Sodium-ion battery technology: Advanced anodes, cathodes and electrolytes

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Abstract—The development of electric vehicles has made massive progress in recent years, and the battery part has been receiving constant attention. Although lithium-ion battery is a powerful energy storage technology contemporarily with great convenience in the field of electric vehicles and portable/stationary storage, the scantiness and increasing price of lithium have raised significant concerns about the battery's developments; an alternative technology is needed to replace the expensive lithium-ion batteries at use. Therefore, the sodium-ion batteries (SIBs) were brought back to life. Sharing a similar mechanism as the lithium-ion batteries makes SIBs easier to understand and more effective in the research. In recent years, the developed materials for anode and cathode in the SIB have extensively promoted its advancements in increasing the energy density, power rate, and cyclability; multiple types of electrolytes, either in the form of aqueous, solid, or ions, offers safety and stability. Still, to rival the lithium-ion batteries, the SIB needs much more work to improve its performance, further expanding its application. Overall, the SIB has tremendous potential to be the future leading battery technology because of its abundance.

1. Introduction
Nowadays, large-scale renewable energy implementation requires the growth of efficient energy storage system production. As renewable energy generation technologies such as solar become more common and integrated into the grid, extending battery technology to large-scale storage will become necessary. Although lithium-ion batteries have already achieved incredible success, there are still problems related to lifetime, cost, and performance due to the similar chemical properties in alkali metals. Sodium-ion battery (SIB) technology has made enormous progress nowadays. Lithium and sodium are two members referred to as group 1 elements of the periodic table. Both are alkali metals and possess one loosely held electron in each valence shell. Alkali metals are very reactive, and their melting point and first ionization energy decrease down the group. Table 1 below lists some physical properties that correspond to the sodium and lithium-ion battery development [1].
Table 1. Physical properties of lithium and sodium [2, 3]

| Property                        | Li         | Na         |
|--------------------------------|------------|------------|
| Atomic mass [g·mol⁻¹]           | 6.94       | 22.99      |
| Electron configuration          | [He] 2s¹   | [Ne] 3s¹   |
| Cationic radius [Å]             | 0.76       | 1.02       |
| Standard electrode potential [V]| −3.04      | −2.71      |
| Melting point [°C]              | 180.5      | 97.7       |
| Density [g·cm⁻³]                | 0.971      | 0.534      |
| First ionization energy [kJ·mol⁻¹] | 520.2    | 495.8      |
| Theoretical gravimetric capacity [mAh·g⁻¹] | 3861     | 1165       |
| Theoretical volumetric capacity [mAh·cm⁻³] | 2062     | 1131       |
| Coordination preference         | Octahedral and tetrahedral | Octahedral and prismatic |
| Cost, carbonates                | $5000/ton  | $150/ton   |

The table demonstrated that the standard reduction potential of Na⁺/Na is −2.71 V while Li⁺/Li referred to as −3.04 V, which is quite essential. Since this potential is corresponding with the thermodynamic minimum limit for the anode, in most cases, the anodic electrode potentials for SIBs will always be higher than those of LIB. Although LIBs have higher volumetric and gravitational, the SIB can still replace the lithium-ion battery position due to its low cost inferred from the table and its vast abundance in nature. The Tesla battery supplier Contemporary Amperex Technology Co. Ltd. unveiled a SIB. This lower-density cell uses cheaper raw materials than batteries made from lithium-ion metals recently, which implied the trend of SIB application [4]. This review will discuss the working principle of battery, anode, and cathode material selection for SIB, electrolyte, and main challenges in the future.

