DOI 10.15302/J-SSCAE-2021.05.013

Challenges and Thoughts on the Development of Sodium Battery Technology for Energy Storage

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Abstract: Energy storage safety is an important component of national energy security and economic development. It has a significant impact on national security, sustainable development, and social stability. Sodium battery technology is considered one of the most promising grid-scale energy storage technologies owing to its high power density, high energy density, low cost, and high safety. In this article, we highlight the technical advantages and application scenarios of typical sodium battery systems, including sodium-sulfur and sodium-metal chloride batteries. Moreover, we propose possible development directions for sodium battery technology in China. Furthermore, we suggest supporting fundamental research and engineering development for sodium batteries, promoting the integration of related upstream and downstream industries, and establishing related standards and a performance evaluation platform. With these objectives, we aim to improve the R&D level and technological maturity of China's sodium battery technologies and provide alternative and reliable choices for safe energy supply in China.
Keywords: electrochemical energy storage; sodium battery; sodium-sulfur battery; sodium-metal chloride battery; ZEBRA battery

1 Introduction

In October 2017, five ministries of China including the National Development and Reform Commission, and the National Energy Administration jointly issued the *Guidance on Promoting the Development of Energy Storage Technology and Industry in China*. This policy noted that accelerating the development of energy storage technology and the industry has strategic significance for establishing a clean, low-carbon, safe, and efficient modern energy industry system. This policy motivated the robust development of the energy storage industry in China during the period of the *13th Five-Year Plan*. The carbon peak and carbon neutralization targets were put forward in April 2021, the beginning of the *14th Five-Year Plan* period, following which the National Development and Reform Commission and National Energy Administration issued the second national comprehensive policy document for the energy storage industry. This policy, titled *Guidance on Accelerating the Development of New Energy Storage (Draft for Solicitation of Comments)*, clearly proposed an energy storage goal of 3×10^7 kW by 2025, and realization of the complete market-oriented development of new energy storage systems by 2030, representing a big leap forward in the development of the energy storage industry. The *Guidance* also stated that the development of energy storage technology should be guided by demand, and insisted on diversified development, which clarified the goals and directions for energy storage technology. A series of support services

Received date: March 26, 2021**;** **Revised date:** August 30, 2021
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Funding program: CAE Advisory Project "Research on China's Energy Storage Development Strategy (2035)" (2019-ZD-20)
Chinese version: Strategic Study of CAE 2021, 23(5): 094–102
Cited item: Hu Yingying et al. Challenges and Thoughts on the Development of Sodium Battery Technology for Energy Storage. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2021.05.013

for energy storage systems for power generation, transmission, distribution, and on the user side have gradually emerged as important components of flexible and efficient power grids [1]. Nevertheless, smaller distributed energy storage systems will be used more widely in homes, businesses, and communication base stations in the future.

The energy storage technology in China presents a trend of diversification. Pumped storage technology has been growing rapidly, and lithium-ion battery technology has rapidly matured. The research and development (R&D) and application of compressed air, flywheel, and superconducting energy storage technologies; supercapacitors; sodium-sulfur batteries (Na-S batteries or NAS batteries); liquid flow batteries; lead-acid batteries; and other energy storage technologies have accelerated, while there has been much progress in hydrogen, heat, and cold storage technologies. The electrochemical (or secondary battery) category offers many technical advantages compared with other categories. For example, these technologies have a response time on the order of milliseconds and a strong ability to track load changes and thus are easy to precisely control. They also have low geographical requirements for implementation and offer bidirectional adjustment ability for power systems. In April 2021, the *Energy Storage Industry Research White Paper 2021* announced by the China Energy Storage Alliance noted that by the end of 2020, China had implemented energy storage projects with a total installed capacity of 35.6 GW, accounting for 18.6% of the total global market, with a year-on-year growth of 9.8%. Among these projects, the installed scale of electrochemical energy storage ranked only second to that of pumped storage.

