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Efficient power supply for electric vehicles: Sodium-ion batteries

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Abstract. Energy is an important way to help daily work in various aspects of daily life. But energy cannot just exist around people without any carriers. Nowadays, sodium-ion batteries have been the best choice to be the carrier or power supply on account of the amount of sodium resources. On the other hand, it was anticipated that employing Na and Al current collectors for the cathode and anode would reduce costs. This paper mainly analyzes the current sodium ion battery structure, materials, and working principle, compared with other batteries' advantages and disadvantages and future development direction. The second part introduces sodium-ion batteries' anode and cathode materials, as well as the current mainstream materials, composition, and comparison between different mainstream materials. Sodium-ion battery is a relatively advanced battery in modern life, and its advantages are significantly greater than the lithium battery that is now used in life, especially in electric vehicles.

Keywords: Sodium-ion battery, power supply, electric vehicle, anode, cathode

1. Introduction

It is widely known that energy storage is important in people’s daily lives. To keep energy in a carrier, usually using energy storage. While it is impossible to transport the energy elsewhere, the gadget can be transported wherever necessary after it is stored. To remove the energy, that is what we do with the carrier. However, we can use a variety of storage viewpoints to serve as the carrier. Batteries, mechanical systems, or thermal storage are available possibilities. There are many types of batteries, such as lithium-ion batteries or sodium-ion batteries, which are available in a variety of sizes and shapes to meet a range of power and duration requirements. A typical battery using thermal systems uses heating and cooling strategies to provide energy [1]. The mechanical system usually infers to flywheels and pumped hydropower. With duration systems being developed, the flywheel only lasts an average of about 15 minutes of high power. They do this by storing energy in rapidly rotating mechanical rotors. Ninety-five percent of storage in use today is provided by pumping water from hydroelectric plants, the most common type of system. Compressed air, superconducting magnets, subsurface pumped energy storage, and hydrogen storage are storage technologies currently being researched at different levels [2].

Originally used in consumer products, lithium-ion batteries are now used in all kinds of systems, from small systems in the home to large systems that simultaneously store large amounts of megawatt-hours for the entire power grid. These systems usually include many widgets or racks that hold batteries. These devices are quite compact relative to the energy they can store. But now, most batteries mainly use lithium batteries, sodium-ion battery technology is not mature enough and rarely put into real life, so sodium-ion battery is still to be developed. The cost of lithium-ion batteries is falling rapidly as companies seek to capitalize on the growing popularity of batteries that are in demand. But this unfair competition can also lead to lower battery quality. The flow battery uses two chemicals dissolved in a liquid and kept in a container for storage and energy. This makes the whole system more stable and suitable for long-term storage. For instance, molten salt holds heat from the sun to be utilized later. Buildings with ice storage need to run the compressor less often and can keep the air conditioning on for several hours. Other systems employ chilled water and dispatchable water heaters. Each time, more energy is expended to fill the storage system with energy before releasing it once it is no longer needed. These devices can balance changes in the supply and demand for electricity because they respond to a control signal that is changed every few seconds. They can also be used in some installations to recover braking energy from electric trains or to supply electricity temporarily during a grid outage in important manufacturing processes where an infrequent power outage could result in the loss of goods.

Turbines use extra electricity to pump water to higher reservoirs during off-peak hours. When there is a large energy demand, the reservoir opens, allowing the blocked water to flow through turbines and generate electricity. The large size of these systems and the required terrain make them challenging to install. However, pumped storage is a good way to provide electricity in some places that require a wide range of conditions. Mountains or glaciers are good places to use pumped storage. Like NYSERDA, many storage businesses can implement various storage technologies using their software. They then purchase the storage technology from a manufacturing partner that best suits the site's requirements [2]. The body heat density (the amount of energy stored per unit volume) is high, indicating that the system accumulates as much energy as possible. They also require excellent load regulation performance, energy storage performance, low system cost, and sustained dependability. If a product component is used in a unique environment, it should be waterproof, high-temperature, low-temperature, or high-pressure resistant [3].