2. Working principle

The working principle of a SIB is similar to that of the lithium-ion battery, which uses the embedding and stripping process of sodium-ion between positive and negative electrodes to realize charge and discharge. Na⁺ is separated from the positive material and embedded into the negative material through the electrolyte during charging. Electrons are transferred to the negative through the external circuit to maintain charge balance. On the contrary, Na⁺ is removed from the negative electrode and embedded into the positive electrode through an electrolyte. Under normal charge and discharge conditions, the insertion and removal of sodium-ion between the positive and negative electrodes do not damage the basic chemical structure of the electrode material. Sodium maintains a stable ionic form throughout the cycle of falling off and embedding. Sodium ions can cause chimera or swing at the battery's two poles, also called "Rocking chair battery".
The main feature of SIBs is to replace expensive Li$^+$ with Na$^+$. The positive, negative, and electrolyte shall be changed accordingly to adapt to the SIB. Since the SIB has no over-discharge characteristics, the SIB is allowed to discharge to zero volts. The energy density of SIBs is greater than 100Wh/kg, which is comparable to lithium iron phosphate batteries. Meanwhile, it has an obvious cost advantage and is expected to replace the traditional lead-acid battery in large-scale energy storage. Since 2010, a series of anode and cathode materials have been designed and developed according to the characteristics of the SIB, which has dramatically improved in capacity and cycle life. Hard carbon materials, transition metals, and their alloy compounds as negative electrodes. Polyanionic, Prussian blue, and oxide materials as positive electrodes, especially Na$_x$MO$_2$ with layered structure and binary and ternary materials, show good charge-discharge specific capacity and cycle stability.

3. Anode materials
The negative electrode forms the lowest potential electrode. In a SIB, as solvated sodium ion works as the primary charge carrier, the thermodynamically lowest electrode potential is produced by the sodium reduction potential. To increase the battery's energy density, a negative electrode with theoretically the lowest potential and highest specific capacity is required. The anode material could be divided into three main types shown below.

3.1. Carbon-Based anode materials
Nowadays, the most used anode material in battery technology is graphite, which could not intercalate sodium to any appreciable extent and is electrochemically irreversible with low capacity and irreversibility of a Na/C (graphite) cell shown in Fig.2 [6]. Many other non-graphitic anodes that consist of various carbonaceous materials are also suitable for inserting Na, such as carbon fiber with pitch based and various polymers [7].

Fig. 1. Schematic diagram of working principle of SIB [5]
Fig. 2. The defects in electrochemical activity were shown in the Na/graphite cell.

Fig. 3. (a) Typical X-ray diffraction patterns (b) graphical representation of the fine structure (c) typical voltage-charge profiles of carbon materials

The most advanced anode material for SIBs is hard carbon, shown in Fig. 2 with its XRD pattern, usually prepared by high-temperature carbonization of solid organic matter and polymer precursors. Its complex microstructure consists of parallel graphene-like layers embedded in a microporous amorphous phase. This structure often takes the "house of cards" model as an example. Hard-carbons, referred as generalized carbon materials, are synthesized at high temperatures around 1000 °C from carbon-based the role of precursors have been more comprehensively characterized and thermally tested in Na batteries. These carbonaceous materials contain graphene, which is considered a choice for "first-generation" anode Na-ion systems. Raman spectra of various carbons are shown in Fig. 4. It is clear that graphite (trace a) has a narrow peak with high intensity (–C=C– stretch) at 1580 cm−1 while the hard carbon material (trace c) has a similar shape with the Raman spectrum of glassy carbon (trace b), which implies they have identical chemical properties and they both have an extra peak at a wavenumber of 1340 cm−1 compared to the original graphite. Hard carbon and glassy carbon have a more disordered structure.
Fig. 4. Raman spectra of (a) graphite, (b) glassy carbon, and (c) the 'hard carbon'

Na NMR studied the electrochemical reaction mechanism of Na and carbon. There are two reversible peak resonances, indicating two independent sites or interaction points with Na cations. First, a narrow resonance occurs at +9 ppm, which is attributed to the interaction of Na with the unaligned graphene layer in the carbon frame, which has more ionic properties. The wider resonance between –24 and –32 ppm occurs at lower voltages, referring to the Na-containing surface film with high diffusion characteristics and Na inserted into the nanocavity [8]. Therefore, most of the reversible capacity of carbon microspheres occurs in nanocavity. This work demonstrates that the insertion of Na into the carbon nanocavities is essential. Measurements show that the pore-filling mechanism occurs at a lower voltage. On the other hand, at higher voltages, the electrochemical reaction mechanism describes the insertion of Na between graphene layers by intercalation. Most importantly, electro-activated carbon has a small particle size, low surface area to volume ratio, and morphology that minimizes side reactions with electrolytes at low voltages. Further work has been done to improve the performance of hard carbon anodes, such as nano templates [9].