Currently, the characteristics and maturity level of each electrochemical storage technology are different, and each technology has been extensively deployed in various locations worldwide. Five battery technologies, namely lithium-ion, Na-S, sodium-metal chloride, flow, and lead-acid batteries, have been recognized as reliable energy supply systems, with capacities on the order of megawatts installed worldwide. Lithium-ion batteries (LIBs) have developed very quickly since 2017, occupying most of the energy storage market in China and the United States, and reaching high levels of technological maturity. The deployment of an increasing number of LIB energy storage systems has led to a concurrent increase in their safety risk; in particular, the frequent accidents caused by the thermal runaway of this battery have aroused public concern. In 2019, the State Grid Corporation of China issued the *Guidance on Promoting the Healthy and Orderly Development of Electrochemical Energy Storage*, which laid down strict regulations for energy storage safety. In addition, because the elements used in LIBs, such as lithium, are usually scarce, expensive, and distributed unevenly in the earth's crust, the long-term and large-scale application of LIBs could pose a challenge. Sodium and lithium have similar physical and chemical properties, but the former element is abundant and widely distributed. Therefore, the development of sodium battery technologies (SBTs) for large-scale energy storage applications is of considerable strategic significance, and has received extensive attention in recent years. Two types of SBTs, namely, high-temperature NAS batteries and sodium-metal chloride batteries based on solid electrolytes, have been widely applied in the field of energy storage. The anode in both batteries is metallic sodium; hence, these batteries can more correctly be referred to as "sodium batteries." A sodium-ion battery (SIB) is typically one with an organic liquid electrolyte, and has emerged as a promising energy storage battery that has seen rapid technical improvements. Currently, over 20 companies are engaged in the SIB industry worldwide. Recently, a 1 MWh SIB-based intelligent microgrid (MG) system launched jointly by the Institute of Physics of the Chinese Academy of Sciences and Haina Technology Co., Ltd., was put into operation in Taiyuan, Shanxi Province. CATL recently announced its first-generation SIB with an energy density of 160 Wh/kg. However, SIBs have not been applied in large-scale energy storage, and their advantages need to be verified. Aqueous electrolyte-based SIBs offer the advantages of environmental friendliness, low cost, convenient manufacturing, good safety, and easy recovery, but present drawbacks such as a low voltage and side reactions of the electrode material, which decrease the cell life. In this paper, SBTs, including NAS and sodium-metal chloride batteries, are reviewed and studied with the aim of achieving energy storage technology that is safe and can be implemented on a large scale.

2 Overview of SBTs for energy storage

2.1 Sodium-sulfur battery

NAS batteries are high-temperature secondary batteries based on solid electrolytes. They use sodium as the anode and sulfur-infiltrated carbon felt as the cathode. The β"-alumina ceramic with conducting sodium ions acts as both, a separator and electrolyte [2]. The battery can be written as (−) Na (l) | β"-Al_2O_3 |S/Na_2S_x (l) |C (+), where x = 3–5. The basic cell reaction is $2Na+xS \leftrightarrow Na_2S_x$. The operating temperature of the battery is between

DOI 10.15302/J-SSCAE-2021.05.013

300°C and 350 °C, at which both sodium and sulfur are liquid, β"-alumina has a high ionic conductivity (~0.2 S/cm), and the battery has fast charge and discharge reaction kinetics. With Na_2S_3 as the final discharge product, the theoretical specific capacity of the battery is approximately 558 mAh/g with an open-circuit voltage of 2.08 V at 350 °C.

NAS batteries are typically designed as tubular structures, in which sodium is loaded into a ceramic electrolyte tube to form a negative electrode. The battery consists of a sodium negative electrode and its safety tube; a solid electrolyte (usually β"-alumina) and its sealing component; a sulfur (or sodium polysulfide) positive electrode and its conductive network (carbon felt); a current collector; and a corrosion-resistant metal case. The solid electrolyte ceramic tube is open at one end and closed at the other. The open end is sealed with insulating ceramics (usually α-alumina) using molten borosilicate glass, and the positive and negative terminals and insulating ceramics are sealed using hot-pressed aluminum rings.