2. The basics of sodium-ion batteries

Sodium resources on the earth are abundant and have minimal mining and production costs. Sodium-ion batteries have numerous clear advantages over the battery technology currently used. Sodium and lithium are members of the same family of elements as lithium and exhibit chemical properties similar to those of lithium-ion batteries. Nevertheless, sodium-ion batteries will be considerably less expensive than lithium-ion batteries and possess a slightly lower energy density, making them safer and more effective. They additionally possess similar power output characteristics. The natural abundance of sodium, abundant resources, and decreased mining costs are the primary benefits of sodium-ion batteries. A sodium-ion battery is a rechargeable battery that uses sodium ions as a charge carrier. The principle and structure of the battery are almost the same as that of lithium-ion batteries. Because lithium and sodium are in the same group of elements, they have similar chemical properties, so that you can use sodium instead of lithium but use the same principle to produce new batteries. The sodium-ion battery will insert or remove Na^+ from the positive electrode and place it on the negative electrode while charging [3]. Furthermore, the Na^+ moves from the cathode to the anode during the charging process of a sodium-ion battery (Figure 1).

Nowadays, lithium batteries are frequently used in daily life. However, Na and Li belong to the same chemical family and have many of the same physical and chemical characteristics. Therefore, theoretically, they can both be employed as battery carriers. Lithium-ion batteries and sodium-ion batteries both functions similarly. Furthermore, sodium ions are taken from the anode during charging and placed in the cathode, which is how sodium-ion batteries operate. As additional sodium ions are added to the negative electrode, the charging capacity increases; conversely, the discharge capacity increases when additional sodium ions are returned to the positive terminal. The differences between the anode and cathode materials and the electrolyte distinguish sodium-ion batteries from lithium-ion batteries [4,5].

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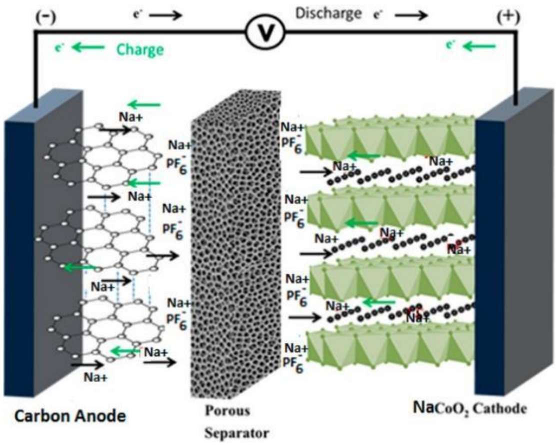

Figure 1. Scheme of a typical Na-ion battery [3].

3. Sodium-ion batteries for electric vehicles

It has been suggested that traditional graphite cannot be used as the negative electrode of sodium ion batteries due to the graphite layer spacing being too small, the sodium ion with a large radius embedded in the graphite layer necessitates more energy, and it cannot be permanently disembedded within an effective potential window. This contrasts with the negative electrode of graphite material used in lithium-ion batteries. Hard carbon, soft carbon, titan-based oxide, and alloy of other materials comprise the anode materials under development for sodium-ion batteries. Most study is being carried out on hard carbon. Hard carbon materials are currently used as the main anode in commercial sodium-ion batteries [6]. The most common anode materials on the market are graphite and silicon, but the sodium storage capacity is not high. The market urgently needs to develop sodium cathode materials with high safety and strong performance to promote the industrial application of sodium-ion batteries. The negative electrode materials of sodium-ion batteries on the market, according to the charging and discharging mechanism of sodium batteries, are mainly four kinds: embedded materials, alloyed materials, transformed materials, and organic materials.

As the name indicates, embedded materials develop whenever negative substances like titanium oxide and compounds made from carbon embed sodium ions. The benefit of these materials is that all through the sodium ion embedding process, parameters such as bond distance, cell volume, crystal phase, and crystal face spacing do not vary, and during charge and discharge, the material volume expands only slightly. The disadvantage of such materials is their low specific capabilities. In particular, sodium-ion batteries choose carbon-based materials (graphite, expanded graphite, non-graphitized carbon, carbon nanomaterials, and carbon-based organometallic skeleton) as the negative electrode because their working principle is similar to that of lithium-ion batteries. In contrast, graphite materials have been commercialized for use in lithium-ion batteries, where their working voltage is low, and their chemical and physical properties are well known. Currently, the preferred anode materials for sodium-ion batteries are compounds made from carbon. However, the market discussion over the "embedded-adsorption" and "adsorption-embedding" concepts has rendered the process of salt storage controversial.