3.2. Metal oxide anode materials

According to reports, metal oxides (MOx) and metal sulfides (MSα), especially layered metal disulfides, are used as anode materials based on conversion reactions. In most cases, the conversion reaction is accompanied by an intercalation or alloying reaction during the sodium insertion process. We consider here that the transformation reaction is the material of the inclusive part of the insertion mechanism.

The generalized formula for Na-based conversion reaction can thus be written as $M_{a}X_{b} + b_{c}Na \leftrightarrow aM + bNa_{c}X$ where X represents either oxygen or sulfur in the host compound, and a, b, and c are the stoichiometric composition of the starting material, and the formed Na-containing compound, respectively. In metal sulfides, sodium is intercalated to form Na$_{x}$MS$_{α}$, and after further intercalation, sodium is decomposed into Na$_{2}$S and M through the conversion reaction. Also, the conversion reaction is associated with slow kinetics and large volume expansion. The reaction path in the conversion reaction based on metal oxides depends on whether the metal M is electrochemically active for alloying. For electrochemically inactive M, such as Fe, Mn, the metal oxide reacts with Na$^{+}$ which is a one-step conversion reaction shown as $MO_{x} + 2xNa^{+} + 2xe^{-} \leftrightarrow xNa_{2}O + M$ and for an electrochemically active M, such as Sb, an alloying reaction further takes place illustrated as $xNa_{2}O + M + Na^{+} + e^{-} \leftrightarrow xNa_{2}O + NaM$. The highest cycle life with 500 cycles was achieved in SIB anode materials that store sodium by a conversion reaction reported for MoO$_{3}$ with a moderate specific capacity. However, this material exhibits a sloping electrode voltage, reaching a high potential of 2.5 V versus Na$^{+}$/Na, undermining its utility as anode material that still requires further research.

3.3. Alloy-Based anode materials

A study of SnSb/C nanocomposites as anodes for Na-ion batteries was reported. This work demonstrated the use of multicomponent Na alloying reactions with metals. Carbon plays a role in the electronic conductivity and mechanical stability of the electrode. At the same time, the Sn and Sb form a single
SnSb phase that provides the very high capacities associated with alloying reactions, and the nanocomposite SnSb/C can adapt to the typical volume change. In a certain mechanism, the reaction of Na with the SnSb single-phase occurs first by combining Na$_3$Sb and Sn, followed by alloying the Sn with Na at a lower voltage to form Na$_{3.75}$Sn in the nanocomposite. Reversible capacities of 544 mAh·g$^{-1}$ and Coulombic efficiencies above 98% were observed during cycling. The experimental capacity matches the theoretical value expected for a 1:1 molar Sn to Sb ratio, indicating that both metals participate equally in the Na alloying reaction [10].

3.4. Anode materials comparison

The electrode performance of the different anode materials in Na cells is reviewed in this section focusing on the reaction mechanisms, the electrode potentials, and the cyclability of the different anodic materials. Although it is desirable to have a low anode potential, there is a huge risk of electrolyte decomposition at this potential. Most organic electrolytes are reduced at potentials below 0.5 V (relative to Na$^+/Na$). Another challenge at low potentials is the risk of metal plating, which occurs at high charging rates. Therefore, it is important to remember these challenges, as low-voltage anodes are being pursued, and their effects on rechargeable batteries' cycle life and safety have been fully demonstrated.

Fig. 5 illustrates voltage and gravimetric capacity comparison of SIB anode materials. The blue circles represent intercalation-based materials, the red squares represent conversion materials, while cyan diamonds represent alloy-based materials.

![Graph showing voltage and gravimetric capacity comparison of SIB anode materials](image)

**Fig. 5.** Average voltage versus the discharge capacity of various sodium-based materials [11, 12]

Fig. 6 compares the number of cycles versus all kinds of anode materials storage capacity. Alloy-based electrodes (diamonds pattern) and conversion-based electrodes (red squares) have a relatively low cyclability, while the intercalation-based electrodes (blue circles) have the highest cyclability on average.
Fig. 6. The number of cumulated cycles during their cycle life versus the storage capacity of the anode material for SIB [11, 12].