NAS batteries possess many excellent characteristics, which are listed as follows [3]: (1) High specific energy. Their actual energy density has reached more than 240 Wh/kg and 390 Wh/L, which is close to that of LIBs. (2) High power density. The powers of the NAS cell and module have reached more than 120 W and >10 kW, respectively, and can be directly used for energy storage. (3) Long life expectancy. The lifecycle of NAS batteries is more than 4500 full cycles or 10–15 years. (4) High Coulombic efficiency. Owing to the use of a dense solid electrolyte, the NAS battery exhibits almost no self-discharge, with a Coulombic efficiency of approximately 100%. (5) Good environmental adaptability. Owing to the constant-temperature operation, the NAS battery adapts to a wide range of ambient temperatures, usually −40 to 60 °C. (6) Pollution-free operation. The battery has a fully sealed structure, with no vibration, noise, or gas emission during operation. (7) Low-cost raw materials, no risk of resource contention, simple cell structure, and convenient maintenance.

2.2 Sodium-metal chloride battery

Sodium-metal chloride batteries (also known as Zero Emissions Batteries Research Activity, ZEBRA batteries) as well as NAS batteries are collectively called Na-Beta secondary batteries. Their structure is like that of the NAS battery, where the negative electrode is liquid metallic sodium and the β"-alumina ceramic serves as a solid electrolyte. However, the ZEBRA battery operates in a slightly lower temperature range of 270–320 °C. The positive electrode consists of a liquid $NaAlCl_4$ electrolyte and a solid metal chloride; for the latter, nickel chloride is the most widely studied. The typical basic cell reaction is $2Na+NiCl_2 \leftrightarrow 2NaCl+Ni$, and the open-circuit voltage is 2.58 V at 300 °C.

Similar to NAS batteries, ZEBRA battery also has the characteristics of long life, high Coulombic efficiency, good environmental adaptability, and pollution-free operation. The actual specific energy of the ZEBRA battery is 110–140 Wh/kg, which is lower than that of the NAS battery, but still approximately three times that of the lead-acid battery. It also presents other attractive advantages [4]: (1) High safety. The ZEBRA battery possesses the characteristics of mild heat release in short circuits and reversible overcharge and over-discharge reactions to ensure high safety in the event of electrical and mechanical abuse. (2) Sodium-free assembly. The ZEBRA battery is assembled in the discharge state, and only the metal powder, sodium chloride, additives, and electrolyte are filled in the positive electrode. Therefore, the manufacturing process is safer. (3) High voltage. The open-circuit voltage of ZEBRA batteries is more than 20% higher than that of NAS batteries. (4) Low maintenance cost. The low-resistance deterioration mode in the event of an internal short circuit significantly reduces the maintenance costs of the system.

2.3 Core manufacturing technologies of sodium batteries for energy storage

The core technologies to manufacture high-temperature NAS cells include β"-alumina fine ceramic sintering technology, cell sealing technology, sodium-wetted safety tube design, anti-corrosion technology of case, and electrode materials loading technology. First, the quality and consistency of β"-alumina ceramics are key, as they considerably affect the electrochemical performance and safety of batteries. Second, damage to any sealing component will lead to direct contact and reaction of the electrodes with air. Third, molten sulfur and sodium polysulfide are highly corrosive to metals; therefore, anti-corrosion technology for the components, including the cathode case and seals against these liquids, is critical for the practical application of NAS batteries. Finally, the effective loading of both electrodes and the wetting layer between the anode and solid electrolyte is essential for a high-performance NAS cell. Compared with the NAS cell, the ZEBRA cell does not need to be corrosion-resistant; nevertheless, high stability technology on the cathode has become one of the core technologies of the battery.

