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# R&D Trends in Next-Generation Batteries from the Perspective of Leading Chinese Researchers

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# Executive Summary

This report summarizes the results of the survey "R&D Trends in Next-Generation Batteries from the Perspective of Leading Chinese Researchers" commissioned in FY2021 by the Asia and Pacific Research Center (APRC) of the Japan Science and Technology Agency (JST) and undertaken by the Japan International Science and Technology Exchange Center (JISTEC). The purpose of this project was to investigate industrial policy and R&D trends related to next-generation batteries, a growing industrial field with expectations for large market expansion, at a time when the realization of carbon neutrality is being called into question. The report was compiled by organizing experts from both China and Japan, and collecting analyzes from their respective professional perspectives.

Chapter 1 (Zhao Ying, Chinese Academy of Social Sciences) provides background on the overall development of China's energy industry from the perspective of slowing economic growth, changes in the industrial structure, the growth of new industries, etc. It explains and analyzes the energy supply structure, the status, characteristics of power generation based on the latest data. In addition, with detailed analysis of the current status, characteristics, and challenges of China's energy storage industry, it states the facts of power industry, background, power supply, power consumption, storage industry, which complies with the goal of "2060 Double Carbon" and prospects of future Chinese economy.

Chapter 2 (Li Huimin, National Research Center of Science and Technology for Development) describes the historical background of the "Three Energy Laws," including the Energy Conservation Law (1997), the Renewable Energy Law (2005), and the Energy Law (2020), which provide an important legal basis for measures related to promoting China's energy structural transformation and energy industry development. It analyzes the content and characteristics of the laws and the role of related institutions. Also, the report provides a comparative analysis of China's national basic policies of national economic and social development, "The 13th Five-Year Plan (2016-2020)" and "The 14th Five-Year Plan for Economic and Social Development (2021–2025) and Long-Range Objectives through the Year 2035 of the People's Republic of China" for policies associated with energy storage technology, and next-generation battery technology. What's more, it provides commentary and analysis of the latest industrial, research, and diffusion policies at the central and local levels accompanying industrial development, technology development, industry standardization for energy storage, energy conservation, and battery technology development and utilization.

Chapter 3 (Zhou Shaodan, Shanghai Institute for Science of Science) examines a quantitative analysis of Chinese battery technology by extracting Chinese articles and patent data from the Web of Science Core Collection and the Chinese patent database CPRS (Patent Search System in China) respectively, analyzing 30 areas of battery technology in categories such as drive method, cathode, electrolyte, anode, additive, phenomenon analysis and structure analysis. The report also outlines and analyses China's national research grant programs by research institutions and target companies.

Chapter 4 (Li Xianfeng, Dalian Institute of Chemical Physics, Chinese Academy of Sciences) analyzes trends in R&D of next-generation sodium-ion battery technology in China, including an overview of R&D of related technologies, the current status and trends of industrial development, and the current status and prospects of industry standardization, through relevant case studies. In particular, in 2020, the research results of a team from the Institute of Physics of the Chinese Academy of Sciences on theoretical research on sodium-ion battery cathode materials attracted world attention, leading both the areas of fundamental research and industrialization. In 2021, China's first sodium-ion battery industry standard, the Common Specification for Sodium-Ion Rechargeable Batteries, which was proposed by the Institute of Physics of the Chinese Academy of Sciences, drafted by companies such as HiNa Battery, Natrium Energy and Huawei. This is to be viewed as a major event that will affect the future development of the industry.

Chapter 5 (Liu Gangfeng and Chang Nana, GUSU Lab) describes and analyzes the trend of research and development of electrolyte technology for next-generation lithium batteries in China, from the technological overview and research characteristics of electrolyte for lithium batteries to the development and current status of China's electrolyte industry, through representative research cases. In fundamental research, it analyzes the latest research trends in the fields of low-temperature electrolytes, high-voltage electrolytes, high-concentration electrolytes, and solid electrolytes, as well as the research results of Chinese researchers. In the area of industrial technology, the report also describes the systematic strengthening of the technological development capabilities of Chinese companies such as CATL, Dongguan Shanshan, Shenzhen Capchem, BYD, COSMX, Gotion High Tech, Zhuhai Smoothway Electronic Materials, Guangzhou Tinci Materials, GTHR, etc.

Chapter 6 (Cui Guanglei, Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences) focuses on the current status and characteristics of fundamental research at Chinese research institutes and universities in the field of all-solid-state lithium batteries and the development trends of companies. While providing specific results of materials research on the bottlenecks in all-solid-state lithium batteries, the report analyzes the development and trends of related companies in China's solid-state battery industry, focusing on various types of solid-state electrolytes with potential commercialization value, with an emphasis on the current status and characteristics of fundamental research and R&D by domestic research teams from the Chinese Academy of Sciences, Tsinghua University, Qingdao University, University of Science and Technology of China, and University of Science and Technology Beijing.

Chapter 7 (Fujishiro Koichi, Mitsui & Co. Global Strategic Studies Institute) looks at the development trends and prospects for next-generation storage batteries in China, analyzes global trends in carbon neutrality and its relevance to storage batteries, and describes the latest trends in the world and China for each major application of storage batteries. The report summarizes development trends in China's power sector and storage batteries, analyzes the challenges and future prospects for next-generation storage batteries.

The final section (Chen Liquan, Chinese Academy of Engineering, Institute of Physics Chinese Academy of Sciences) concludes with overall comments stating that the results of research and development of next-generation batteries will promote the development of the electric vehicle and energy storage industries in China and Japan, international exchanges and partnerships, and achieve the goals of reducing peak carbon emissions and carbon neutrality.

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# Introduction

China is the world's largest power producer and power consumer, as well as the world's largest emitter of $CO_2$, account for 30% of the world's carbon emissions. Based on the 14th Five-Year Plan for Economic and Social Development (2021–2025) and Long-Range Objectives through the Year 2035 of the People's Republic of China that was adopted in March 2021 and the presentation of carbon neutral-related priority policies by the National Development and Reform Commission, it is expected that China's research and development on carbon neutrality will accelerate.

In order to achieve carbon neutrality, it is important to resolve issues such as grid stabilization measures for renewable energy systems, effective use of energy in each sector, and full-scale spread of next-generation vehicles. Of these, energy storage technologies, and next-generation storage batteries in particular, are one of the key technologies, and, at the same time, are also a growing industrial sector where significant market expansion is anticipated. China is also showing momentum in the field of basic research on and manufacturing of next-generation storage batteries, as evidenced by its establishment of joint research institutes with overseas organizations. As such, the purpose of this report is to investigate the current state of China's energy sector as well as trends in industrial policy and research and development in the field of next-generation storage batteries, and also to provide information that will contribute to the open/closed strategies of Japanese companies and research and development institutions.

In response to the wide range of analytical themes, this report organized up-and-coming researchers from China and Japan to gather analyses from their respective professional perspectives and then compiled them into this report. In doing so, the results highlight the current state, challenges, and future prospects for research and development related to next-generation storage batteries.

March 2022

# 1 Current state of and outlook for the development of China's energy industry

## 1.1 Current state of the development of China's energy industry

### 1.1.1 Industrial development background

#### (1) Slowdown in economic growth rate

China's economic growth rate has gradually been slowing and has entered a new normal, averaging around 6% per year. Industrialization has entered the late stages of development, and the room for expansion of the industrial market is gradually shrinking. In the future, high-quality and highly inclusive (intensive) development will be required for economic growth and industrial development.

#### (2) Sustainable evolution of industrial structure

Although China's industrial structure is continuously evolving, the traction of its industry, which has led to the development of the national economy, is weakening. Since 2000, China promoted industry-led economic growth, but not the secondary and tertiary industries that are gradually gaining strength and that together are driving economic growth.

In 2020, China's gross domestic product (GDP) reached CNY101,598.6 billion, a year-on-year (YoY) increase of 2.3%. When converted at exchange rates (annual averages), China's share of the world's total economy in 2020 exceeded 17%. Of this, the value of industrial growth (added value) from primary industry was CNY7,775.4 billion (+3% YoY), from secondary industry was CNY38,425.5 billion (+2.6% YoY), and from tertiary industry was CNY 55,397.7 billion (+2.1% YoY). Industrial growth as a percentage of GDP was 7.7% for primary industry, 37.8% for secondary industry, and 54.5% for tertiary industry. In tertiary industry, new industries, particularly the internet, have become a major force in driving China's economic growth.

In 2020, there was CNY 1,330.2 billion investment in primary industry (+19.5% YoY), CNY 14,915.4 billion investment in secondary industry (+0.1% YoY), and CNY35,645.1 billion investment in tertiary industry (+3.6% YoY).[1] In 2020, six major energy-intensive industries (steel, nonferrous metals, building materials, petrochemicals, chemical industry, and electricity) accounted for 33% of GDP (compared to approx. 20% in the United States). Energy-intensive industries account for approx. 30% of industry, but accounted for approx. 70% of industry's energy consumption.[2] Additionally, although China's resources and energy are primarily concentrated in its midwest region, a higher share of its electricity consumption is in the eastern region, and this imbalanced structure is the main reason for the unbalanced carbon intensity ($CO_2$ emission volumes) in various parts of China.

1 National Bureau of Statistics of China, "Statistical Communiqué of the People's Republic of China on the 2020 National Economic and Social Development", February 28, 2021

2 China Institute of Electronic Science, China Enterprise Confederation, Development Research Center of the State Council, "Strategic Pathways for Decreasing Carbon Intensity through Industrial Structural Adjustment," October 2021

Due to its overemphasis on industrial structure and a high investment ratio in its energy industry, China's energy consumption per unit of GDP is approx. three times that of OECD (Organization for Economic Cooperation and Development) member countries and 1.5 times the global average level.

### (3) $CO_2$ peaking and carbon neutrality

China has pledged to the international community that it will achieve its goals of "peak $CO_2$ emissions" and becoming "carbon neutral." In September 2020, President Xi Jinping stated in his speech at the 75th UN General Assembly that, "China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have $CO_2$ emissions peak before 2030 and achieve carbon neutrality before 2060." This goal is being embodied in the specific directions, plans, and policies for China's industrial development, which will greatly facilitate the development of high-tech industries and the structural transformation and upgrading of traditional industries.[3]

### (4) Sustainable growth of new industries

China's new industries[4] continue to grow at a sustainable pace, with high-tech manufacturing accounting for +7.1% YoY of the total industrial growth of industries above a certain size in 2020, which accounts for 15.1% of all industries above a certain size. The equipment manufacturing industry grew at a rate of +6.6% YoY, which accounted for 33.7% of the total. Investment in high-tech industries increased by +10.6% YoY. Additionally, full-year production of new energy vehicles (NEV) reached 1,456,000 units, an increase of +17.3% YoY.

The basic development trends in China's economy and society will lay the foundation for the sustainable growth of energy and power, chart its direction, and have a decisive impact on the future of its energy and power industries.

## 1.1.2 Current state of energy supply in China

### (1) Energy supply structure

In 2021, China's energy production showed a steady upward trend. Raw coal, crude oil, natural gas, and electricity production had YoY increases of +4.7%, +2.4%, +8.2%, and +8.1%, respectively.

Raw coal, crude oil, and electricity production accelerated from the previous year, while the growth rate of natural gas production slowed. Annual production volumes for each were 4.07 billion tons of raw coal (+4.7% YoY and +5.6% when compared to 2019; an average annual growth rate of +2.8% over the two years), 198.98 million tons of crude oil (+2.4% YoY and +4% when compared to 2019; an average annual growth rate of +2%), and 205.3 billion $m^3$ of natural

3 Xinhua News Agency website: Ministry of Industry and Information Technology Publishes "Industrial Green Development Plan for the 14th Five-Year Plan", December 3, 2021, http://www.gov.cn/zhengce/zhengceku/2021-12/03/5655701/files/4c8e11241e1046ee9159ab7dcad9ed44.pdf

4 In China, the term "new industry" refers to the application of new scientific and technological achievements and emerging technologies to form a new type of economic activity of a certain scale. Specifically, it includes new industries directly created by the industrialization of applications of new technologies and new industries formed by conventional industries that incorporate modern information technologies. The high-tech industries included in these new industries are various industrial fields related to "bio and new pharmaceutical technology, new materials and applied technologies, advanced manufacturing technology, aerospace technology, marine technology, applied nuclear energy technology, new energy and energy saving technology, new technology for environmental protection, modern agricultural technologies, and new technologies that can be applied to reforming other conventional industries."

gas (+8.2% YoY and +18.8% when compared to 2019; an average annual growth rate of +9.0%).

The amount of electricity generated in 2021 was 8,112.2 billion kWh (+8.1% YoY and +11% when compared to 2019; an average annual growth rate of +5.4%). China generates the highest amount of electricity in the world, and in 2021 both its amount of electricity generated and its amount of electricity consumed reached record highs.[5]

Looking at the amount of electricity generated by type, although new energy sources continue to rapidly develop, thermal power generation continues to play a central role. In 2021 electricity generated via thermal power increased by +8.4% YoY to approx. 5,770.3 billion kWh, which accounted for the largest share of China's total power generation at approx. 71.1%. Among all provinces, Shandong province generated the largest amount of thermal power at 521.73 billion kWh, followed by Inner Mongolia at 486.3 billion kWh, Jiangsu province at 483.6 billion kWh, and Guangdong province at 462.9 billion kWh.[6]

After thermal power, hydroelectric power generation was the second largest source of power generation, producing 1,184 billion kWh and accounting for approx. 14.6% of the total. However, this was a decline of -2.5% when compared to 2020 because of lower-than-usual summer rainfall in some regions, which prevented several hydroelectric power units from operating at full capacity. Hydroelectric power generation in Guangdong province decreased by -22.8% YoY, in Shanxi province by -21.2% YoY, in Henan province by -20.9% YoY, in Qinghai province by -16.7% YoY, and in Guangxi province by -15.4% YoY. The rates of decline in Gansu, Jiangxi, Guizhou, and Hunan provinces also exceeded -10%.