The technique of storing sodium in carbon-based materials involves two steps, according to the "embedded adsorption" principle. The first is the charge-discharge curve's slope area, represented by embedding sodium ions into disordered graphene sheets. The second involves filling the platform region of the nanopore with sodium ions. The ramp zone of charge and discharge relates to the loading of sodium ions into the carbon-based material nanopore according to the adsorption-embedding process. In contrast, the platform region corresponds to embedding sodium ions into the disordered graphite microcrystals. As an anode material for sodium-ion batteries, titanium oxide offers many benefits, such as a good working voltage, low cost, and low toxicity. Potential sodium ion battery anode materials include one of the most popular titania-based oxides, the nano-treated anatase type, smaller particle size, or carbon-doped lithium spinel titanate, with specific capacities up to 311 mAh/g. The periodic table's

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Si, Ge, Sn, Pb, and VA elements and P, As, Sb, Bi, and other elements are alloyed materials. Sodium can combine with these elements to generate alloy compounds. The benefit of this type of material is that each atom can react with several sodium ions. The drawback is that the material volume expands substantially during charge and discharge, which negatively affects the cycle performance of sodium batteries.

Si theoretical specific capacity is especially low, Ge capacity retention rate decreases significantly after cycling, and As is an element that causes cancer; thus, they are unsuitable as sodium ion battery anode material. $Na_{15}Sn_4$ has a maximum theoretical capacity of 847 mAh/g when synthesized from pure sodium of Sn. The first-time reversible capacity of a Pb sodium battery anode material was measured to be 477 mAh/g, with a capacity retention rate of up to 98.5% after 50 cycles. The theoretical specific capacity of Sb is 660 mAh/g. P, a potential anode material for sodium-ion batteries, has a theoretical specific capacity of up to 2596 mAh/g.

4. The design of electrode materials

Metal oxides, metal sulfides, metal selenides, and metal phosphates are conversion materials because they can go through conversion reactions to store sodium. The benefit of this type of material is that many electrons engage in the reaction, increasing specific capacity up to 200-1800 mAh/g; the drawback is that the volume of the material swells significantly during charge and discharge, resulting in subpar cycle performance for sodium batteries. To reduce mechanical stress brought on by volume changes during the reaction process and improve the material's intrinsic conductivity, metal oxides like $NiCo_2O_4$, Sb_2O_3, Co_3O_4, Fe_3O_4, Fe_2O_3, SnO, SnO_2, NiO, CuO, MoO_3, and MnO_2 are typically used in conjunction with nanotechnology, carbon coating, and composite technology. FeS, SnS_2, CoS, Ni_2S_3, MoS_2, ZnS, TiS_2, WS_2, Sb_2S_3, and other metal sulfides exhibit better intrinsic conductivity and less volume expansion compared to metal oxides. The performance of salt storage can be increased when combined with NaNo, unique morphology, and carbon coating technique. Sulfide compounds lack multilayer structures, and metallic selenides like SnSe, Sb_2Se_3, $MoSe_2$, $FeSe_2$, ZnSe, and NiSe exhibit superior electrical conductivity, magnification, and coulombic efficiency. Materials' characteristics can be enhanced by adding a carbon conductive network and creating a certain shape. Metal phosphates such as Se_4P_4 and Sn_4P_3 have good electrical conductivity, and the presence of metal can effectively buffer the volume change of the anode material during the charging and discharging process. The alloying and conversion reactions combined can also improve the material's specific capacity. Materials made of organic chemicals, primarily organic polymers and small molecule compounds (Schiff base compounds, polyamide, polyquinone, conductive polymers, etc.).

These materials' benefits include their abundant supply, low cost, diversified structure, capacity for many-electron reactions, and superior electrochemical performance. The material's low electronic conductivity and significant volume expansion during charging and discharging have the drawback of causing material crushing and poor stability in organic solvents, respectively. Copolymerized carboxylate is a small molecular organic molecule with a high reversible specific capacity (up to 250 mAh/g) and outstanding cycling performance. The atomic layer deposition approach can address the issue of low coulombic efficiency on the surface of the disodium terephthalate-coated Al_2O_3 nanolayer. The reversible specific capacity of Schiff base compounds can reach 350 mAh/g under appropriate circumstances, and the capacity retention rate of polyamide after the cycle is higher. After 500 cycles, the capacity retention rate may reach 90% under specific circumstances.