The core technologies for high-temperature sodium battery modules include thermal insulation, thermal management, in-module/inter-module fire prevention, battery management systems, and protection circuit design. The high operating temperature of the battery imposes high requirements on the battery incubator. On the one hand, the incubator must ensure low power consumption in the standby level of the battery; on the other hand, a lightweight incubator is needed to improve the overall energy density. Because the chemical reaction in the discharge mode is exothermic, the temperature inside the module increases by 22–35 ℃ during discharging and decreases to the standby level during charging. The thermal cycle in the incubator not only tests the thermomechanical properties of the sealing components, but also demands a quick response for the module thermal management system. The in-module/inter-module fire prevention technology, battery management system, and protection circuit design are also of significance for the long-term safe operation of the batteries.

3 Application of SBTs for energy storage

Sodium batteries can serve as large-capacity, safe, and reliable energy storage systems for wind, solar, and other renewable energy generation enterprises under extreme environments (such as extreme temperatures and salt corrosion); as a power supply for manned submarines, military vehicles, and underwater platforms to serve the national defense science and technology industry; and as backup power for large indoor requirements such as 5G communication base stations and data centers that contribute to the national carbon neutrality target. SBT can complement LIB technology, and its main application fields are discussed in this section.

3.1 Applications under extreme environments

Global warming has led to the increasing prevalence of extremely high temperatures of over 50 °C worldwide, especially in sub-tropical and tropical regions. The high-temperature operation of batteries has thus received much attention recently. The temperature in oil and gas exploration wells can exceed 170 °C, and a few types of batteries can operate at such high temperatures, such as lithium primary batteries [5]. Military batteries are required to adapt to harsh environments and operate in a temperature range of −50 to 70 ℃. As an important part of next-generation wireless communication systems, the high-altitude communication platform system (HACPS) is a system located in a high-altitude area, which connects satellites and unmanned aerial vehicles (UAVs) at low altitudes and ground nodes, and acts as an air base station or relay node to enable fast, stable, and flexible emergency communication. The HACPS vehicle is a stationary carrier that remains at an altitude of 20 km for five years. The carrier is equipped with solar panels, which require energy storage batteries with a high specific energy (> 110 Wh/kg), high reliability and stability (> five-year life and performance reduction of <10%), and ultra-low-temperature operation (−55 °C) [6]. In addition, islands, offshore environments, and other high-salt fog environments limit the application of a number of battery systems.

Studies have shown that the application of LIBs in UAVs is significantly limited by high- and low-temperature environments [7]. The normal operating temperature of LIBs ranges from −15 to 50 °C; at lower temperatures, LIBs will face serious lithium dendrites and ion diffusion delays, whereas at higher temperatures, the accelerated side reaction of the solid-liquid interface of the cathode and electrolyte degradation can even lead to thermal runaway [8]. In fact, it is difficult for traditional liquid electrolyte-based secondary batteries to meet the requirements of extremely high- or low-temperature applications. To this end, solid electrolyte-based NAS and ZEBRA cells with a high energy density, lifespan of more than 10 years, and insensitivity to ambient temperature have proven to be suitable. In the United Arab Emirates, which has a tropical desert climate, NAS batteries are preferred over LIBs. In Japan, NAS batteries have been chosen as backup power sources for rocket launch sites. The ZEBRA battery, as a reliable and durable secondary battery under high and low temperatures, has now emerged as the preferred technology for the power supply of mining equipment [5], and an application demonstration has also been carried out for HACPS carriers [6].