Wind power generation was the third largest source of power generation, producing 566.7 billion kWh (+29.8% YoY), and its overall share rose to 6.99%. Following this, nuclear power generation accounted for 5.02% of the total, producing 407.5 billion kWh (+11.3% YoY). Solar power generation produced 183.7 billion kWh (+14.1% YoY), accounting for 2.26% of the total.

In 2021, China's installed renewable energy power generation capacity took a historic step forward, surpassing 1 billion kW. It began doubling from the end of 2015 and, by the end of November 2021, had reached approx. 2.32 billion kW, a +9% YoY increase. This represents 43.5% of China's total power generation. Of this, installed wind power generation capacity is approx. 300 million kW, a +29% YoY increase, and solar power generation is approx. 290 million kW, a +24.1% YoY increase. China's hydroelectric, wind, solar, and biomass power generation capacities are all world leaders.

### (2) Current state and composition of power generation

In 2020, China's total power generation was 7,620 billion kWh a +4% YoY increase. During the 13th Five-Year Plan, the average annual increase was +5.8%. From 2011 to 2021, China's total electricity consumption has also been increasing year by year. This is mainly due to increases in electricity consumption by primary, secondary, and tertiary industries, as well as by households.[7] Looking at power generation composition, the amount of power generated using new energy sources (nuclear, wind, and solar power) has been continuously increasing, and their proportion of the total has been

5 National Energy Administration, "2021 National Electricity Statistics Data", https://news.bjx.com.cn/html/20210617/1158624-2.shtml

6 National Energy Administration, "2021 National Electricity Statistics Data", https://news.bjx.com.cn/html/20210617/1158624-2.shtml

7 Zhao Ying, "China's Robot and Automobile Industries in the Fourth Industrial Revolution," research report, Institute of Industrial Economics of the Chinese Academy of Social Sciences, January 2022.

gradually rising (Table 1-1).

**Table 1-1: Power generation composition in China (2011 to 2020, units: billion kWh)**

| Year | Thermal | Hydroelectric | Nuclear | Wind | Solar |
|---|---|---|---|---|---|
| 2011 | 38,337 | 6,989 | 864 | 703 | 6 |
| 2012 | 38,928 | 8,721 | 974 | 960 | 36 |
| 2013 | 42,470 | 9,203 | 1,116 | 1,412 | 84 |
| 2014 | 44,001 | 10,729 | 1,325 | 1,600 | 235 |
| 2015 | 42,842 | 11,303 | 1,708 | 1,858 | 395 |
| 2016 | 44,371 | 11,841 | 2,133 | 2,371 | 665 |
| 2017 | 47,546 | 11,979 | 2,481 | 2,972 | 1,178 |
| 2018 | 50,963 | 12,318 | 2,944 | 3,660 | 1,769 |
| 2019 | 52,202 | 13,044 | 3,484 | 4,057 | 2,240 |
| 2020 | 53,303 | 13,552 | 3,663 | 4,665 | 2,611 |

Source: National Bureau of Statistics of China, National Energy Administration, China Electricity Council[8]

## (3) Energy industry development characteristics

1. There is still significant room for market growth due to the expansion of production capacity and scale in the energy and power industry.
2. Adjustments to and optimizations of the energy and power composition will continue, as will the expansion of clean energy and power.
3. Energy conservation and emission reductions will be a primary axis for development trends in the energy and power industry. There will be a gradual increase in resource usage in the energy and power industry, and the availability of energy and power systems will also gradually increase, thereby improving their quality, stability, and durability.
4. Digitalization, networking, and smart technologies in the energy and power industry will steadily become more sophisticated.
5. The energy storage industry will achieve rapid and sustainable development and become an important guarantee for supporting new energy and power systems.

[8] National Bureau of Statistics of China: http://www.stats.gov.cn/; National Energy Administration: http://www.nea.gov.cn/; China Electricity Council: https://www.cec.org.cn/

# 1.2 Current development state of China's energy storage industry

## 1.2.1 Characteristics of the development of the energy storage industry

Various energy and power industries have been rapidly developing in line with the sustained growth of China's energy and power industry, the structural transformation and increased sophistication of industry, and the Chinese government's strategic goals of "peak $CO_2$ emissions" and "carbon neutrality." This has consequently created room for growth in the energy storage industry, which has entered a period of development.

Within the industry, 2021 is referred to as "the first year of scaling development for energy storage in China." Under the guidance of the "double carbon" development goal (that is, peak carbon emissions and becoming carbon neutral), timely incentive policies were launched and key policies combining wind and solar power generation and energy storage in each province were successively implemented. By the end of the 14th Five-Year Plan period, it is expected that China's energy storage capacity will have reached 50 to 60 GW, and that the energy storage market will have reached approx. CNY1 trillion. Additionally, in 2021 China's energy storage industry also moved from the early stages of commercialization to the large-scale development stage. The primary reasons for this were, first, a significant increase in energy storage capacity; second, a variety of energy storage technologies achieved breakthroughs; third, a series of supportive policies were launched; and fourth, in the grid interconnections and ancillary services market, energy storage companies clarified their own unique role as market entities that are independent from electric power companies.

According to estimated statistics from the China Energy Storage Alliance (CNESA),[9] as of the end of 2021 the cumulative installed capacity of energy storage projects in operation (physical storage, electrochemical storage, molten salt thermal storage, etc.) was +29% YoY, reaching 45.7 million kW. Of note is the remarkable growth installed capacity for electricity storage, which increased by an impressive +220% YoY. Among energy storage, pumped storage had the largest installed capacity at 8.05 million kW. Next came electrochemical energy storage, with an installed capacity of 1.87 million kW and which has plans to exceed 20 million kW of installed capacity that is currently under construction (not yet in operation). Meanwhile, the installed capacity for newly operating energy storage reached 10.1 million kW. In particular, newly installed capacity for compressed air energy storage was 0.17 million kW, a significant 15 times increase from the end of 2020. The primary factors that increased the newly installed capacity include the deployment on the power supply side of storage facilities utilizing new energy and of independent energy storage facilities.[10]

As the scale of power generation facilities utilizing new energy expands, energy storage has become an essential part of the configuration for new power systems. Energy storage will be widely applied in a variety of situations, including on the power supply side, the grid side, and the user side, and its market potential cannot be underestimated. On the other hand, energy storage technologies, active capital markets, and supportive policies from local governments have emerged one after another to promote sustainable improvements in energy storage's safety and economic efficiency.

9 http://esresearch.com.cn/#/main

10 This data is basic statistics from the China Energy Storage Alliance (CNESA), and official data will be announced in April 2022 in the "Energy Storage Industry Research White Paper" (2022).

### 1.2.2 Direction of and challenges for the development of the energy storage industry

In 2021, under the guidance of China's "double carbon" development goal, the energy storage has formed a common understanding of the technology. The sophistication of physical and chemical energy storage technologies combined with long-duration energy storage technologies (LDES) has been gradually gaining attention. In the short term, lithium-iron-phosphate and pumped storage energy are indicators of development, but in the long term, a variety of technologies such as sodium-ion batteries, compressed air, and hydrogen energy will complement existing systems and create more options.

Industry players consider energy storage systems to be more than just simple battery cells. They believe that the energy storage industry should pay more attention to systems, and that smarter and more precise cell management and the systemization of safety designs will strengthen the security guarantees of the entire energy storage system, which will ultimately lead to the healthy development of the energy storage industry.

There are numerous types of energy storage technologies, and their application scenarios are complex. In 2021, many business models were tried out in the energy storage industry in accordance with the new roles for the electricity market. Additionally, new types of energy storage systems that integrate "power sources / networks / loads (source-network-load)" are also gradually being explored.[11]

In 2021, safety issues in the energy storage industry received a significant amount of attention. On the other hand, the effects of frequent fire accidents continue to cast a dark shadow over the industry as a whole. Industry players also generally recognize that the safety of energy storage systems must be of paramount importance. The safety of energy storage systems is supported by complex system engineering, including cell-module-system integration and structure-electrical-control, etc., and technologies and products must be updated with the goal of making them highly safe. At the same time, the energy storage industry must urgently address the challenges it faces, such as the lack of investment recovery mechanisms, incomplete operational control mechanisms, and the lack of established industry standard systems.

## 1.3 Outlook for China's economy and energy industry

### 1.3.1 Outlook for China's economy

During the 14th Five-Year Plan, China's economy will maintain a growth rate of around 6%, but, as it progresses to the 15th and 16th Five-Year Plans, the growth rate is expected to gradually slow down to around 5% and 4.5%, respectively. After 2035, China's economic growth rate is expected to decline even further to 4% level. Meanwhile, the quality of China's economic development has continued to improve, with energy conservation and emission reductions becoming increasingly important.

The following future development trends in the Chinese economy will deeply affect the form and structure of the power and energy industry and will significantly alter its development from within.

[11] Same as 9

1. The development of primary, secondary, and tertiary industries will move towards coordination. Secondary industries' share of GDP will remain roughly stable, while tertiary industries will continue to play an important role in economic development.
2. High-tech industries will continue to grow rapidly, and their independent research and development capacity will continue to improve. The development of the digital economy and of digital industry will become more apparent, and industrial integration will become even more sophisticated.
3. Industrial and supply chains will be improved and made more secure.
4. Exports of industrial products will further expand, particularly in areas covered by the Belt and Road Initiative. Service exports will also steadily improve.
5. Independent research and development capabilities will be continuously improved, and the level of security for core technologies, key components, and key raw materials will be significantly improved.
6. By 2035 China will realize its transformation from an "industrial powerhouse" to an "industrial great power".

### 1.3.2 Outlook for China's energy industry

China's final energy consumption demand is projected to moderately increase until 2025, peak between 2025 and 2030, and then follow a downward trend after 2030. It is expected to reach a maximum of 3.4 to 3.82 billion tons (standard coal equivalent) in 2035, but will decline to 2.84 to 3.37 billion tons in 2050 and then to 2.35 to 3.06 billion tons (standard coal equivalent) in 2060.[12]

In line with the Chinese government's implementation of the goals of "peak $CO_2$ emissions" and becoming "carbon neutral" as well as with its promulgation of energy conservation and emission reduction policies, heavy and chemical industries will stop expanding at scale, and the industrial sector will make structural adjustments and improve its technological level. Many industries will undergo inclusive development, and industries will accelerate their structure transformations and shifts to becoming more sophisticated. As a result, the industrial sector's share of final energy consumption will steadily decline, with it being expected to be 53 to 54% in 2025, below 45% around 2035, and 34-35% in 2060.

Due to consumer diversification and the increase in residential consumption, the construction sector's share of final energy consumption will rise for a time before turning negative, with it being said to remain between 26% to 27% in 2025 and then rising to 34% to 37% in 2060.

The transportation sector is affected by people's increased mobility, changes in transportation structure, and technological revolutions in transportation methods, and its share of final energy consumption will slightly rise and then decline, with it being said to reach 17 to 18% in 2025 and 27 to 30% in 2050 before falling to 25-29% in 2060.

For the time being, fossil fuels will be used as basic resources to support new resources. From 2020 to 2025, the replacement of coal with other fuels will accelerate, and the demand for and share of coal in final energy consumption

12 National Network and Energy Research Institute Co., Ltd. "China Energy and Power Development Outlook" (2020)

will steady decline, with coal's share rising to 11 to 13% in 2035 and then being expected to fall to below 3% in 2060.[13]

Similarly, the demand for and share of petroleum products and natural gas in final energy consumption will decline. The share of petroleum products will peak at 24 to 25% around 2030 and then fall to 17% in 2060. Natural gas will peak at 19% around 2040. Petroleum products will enter a stagnation phase earlier than natural gas, but the decline will eventually accelerate for both.[14]

Hydrogen energy will be applied on a large scale around 2030, primarily in the automobile industry.[15] Electricity will gradually some to occupy a central position in final energy consumption. Electricity's share of final energy consumption will continue to rise, and by 2025 it will overtake coal as the most important component of final consumption, with it being expected to rise to 37 to 45% in 2035, 45 to 60% in 2050, and 50 to 70% in 2060.[16]

Clean energy installed capacity will continue to increase. In 2019 it was around 820 million kW, but it is expected to reach 1,500 to 1,770 million kW in 2025; 2,750 to 3,310 million kW in 2035; 3,930 to 4,930 million kW in 2050; and 4,160 to 4,930 million kW in 2060.[17] Clean energy's share in the power supply composition will continue to rise from approx. 41% today to approx. 82% in 2050 and approx. 86% in 2060.

Under the normal model, the installed capacity for onshore wind power will reach 1,190 million kW in 2050 and 1,240 million kW in 2060. Offshore wind power will reach 140 to 170 million kW in 2050 and 150 to 200 million kW in 2060. Solar power will reach 1,400 million kW in 2050 and 1,470 million kW in 2060. Solar thermal power will reach 150 to 170 million kW in 2050 and 200 to 250 million kW in 2060. Installed capacity for coal-fired power will decline to approx. 680 million kW in 2050 and to approx. 400 million kW in 2060. Natural gas power will be approx. 210 million kW in 2050 and approx. 220 million kW in 2060. Installed capacity for nuclear power and hydroelectric power will reach approx. 220 million kW and approx. 410 million kW, respectively, in 2050, and remain stable after that.[18]

### 1.3.3 Outlook for China's energy storage industry

China's economic development has been accompanied by high-quality economic development, industrial upgrading, sustained urbanization, and improved living standards for the people. Additionally, the strategies for "peak $CO_2$ emissions" and becoming "carbon neutral" has created vast and diverse market needs as well as development room for China's energy and power industry and energy storage industry to grow.

