and extraction of sodium ions cause significant volume changes in the electrodes, leading to mechanical stress and degradation over time. This can reduce the battery's overall lifespan and lead to capacity loss. The issue of volume expansion is particularly pronounced in anode materials like alloy-based electrodes, which undergo significant structural changes during cycling. For large-scale applications like grid storage, where long cycle life and stability are crucial, Na-ion batteries must demonstrate excellent cycling performance to be competitive. If the capacity of Na-ion batteries deteriorates too quickly, it will limit their adoption for long-term energy storage. Researchers are focused on improving cycling stability by developing advanced electrode materials that can better accommodate the volume changes associated with sodium ion insertion. For example, hard carbon anodes, which are currently the most widely used in Na-ion batteries, are being optimized to enhance stability. Coatings and surface modifications to prevent degradation, along with the development of solid-electrolyte interphase (SEI) layers that reduce side reactions, are also areas of active research. The comparison of parameters between Na-ion and Li-ion batteries is presented in the **Table 1**.

Table 1. Comparison between of sodium ion vs lithium-ion battery.

Parameter	**Sodium-Ion battery**	**Lithium-Ion battery**
Specific energy	120–190 (Wh/ kg)	93–186 (Wh/ kg)
Cycle Life	2000 to 6000 cycles	3000 cycles
Low temperature performance	At −20 °C capacity retention rate is above 90%	At −20 °C capacity retention rate is above 70%
Heating test (130 °C)	No fires, no explosions	-----------
Discharge rate	3C–5C	1C-3C
Cost	Cheap	Expensive
Flammability	Non-flammable	Flammable
Toxicity of materials	Non-toxic materials, environmentally friendly	Toxic electrolyte materials
Applications	Large-scale energy storage, potential EVs	EVs, consumer electronics, energy storage
Anode material	Hard carbon, Sodium titanate	Graphite
Cathode material	Sodium containing compounds	Lithium containing compounds
Raw material abundance	Sodium (less abundant)	Lithium (abundant)

7.4. Slower ion diffusion and ionic conductivity

Sodium ions are larger than lithium ions, which makes their diffusion through the electrolyte slower. This leads to lower ion conductivity in Na-ion batteries, which in turn limits their power output and rate capability. Fast charging and high-power discharge, which are important in many high-performance applications like electric vehicles and fast grid response systems, can be problematic for Na-ion batteries due to this slower ion movement. The slower ion mobility in Na-ion batteries could hinder their performance in applications that require rapid charge and discharge cycles, such as electric vehicles, high-rate energy storage, or frequency regulation for the grid. Advances in electrolyte chemistry, such as the development of ionic liquids and solid-state electrolytes, are being explored to enhance ionic conductivity. Additionally, optimizing the microstructure of electrode materials (e.g., nano-structuring) and developing new separator technologies can improve the rate capability of Na-ion batteries, allowing them to perform better in high-power applications.

7.5. Manufacturing and scalability issues

While sodium is abundant, Na-ion battery technology still faces challenges in scaling up production to match the efficiency and cost-effectiveness of lithium-ion batteries. Lithium-ion batteries benefit from a well-established manufacturing infrastructure that allows for significant cost savings through economies of scale. In contrast, the production framework for Na-ion batteries is still in its early stages, and ramping up output could be a significant challenge. For Na-ion batteries to become commercially viable, they must be produced at a competitive price. If manufacturing methods remain costly or inefficient, Na-ion batteries will struggle to capture market share, particularly in applications where cost is a key factor, such as large-scale energy storage. Efforts are underway to improve the manufacturing processes for Na-ion batteries, including optimizing the production of key components like sodium-based cathodes and anodes, as well as enhancing electrode fabrication techniques. Additionally, reducing the environmental and financial costs associated with sodium extraction and processing could further improve the cost-effectiveness of Na-ion batteries. As research advances, manufacturing processes are expected to become more efficient, leading to lower costs and better scalability for Na-ion technology.

7.6. Market competition and commercial adoption

Na-ion batteries face significant competition from Li-ion batteries, which currently dominate the energy storage market. Li-ion technology benefits from continuous improvements in energy density, cycle life, and manufacturing processes, making it a formidable competitor for Na-ion batteries. The high energy density of Li-ion batteries makes them the preferred choice for applications like electric vehicles (EVs) and portable electronics, where space and weight are critical factors. For Na-ion batteries to successfully enter the commercial market, they must offer distinct advantages over Li-ion batteries, particularly in terms of cost and sustainability. While Na-ion batteries hold promise for being more affordable and environmentally friendly, they need to prove that they can deliver comparable or even superior performance in specific use cases. Na-ion batteries are likely to carve out a niche in large-scale, stationary energy storage applications, where factors like cost-effectiveness, long cycle life, and safety outweigh the need for high energy density. Grid storage for renewable energy is an ideal area for Na-ion batteries, as they could provide an affordable, scalable solution for storing excess energy from solar or wind sources. If Na-ion technology can be optimized for these applications, it could serve as a valuable complement to Li-ion systems, offering a sustainable and cost-effective alternative for large-scale energy storage.

7.7. Path to commercialization of Na-ion batteries

Na-ion batteries offer a promising, cost-effective alternative to Li-ion batteries, especially for large-scale energy storage, thanks to the abundance of sodium. However, challenges remain in improving energy density, cycle life, and low-temperature performance. Key steps for commercialization include:

7.7.1. Performance improvements

Advancing cathode, anode, and electrolyte materials is essential for improving energy storage technologies, especially in the context of rechargeable batteries, such as lithium-ion (Li-ion) batteries and next-generation batteries. Improving energy density, cycling stability, and rate capability is crucial for applications ranging from electric vehicles (EVs) to portable electronics, as these characteristics directly impact performance, longevity, and overall efficiency.

7.7.2. Manufacturing scale-up

Optimizing production processes to lower costs and achieve economies of scale is crucial for making advanced materials and technologies more accessible, efficient, and cost-effective. This optimization is particularly important in industries like energy storage (e.g., battery manufacturing), electronics, automotive, and renewable energy, where large-scale production is needed to meet increasing demand and reduce unit costs.

7.7.3. Grid storage applications

Na-ion batteries are ideal for stationary storage, especially for renewable energy integration, where cost and longevity are more important than energy density.

7.7.4. Regulatory support

Policy incentives and industry standards will accelerate adoption and drive market growth. With continued research and advancements, Na-ion batteries have strong potential for large-scale, sustainable energy storage.

8. Conclusion

Sodium-ion (Na-ion) batteries present a promising, cost-effective alternative to lithium-ion (Li-ion) batteries, particularly for large-scale energy storage. While challenges remain, such as lower energy density, shorter cycle life, and performance issues at low temperatures, substantial progress is being made in improving Na-ion technology. Advances in materials, electrolytes, and manufacturing techniques are gradually addressing these limitations, making Na-ion batteries more competitive. The abundance and affordability of sodium give Na-ion batteries a distinct advantage, especially for applications like grid energy storage, where factors like cost-effectiveness, long lifespan, and sustainability are more important than high energy density. As research and production capabilities grow, Na-ion batteries are well-positioned to complement Li-ion technology, providing a more affordable and eco-friendly solution for storing renewable energy. In the long run, Na-ion batteries could transform the energy storage market, offering a reliable and sustainable alternative to conventional technologies. With ongoing innovation and strong industry backing, Na-ion batteries have the potential to play a vital role in advancing the transition to a cleaner, more sustainable energy future.

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