3.2 High-security applications

A high-security application refers to a scenario in which it is difficult to limit the loss when accidents occur or the accident cost is high. In recent years, the development of big data, Internet of Things, cloud computing, and other technologies has led to a surge in the construction speed of large data centers. Data centers need a large amount of power to carry out normal operations, and the cost of electricity is relatively high compared to the total cost of the data center. Reducing the energy consumption through intelligent MGs has become an important approach to decrease costs and increase efficiency. Data centers, on the other hand, need to be equipped with very

DOI 10.15302/J-SSCAE-2021.05.013

safe and reliable backup power systems in the event of an emergency. The high-security application of indoor energy storage or backup power supply systems, such as to large data centers, has strict requirements. In the field of transportation, vehicles carrying dangerous chemicals, underground loaders, other vehicles, as well as manned submersible and deep-sea platforms, require safe power supplies.

The ZEBRA battery, as an intrinsically safe electrochemical battery system, offers unique advantages for high-safety applications. It was selected as the power source for LR7 deep-diving rescue boats by the United Kingdom and North Atlantic Treaty Organization [5]. In 2013, ZEBRA batteries produced by General Electric (GE) successfully served as a power support for mining forklifts in Alum Creek, West Virginia, USA [9]. With increasing emphasis on energy security, ZEBRA battery systems will acquire a position of significance.

3.3 Long-duration energy storage

Long-duration electrochemical storage systems aim to manage the intermittency of wind and solar flexibilities within half a day or even a few days, transforming renewable energy into an all-climate resource, and paving the way for a carbon-free grid. As the use of renewable energy increases, eliminating the variability associated with renewable energy production over weeks or months will be challenging. It is therefore imperative to develop long-duration energy storage technologies. LIBs have dominated new electrochemical energy storage in recent years, but rarely operate continuously for more than four hours. Although LIBs are technically capable of discharging for longer periods of time, the cost of using them often exceeds their own value owing to material scarcity and safety concerns.

NAS batteries, when used in energy storage systems worldwide, have presented capacities of over 540 MW/3780 MWh, with effective peak shaving, load balancing, and the capability to save energy and reduce emissions. Hence, they are considered to be among the most effective long-duration electrochemical energy storage technologies with a rated output of more than six hours [10]. NAS batteries implement modular amplification, which has the potential to run an energy storage system for over eight hours. ZEBRA batteries manufactured by the FIAMM Energy Technology (FIAMM) have also been deployed in several MW-class energy storage projects in Italy, France, Guyana, and South Africa. These practical demonstrations have proved the maturity of SBTs for large-scale energy storage [11].

4 Worldwide development and application status of SBTs

4.1 Worldwide development and application status of NAS batteries

Although NAS batteries were employed in aerospace and electric vehicles in the early stage of development, the commercial application of NAS batteries began in 1983 through cooperation between NGK Insulators, Ltd. and Tokyo Electric Power Co., Ltd. (TEPCO) for static energy storage. In 2002, NGK began the mass production of NAS batteries and put them into commercial operation in cooperation with TEPCO. Currently, NGK operates more than 200 energy storage station projects worldwide, with over 4 GWh of NAS battery energy storage systems [10]. However, in September 2011, a fire broke out in an NAS battery system (produced by NGK) installed by TEPCO in the Tsukuba factory of Mitsubishi Materials Co. To a certain extent, this incident caused concerns regarding the safety of NAS batteries. Subsequently, NGK first inspected and maintained the operating NAS modules and systems to avoid potential safety risks and adopted various measures to improve the safety at the cell and module levels for newly produced batteries [12]. Through a series of countermeasures, the NAS batteries of NGK have continued to operate in large energy storage projects in Japan, the United Arab Emirates, and Europe since 2013. In March 2016, NGK and Kyushu Electric Power Co., jointly launched an NAS battery energy storage system project with a capacity of 50 MW/300 MWh to balance the power supply and demand; this was the world's largest energy storage power station at that time (Fig. 1a) [10]. In 2019, NGK completed an NAS battery energy storage system project with a capacity of 108 MW/648 MWh in Abu Dhabi with a sustained discharge time of six hours. Fig. 1b shows a photograph of a part of the 34.8 MW NAS battery storage power station applied to a high-voltage power grid in southern Italy [12]. In Italy, NAS cells and modules undergo rigorous safety assessments, including under extreme operating conditions such as short circuits, external fires, earthquakes, floods, direct and indirect lightning, sabotage, and high-altitude falling. An evaluation report showed that the improved NAS battery technology has high safety and reliability [13].