The development of high-tech industries and promotion of the digital economy have provided the energy storage industry with a technological foundation and have created an ecosystem to utilize it.

New energy and clean power will gradually come to occupy a central position in the energy and power mix, becoming a direct and powerful driving force for the energy storage industry. In order to build a clean, low-carbon,

13 Forecasts were made under three conditions: normal, accelerated electrification, and strengthened emission reductions. According to the authors' research, the Chinese government has recently launched a series of policies that place renewed emphasis on the clean use of coal. The authors' research findings support the relatively conservative forecast results under normal circumstances, and the prediction results under normal circumstances will be adopted here.

14 National Network and Energy Research Institute Co., Ltd. "China Energy and Power Development Outlook" (2020)

15 Zhao Ying, "China's Robot and Automobile Industries in the Fourth Industrial Revolution," research report, Institute of Industrial Economics of the Chinese Academy of Social Sciences, January 2022.

16 National Network and Energy Research Institute Co., Ltd. "China Energy and Power Development Outlook" (2020)

17 National Network and Energy Research Institute Co., Ltd. "China Energy and Power Development Outlook" (2020)

18 National Network and Energy Research Institute Co., Ltd. "China Energy and Power Development Outlook" (2020)

safe, and highly efficient modern energy system under the “double carbon” development goal, it will be necessary to combine new energy power generation and final energy consumption into one. The conventional energy and power supply system model is based on centralized and unified transmission utilizing fossil fuels. The new model, on the other hand, integrates new energy storage equipment, clean and renewable power generation equipment, and electrical equipment (consumer-level electricity usage equipment), and realizes integration of “power sources / networks / storage / loads (source-network-storage-load)”. This will be the direction of the revolution in the energy and power industry.

The large-scale construction and operation of energy storage facilities will change the characteristics of electricity because they simultaneously integrate power generation, transmission, supply, and usage. The real-time connection between supply and demand will be replaced by a connection that spans time zones, enriches methods for adjusting the balance between electricity supply and demand, increases the durability and stability of the power grid, and improves power transmission efficiency. Energy storage equipment will leverage its interactive nature to support and guarantee peak shifting and frequency modulation for power systems, consumption management of new energy, and operation of new energy transportation systems.

Among the power sources in a power system, energy storage plays a significant role in regulating power for hydroelectric, wind, and solar power. Hydroelectric power plants in China, particularly in the western region, still face the unresolved problem of large-scale power losses (abandoned power) that occur during off-peak periods of power consumption during their operational processes. Wind and solar power, due to their technology-driven economic characteristics, rely on energy storage devices, but the difficult issue of managing the output and consumption of hydroelectric, wind, and solar power have yet to see obvious improvement. The combined power loss from China’s so-called “three abandons” (abandoned hydroelectric, wind, and solar power) in 2018 was more than the power generated by the Three Gorges Dam hydroelectric power plant, which is the world’s largest generator of hydroelectric power. In the future, the stable operation of power grids based on clean energy and green power will rely on having highly stable and efficient energy storage systems.

China’s new energy vehicles have ranked first in the world in both production and sales for seven consecutive years, with sales in 2021 reaching approx. 3.52 million units, and exports tripling YoY to 310,000 units. Of these, new vehicle sales accounted for 61% of the global market share. Meanwhile, by 2022 electric vehicles are expected to achieve ahead of schedule the government’s goal of “acquiring a 20% share of the Chinese automobile market by 2025”.[19]

The composition of new energy vehicles is constantly changing. In 2019, China’s new energy vehicles consisted of 972,000 pure electric vehicles (BEVs), 232,000 plug-in hybrid vehicles (PHEVs), and 2,737 hydrogen vehicles, accounting for 80.6%, 19.2%, and 0.2% of the total, respectively. Pure electric and hybrid vehicles are mainly concentrated in the passenger car sector, while hydrogen vehicles are being tested mainly in the commercial vehicle sector.

By 2030 at the latest, China’s automobile industry will completely shift its product focus from conventional gasoline-powered vehicles to new energy vehicles.[20] The development of new energy vehicles has not only opened up a vast market for the energy storage industry, but has also promoted diversification of energy storage technologies.

[19] China Passenger Car Association (CPCA) forecast, December 27, 2021

[20] Zhao Ying, “China’s Robot and Automobile Industries in the Fourth Industrial Revolution,” research report, Institute of Industrial Economics of the Chinese Academy of Social Sciences, January 2022.

Furthermore, it has given rise to new challenges for the energy storage industry ecosystem, such as connecting automotive energy storage devices to the transmission grid and the cascading use of car batteries.

China's power storage facilities remain centered around pumped storage power plants, with a pumped storage installed capacity of approx. 8.05 million kW in 2021, which is expected to reach 120 million kW in 2035 and 170 million kW in 2060. However, as technologies mature and costs continue to fall, new types of energy storage, such as electrochemical energy storage, will enter a period of development. By 2040, new energy storage is expected to overtake pumped storage as the main form of energy storage in power systems. Total installed capacity for new energy storage is expected to reach approx. 70 million kW in 2035 and 420 million kW in 2060. In addition, energy storage priority areas will be designated in North China, Northwest China, East China, and South China, where energy storage cities will be built with new energy power generation bases and load adjustment centers. In the future, lithium-ion batteries and lead-acid batteries will be the primary energy storage sources, with others being used as complementary technologies. Cascading usage of secondary batteries will also become an important component of energy storage in power systems.

In 2021, the National Development and Reform Commission and the National Energy Administration promulgated the "Guiding Opinions on Accelerating the Development of New Energy Storage,"[21] and set a goal of moving new energy storage from early-stage commercialization to large-scale development by 2025. The document calls for greatly improving the innovation capabilities of new energy storage technologies and the level of autonomous control for the core technologies and equipment, achieving equipment scales of 30 million kW or more, and the full-scale market development of new energy storage by 2030, as well as having the core technologies and equipment for new energy storage enable autonomous control and having the industry's technological innovations and industrial standards rank among the best in the world. It also aims to have standardized systems, market mechanisms, and business models that will be mature and sound, and to achieve advanced integration and development with each stage of the power system, with installed capacity that will nearly meet the demand for new power systems. The document also positions new energy storage as one of the key pillars for realizing peak $CO_2$ emissions in the energy sector and for achieving carbon neutrality.

Along with the realization of these goals, China's energy storage industry will play an important role in the process of promoting the development of the national economy, for the efficient and stable operation of the energy and power system and the efficient and clean operation of transportation and traffic.

21 https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202107/t20210723_1291321.html?code=&state=123

**Table 1-2: Outlook for China's economy and energy industry**

| | 2019 | 2035 | 2050 | Notes (forecasting agency) |
|---|---|---|---|---|
| Total population (100 million) | 14.0 | 14.3 | 13.95 | National Health Commission of the People's Republic of China |
| Urbanization rate (%) | 47.3 | 70.0 | 80.0 | 2035: China Development Research Foundation<br>2050: Chinese Academy of Social Sciences |
| GDP (trillion USD) | 14.4 | 32 | 53 | 2035: Guanghua School of Management<br>2050: Goldman Sachs |
| Tertiary industry ratio (%) | 53.9 | 70 | 80 | 2035/2050: Chinese Academy of Social Sciences |
| Primary energy consumption (100 million tce) | 48.6 | 40.0 | 25.0 | 2035: National Energy Administration<br>2050: Energy Transitions Commission |
| Coal ratio (%) | 57.7 | 40 | 8 | 2035: National Development and Reform Commission<br>2050: National Economics and Technology Research Institute |
| Renewable energy ratio (%) | 12 | 40 | 70 | 2035: State Grid Energy Research Institute<br>2050: Energy Transitions Commission |
| Electricity consumption (trillion kWh) | 7.2 | 9.6 | 15.0 | 2035: State Grid Energy Research Institute<br>2050: Energy Transitions Commission |
| Renewable energy ratio in electricity generated (%) | 26 | 40 | 100 | 2050: Full decarbonization of the electricity sector, Energy Transitions Commission |
| $CO_2$ emissions (100 million tons) | 88.9 | 72.7 | 4.3 | Achieve net zero via measures such as planting trees and $CO_2$ capture/storage |

tce; ton of coal equivalent
Source: "Energy Data 2020" p. 20[22]

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# 2 Relevant policies and measures to promote research and development and industrial formation of next-generation battery technologies in China

## Introduction

Since its reform and opening-up, China has promoted the overall, coordinated, and sustainable development of energy to meet the needs of its rapidly developing economy and society. China has now grown to become the world's largest energy producer and consumer, and its energy usage efficiency is increasing at the fastest rate in the world. After the 18th National Congress of the Communist Party of China, the country's development entered a new era and China's energy development also embarked upon a new era.

In June 2014, President Xi Jinping launched a new strategy for energy security, known as the "Four Reforms and One Cooperation," which indicated the direction for China's energy developed as it entered a new era and opened up a new path to distinctive energy development. China adheres to the new development philosophy of "innovative, coordinated, green, open and shared development," and has set "high-quality" development as the theme that it is promoting. While focusing on deepening supply-side structural reforms, China's energy had entered a new stage of development that promoted quality development by comprehensively advancing reforms to the energy consumption system, building a pluralistic and clean energy supply system, implementing innovation-driven development strategy, continuous deepening of energy system reforms, and continuous promotion of international collaborations in the energy sector.

However, on the other hand, there was still a wide gap in terms of core technologies, industry-academia-government collaboration, innovation systems, and strategic planning in terms of the requirements to be a global energy science and technology great power and for a nation leading the energy revolution. Chinese companies were not sufficiently leading as innovation agents, and innovation activities were inconsistent with industrial needs, so there was a need to strengthen the market's role in promoting scientific and technological innovation. China is confronted with the challenges of an increasingly advanced global energy structure, an accelerating global response to climate change, intensifying technological competition between countries, the arrival of a new normal for the Chinese economy, and the continued strengthening of resource and environmental constraints. As a next step, it must strengthen its overall strategic planning and promote reforms in its energy consumption, supply, technology, and systems. The world's major countries view energy technologies as a breakthrough for the coming scientific/technological revolution and industrial revolution. China has enacted a variety of policies and measures to gain a developmental advantage, and is striving to strengthen its international competitiveness and to maintain its top-class status. Against this background, China has launched a series of laws, regulations, policies, and measures, aiming to accelerate energy science/technology innovation and industrial development.

## 2.1 China's "Three Energy Laws"

China is currently in the process of building a modern rule of law state, and is constantly promoting the systemization of its legal system in order to improve the effectiveness of law enforcement. In the energy industry sector, the "Energy Conservation Law," the "Renewable Energy Law," and the "Energy Law (draft for public comments)" are an important legal foundation for policies and measures to promote the structural transformation of China's energy, to build and perfect its energy system, and to promote the development of the energy industry. The emphasis and positioning of the three laws differs, with the Energy Conservation Law and the Renewable Energy Law being single laws for the energy conservation and renewable energy sectors, respectively, while the Energy Law is not limited to a single sector and is instead positioned as a charter law for China's energy sector. This law, also known as the "Energy Constitution," clarifies issues related to the direction, strategy, and overall nature of China's energy development, and governs and coordinates the relationships between various energy laws.

### 2.1.1 Energy Conservation Law (1997)[23]

In the mid-late 1990s, the energy consumption of China's major industrial products was 30-60% higher than that of developed countries, and energy usage efficiency was around 30% that of developed countries. However, at the time the relatively rapid pace of China's economic development and the improvements in the people's standards of living at that time gradually led a strain on energy supplies becoming apparent, and energy shortages became a limiting factor for economic development. Therefore, in order to solve this energy shortage, it was necessary to simultaneously promote energy conservation and development in parallel, both by increasing energy production capacity via the discovery of new energy sources and by improving production efficiency via energy conservation. Against this backdrop, there was an objective need to enact basic legislation to promote energy conservation activities.

On November 1, 1997, the 28th Session of the Standing Committee of the 8th National People's Congress passed the Energy Conservation Law of the People's Republic of China, which then officially came into effect on January 1 of the following year. Since then, the Chinese government has revised the law twice, in 2007 and 2016, in line with new needs arising from the development situation. Revision work on the latest version of the law was conducted from 2016 to October 26, 2018, and it was then passed at the 6th Session of the Standing Committee of the 13th National People's Congress.

The Energy Conservation Law consists of 7 chapters and 87 articles, and includes sections on general provisions, energy conservation management, rational use and energy conservation, progress in energy conservation technologies, incentives, and legal responsibilities. The general provisions consist of 10 articles, specifying legislative objectives (Article 1), concept definitions (Articles 2 to 3), basic strategies (Article 4), and the positioning of the responsibilities of the relevant entities (Articles 5 to 10). The specific contents of this law can be summarized into the following three sections.

23 Energy Conservation Law of the People's Republic of China (npc.gov.cn)

### (1) Legislative objectives and basic national policy

The law aims to “promote energy conservation throughout society,” “improve energy use efficiency,” “protect and improve the environment,” and “promote the overall, harmonious, and sustainable development of the economy and society.” Furthermore, it states that “Resource conservation is China’s basic national policy. China will promote conservation and development in parallel, and will implement energy development strategies with conservation as the top priority,” which clarified the importance of energy conservation in national policy and energy development strategy.

### (2) Specific management and measures

1. Implement an energy conservation target responsibility system and an energy conservation audit and evaluation system. Incorporate energy conservation activities into local government audit and evaluation systems.
2. Systemize sound energy conservation standards. Establish compulsory energy efficiency standards for energy-using products and equipment, and energy consumption limit standards for per unit product for high-energy-consuming products (that are currently in production).
3. Implement an energy conservation evaluation and audit system for fixed asset investment projects (new construction, renovations, and expansions).
4. Implement a culling system for energy-consuming products, equipment, and manufacturing technologies that are obsolete and that consume significant amounts of energy.
5. Apply energy consumption limit standards per unit product to high-energy-consuming products (currently in production).
6. Clarify energy conservation regulations related to industry, architecture, transportation, and public institutions, etc.