4. Cathode materials

4.1. Metal oxides MOx
Metal oxides MOx are considered a SIB cathode alternative due to the low cost of the experiment and good electrical conductivity compared with others. Sodium-free MOx cathode materials can also show incredible electrochemical properties related to specific capacity, rate capability, and cycling stability.

For example, due to its excellent structural flexibility, low cost, and high abundance, vanadium oxide has been considered as an encouraging positive electrode for SIBs so far. Fig.7a shows the calculated formation energy relative to the number of sodium ions in the \( \text{VO}_2 \) molecule. When the inserted sodium ions are increased from 0 to 1, the greater the negative formation energy, the more stable the formed phase. However, when the content of Na ions x exceeds 1, compared with the case of NaVO\(_2\), the corresponding formation energy increases, accompanied by the volume expansion caused by the violent Na insertion and the rupture of the VO tunnel (Fig.7b). Then, from VO\(_2\) to the stable NaVO\(_2\) phase, the Na insertion process can occur continuously. Correspondingly, the transition of Na ions during charge and discharge is shown in Fig.7c. In the first discharge process, a Na ion is inserted into the VO\(_2\) molecule to form the NaVO\(_2\) phase, and followed by a subsequent charging process where NaVO\(_2\) is oxidized to Na\(_x\)VO\(_2\). Based on the single sodium insertion method, the theoretical capacity of VO\(_2\) is calculated to be 330 mAh·g\(^{-1}\). The illustration in Fig. 7a shows the first charging and discharging behavior of a VO\(_2\) cathode operating with voltage range of 1.5-4.0 V (relative to Na\(^+\)/Na) at 50 mA·g\(^{-1}\). [13-15].
4.2. Layered oxides
Layered oxide compounds, which are of interest as cathode materials for SIB, often have a formula NaₓMO₂, where M is referred to as different types of transition metals such as Cr and Mn. Actually, this type of compound was first used experimented in the LIB. Since the layered oxides have a content of sodium, they could be classified into different types, O3, P2 or P3. The letter P is referred to as the trigonal Prismatic coordination, while the letter O represents the octahedral Prismatic coordination. On the other hand, numbers 2 and 3 are related to the layer numbers in the original cells. Due to the difference between the size of sodium and lithium ions, NaₓMO₂ could achieve more types of compounds than lithium, capable of sodium reversible incorporation. For example, the Na₀.₅MO₂ compound referred to the O3 type and is thermodynamically not inclined to switch to spinel structure compared to Li₀.₅MO₂. Also, the transition metal atoms in the sodium compounds with O3 types are more stable than those in the lithium compounds. With the development of SIB, the study of sodium intercalation to these compounds above have achieved great success [16-19].

4.3. Polyanion phosphate compounds
Compared with monoanionic compounds, the redox potential of transition metals in polyanionic phosphates can be adjusted by the ionic covalent properties of OM bonds and polyanions (PO₄²⁻) that move metal redox pairs (such as Fe³⁺/Fe⁴⁺) and presents a higher working voltage. Regarding the success of lithium-ion batteries, polyanionic phosphate compounds have also been considered as cathode materials for SIBs. They usually have the advantages of high structural stability and diversity, high operating potential, thermal safety, and excellent cycle performance due to the highly negative anions themselves.
4.4. Cathode material comparison

Three potential cathode materials have been discussed, mainly focusing on their sodium storage performance. Despite the low working potential, transition metal oxides can provide a specific capacity with an attractive specific energy of up to 600 Wh·kg⁻¹. However, the oxide cathode's cycle stability and rate performance still require further improvements due to the inevitable lattice expansion and multiphase transition. Phosphate has good cycle stability, but the low specific capacity limits its performance.

5. Electrolyte

Nowadays, SIBs generally use NaPF₆ or NaClO₄ as sodium salt and carbonate as the organic solvent. This kind of electrolyte has been successfully matched with various positive and negative materials of SIBs and shows good comprehensive performance. However, this kind of electrolyte will corrode the metal sodium electrode in the long-term working process. This phenomenon affects the stability of the SEI membrane and causes the attenuation of the electrochemical performance of the battery. In addition, liquid electrolytes also generally have potential safety hazards such as liquid leakage and combustion. For the relatively mature liquid electrolyte of SIB, further attention should be paid to the interface of its electrode process. Improve its safety and improve its compatibility with electrode materials and battery accessories.