In recent years, NAS battery technology has been promoted in countries other than Japan, including the United States, China, South Korea, and Switzerland. In 2006, the Shanghai Institute of Ceramics, Chinese Academy of

Sciences (SICCAS) collaborated with Shanghai Electric Power Co., Ltd. to develop NAS batteries for large-scale energy storage applications. SICCAS introduced 30 Ah and 650 Ah NAS cells with good stability and a battery lifetime of over 1200 cycles [14]. Since then, a pilot production line for NAS batteries with 650 Ah cells, with an annual capacity of 2 MW, has been built. During the 2010 Shanghai World Expo, SICCAS and Shanghai Electric Power Co., Ltd. collaborated to realize the online operation of a 100 kW/800 kWh NAS battery energy storage system (Fig. 1c). In October 2011, the Shanghai Electric Group signed a joint venture contract with SICCAS and Shanghai Electric Power Co., Ltd. to establish Shanghai Electric Sodium-sulfur Energy-Storage Technology Co., Ltd., and commenced the industrialization of NAS batteries. They also demonstrated an MWh-class commercial application at a wind power plant in the Chongming Island in 2015 (Fig. 1d). The Institute of Solid State Physics, Chinese Academy of Sciences, has also developed a preparation technology for ceramics in recent years, mastered the core technologies of ceramic sintering, ceramic-glass, and metal-ceramic sealing, and is in the pilot stage of NAS battery development. In addition, South Korea's Research Institute of Industrial Science and Technology (RIST) conducted systematic engineering development for flat and tubular NAS batteries [15]. RIST began to apply for patents on NAS battery materials and manufacturing in 2005, and currently owns over 53 relevant valid patents.

(a) 50 MW/300 MWh NAS battery energy storage system in Japan

(b) 34.8 MW NAS battery energy storage station for a high-voltage grid in southern

(c) 100 kW/800 kWh NAS battery energy storage system demonstrated at Shanghai World Expo 2010 by SICCAS and Shanghai Electric Power Co., Ltd.

(d) MWh-class commercial application demonstration for a wind power plant on Chongming Island

Fig. 1. Commercial application of NAS battery energy storage system/power station.

4.2 Worldwide development and application status of ZEBRA batteries

GE purchased ZEBRA battery technology from the Beta R&D Company in 2007 and established the "Durathon" battery brand. GE invested over 400 million USD during 11 years of project development. In the early stages, the ZEBRA battery was mainly used in vehicles. Fig. 2a shows a photograph of a mining vehicle loaded with a Durathon battery. GE presently operates over 30 ZEBRA battery energy storage projects with a total power of more than 15 MW in the field of power grids and telecommunications in many countries and regions around the world. Fig. 2d shows photographs of extended energy storage systems with a Durathon battery. In January 2017, the Chilwee Group technically collaborated with GE and set up Zhejiang Lvneng (Anli) Energy Co., Ltd. to enter the domestic energy storage battery market.

In 2010, MES-DEA, a company sharing the same technology source as GE, and FIAMM, an Italian power company, established a new company "FZ SONICK SA," and launched the "SONICK" ZEBRA battery brand, which is mainly applied in electric vehicles and backup power systems. In 2015, the ZEBRA battery storage solution provided by FZ SONICK was selected by Bombardier Inc., a German multinational airline and