### (3) Encouraging innovation in energy conservation technologies

Clarify the nature of energy conservation technologies and take “technically feasible, economically rational, and environmentally and socially acceptable measures.”

1. Central government and provincial/municipal finances will establish special energy conservation project funds to support research and development of energy conservation technologies.
2. Focus promotion on modifying energy conservation technologies held by companies in major energy-consuming industries such as electric power, steel, nonferrous metals, building materials, petroleum processing, chemical industry, and coal, etc.
3. Encourage manufacturing companies to adopt technologies such as combined heat and power (cogeneration), residual heat and pressure utilization, clean coal technology, and advanced monitoring and control of energy use.
4. Promulgate a popularization inventory of energy conservation technologies and products, and implement support policies such as tax incentives.
5. Through financial subsidies, support the spread and use of energy conservation products such as energy-saving lighting equipment.
6. Encourage imports of advanced energy conservation technologies and equipment through the operation of

tax revenue and other policies. Restrict the export of products that, during the manufacturing process, have high energy consumption and high levels of pollution.

7. The Chinese government will preferentially purchase products and equipment that have obtained energy conservation product certification.
8. Guidance will be given to financial institutions to expand lending support for energy conservation projects.
9. Launch and implement important projects in energy conservation scientific research, and spread the use of renewable energy technologies such as biomass energy, solar energy, and wind energy.

### 2.1.2 Renewable Energy Law (2005)

Since the 1990s, with the rapid growth of its economy, problems such as a lack of energy resources, an irrational structure, and serious environmental pollution became increasingly apparent in China, and its dependence on foreign oil continued unabated, which gradually brought the issue of energy security into relief. Accelerating the development and use of renewable energy such as wind, solar, hydroelectric, biomass, geothermal, and ocean energy became a trend not only in China, but also internationally. With its extremely abundant renewable energy resources, China has great potential for development. From a long-term perspective, accelerating the development and use of renewable energy has important implications for China in improving the energy structure, protecting the environment, and ensuring energy security. With the aim of promoting the development and use of renewable energy and of overcoming current legal and policy obstacles, the Renewable Energy Law of the People's Republic of China was approved on February 28, 2005 after deliberations at the 13th and 14th Sessions of the Standing Committee of the 10th National People's Congress, and came into effect on January 1 of the following year.

The Renewable Energy Law consists of 8 chapters and 33 articles, and includes sections on general provisions, resource surveys and development planning, industrial guidance and technical support, dissemination and application, price controls and cost sharing, economic incentives and supervisory measures, legal responsibility, and supplementary provisions. Overall, the legislative principles reflect the interconnectedness of three aspects: "state responsibility and support for society as a whole," "governmental guidance and market operation," and "current demand and long-term development." Through administrative regulations and market incentives, the law induces and encourages various economic entities to actively participate in the development and use of renewable energy in order to create a market environment in which renewable energy can fairly compete with conventional energy. It has also led to effectively accelerating the development and utilization of renewable energy in China, and the law's important legal systems are as follows.

#### (1) Renewable Energy Overall Target System

The Renewable Energy Law grants the supervising energy department of the State Council the authority to formulate and publish medium- to long-term overall targets for the development and use of renewable energy in China, and also to work with local governments to determine and publicize medium- to long-term goals for the development and use of renewable energy in each administrative region. Plans for the development and use of renewable energy are created based on medium- and long-term goals. By first setting goals and then creating the plans, it is made clear that the primary purpose in creating plans is to achieve medium- to long-term goals, and the plans then become part of the overall target system.

### (2) Examination of grid-connected power generation via renewable energy and total purchase system

The law states that the Chinese government encourages and supports grid-connected power generation via the use of renewable energy. It stipulates that all electricity generated by grid-connected renewable energy power generation projects that have obtained or applied for administrative licenses must be purchased by power grid companies, and that power grid companies must provide grid connection services. This is a legal obligation for power grid companies with monopoly positions, and helps to solve the grid interconnection issues faced by current renewable energy sources. It is also an essential prerequisite for scaling up the development of renewable energy power generation, and an important measure for renewable energy companies to survive and gradually improve their competitiveness in the energy market.

### (3) Renewable energy electricity prices and cost sharing system

The law stipulates different electricity prices depending on local conditions and technology type (such as wind power generation, solar power generation, small-scale hydroelectric power generation, and biomass power generation). Based on the principle of price determination, the electricity price standard is determined by adding a reasonable profit to the average power generation costs in each area. This pricing mechanism allows renewable energy power generation investors to obtain relatively stable and reasonable returns, which will induce them to invest in the renewable energy power generation sector. Overall, if the purchase price of electricity generated from renewable energy exceeds the price of regular energy, then the difference is distributed and added to the electricity sales price for consumers, with specific measures being formulated by the pricing division under the State Council.

### (4) Fiscal incentives

Given that the investment costs for the development and use of renewable energy are currently relatively high, state support is still required to accelerate technology development and market formation. The law therefore provides financial support measures, including the establishment of a special project fund for renewable energy development, preferential loan measures with interest subsidies for renewable energy development and utilization projects, and tax incentives for projects included in the renewable energy industry development guidance index.

## 2.1.3 Energy Law (draft for public comments) (2020)

The Energy Law of the People's Republic of China is a charter law for China's energy sector, and is also known as the "Energy Constitution". Its core purpose is to put China's energy management on the path to the rule of law. The law's promulgation will supplement the lack of a basic law in China's energy legal system. It not only provides a legal basis for enacting and amending energy-related laws, but also helps to coordinate and unify energy laws with each other and with other laws. It also provides a basis for state enforcement, implementation of energy strategies, and security of the energy economy.

In the early 1980s, the State Council established the National Energy Commission and formed the "Energy Law Research Project Team". Through research on the legal framework for an energy law, it was hoped that comprehensive legal norms would be established for the energy industry to jointly abide by, however, administrative management of energy became increasingly decentralized and energy-related legislation was almost completely shelved. This situation continued until 2005, when work on drafting the Energy Law resumed in early 2006 under the recommendations and promotion of the former Energy Bureau, which was then part of China's National Development and Reform Commission. On February 1st of the following year, the Energy Law (draft for public comments) was promulgated, and since then the government has been soliciting opinions and comments from the general public, while research and drafting have continued.

On June 13, 2014, President Xi Jinping launched a new strategy for energy security, known as the "Four Reforms and One Cooperation," at the 6th Session of the Central Financial and Economic Affairs Commission. This strategy was meant to drive the development of China's energy industry and move it into a new era. In order to implement the strategy, China promoted improvements to the soundness and completeness of its energy management system, modernizations to its energy management capabilities, and the development of high-quality energy. Starting in 2017, under the guidance of the Legislative Office of the State Council and the Ministry of Justice, the National Development and Reform Commission and the National Energy Administration have formed an expert group and a working team which implemented further revisions and improvements to the "Energy Law of the People's Republic of China (draft for review)" and created the new "Energy Law of the People's Republic of China (draft for public comments)." On April 10, 2020, the National Energy Administration published a public notice inviting comments on the "Energy Law of the People's Republic of China (draft for public comments)."

The new Energy Law (draft for public comments) consists of 11 chapters and 117 articles. It covers energy strategy and planning, energy development and processing/conversion, energy supply and use, energy markets, energy security, scientific and technological progress, international partnerships, management oversight, and legal responsibility, etc., and stipulates the scope of application, strategy and structure, and structural optimizations. The main content of the law is as follows.

### (1) Proposing the direction for the development of the "marketization of energy"

The draft for public comments clearly sets forth the principle of the "marketization of energy" in the general provisions, and calls for the creation of a market structure and mechanism that allows effective competition, as well as for the creation of a system in which energy prices are primarily determined by the market in a competitive field. Furthermore, in Chapter 5, "Energy Markets," energy market elements such as the market entities, market system, price mechanism, and market management and supervision are all stipulated in technical detail. This means that "energy marketization" is recognized through the form of a law, thereby putting to an end the controversy between planning and markets in the energy sector and laying the groundwork for further deepening energy marketization reforms.

### (2) Emphasis on universal energy services and their compensation principles

Energy concerns a nation's economy and its people's livelihoods. In order to ensure that every citizen has access to basic energy supplies and services, energy-related services must emphasize the principle of universal service. The draft for public comments proposes that companies contracted to supply energy such as electricity must fulfill corresponding universal service obligations based on relevant national regulations. The specific methods of compensation for universal energy services will be formulated by the supervising energy department of the State Council in collaboration with the finance department, pricing department, and other related departments, and will be promulgated and implemented after approval by the State Council.

### (3) Coordinated relationship between fossil and non-fossil fuels

The draft for public comments clearly calls for optimization of the energy structure. Items related to fossil fuels use modest expressions such as "regional development," "clean and efficient usage," and "low-carbon development" without explicitly mentioning regulations or other negative details. Items related to non-fossil fuels include positive content such as "accelerating development," "improving the ratio," and "development support," and provides specific subdivisions of the consumption management guarantee system for renewable energy and the corporations' guarantee obligations. The relationship between fossil and non-fossil fuels is not an antagonistic relationship, in which one is superior and one is inferior, and but rather a cooperative and unified relationship in which if one is considered good, then the other will strive to surpass it.

### (4) Introduction of energy security strategy into national strategy

In the law, the state sets out a policy to control and coordinate energy security and to incorporate energy security strategy into national security strategy. Additionally, Chapter 6 "Energy Security" stipulates in detail safety and protection of energy facilities and locations, network and information security, energy reserves, forecasting and early warning, and emergency response systems, with the state comprehensively enhancing its energy security capabilities.

## 2.2 Main policies of the central government

### 2.2.1 Analysis of major policies at the national level

At China's two national conferences held in March 2021 (the National People's Congress and the Chinese People's Political Consultative Conference), the "14th Five-Year Plan for Economic and Social Development (2021–2025) and Long-Range Objectives through the Year 2035 of the People's Republic of China" (hereinafter referred to as the "14th Five-Year Plan") was promulgated.[24] It lays out a grand blueprint for paving a new path toward the comprehensive construction of China's modern socialist state and serves as a roadmap for the basic realization of socialist modernization by 2035. Compared to the "13th Five-Year Plan for Economic and Social Development of the People's Republic of China" (hereinafter referred to as the "13th Five-Year Plan"), which was promulgated five years earlier in March 2016, despite the fact that China's developmental situation has become increasingly complex, in the 14th Five-Year Plan outline, China's national strategy intentions are extremely clear and the priority points for the government's activities are laid out in a distinct and orderly manner. Furthermore, it also includes firm implementation measures for development goals over the next 5 to 15 years.

### (1) Strategic goals and development stages focused on the realization of "building China into a modern socialist country in all respects" and on simultaneously promoting economic growth and green development

When compared to the 13th Five-Year Plan, the 14th Five-Year Plan outline places more emphasis on the importance

[24] (Promulgated under the authority of both conferences) Outline of the 14th Five-Year Plan for Economic and Social Development (2021–2025) and Long-Range Objectives through the Year 2035 of the People's Republic of China (xinhuanet.com)

of China's modernization and makes it clear that China will embark on a new path towards "building China into a modern socialist country in all respects." The purpose of the 14th Five-Year Plan period is to open up a favorable situation for "building China into a modern socialist country in all respects" and get the country off to a good start towards this goal. The overall plans for economic development, political development, cultural development, social development, and ecological civilization development will be promoted in a unified manner, and harmonized with the promotion of "building China into a modern socialist country in all respects." It emphasizes that China must meet the modernization needs of economic development, but also that it must adhere to a green and sustainable modernization path. It clarifies that "realization of new progress in building an ecological civilization" is set as the primary economic and social development goal during the 14th Five-Year Plan period, and sets the development goals of reducing energy consumption and $CO_2$ emissions per unit of GDP by 13.5% and 18%, respectively.

During the 13th Five-Year Plan period, governments at all levels faced unprecedented economic growth pressures with the goal of completing the comprehensive construction of a moderately prosperous society. As such, although the green development strategy was steadily progressing at a moderate speed and in step with economic growth, in reality, economic development was given priority. In September 2020 at the UN General Assembly, President Xi Jinping stated that, "China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have $CO_2$ emissions peak before 2030 and achieve carbon neutrality before 2060." The 14th Five-Year Plan outline included an action plan with two major goals: reaching "peak $CO_2$ emissions" and becoming "carbon neutral" (Table 2-1).

China today not only has the determination to achieve these two goals, but also the foundations to achieve them. China has already almost completely achieved a "comprehensive moderately prosperous society," and has a sufficient economic base, having grown to become the world's second-largest economy in 2010. Additionally, due to the sudden outbreak of COVID-19 in 2020, economic data is no longer the sole reference standard for determining social development, with green development becoming increasingly important. The theme of Chapter 11 of the 14th Five-Year Plan is "Promotion of Green Development and the Harmonious Coexistence of People and Nature." Adhering to this philosophy means simultaneously promoting both economic growth and green development. From the perspective of "domestic general circulation," economic growth must achieve green development, and green development must drive economic growth.

### (2) Concrete measures to promote the comprehensive development of the energy system

1. Build a modern energy system and place greater emphasis on the development of clean energy and nuclear power generation.

The 14th Five-Year Plan retains the core content related to "building a modern energy system" from the 13th Five-Year Plan. Although the number of characters related to this content decreased, the overall development direction has not changed, and, in fact, even more emphasis has been placed on it. The 14th Five-Year Plan aims to accelerate the development of non-fossil fuels, adhere to simultaneously promoting centralized and decentralized systems, and build a multi-energy and mutually complementary clean energy base, as well as increasing the share of non-fossil fuels in total energy consumption to approx. 20%. In the "project for the construction of a modern energy system," "large-scale clean energy bases" and "coastal nuclear power generation" retain relatively high and important positions, which echoes China's key goal of carbon neutrality. It will also improve clean energy consumption management/storage capacity and power transmission/distribution capacity to remote areas, promote flexibility for coal-fired power generation, and accelerate the construction of pumped storage power plants and the scaling application of new energy storage technologies.