5.1. Sodium-Ion aqueous electrolyte

The water-soluble SIB has the characteristics of reasonable safety, a friendly environment, low price, and minor corrosion. Theoretically, the water-soluble electrolyte has a better application prospect. At present, Na₂SO₄ aqueous solution is a widely studied aqueous electrolyte. Na₂SO₄ is a strong electrolyte, providing Na⁺ in an aqueous solution. When the secondary battery is charged, sodium-ion is separated from the cathode material. Sodium-ion enter the electrolyte. It reaches the negative electrode through the diaphragm and is embedded in the lattice of the negative electrode material. The electrochemical reaction will result in low lithium content in the positive electrode and high lithium content in the negative electrode. During discharge, sodium-ion is separated from the negative material. Sodium-ion enter the electrolyte. It passes through the diaphragm to the positive and is embedded in the lattice of the positive material. This way, sodium-ion de sodium and sodium intercalation between the positive and negative electrodes occurs during charging and discharging.

During the first charge and discharge of the liquid SIB, the electrode material reacts with the electrolyte at the solid-liquid interface to form a passivation layer covering the surface of the electrode material. The passivation layer is an interface layer with the characteristics of the solid electrolytes. The passive film is called the solid electrolyte film called SEI film. The results show that the stable SEI layer can be designed by pre circulating the electrode in the required sodium-based electrolyte. The ion transport can be adjusted by prefabricating the SEI layer with specific components [20, 21].

![Fig. 8. SEI formation in Li-ion battery systems (Sodium-ion have similar electrochemical reactions) [22]](image)
5.2. Sodium-Ion solid polymer electrolyte
To avoid potential safety hazards such as liquid leakage and combustion of liquid electrolytes, the development of solid electrolytes with high safety and high energy density has become a new way to improve the above problems. Solid polymer electrolyte is the most widely used solid electrolyte in SIBs. Compared with liquid electrolytes, it has a similar CV curve, good reversibility, and cycle stability. Most solid electrolytes have higher conductivity and lower activation energy at room temperature. These properties reduce the difficulty of converting chemical energy into electrical energy. However, there are few studies on sodium-ion solid electrolytes as batteries. This is mainly due to the relative difficulty of diffusion of ions in solid electrolytes. The low conductivity in batteries limits its application in SIBs.

5.3. Ion electrolyte of SIB
The ionic electrolyte of SIB is a liquid composed of all ions. At or near room temperature, substances with long enough ions are called greenhouse ions, or ionic liquids. It is generally composed of inorganic anions and organic cations. The ionic liquid electrolyte has the advantages of the wide electrochemical window, non-flammability and non-volatile. Meanwhile, polyconic liquids are derived from ionic liquid monomers. The cations or anions, or both monomers, are incorporated into the polymer skeleton. Polyconic liquids have both physical and chemical properties of ionic liquids and macromolecular compounds. Polyconic liquid electrolytes prepared by direct polymerization of ionic liquid monomers have rich lithium-ion channels, stable and solid mechanical properties, and a wide electrochemical stability window. The processability, impermeability, and mechanical stability of polyconic liquids have been improved, so they are regarded as potential polymer electrolytes. Ionic liquids can chemically modify some natural polymers to produce free anions or cations in their pore structures to increase ionic conductivity. This type of polyconic liquid electrolyte can effectively maintain the excellent mechanical properties of the original polymer electrolyte. The ionic liquid electrolyte has high safety and can achieve appropriate conductivity through compounding. However, because the cost of ionic liquid electrolytes is still high, it is not conducive to large-scale application.