Although the anode material in a sodium-ion battery only contributes 14% of the entire cost, it greatly impacts the battery's overall performance. For a sodium ion battery, the ideal anode material should satisfy the following four requirements: To store more sodium ions in a given volume while maintaining a uniformly high volume and mass-specific capacity, every component in the negative electrode material should be light in weight and low in density. The potential of anode materials and metallic sodium should be close to the other to raise the functioning voltage of sodium batteries. The stability of the negative substance in the solvent of the electrolyte. The substance must be inexpensive, environmentally friendly, and possess strong electronic and ionic conductivity. Embedded, alloyed, changed, and organic materials have pros and cons based on the aforementioned four circumstances. Their particular capacity has growth potential, and problems with cycle stability and low starting coulomb efficiency must also be resolved. Carbon-based materials are among them since they're stable by nature, reasonable, rich in raw ingredients, and environmentally beneficial. The three improvements demand an in-depth knowledge of the sodium storage mechanism in carbon-based materials, an issue that has not yet been resolved. Additionally, the converted material's theoretical specific capacity can reach 800-1200 mAh/g, while the alloyed material's theoretical specific capacity can reach 2569 mAh/g. However, the material's huge volume deviations while charging and discharging fall far short of the 20 percent industry need. Nanomaterials, the design of hollow or porous structures, and carbon cladding are effective solutions [6].

Based on their chemical makeup, the primary cathode components of sodium-ion batteries can be classified as layered metal oxides, polyanionic compounds, and Prussian blue compounds [7]. Layered oxides are materials made of oxides having a layered structure; sodium ion batteries employ layered oxidation the most frequently. Sodium, nickel, cobalt, manganese, and other components make up the NCM substance. It has good cycling performance, a high specific capacity, high energy, and maximum density. NCM is also a potential battery material due to its low cost and facile preparation [8-10]. Polyanionic compounds, such as $Na_3V_2(PO_4)_3$ and $NaFePO_4$, could be widely used. The olivine-type crystal structure of lithium iron phosphate is mostly, which has good long-term cycle stability and high safety. The layered oxide crystal's structure is comparable to the three cathode materials, which benefits cycle life and energy density. The stability is slightly less stable than other cathode materials, which is a drawback. With 2000–3000 cycles, the current specific capacity of the layered oxide typically ranges from 100–145 mAh/g. Prussian blue compounds have a high potential energy density and good rate performance. The synthesis technique, meanwhile, is inexpensive and rather straightforward. The crystal water in the Prussian blue compounds has the drawback of lowering the material's actual specific capacity and cycle performance. Prussian blue (white) compounds present a specific capacity of 70–160 mAh/g and a cycle performance of 1000–2000 times. The majority of polyanionic compounds have olivine crystal structures comparable to lithium iron phosphate, which have good long-term cycle stability and high safety. Polyanionic compounds have different three-dimensional structures and stable structures. The majority of polyanion compounds have above 4000 cycles. One disadvantage of polyanions is that they have a specific capacity of only around 100 mAh/g.

5. Conclusions

A sodium-ion battery has advantages and specific applications compared to a lithium-ion battery. Firstly, the crustal abundance of sodium resources is 423 times that of lithium resources, and the distribution of sodium resources is all over the world, while the distribution of lithium resources is very uneven -- 75% of the distribution is in the Americas. Therefore, the price of sodium resources is much lower than that of lithium resources, only 1.33% of the latter. Secondly, sodium will not react with aluminum, so sodium ion battery positive and negative set fluid can use cheaper aluminum foil. However, lithium will react with aluminum, so lithium-ion battery negative set fluid can only use higher price copper foil. What’s more, the positive electrode of a sodium ion battery can use cheap transition metal. The cost is lower than that of a lithium-ion battery. Sodium-ion batteries can cost 30-40% less than lithium-ion batteries, which is not a big cost advantage. However, there are also many challenges of sodium ion battery, the possible solutions, and the prospect of future development direction we should consider.

One of their main flaws is that sodium-ion batteries lose charge more quickly than lithium-ion batteries, making them less viable as commercial lithium-ion battery substitutes. The protective film on a device's anode or negative electrode tends to disintegrate when the electrolyte used in sodium-ion batteries is used. Because it permits sodium ions to travel through the anode while preserving the battery's life, the protective film is an essential component of the battery. To address this issue, the researchers stabilized the protective film on the anode (negative electrode) and added a very thin protective layer to the cathode (positive electrode). While sodium-ion batteries perform better than earlier sodium-ion batteries, they are still not as well as lithium-ion batteries. However, according to the researchers, this is one of the most encouraging studies so far for improving the design of sodium-based batteries. Searching for cathode materials with high functional and energy densities. Search for negative electrode materials that experience minimal cycle-to-cycle volume change. These directions are our future development and improvement direction of sodium-ion batteries.

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