2. Adhere to technological innovation-driven development, improve the driving force of technology in the energy industry, and grand development of strategic emerging industries

The 14th Five-Year Plan still places great emphasis on scientific and technological innovation. It mentions that energy technology innovation will be actively promoted and that a national laboratory will be established to focus on key innovation areas such as modern energy systems. At the same time, it further emphasizes the driving force of technological innovation in the industry.

In order to unwaveringly improve the competitiveness of the entire industrial chain for power equipment and new energy sectors, China will begin building a strategic and comprehensive industrial chain, starting with finished products that are consistent with the direction for future industrial transformation. In addition, China is setting its sights on strategic emerging industries such as new energy, new energy vehicles, and green and environmental production, as well as accelerating the innovation and application of important core technologies and strengthening the security of its resource supply. It is fostering businesses that will become a new driving force for achieving grand development and constructing new pillars for its industrial system. On the other hand, in the fields of cutting-edge science and technology and industrial transformation, such as hydrogen energy and energy storage, China is planning to create future-oriented industries by incubating and accelerating future industries and by creating a series of industry deployment plans. Meanwhile, it is also integrating the development goals of digitalization, building 5G-based application scenes and an industrial ecosystem, and developing application model trials in key areas such as smart energy.

3. High emphasis on energy storage technologies

The term “energy storage technology” refers to the construction of a new type of power system, and is one of the key technologies for China to achieve its two goals of peak $CO_2$ emissions and carbon neutrality. The 14th Five-Year Plan mentions energy storage technology many times before and after the section on energy storage technologies, and clearly calls for the “construction of pumped storage power plants and acceleration of large-scale application of new energy storage technologies.”

**Table 2-1: Comparison of China's 13th Five-Year Plan and 14th Five-Year Plan**

| Point of Comparison | 13th Five-Year Plan | 14th Five-Year Plan |
| --- | --- | --- |
| Development stage | Part 1, Introduction: Final stage of the comprehensive construction of a moderately prosperous society | Part 1 Theme: Stage of embarking upon a new path toward building China into a modern socialist country in all respects |
| Macro development goals | Part 1 Introduction: Ensure the steady completion of the comprehensive construction of a moderately prosperous society | Part 1, Chapter 2, Section 1: Create an advantageous situation and get off to a good start toward the comprehensive construction of a modern socialist country |
| Ecological construction goals | Part 1, Chapter 3: Overall improvement in the quality of the ecological environment. Effectively suppress total $CO_2$ emissions. | Part 1, Chapter 3, Section 2: Achieve new progress in building an ecological civilization. Reduce energy consumption and $CO_2$ emissions per unit of GDP by 13.5% and 18%, respectively. |
| Construction of a modern energy system | Part 7, Chapter 30 Theme | Part 3, Chapter 11, Section 3 Theme |
| Major energy projects (dedicated column) | Part 7, Chapter 30, Section 2, Dedicated Column 11: Smart power systems, coal-fired power generation, renewable energy, nuclear power generation, unconventional oil and natural gas, energy transportation routes, energy storage facilities, and core energy technology/equipment | Part 3, Chapter 11, Section 3, Dedicated Column 6: Clean energy, nuclear power generation, external electricity transportation routes, power system adjustments, and oil and natural gas storage and transportation capacity |
| Energy storage technology | Part 5, Chapter 23, Section 1: Greatly promoting high-efficiency energy storage and distributed energy systems | Part 3, Chapter 9, Section 2: Create future industry incubation and acceleration plans and a series of future industry deployment plans in the fields of cutting-edge science and technology and industrial transformation, such as hydrogen energy and energy storage. Accelerate the construction of pumped storage power plants and the scale-up application of new energy storage technologies. |

Source: 13th Five-Year Plan[25] and 14th Five-Year Plan[26]

[25] http://www.gov.cn/xinwen/2016-03/17/content_5054992.htm

[26] http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm

### 2.2.2 Analysis of major policies at the ministerial level

#### (1) "Innovation Action Plan for Energy Technology Revolution (2016-2030)" (National Development and Reform Commission and National Energy Administration)[27]

In June 2016, the National Development and Reform Commission and the National Energy Administration jointly promulgated the "Innovation Action Plan for Energy Technology Revolution (2016-2030)," which sets forth a policy to achieve technological breakthroughs in the following 15 technology areas during the 2016-2030 period.

1. Coal detoxification mining technology
2. Development technology for unconventional oil and gas, and for deepwater and deep-sea oil and gas
3. Highly efficient clean coal technology
4. $CO_2$ capture, utilization, and storage technology
5. Advanced nuclear power technology
6. Spent nuclear fuel processing technology and technology for the safe treatment of highly radioactive waste
7. Highly efficient solar energy utilization technology
8. Large-scale wind power generation technology
9. Hydrogen energy and fuel cell technology
10. Biomass/oceanic/geothermal energy utilization technology
11. High-efficiency gas turbine technology
12. Advanced energy storage technology
13. Key technology for modern power grids
14. Energy internet technology
15. Energy conservation and energy efficiency improvement technology

The Innovation Action Plan set the following goals for 2020: a significant improvement in energy independence innovation capabilities; a series of key technology breakthroughs; significant reduction in dependence on external sources for energy technology equipment, key components, and materials; significant improvement in the international competitiveness of the energy industry; and basic construction of an energy technology innovation system. It also set the following as goals to achieve by 2030: comprehensive improvement in energy independence innovation capabilities; completion of a well-organized energy technology innovation system adapted to national conditions; raising the overall level of energy technology to an internationally advanced level; support for the harmonious and sustainable development of the energy industry and the ecological environment; joining the ranks of the world's energy great powers.

Of these goals, with regards to the key mission of "advanced energy storage technology innovation," the plan specifies research in the following: high-efficiency and high-temperature storage technology using solar heat; high-capacity heat storage (cooling) technology for distributed energy systems; physical energy storage technology aimed at improving the efficiency of power grid peak shifts and applying it to regional energy supplies; and energy

27 Notification of the "Innovation Action Plan for Energy Technology Revolution (2016-2030)" by the National Development and Reform Commission and National Energy Administration - National Energy Administration (nea.gov.cn)

storage technology for applying renewable energy to grid-connected, distributed, microgrid, and electric vehicles. The plan calls for establishing key core technologies at each phase of energy storage technology, completing model verifications, raising the overall level of technology to a world-class level, and leading the world's energy storage technology and industrial development. In addition, it also aims to make breakthroughs via active exploration and research in the following: high-density and low thermal retention cost energy storage technology; new concept energy storage technology (liquid batteries and magnesium batteries, etc.); and multifunctional new hybrid energy storage technology based on superconducting magnetism and electrochemistry.

The Innovation Action Plan identifies three strategic directions for advanced energy storage technology innovation: thermal storage, physical energy storage, and chemical energy storage. By 2020, the plan aims to achieve breakthroughs in the following: material screening and equipment design technology for high-temperature heat storage; key part design and manufacturing technology for compressed air energy storage; core technology chemical energy storage (formulation and preparation of various new materials, integration of energy storage systems, and energy management systems, etc.). In addition, the following maturing energy storage technologies will be promoted on a trial basis: supercritical compressed air energy storage systems (10,000 kW / 100,000 kWh); flywheel energy storage array units (1,000 kW / 1,000 MJ); all vanadium redox flow battery energy storage systems (100,000 kW class); sodium-sulfur battery energy storage systems (10,000 kW class); lithium-ion battery energy storage systems (100,000 kW class), etc.

In the plan, by 2030 China will have fully established advanced energy storage technology, which is the focus of the strategic direction. It will carry out model verification at various scales, and, at the same time, will build a relatively complete standards system and a complete industrial chain for energy storage technology. The goal is to comprehensively disseminate most of the energy storage technologies in the application field, and to have China's overall technology level catch up with and surpass that of the advanced international level. Furthermore, as a vision for 2050, it aims to actively explore new materials and methods and to accumulate superior advanced energy storage technologies, as well as aiming to achieve breakthroughs and completely establish core technologies at each stage (including the materials, equipment, and systems stages) in the following: high density and low thermal retention cost thermochemical energy storage; new concept electrochemical energy storage technology (liquid batteries and magnesium batteries, etc.); and multifunctional new hybrid energy storage technology based on superconducting magnetism and electrochemistry. It will complete the overall construction of China's energy storage technology system, raise China's overall level to a world-class level, and have China lead the world's energy storage technology and industrial development.

### (2) "Strategies for Energy Production and Consumption Revolution (2016-2030)" (National Development and Reform Commission and National Energy Administration)

In December 2016, the National Development and Reform Commission and the National Energy Administration jointly promulgated the "Strategies for Energy Production and Consumption Revolution (2016-2030)," which is a comprehensive strategic arrangement for China's energy revolution over the next 15 years, with both practical and long-term significance.

The strategy notes that China's energy development is entering a new stage, transitioning from expanding total capacity to development that improves quality and efficiency. This reflects the demand for supply-side structural reforms that for high-quality development of the economy, which means that long-term and sustainable development must be achieved through liberation from resource and environmental constraints, improvements to air and water pollution, promotion of the construction of an ecological civilization, and active response to climate change. Furthermore, it is an expression of the expectation to accelerate the construction of a modernized nation in which energy public services will increase and benefit all people. The strategy is built on the 13th Five-Year Plan for Energy Development[28] that had already been promulgated, and sets out goals for an even more advanced energy revolution.

The goal for 2030 is to continuously increase the use of renewable energy, natural gas, and nuclear energy, and to significantly reduce the use of high-carbon and fossil fuels. The share of non-fossil fuels in total energy consumption is to be increased to around 20% and natural gas to at least 15%; in other words, the share of low-carbon energy is set to exceed 35%. Meeting the demand for new energy will primarily rely on low-carbon and clean energy sources. The aim is to promote the clean and efficient use of fossil fuels and to have $CO_2$ emissions peak around 2030 or sooner. In fact, China's energy consumption per unit of GDP has already reached the global average level at this point (in 2015, China's energy consumption per unit of GDP was 1.5 times the global average level). China's level of energy science and technology is also among the highest in the world. The outlook for 2050 aims to "basically stabilize total energy consumption and to increase the share of non-fossil fuels to more than half," as well as completing a modern energy system that is green, low-carbon, and highly efficient.

The strategy summarizes the energy supply revolution as "building a new system of clean and low-carbon energy." As a specific strategy, it promotes energy usage methods centered around distributed natural gas and distributed renewable energy. Furthermore, by comprehensively constructing a smart energy network based on the "Internet+," it promotes the advanced integration of energy and modern information technology. The strategy also relies on technologies such as new energy, energy story, flexible networks, and microgrids in order to flexibly and efficiently connect distributed energy, thereby enabling the integration of production and consumption. It promotes the integration of "power sources, power networks, loads, storage, and usage (source-network-load-storage-use)" and builds an integrated and mutually complementary energy internet.

As for promoting innovation in related technologies, it focuses on a policy of advancing smart energy technologies. It promotes the advanced integration of distributed energy technologies, advanced grid technologies, energy storage technologies, and the internet. In particular, for energy storage it focuses on evolving variable speed pumped storage energy storage; flywheels; high parameter and high temperature heat storage; phase transitions; research, development, and applications of physical energy storage technologies such as new compressed air; and chemical storage technologies such as high-performance fuel cells and electric double layer capacitors. At the same time, there will also be research and development of energy storage facilities that are compatible with plug-and-play (PnP) and highly flexible transactions.

### (3) "Guiding Opinions on Promoting Energy Storage Technology and Industry Development" (National Development and Reform Commission)

In October 2017, five departments, including the National Development and Reform Commission and the National Energy Administration, jointly promulgated the "Guiding Opinions on Promoting Energy Storage Technology and

28 http://www.nea.gov.cn/135989417_14846217874961n.pdf

Industry Development"[29], which clarified the important significance of, priority issues with, and safeguard measures for promoting China's energy storage technology and industrial development. The document points out that energy storage is an important component and a key technology for supporting smart grids, energy systems with a high proportion of renewable energy, and smart energy through the Internet+, and also that energy storage is a key technology for supporting those goals. It is also a means of improving flexibility, economic efficiency, and safety of the conventional power system, and a key technology for promoting the transition from fossil fuels to renewable energy sources. Furthermore, it is a core foundation for building an energy internet, for promoting electricity system reform, and for promoting the development of new energy business formats. In recent years, China's energy storage has exhibited a favorable stance towards multidimensional development, and, overall, it can be said that it has mostly laid the foundations for industrialization.

The guiding opinion also focuses on the overall long-term development needs of the energy industry, and emphasizes promoting energy storage technology and industrial development. Focusing on breakthroughs in mechanisms, based on technological innovation and utilizing application models as the means, it will also greatly develop "Internet+" smart energy. It also states that China must focus on promoting the following priority issues: research and development models for energy storage technology equipment; applied models for increasing the utilization rate of renewable energy through energy storage; application models for improving the flexibility and stability of energy power systems; application models for smarter energy usage improvements; and energy internet application models supported by diversified applications of energy storage. In order to systemize China's modern energy industry, which is aiming to be "clean, low-carbon, safe, and highly efficient," the guiding opinion proposes making new contributions by promoting structural reforms on the supply side and reforms to energy production and usage methods in the China's energy industry. At the same time, this will lead to the overall development of industrial chains, from material formulation and preparation to system integration, and will provide a new driving force for raising the level of industrial development and for promoting social and economic development. Additionally, based on the principles of "government guidance and business participation," "driven innovation and leading models," "market leadership and support for reforms," and "unified planning and cooperative development," it calls for various relevant organizations to appropriately promote energy storage technology and industrial development through measures such as strengthening organization and leadership, developing policies and regulations, trialing applied models, building compensation systems, encouraging social investment, and promoting market reforms.