6. The distinctive superiorities and key challenges
Many advantages of the SIB have been receiving a surge of interest, and the most attractive one is the abundance of sodium on earth, providing over 23600 ppm compared to lithium with only 20 ppm [20]. Therefore, the production processes, including extraction and purification of sodium from sodium carbonate, also became relatively cheaper [20, 21]. Besides the raw material cost, the SIB's cycling ability and life duration stand out among all properties. Fig.9 gives an example of a 75 Wh·kg⁻¹ cylindrical SIB with approximately 4000 cycles at 1 C discharge rate, room temperature, and 100% depth of discharge [22]. The trend indeed shows a big drop from 100% to 94% of the capacity retention after the first 100-200 cycles, but it gradually becomes a relatively flat curve which still gives about 80% at the end of life. On the other hand, the pouch cell from Novasis Energies demonstrates 95% capacity retention after 200 cycles at 45 °C, as mentioned by Chayambuka et al. [22], showing SIBs' good cyclability in extreme temperatures. In terms of safety issues, the SIB even shows superiority over lithium-ion batteries. The 18650 cylindrical SIB cell or the Novasis Energies pouch cell exhibits excellent stability under nail penetration. The short-circuited ones show no temperature variation under crush test and nail penetration [22]. Under the ARC test where the cells are heated to measure their self-heating temperature, two groups are being compared, including the NMC (lithium-ion battery) to Sumitomo SIB and the LCO and LFP (lithium-ion battery) to Faradion SIB; both the SIB cells outperformed the lithium-ion ones, showing their magnificent stability [22]. It must be noticed that battery safety is a big issue in application in either electric vehicles or energy storage and the transportations of these battery cells. If the battery itself has insufficient bearing capacity under certain situations, the potential damage may cause unexpected financial losses and personnel casualties.
The advantages of SIBs seem promising, but their limitations deserve broad attention. Naturally, sodium ions are less suitable for a battery than lithium ions due to their larger radius and heavier weight, which affects the phase behavior and diffusion properties. Sodium ions also have a bigger electrode potential (-2.71 V vs SHE) compared to that of lithium ions (-3.04 V vs SHE), limiting the energy density of the SIB [21-23]. Moreover, the discharge voltages of SIBs are currently falling behind lithium-ion batteries. As shown in Table 2, the 18650 SIBs reported by PNNL-WSU with the highest estimated specific energy and energy density only have a voltage of 2.7 V, which is relatively lower than the voltages of any of the lithium-ion batteries in the same format [20]. This kind of SIB with an estimated specific energy of 150 Wh kg\(^{-1}\) and energy density of 250 Wh L\(^{-1}\) seems to match with the low-energy lithium-ion batteries, it still falls behind compared to those newer and more advanced lithium-ion batteries with higher specifications, not to speak of the 18650 lithium-ion battery used in Tesla Model S with a specific energy of 243 Wh kg\(^{-1}\) and energy density of 676 Wh L\(^{-1}\) [20, 24].

Even though the cost of raw materials for the SIB is significantly cheaper than lithium-ion batteries, the cost-effectiveness of the battery does not only depend on sole material costs. The cost from raw materials to applications, including the processing and overheads, of HC/NVPF SIB cell is 320 $ per KWh, while the graphite/LFP lithium-ion battery cell is 280 $ per KWh, which shows that SIB has not yet reached satisfying cost-effectiveness, primarily due to technological immaturity [22]. Using the Argonne National Laboratory's BatPac model to calculate the cost of a battery, the cost for SIB, LFP, and NMC types are respectively 223, 229, and 168 € per KWh, where the NMC lithium-ion battery uses the most expensive materials, such as cobalt and manganese [22]. Therefore, the higher the energy density of the active materials, the more cost-competitive the battery becomes.
Table 2. Comparison between lithium-ion batteries and SIBs in 18650 formats. Obtained from ref [20]

| Battery (18650 cell)               | voltage (V) | specific energy of 18650 Li-ion cell (Wh/kg) | energy density of 18650 Li-ion cell (Wh/L) |
|------------------------------------|-------------|---------------------------------------------|------------------------------------------|
| graphite(C)/LiCoO2 - (Li-ion)      | 3.7         | 206                                         | 530                                      |
| C/LiNi0.33Mn0.33Co0.33O2 - (Li-ion)| 3.6         | 210                                         | 530                                      |
| C/LiN0.8Co0.15Al0.05O2 - (Li-ion)  | 3.6         | 285                                         | 785                                      |
| C/LiFePO4 - (Li-ion)               | 3.4         | 126                                         | 325                                      |
| C/LiMn2O4 - (Li-ion)               | 3.8         | 132                                         | 340                                      |
| CNRS CEA 18650 cell- (Na-ion)      |             | 90                                          | 250(Estimated)                           |
| PNNL-WSU 18650 cell - (Na-ion)     | 2.7         | 150                                         | 375                                      |
| ALISTORE 18650 cell - (Na-ion)     | 3.5         | 75                                          |                                          |