DOI 10.15302/J-SSCAE-2021.05.013

transportation company, to provide backup power for the Innovia Monorail 300 platform train project [16]. Figs. 2b and 2e show photographs of the SONICK battery applied to MG energy storage and its energy storage units, respectively. FZ SONICK also supplied a smart grid energy storage system to the University of Savona [17]. The Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) began developing ZEBRA batteries in 2016. In March 2019, IKTS developed a high-temperature sodium-nickel chloride battery “Cerenergy,” that featured at the Energy Storage Europe exhibition. The battery module consisted of 20 single cells and had a capacity of 5 kWh, costing less than 100 Euros per kWh. In November 2015, the U.S. Department of Energy supported Ceramatec Company in Salt Lake City, Utah, and Georgia Institute of Technology, in a sub-project of the SunShot Concentrated Solar Power Apollo program, with a total funding of more than 2.3 million USD, focusing on developing a high-temperature sodium molten-salt energy storage system. Its storage efficiency is expected to exceed 92%. Meanwhile, the Pacific Northwest National Laboratory, funded by the U.S. Department of Energy, continues to conduct industrial R&D on flat sodium salt batteries. In China, SICCAS has been promoting research on sodium-nickel chloride batteries since 2014, based on the early R&D of NAS batteries. In 2017, SICCAS invested in Shanghai Arohora Energy Technology Co., Ltd., to realize the industrial development of ZEBRA batteries. As shown in Figs. 2c and 2f, the company completed the construction and equipment preparation of a 100 MWh-capacity ZEBRA battery factory and entered the pilot production stage of the first-generation product.

(a) ZEBRA battery “Durathon” as the power source of a mining vehicle

(b) FZ SONICK ZEBRA battery for microgrid energy storage

(c) 100 MWh ZEBRA battery production line of Shanghai Arohora Energy Technology Co., Ltd.

(d) “Durathon” battery energy storage system

(e) FZ SONICK ZEBRA batter energy storage units

(f) The first-generation product of “Arohora.”

Fig. 2. Sodium-metal chloride battery products for energy storage and examples of their commercial application.

5 Challenges in the development of SBTs in China

SBTs offer remarkable application advantages in the field of grid and telecommunication systems, and have been widely recognized in the global energy storage market. However, owing to technical difficulties, the maturity of sodium batteries is only controlled by a few foreign enterprises, such as NGK in Japan, GE in the United States, and FIAMM in Italy. The development of SBTs in China still faces several challenges.

5.1 SBTs are almost monopolized by foreign countries

In recent years, SICCAS has focused on technological innovation and application demonstration of sodium batteries for energy storage, mastered the entire NAS battery and sodium-nickel chloride battery technology, and established a complete technical route with independent intellectual property rights. However, the maturity level of sodium storage battery technology in China is generally not high. Large-scale production equipment requires high-cost customization, and a mature product system for sodium storage batteries has not yet been developed. The attempt by the Chilwee Group to domesticate sodium batteries has yet to succeed in both domestic and international markets. This is because the development of SBTs in China solely relies on importing the technology of Japanese and US companies. China is not yet capable of developing the next generation of sodium batteries independently that also meet the needs of the market.

5.2 Incomplete industry chain of sodium batteries leads to high costs

High-temperature technology is a bottleneck of SBTs, and greatly decreases the number of research institutes and enterprises involved in this field, resulting in difficulties in promoting an industrial chain of sodium batteries. The cost of production for a 1 GWh sodium-nickel chloride battery production line was estimated to be approximately 1050 CNY/kWh. When the production capacity was increased to 10 GWh, the cost of the battery could be reduced to less than 800 CNY/kWh. However, the current production scale of sodium storage batteries is not sufficient to drive the rapid development of industrial chains. For components such as the corrosion-resistant case of NAS batteries and T255 nickel powder (UK Inco Ltd.), a key raw material of sodium-nickel chloride batteries, China is still dependent on imports, and localized alternatives are scarce. The operating temperature of sodium batteries demands a strict downstream supply, such as an insulation incubator, but there is no similar product in China. The lack of an industrial supply chain has proved to be a major obstacle in achieving the development and cost control of SBTs.