Implementation plans during the 13th Five-Year Plan period include the launch of application model trial projects consisting of various types of technologies and application examples; research and development of important key technologies and core equipment; setting standards and norms for key energy storage technologies; searching for business models that can be spread; and the development of competitive market actors. By encouraging the energy storage industry to enter the early development phase of commercialization, the critical role of energy storage systems has begun to emerge in the structural transformation of the energy system. On the other hand, implementation plans during the 14th Five-Year Plan period call for building a relatively well-organized industrial system; complete establishment of world-class key technologies and core facilities for energy storage; building a relatively complete technology and standards system; forming internationally competitive market entities; rapid growth of various energy

29 http://www.nea.gov.cn/2017-10/11/c_136672015.htm

storage business models based on power and energy markets; and large-scale development of the energy storage industry. The plan brings into full focus the role of energy storage in promoting the energy transformation and the development of the energy internet.

In order to implement the guiding opinions, on June 25, 2019, the National Development and Reform Commission, the Ministry of Science and Technology, the Ministry of Industry and Information Technology, and the National Energy Administration jointly established the “2019-2020 Action Plan for Implementing the Guiding Opinions on Promoting Energy Storage Technology and Industry Development.”[30] The following six items clarify the main functions and specific roles of these four departments.

1. Strengthen research and development of advanced energy storage technology and update smart manufacturing
2. Complete and implement policies to promote energy storage technology and industrial development
3. Promote the development of pumped storage
4. Promote applied models for energy storage projects
5. Promote the application of energy storage in power batteries for new energy vehicles
6. Accelerate standardization of energy storage

### (4) “Guidance on Accelerating the Development of New Energy Storage” (National Development and Reform Commission and National Energy Administration)

On July 23, 2021, the National Development and Reform Commission and the National Energy Administration promulgated the “Guidance on Accelerating the Development of New Energy Storage,”[31] which sets out a policy to firmly maintain the diversification of energy storage technologies. It calls for facilitating continued cost reductions and commercialization of relatively mature new energy storage technologies, such as lithium-ion batteries. Additionally, it also calls for long-term energy storage technologies (LDES), such as compressed air and redox flow batteries, to enter the early development phase of commercialization, and for accelerating the large-scale deployment of model trials for technologies such as flywheel energy storage and sodium-ion batteries. In anticipation of demand, research and pilot operations of hydrogen storage, thermal storage, and other innovative energy storage technologies will also be explored.

The guidance proposes the following three points in order to develop a unified special project plan for energy storage. First, determine the scale and project layout of each area to ensure precise consistency with related plans. Second, actively promote the rationalization of energy storage placement on the grid side (power generation equipment side). Deploying energy storage on the power grid side through key nodes will improve flexible adjustment capabilities and the safety and stability of the energy system after connecting large-scale and high-proportion new energy. Third, actively support the development of diversified energy storage on the user side. Encourage the exploration of new applications arising from integrated development of energy storage around other end-users such as decentralized new energy, microgrids, big data centers, 5G base stations, charging equipment, and industrial parks.

On the other hand, the primary goal of the guidance is to realize by 2025 the transition from early commercialization

30 http://www.gov.cn/zhengce/zhengceku/2019-07/01/5457986/files/cd749b80b90a452590406bdf1e544912.pdf

31 http://www.sanmen.gov.cn/art/2021/8/5/art_1229323656_3727153.html

to large-scale development of new energy storage. It looks to greatly improve the innovation capabilities for new energy storage technology and the level of autonomous control over core technology facilities, as well as to make rapid progress in a short period of time in terms of high safety, low cost, high reliability, and long service life. The guidance aims to have the standard system nearly complete and to have the industrial system perfected day by day. The market environment and business model will have largely matured, with installed capacity reaching over 30 MW. New energy storage will have a remarkable effect in promoting peak $CO_2$ emissions and carbon neutrality in the energy sector. The goal is to achieve full market development of new energy storage by 2030. In order to do so, the core technology equipment for new energy storage will be autonomously controlled, and China's technological innovation and industrial level should be among the top in the world. Standards systems, market mechanisms, and business models should mature and become sound, while advanced integration and development with each stage of the power system will be achieved. Installed capacity will nearly meet the demand for new power systems, and new energy storage will be one of the key pillars for achieving peak $CO_2$ emissions and carbon neutrality in the energy sector.

### (5) "National Industrial Energy Conservation Technology Recommendation Catalog (2021)" (Ministry of Industry and Information Technology)

On December 9, 2021, the Ministry of Industry and Information Technology promulgated the "National Industrial Energy Conservation Technology Recommendation Catalog (2021)."[32] The catalog includes a total of 69 energy conservation technologies across 8 categories, including the steel industry, non-ferrous metal industry, building materials industry, petroleum and chemical industry, energy storage, renewable energy, smart energy management, and utilization of residual heat and pressure. Of these, the following six types primarily relate to energy storage and renewable energy.

1. High-voltage, high-output solid-state electric regenerative furnace plants

An automatic control system turns on high-voltage switchgears during pre-defined grid off-peak hours or during wind power outage periods. A 66kV high-voltage power grid supplies power to the high-voltage heating elements, which convert electrical energy into thermal energy that is constantly absorbed into the high-temperature heat storage chamber. When the temperature in the high-temperature heat storage chamber reaches the upper limit of its set temperature, or when the power grid's off-peak time ends, the automatic control system turns off the high-voltage switch gears, the power supply from the high-voltage grid is cut off, and the high-voltage heating elements stop working. There is a heat output controller between the high-temperature heat storage chamber and the high-temperature heat exchanger, and the high-temperature heat exchanger converts the high-temperature thermal energy stored in the high-temperature heat storage chamber into hot water, hot air, or steam, etc., and then outputs it. This technology can be applied to the energy storage peak shifting and clean heat supply sectors.

Current penetration rate: 15%; predicted penetration rate by 2024: 30%

2. Power compensation and energy conservation technology for generators via the use of flywheel energy storage

A flywheel energy storage device is connected in parallel to the DC bus, and, when the load releases energy, the

[32] Announcement by the Ministry of Industry and Information Technology of the People's Republic of China (miit.gov.cn)

gravitational potential energy of the load can be converted into flywheel kinetic energy and stored through the power electronics equipment. When the energy consumption of the load increases, the flywheel quickly releases high power energy to compensate for the generator's lack of output power, which allows the diesel generator to smoothly output power. By utilizing the system's surplus energy in this way, the installed capacity of diesel generators can be reduced, thereby reducing diesel fuel consumption and increasing energy savings. This technology can also be applied to energy-conservation innovations in generator power compensation.

Current penetration rate: 1% or less; predicted penetration rate by 2024: 2%

3. Key technologies for user-side distributed smart energy storage

Centered around high-efficiency and long-life lithium-iron-phosphate batteries, "real-time monitoring, two-way communication, and smart control" smart energy storage systems are built based on battery management systems (BMS), distributed energy management systems (EMS), automatic fire suppression systems (AFS), together with energy storage inverters (PS) and IPSCP cloud platforms. Each distributed energy storage facility connects in real time with the IPSCP cloud platform via 4G mobile communication networks, and the cloud platform establishes functions such as data collection analysis, and storage that are then displayed via an app. This technology can also be applied to technological innovations in energy informatization.

Current penetration rate: 1% or less; predicted penetration rate by 2024: 20%

4. Frequency control and power quality management technologies realized through time-sharing

This technology enables time-sharing frequency control and power quality management, and is being developed based on a high-voltage frequency converter platform. It has two operating modes: frequency conversion and reactive power compensation, and can perform operations according to the needs of the situation, realizing both frequency control for motors and reactive power compensation for power grids. This technology can also be applied to energy conservation innovations in motor frequency control.

Current penetration rate: 1% or less; predicted penetration rate by 2024: 20%

5. Highly efficient power quality control equipment for new energy connections

Synchronous encoding switch technology is adopted for the design of capacitors that automatically switch at the zero-crossing point (the point at which voltage passes through zero), and this is then applied to low-voltage distribution areas. Through harmonic compensation, reactive power, and three-phase balance adjustments, it achieves the objective of reducing line losses and transformer wear, and improves power quality and power supply quality. This technology can be applied to the field of microgrid systems that utilize new energy, such as wind power generation and solar power generation.

Current penetration rate: 2%; predicted penetration rate by 2024: 5%

6. New energy conserving high frequency and high voltage power supply and control technology for electrostatic precipitators (ESP)

Three-phase commercial power frequency is rectified to generate direct current, an inverter circuit generates high-frequency alternating current, and, after being boosted and rectified again, high-frequency pulsating current is generated and supplied to a precipitator. This enables an operating frequency of 20 to 50kHz, and a precipitation efficiency of 99.99%. Additionally, dynamic reactive power compensation and harmonic removal through IGBTs and inverter circuits can increase the power factor of the power grid to more than 0.98, significantly reducing energy consumption of existing power supplies. This technology can be applied to energy conserving modifications for electrostatic precipitators.

Current penetration rate: 35%; predicted penetration rate by 2024: 55%

### (6)National Priority Research and Development Plan "Energy Storage and Smart Grid Technology" Priority Special Projects

On December 9, 2021, the Ministry of Science and Technology promulgated the "2021 Scheduled Project Announcement List"[33] for the national priority research and development plan "Energy Storage and Smart Grid Technology" priority special projects. In the list, there are a total of 8 projects related to energy storage technologies, each with a project implementation period of 3 to 4 years, as shown below (Figure 2-1).

1. GWh-class lithium-ion battery energy storage system technology (fundamental key technology)

   Leading company: Contemporary Amperex Technology (CATL)

   Technical requirements: MWh-class lithium-ion battery energy storage system (single cell) with cycle life ≥ 15,000 cycles, service life (estimated) ≥25 years, lithium-ion battery energy storage system output capacity ≥1GWh, power with equivalent energy efficiency cost ≤0.1 RMB/kWh

2. MWh-class intrinsically safe solid-state lithium-ion energy storage battery technology (fundamental key technology)

   Leading company: RiseSun MGL

   Technical indicators: Battery (single cell) with cycle life ≥15,000 cycles, 10MWh class solid state energy storage lithium-ion battery system development research, system cycle life ≥12,000 cycles, power with equivalent energy efficiency cost ≤0.2 RMB/kWh

3. Research and development of intrinsically safe metal sulfide energy storage battery

   Leading institution: Shanghai Jiao Tong University

   Technical requirements: Research and development of 100kWh class metal sulfide energy storage battery system, system energy conversion efficiency ≥80%, cycle life ≥12,000 cycles, system cost ≤0.6 RMB/Wh

4. Key materials and technologies for low-cost hybrid supercapacitors (electric double layer capacitors) and MW class system model (fundamental key technology)

   Leading company: GMCC

   Technical requirements: Stand-alone energy ≥15Wh, specific energy ≥70Wh/kg, specific power ≥10kW/kg for 10 seconds of charge and discharge, measured maximum specific output ≥30kW/kg. Cycle life ≥200,000 cycles with 80% discharge capacity, energy retention rate ≥60% at -40°C/5C rate, safety that meets standards. Energy storage system

33 http://www.ncsti.gov.cn/kjdt/tzgg/202112/P020211209618603048649.pdf

≥200kWh, power response ≥1MW, optimal charge/discharge energy efficiency ≥95%. System cost ≤1 RMB/W under 15-minute energy storage operating conditions, system cost ≤0.4 RMB/W under 1-minute energy storage operating conditions.

5. Research and application of key technologies for smart cooperative control of large-scale energy storage system clusters (fundamental key technology)

Leading company: China Three Gorges Corporation

Evaluation indicators: Research on smart cooperative control policies for large-scale energy storage system clusters. Systematization of evaluation indicators for active support capabilities with large-scale energy storage systems power grids. Standardization of large-scale energy storage deployment and operation management. Research and development of a smart cooperative control platform for large-scale energy storage clusters (connected control targets of 30 or more energy storage power plants, capacity scale of 0.5GW or more). Establishment of operational optimization by combining large-scale energy storage and various power sources, highly stable cooperative support functions, and quantitative analysis of marginal costs for external transportation of clean energy and auxiliary services. Energy storage cluster control accuracy ≥1%, energy storage cluster control command response time ≤5s, emergency output control response time ≤300ms.

6. Research on accelerated deterioration analysis and lifespan prediction technology for energy storage batteries (fundamental key technology)

Leading company: China Electric Power Research Institute

Evaluation indicators: Development of high-precision evaluation method for thermodynamic state of batteries, with absolute error bar for predicted battery capacity from SOC-OCV (state of charge/open circuit voltage) curve ≤1%. With relative error of measurement ≤ 2%, establishment of quantitative evaluation methods and evaluation devices/platforms for critical decay factors such as electrolyte consumption/infiltration/residue, battery expansion rate, and intra-battery gas generation. Accuracy ≥90% for analog and simulation results for state of health (SOH), state of charge (SOC), temperature distribution, and expansion of batteries used in the device. Establishment of a lifetime prediction mechanism model using electrochemical algorithms to achieve reliable battery system decay maps (≥25 years) predicted from measured lifetime data (3 months for single battery cells and 1.5 months for battery modules).