Many advancements were being conducted in recent years, and there is more to expect. According to the news released by CATL, its first-generation SIB demonstrated excellent performance, such as "high-energy density, fast-charging capability, excellent thermal stability, great low-temperature performance and high-integration efficiency," etc. [25], as demonstrated in Fig. 10. This new SIB, using newly designed Prussian white materials as cathode and porous hard carbon anode to improve its energy and cycling capacity significantly, has a specific energy of up to 160 Wh·kg⁻¹, surpassing the one announced by PNNL/WSU [25]. This new development has raised huge excitement among researchers and producers, for which it shows tremendous potentials for the SIB to be at higher levels. Besides that, the new carbon nanotube materials in composition with most of the traditional electrode materials can also help improve the performance of the SIB. Tao et al. [26] mention that due to their unique 1D structure, the carbon nanotubes with large surface area, excellent conductivity and flexibility, and chemical stability can enhance the electronic conductivity in the electrode materials to improve SIB's storage properties further.
Even though the current situation looks suitable for SIBs, this technology is still developmental. Many significant issues remain to be solved, such as low energy density and voltage and costly fabrication processes. To overcome these obstacles for SIBs, better electrode materials and more mature processing techniques are of necessity to improve the batteries' overall performance to rival the state-of-the-art lithium-ion batteries. The most promising aspect of SIBs is sustainability. The abundance of sodium, less use of rare material, and similarity with the lithium-ion batteries provide confidence and convenience at either research or production in the field. As stated by the CATL, the compatibility of the products and processes equipment between the SIB and lithium-ion battery made it possible for industries to switch the manufacture quickly and efficiently between the two different types of batteries [25]. Since the year 2020, the EV market has been growing exponentially due to technological innovations. The carbon-neutral plans of the mid-20th century announced by many countries, including China and European nations, further accelerated the development of electric vehicles. Battery, as the core technology of all EVs, obtains most of the attention and resources. As a new member joining the battery family, SIB can have great potential to achieve the best sustainability and practicability to increase its commercialization and applications.

7. Conclusion

With the rapid development of electronic equipment and electric vehicles in recent years, research on energy storage materials with high efficiency, environment-friendly and rich resources is necessary for society to achieve sustainable development. It is not enough to measure battery materials only by energy density and discharge rate to meet the enormous market demands. Whether batteries' manufacturing cost and energy consumption pollute the environment and the recycling rate of resources have also become important indicators to evaluate battery materials. Sodium has similar chemical properties to lithium, which can also be used in a lithium-ion battery system. SIBs have many advantages over lithium-ion batteries: low cost, good safety, and rich output. With the deepening of research, the SIB is one of the new secondary battery technologies that can replace lithium-ion batteries for large-scale energy storage in the future.

From the current technical status, although several different sodium-embedded anode and cathode materials show considerable capacity and good recyclability, the energy density and power density need to be improved. Transition metal oxide and cyano cathode materials and hard carbon and alloy cathode materials are most promising for SIB systems. However, the initial charge-discharge efficiency and cycle stability of these materials still need to be improved. At present, organic electrolytes, which are relatively mature in SIBs, show good comprehensive properties. However, safety needs to be improved.

The emergence of many electric vehicles is also urgently needed for a battery with high efficiency, environmental protection, and rich raw materials. The development of new batteries is conducive to saving the earth's limited resources. Further, the research of SIBs is in line with the strategy of sustainable development. With the establishment of the industrial chain of SIBs, more and more enterprises are investing in the research and production of SIBs. It can be predicted that the development of sodium-ion will bring new scientific and technological changes.

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