5.3 Lack of evaluation standards and platform for SBTs

In 1998, the National Renewable Energy Laboratory of the U.S. Department of Energy issued a research report on the health status, safety characteristics of abuse, and recycling of ZEBRA batteries [17]. In 2017, SONICK tested the safety of its ZEBRA battery product according to the UL 9540A standard. The system was evaluated at the cell, module, and battery rack levels. In 2018, the IEEE Standards Society published a guideline titled “Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications” (publication number: IEEE Std 1679.2-2018). This standard provides guidance for users of stationary energy storage applications to evaluate the performance and safety, carry out qualification testing, and regulate sodium-beta batteries. The establishment of these research reports and standards has largely stimulated the standardization and marketization of SBTs in the United States and Europe. As the industrialization of SBTs in China is in the early stage, relevant evaluation and testing standards are missing, and the existing evaluation platforms and institutions do not support the performance and safety evaluation of sodium storage batteries, hindering the progress of the sodium battery industry.

6 Countermeasures and suggestions

6.1 Supporting the R&D of materials science and engineering technology related to SBTs

Based on the development experience of other countries, some initial output of sodium storage batteries came from applied research and technical projects organized by national energy departments or user departments. In January 2020, the Ministry of Education, National Development and Reform Commission, and National Energy Administration jointly issued the *Action Plan for Energy Storage Technology Discipline Development (2020–2024)* aimed at coordinating and integrating higher education resources in view of the demand for the development of the energy storage industry, accelerating the development of energy storage technology disciplines, driving the development of professionals in the energy storage field to focus on common and bottleneck technologies, enhancing the ability to tackle key technologies and drive independent innovation, and promoting the high-quality development of the energy storage industry. The Action Plan will provide new impetus for the development of the energy storage industry. To improve the technical maturity of sodium storage batteries with independent intellectual property rights in China, the R&D of related energy materials should also receive focus. For the sake of rapid improvement in SBT maturity, it is more important to ensure cooperation between experienced enterprises and scientific research institutes to break through core engineering technology from a strategic perspective, provide relevant project support, focus on solving the bottlenecks of SBTs, and promote the upgradation of sodium storage batteries based on international experience.

6.2 Promoting the aggregative development of an industrial chain of sodium batteries

Achieving industrial-scale production is key for the development of sodium storage batteries, and facilitating large industrial clusters is crucial to reduce their manufacturing cost and improving their market competitiveness. In the intermediate and later stages of improving technical maturity, the aggregative development of related upstream and downstream industries is essential for sodium storage batteries to enter the market. We suggest arranging the industrial chain around the technological innovation chain by introducing social capital and

DOI 10.15302/J-SSCAE-2021.05.013

strengthening the integration of technology, capital, and industry. Through industrial chain cooperation and collaboration, the resource utilization efficiency and market competitiveness of sodium storage batteries can be enhanced. The planning and implementation of large-scale demonstration projects with sodium storage batteries may be an opportunity to promote the development of relevant industries, and can stimulate the development of SBTs in China.

6.3 Developing the relevant standards of SBTs and establishing an evaluation platform for high-temperature sodium batteries

Since 2018, frequent fire accidents around the world have led to increased focus on the energy storage industry, with the safety issue of energy storage occupying the limelight. Experts in the field believe that accidents are a standard problem rather than a simple technical problem. Standards are a summary of technological development and need guidance from policies and regulations. The National Energy Administration, together with other departments, has issued several documents to promote the standardization of energy storage systems, and requires the establishment of systematic energy storage standards. The lack of standards for SBTs is particularly notable, making it imperative to establish and improve the relevant testing and evaluation standards. If relevant industrial standards or even national standards can be issued in China, it is expected that the commercial development of sodium storage batteries can be further accelerated. Certification authorities can construct high-temperature battery evaluation platforms according to existing standards to drive the standardization of the sodium storage battery market from a policy perspective and facilitate the large-scale application of SBTs and integration within the market.

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