7. Smart sensing technology for energy storage lithium-ion batteries (fundamental key technology)

Lead institution: Beijing Institute of Technology

Technical indicators: Impact of embedded sensors on energy storage lithium-ion battery capacity (500 cycles) ≤5%. Impact of electrolyte environment on embedded sensors ≤5%. Sampling frequency ≥100Hz for various types of signal transmission. Internal temperature measurement range -40 to 60°C, accuracy ±0.2°C. Internal strain measurement range 3000με, error ≤5με. Internal pressure measurement range 2MPa, accuracy 0.1MPa. Two or more types of internally generated gas measurements, with accuracy of 0 to 100% (volume percent). Internal voltage measurement range 2.3 to 6.0V, error ≤5%. Internal current measurement error ≤5%. Establish the relationship between the sensing signals obtained by the battery's internal/external sensors and the battery's external electrochemical characteristics and thermal runaway. The integrated sensing energy storage smart control system collects single sensing signals in real time, realizes wired or wireless transmission, and issues early warnings based on the sensing information automatically analyzed by the control unit.

8. Safety technology applied to the life cycle of lithium-ion battery energy storage systems (fundamental key technology)

   Leading company: China Southern Power Grid

   Evaluation indicators: Development of energy storage big data monitoring and control system applicable to GWh class energy storage, issuing early warning to notify of accidents 15 minutes in advance. Research and development of advanced fire extinguishing technology for lithium-ion battery energy storage system, complete initial fire extinguishment of the battery within 5 seconds of issuing the fire alarm signal, prevent re-ignition within 24 hours, coverage range ≥1MWh.

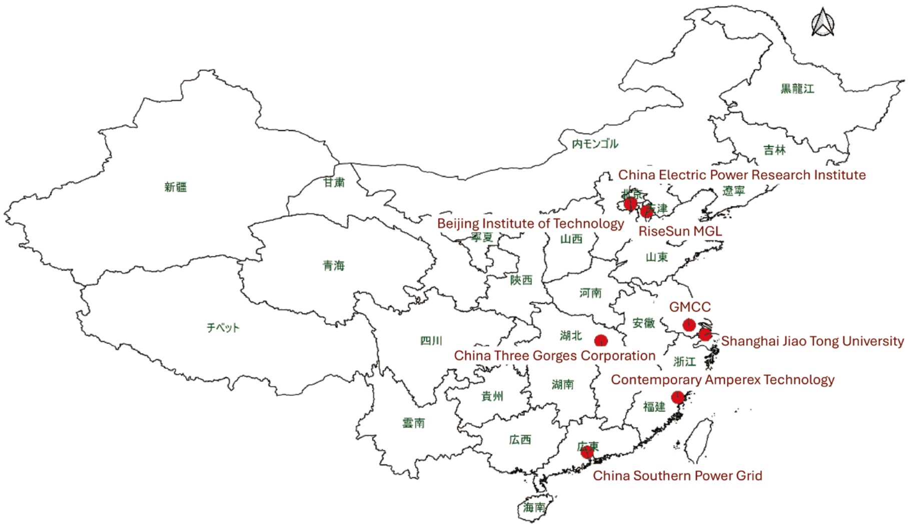


**Figure 2-1: Location of companies/institutions selected for the National Priority Research and Development Plan "Energy Storage and Smart Grid Technology" Priority Special Projects**

## (7) "14th Five-Year Plan Implementation Plan for the Development of New Energy Storage (2022)" (National Development and Reform Commission and National Energy Administration)

In February 2022, the National Development and Reform Commission and the National Energy Administration promulgated the 14th Five-Year Plan Implementation Plan for the Development of New Energy Storage (2022).[34]

In order to further develop the energy storage industry, the implementation plan was formulated and published based on the "14th Five-Year Plan for Economic and Social Development (2021–2025) and Long-Range Objectives through the Year 2035 of the People's Republic of China" and on the "Guidance on Accelerating the Development of New Energy Storage" prepared by the National Development and Reform Commission and the National Energy Administration.

Its primary development goals are as follows.

34 https://www.ndrc.gov.cn/xwdt/tzgg/202203/P020220321550104020921.pdf

The plan states that, by 2025, the new energy storage industry will develop from the initial stage of commercialization to the large-scale commercialization stage, and, at the same time, that it will significantly improve the innovation ability of new energy storage technology and the ability to independently develop core technologies for equipment, that the system for establishing standards and norms will be mostly complete, and that the business model will be matured.

The implementation plan specifies that, in order to further improve the performance of electrochemical energy storage technology, the cost of associated energy storage systems will be reduced by more than 30%. Meanwhile, new energy storage technologies that rely on conventional electricity (such as energy storage technologies utilizing steam from thermal power generation and nuclear power generation units) will achieve practical application of compressed air energy storage technologies in the 100 megawatt class. Furthermore, breakthroughs will be made in long time-scale energy storage technologies such as hydrogen energy storage and thermal (cold) energy storage technologies.

By 2030, the new energy storage industry will be fully commercialized. At that time, all core technologies and equipment for new energy storage will have been independently developed, and the level of technological innovation and industry will steadily reach the highest level in the world. In addition, market mechanisms, business models, and standards and norms will be matured and deeply integrated into the power system in all aspects to meet the needs of new power systems.[35]

## 2.3 Main policies of local governments

### 2.3.1 Direct subsidy policies

2021 has been called a "successful year for Chinese energy storage policy." From the national to local levels, more than 200 energy storage-related policies were promulgated at various administrative levels, and the policies cover a variety of areas, including market transaction rules, electricity pricing mechanisms, direct financial support, and construction plans. At the local level, the four primary energy storage-related support methods are as follows.

In 2021, 12 provinces, directly controlled municipalities, and autonomous regions in China promulgated direct subsidy policies for energy storage. Compared to previous policies, this represents a considerable jump in the scale and form of subsidy support. The subsidies primarily take the form of investment support and operational support, which effectively increases the economic efficiency of local energy storage projects. The policies are also linked to local electricity market reforms and energy use demands, which enables the development of multidimensional business models.

In November 2021, the Zhejiang Provincial Development and Reform Commission promulgated the "Implementation Opinions on Accelerating the Application of New Energy Storage Models in Zhejiang Province."[36] The implementation opinion states that capacity compensation will be provided for peak shifting projects with annual usage of 600 hours or more, with a provisional subsidy period of 3 years, with yearly reduction in the compensation standards from 200 RMB/kW to 180 RMB/kW to 170 RMB/kW. For electric frequency modulation model projects combined with a thermal power generation unit, if the KPD value (overall performance adjustment index) exceeds 0.9, then a frequency modulation incentive of 200,000 kWh/MW per month will be granted according to the energy storage capacity. This was the first policy at the provincial level to explicitly mention subsidies for new energy storage.

35 http://www.tepia.co.jp/tepiamonthly/pdf/tepia-monthly20220323.pdf

36 Zhejiang Provincial Development and Reform Commission and Zhejiang Energy Administration Promulgate the "Implementation Opinions on Accelerating the Application of New Energy Storage Models in Zhejiang Province" (zj.gov.cn)

On December 17, 2021, the Zhejiang Province Haining City Development and Reform Commission also promulgated the “Implementation Opinions on Accelerating the Promotion of New Energy Storage Development (draft for public comments).”[37] By commercializing new energy storage, the opinion realizes operation throughout the entire lifecycle while also providing support and guidance for commercialization. During the transition period toward commercialization, capacity compensation will capacity compensation will be provided to peak shifting projects that use energy for more than 600 hours per year and accept centralized management, with yearly reductions in the compensation standards tentatively set at 200 RMB/kW, 180 RMB/kW, and 170 RMB/kW. Note that projects that have already received provincial funding cannot receive duplicate funding. In addition, on July 28, 2021, the government of Yueqing City in Zhejiang Province also released a document stating that, “The Yueqing City government has already launched a subsidy policy that applies electricity prices to energy storage, with a compensation of 0.89 RMB/kWh based on the current amount.”[38] Additionally, the Jiangsu,[39] Guangdong,[40] Shaanxi,[41]

37 http://www.haining.gov.cn/art/2021/12/17/art_1688518_160977.html

38 https://www.in-en.com/article/html/energy-2306457.shtml

39 In March 2019, the Suzhou Industrial Park Administrative Committee promulgated the “Suzhou Industrial Park Green Development Special Project Guidance Fund Management Administrative Regulations.” These administrative regulations make it clear that subsidies will be provided to green development projects, with distributed turbine projects and energy storage projects that have been registered and implemented within the industrial park and that have already started grid-connected operation being eligible for 0.3 RMB/kWh being issued to the business entity for a three-year period from the start of project operation and according to the amount of power generated. At the end of November 2021, Suzhou City promulgated the “Large-scale Development Implementation Plan for Distributed Solar Power Generation in the Wujiang District of Suzhou City.” This was the first province-wide solar power generation implementation plan to incorporate energy storage subsidies, and at the time it was also the most supportive subsidy policy at the provincial level for distributed solar energy storage systems. The maximum subsidy for solar energy storage projects is 1.1 RMB/kWh. In addition, on June 16, 2021, the Nanjing Municipal Finance Bureau of Jiangsu Province promulgated the “Administrative Regulations on Financial Subsidies for the Construction and Operation of Charging Facilities in Nanjing in FY2020.” The policy provides a subsidy of 0.2 RMB/kWh for the operation of public charging facilities with a photovoltaic power generation capacity of 100 kW or more and a storage capacity of 500 kWh or more.

40 In September 2021, Zhaoqing City in Guangdong Province promulgated “Various Measures to Support the Manufacturing Industry through Energy Conservation in the Development of the Manufacturing Industry in the Zhaoqing High-Tech Zone.” If a company in the high-tech zone launches an energy storage or ice thermal storage project, it will receive a subsidy of 150 RMB/kW from the start of operation after construction is completed, and a maximum of CNY1 million in subsidies per company. The power storage load can be offset against the peak shift power consumption load index. For self-consumption solar power generation projects, a subsidy of 300 RMB/kW will be provided from the start of operation, with a maximum of CNY1 million per company. Some solar power generation loads are not included in the load index for peak-shifted power consumption. Additionally, from May 2021, districts in Shunde, Foshan City, Guangdong Province will be able to receive large subsidies for purchasing and leasing energy storage equipment. Subsidies of up to CNY300,000 will be available in Leliu and Ronggui, up to CNY200,000 in Daliang, Longjiang, and Jun’an, and up to CNY100,000 in Beitan. The Industrial Information Administration of Guangzhou City, Guangdong Province also promulgated the “Guangzhou City Virtual Power Plant Implementation Regulations (draft for public comments),” which states that, when guiding users to peak cuts and peak shifts, up to 5 RMB/kWh will be received for peak cuts and up to 2 RMB/kWh will be received for peak shifts ([subsidy cost] = [effective response energy amount] x [subsidy standard] x [response coefficient]).

41 On May 21, 2021, the Shaanxi Provincial Development and Reform Commission promulgated the “2021 Shaanxi Province Electricity Demand Response Work Plan.” The plan encourages the implementation of peak shifts via energy storage, and provides subsidies of up to 35 RMB/kW per usage for emergency peak cut demand, and up to 15 RMB/kW per usage for economical non-resident demand. In addition, on December 25, 2020, the Xi’an Industry and Information Technology Bureau of Shaanxi Province promulgated the “Opinions on Further Promoting the Sustainable and Health Development of the Solar Power Generation Industry (draft for public comments).” The document announced a policy of granting a subsidy of 1 RMB/kWh to newly constructed solar energy storage projects from January 1, 2021 to December 31, 2023, with the annual grant amount capped at CNY500,000.

Liaoning,[42] Tianjin,[43] Qinghai,[44] Ningxia,[45] Xinjiang,[46] and Shandong provinces and autonomous regions[47] have also announced energy storage peak-shift subsidy policies.

### 2.3.2 Mandatory energy storage facility deployment policies

New energy projects must follow a certain power ratio, and energy storage facilities must be deployed on the generation side. In 2021, more than 20 provinces, municipalities, and autonomous regions in China have already launched the construction of "wind, solar, and storage integration," and 17 provinces, municipalities, and autonomous regions have required that new energy must be deployed with a certain ratio of energy storage. The basic ratio is 5-20%, but many provinces further require new energy power plants to have 10-20% deployment and energy storage systems to have a 2-hour storage capacity.

On June 21, 2021, the Henan Provincial Development and Reform Commission promulgated the "Notice of Matters Pertaining to the Construction of Wind Power and Solar Power Generation Projects in 2021"[48] and established the "Provincial New Energy Power Consumption Management Guidelines." For Category I areas,[49] the guidelines require a consumption management scale of 3,000,000 kW, a 10% allocation ratio for new energy equipment, and an energy storage capacity that allows for two hours of normal operation, with a total energy storage scale of 300,000 kW/600,000 kWh. For Category II areas,[50] the guidelines are predicted to require a consumption management scale of 1,000,000 kW, a 15% allocation ratio for new energy, and an energy storage capacity that allows for two hours of normal operation, with a total energy storage scale of 150,000 kW / 300,000 kW. For Category III areas,[51] the guidelines will determine consumption scale through consultation, and will require a 20% allocation ratio for new

42 In April 2021, the Shenyang City government promulgated the "Implementation Plan for Accelerating the Innovative Development of and Spreading Applications for Shenyang City's New Energy Vehicle Industry (draft for public comments)," which set a policy of encouraging 10% of the investment amount for solar energy storage and charging model stations, with a maximum of CNY500,000 per station.

43 In February 20221, the Tianjin Municipal Bureau of Industry and Information Technology promulgated the "Notice on the Development of Electricity Demand Response Operations in 2021," which states that energy storage power plants with a capacity of 500kW or more can apply for a peak cut/peak shift subsidy system, which adopts a peak shift subsidy at a fixed price of 1.2 RMB/kWh, a variable price at 1.2 to 2 RMB/kWh, and a fixed amount for peak cuts.

44 In January 2021, the Qinghai Provincial Development and Reform Commission, Science and Technology Agency, Industry and Information Technology Agency, and Energy Bureau jointly promulgated the "Notification of Various (Trial) Measures to Support the Development of the Energy Storage Industry" and the "Various Measures (Trial) to Support the Development of the Energy Storage Industry." The measures grant a subsidy of 0.1 RMB/kWh to new energy storage deployment projects, and an additional subsidy of 0.05 RMB/kWh to projects that use 60% or more energy storage batteries generated in the province.

45 In November 2021, the Ningxia Hui Autonomous Region Development and Reform Commission promulgated the "Draft for Public Comments on Trial Area for Energy Storage Projects," which granted a subsidy of 0.8 RMB/kWh for new energy storage installation projects.

46 In May 2020, the Xinjiang Uygur Autonomous Region Development and Reform Commission promulgated the "Xinjiang Regional Power Generation and Energy Storage Management Provisional Regulations," which granted a subsidy of 0.55 RMB/kWh for new energy storage deployment projects.

47 In April 2021, the Shandong Provincial Development and Reform Commission promulgated the "Implementation Opinions for the Shandong Energy Storage Model Application," which granted a subsidy of 0.2 RMB/kWh for new energy storage deployment projects.

48 https://www.pvmeng.com/2021/09/18/21380/

49 Category I areas in China primarily refer to directly controlled municipalities and to provincial and autonomous region-level administrative areas.

50 Category II areas in China primarily refer to city-level administrative areas.

51 Category III areas in China primarily refer to county-level administrative areas.

energy and an energy storage capacity that allows for two hours of normal operation.

On June 7, 2021, the Tianjin Municipal Development and Reform Commission promulgated the “Notification of 2021-2022 Wind Power and Solar Power Project Development and Construction, and 2021Guaranteed Grid Interconnections.” [52] It commits projects with stand-alone capacities exceeding 50,000 kW to build a certain percentage of energy storage facilities as ancillary construction and to provide a reasonable amount of peak shifting capacity. The energy storage ratio for solar power projects is committed to at least 10% of the installed capacity (with at least one hour of continuous energy storage), and wind power projects are committed to at least 15%. Energy storage facilities, even those in power generation projects, must be uniformly managed for the guaranteed grid interconnection scale in 2021.

The installation of new energy storage facilities in various regions has rapidly increased, which has promoted the rapid development of the energy storage market. According to statistics from China Energy Net,[53] in the first half of 2021, there were 257 new energy storage projects in China with an energy storage scale of 11.8 GW, up 1.6 times and 9 times, respectively, from the same period last year. The scale of new projects that began operation was 304,000 kW /624,000 kWh, which is 8.5 times the number of projects over 100,000 kW compared to the same period in the previous year. The total installed capacity for “wind power generation + solar power generation” in 2021 is expected to exceed 127 million kW, and, if the installed capacity of energy storage is calculated as 10%, then the actual energy storage installed capacity is expected to exceed 12 million kW.

### 2.3.3 Priority support policies

For new energy projects with energy storage capacity, in addition to incentives for the deployment of generation-side energy storage based on a certain electricity ratio, emphasis is also being placed on policies and treatment in terms of project approval and grid interconnections, and governments have come up with effective incentive plans to prioritize project developments.

On June 15, 2021, Henan Province issued province-wide new energy power consumption management guidelines, and also promulgated the “Guiding Opinions on Accelerating the Promotion of Energy Storage Facility Construction in Henan Province”[54] to encourage the construction of energy storage facilities for new energy projects. It promises that new energy projects with an energy storage deployment ratio of 10% or more and a continuous energy storage time of 2 hours or more will be provided with preferential acquisition of development rights for wind and solar resources under equal conditions, preferential grid connections for power grid companies, and preferential consumption management guarantees.

Tianjin City[55] has promised that projects with a single capacity of more than 50,000 kW will receive 20 points if the construction ratio of energy storage facilities meets the minimum requirements or if they provide appropriate peak shift capacity. Furthermore, 2 points are added for every 1% increase in the ratio, up to a maximum of 30 points. Energy storage facilities must be deployed based on the criteria of at least one hour of continuous energy storage

52 https://www.china5e.com/news/news-1130486-1.html

53 http://mm.chinapower.com.cn/xw/gnxw/20220303/136681.html

54 https://chuneng.bjx.com.cn/news/20210618/1158872.shtml

55 https://pdf.dfcfw.com/pdf/H3_AP202108111509398948_1.pdf?1628689514000.pdf

and a system operating life of at least 10 years, and under the conditions that the power generation project and grid interconnection must be completed and operational by 2023.

In addition, Guangxi Province[56] has announced that energy storage equipment deployment projects can earn up to 15 points under the 2021 wind and solar power competitive deployment scoring method. In Shandong Province,[57] for the construction of new centralized wind power generation and solar power generation projects, in principle, the construction and leasing costs of energy production facilities must be at least 10%, and a continuous charging time of at least two hours must be guaranteed. In addition, for wind and solar power generation projects, a model project for the construction and leasing of energy storage facilities will be initiated according to the percentage of deployment, and integration into priority grid connections and priority consumption management will also be implemented.

### 2.3.4 Model project promotion

Some local energy storage incentives are still in their early stages of development, and as such the promotion of model projects and the exploration of economic instruments (improving peak price differentials and setting electricity prices) are often important means of dissemination and support.

On May 6, 2021, in Shandong Province, the Energy Administration of Shandong Province accepted applications for the "2021 Energy Storage Model Project" and, the following month, published the "2021 Energy Storage Model Project List"[58] on June 21. Five peak shift projects and two frequency modulation projects were selected, bringing the total energy storage scale to 520MW/1,041MWh. After six months of construction, the first of these energy storage power plant models are now nearly complete and operational. On February 10, 2022, the Energy Administration of Shandong Province also promulgated the "Notification on Development of the Call for Proposals for 2022 Energy Storage Model Project Library."[59] The scope of the call for proposals is primarily focused on energy storage peak shift projects, including technologies such as lithium batteries, compressed air, redox flow batteries, thermal storage for coal-fired power generation, and hydrogen production and storage. The peak shift project is also adopting new low-cost, long-lasting, and high-capacity technologies for energy storage, including aluminum-ion batteries, sodium-ion batteries, and gravitational energy storage. Additionally, the "Zhejiang Province Renewable Energy Development for the 14th Five-Year Plan" explicitly mentions that it will "encourage the development of energy storage model projects and support breakthroughs in core energy storage technologies. In addition to promoting the "renewable energy + energy storage" model, it will build a renewable energy model base that embodies the "integration of wind power, solar power, hydroelectric power, and storage," and encourages trials of model projects that apply new technologies and methods.

56 https://pdf.dfcfw.com/pdf/H3_AP202108111509398948_1.pdf?1628689514000.pdf

57 https://pdf.dfcfw.com/pdf/H3_AP202108111509398948_1.pdf?1628689514000.pdf

58 http://nyj.shandong.gov.cn/art/2021/6/21/art_100393_10288142.html?xxgkhide=1

59 http://nyj.shandong.gov.cn/art/2022/3/1/art_59960_10291692.html

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# 3 Quantitative analysis of China's storage battery technology

Since the beginning of the 20th century, the Chinese government has aimed at independent innovation, and in 2006 and 2008 it published the "Outline of National Medium- and Long-term Program for Science and Technology Development (2006-2020)"[60] and the "Outline of the National Intellectual Property Strategy,"[61] respectively, and began to focus on research and development and the promotion of intellectual property. This leads to further development, and China now ranks first in the world in terms of the number of research papers published and patent applications filed.[62] Based on research papers and patent data from 2010 to 2021, this chapter will look at the state of research and development of storage battery technology in China.

A storage battery is a battery that can be repeatedly used by charging it with electrical energy. Storage batteries are also attracting attention as an essential technology for the low-carbon society of the future, and it has been pointed out that attempts to increase the energy density of current lithium-ion batteries can pose safety issues such as ignition and fires. As such, there are extremely high levels of interest in the research, development, and spread of next-generation storage batteries that focus on drive systems, cathodes, anodes, electrolytes, and additives, not only in China, but also in Japan and other major countries, with new projects being established and research infrastructure being strengthened.

## 3.1 China's storage battery-related technology as seen from research papers

Chinese universities and research institutes have a culture in which English-language papers submitted to journals included in the Science Citation Index (SCI) are recognized as outstanding research. Therefore, in this section, based on the Web of Science Core Collection database, which provides the SCI service, for the 2010 to 2021 time period the authors 1) narrowed the list of fields to chemistry, materials science, fuels, engineering, other technologies, physics, electrochemistry, crystallography, polymer science, mathematics, automatic control systems, and computer science; 2) restricted the search to English-language review papers and research papers; 3) searched for information on papers about energy storage batteries and related technologies; and 4) obtained the following data.

[60] http://www.gov.cn/jrzg/2006-02/09/content_183787.htm

[61] http://www.gov.cn/zwgk/2008-06/10/content_1012269.htm

[62] According to the World Intellectual Property Report 2019 by WIPO, the number of patent applications reached 3.33 million in 2018. Looking at the number of patent applications by country/region, China had the highest number of patent applications at 1.54 million, which accounted for 46.4% of the world's total number of patent applications.

### 3.1.1 Changes in the number of papers from China on storage battery technology

China currently has an overwhelming presence in papers on storage battery-related technologies. As shown in Figure 3-1, by 2011, the number of papers from China was second only to the United States, and has steadily increased since then, reaching 5,369 in 2021. This is approximately 2.5 times more than the United States (in 2nd place with 1,190 papers) and more than 15 times more than Japan (in 8th place with 257 papers). This is largely due to the rapid increase in solar power generation in China from around 2012 and 2013 (from 3.41 million Kw to 15.89 million Kw), which led to a rapid increase in the need for new storage batteries.

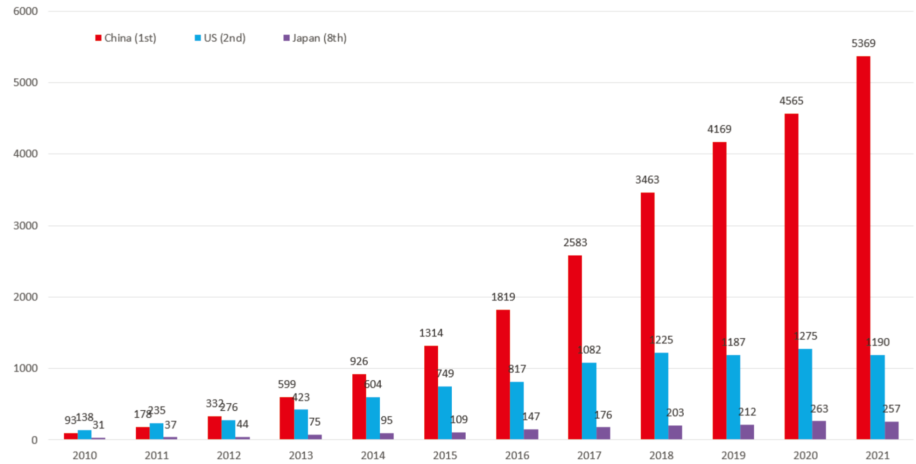



**Figure 3-1: International comparison of the number of storage battery-related papers (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

### 3.1.2 China's leading institutions for storage battery technology research

A total of 25,409 storage battery-related Chinese papers were submitted between 2010 and 2021. Table 3-1 shows the results when organized by author affiliation. The Chinese Academy of Sciences ranks first with 6,735 publications, Tsinghua University (2,272) ranks second, the University of Chinese Academy of Sciences (1,939) ranks third, and the University of Science and Technology of China (1,782) ranks fourth. In particular, the universities in both third and fourth places are affiliated with the Chinese Academy of Sciences, which means it accounts for 40% of the total number of papers when the papers the third and fourth spots are attributed to it. Note that Table 3-1 does not necessarily match the number of submitted papers and share, as some authors are affiliated with multiple institutions.

**Table 3-1: Top 20 institutions for storage battery technology-related research (2010-2021)**

| Rank | Institution | Number of Papers | Share (%) (out of 25,409) | Region |
|---|---|---|---|---|
| 1 | Chinese Academy of Sciences | 6,735 | 26.51 | Nationwide |
| 2 | Tsinghua University | 2,272 | 8.94 | Beijing |
| 3 | University of Chinese Academy of Sciences | 1,939 | 7.63 | Beijing |
| 4 | University of Science and Technology of China | 1,782 | 7.01 | Anhui Province |
| 5 | Nankai University | 1,260 | 4.96 | Tianjin City |
| 6 | Beijing Institute of Technology | 1,259 | 4.95 | Beijing |
| 7 | Huazhong University of Science and Technology | 1,259 | 4.95 | Hubei Province |
| 8 | Zhejiang University | 1,222 | 4.81 | Zhejiang Province |
| 9 | Tianjin University | 1,220 | 4.80 | Tianjin City |
| 10 | Harbin Institute of Technology | 1,197 | 4.71 | Heilongjiang Province |
| 11 | Shanghai Jiao Tong University | 1,115 | 4.39 | Shanghai City |
| 12 | Wuhan University of Technology | 1,035 | 4.07 | Hubei Province |
| 13 | Shandong University | 1,018 | 4.01 | Shandong Province |
| 14 | Fudan University | 1,000 | 3.94 | Shanghai City |
| 15 | Zhengzhou University | 998 | 3.93 | Henan Province |
| 16 | Jilin University | 951 | 3.74 | Jilin Province |
| 17 | Peking University | 948 | 3.73 | Beijing |
| 18 | Southern University of Science and Technology | 935 | 3.68 | Guangdong Province |
| 19 | Hunan University | 932 | 3.67 | Hunan Province |
| 20 | Central South University | 882 | 3.47 | Hunan Province |

Source: Created by the authors from Web of Science Core Collection

All of these research institutes have strengths in chemistry and materials, and most of them are located in the Jingjinji metropolitan area[63], the Yangtze River delta metropolitan area, the Big Bay area, and the four cities of the Wuhan metropolitan area (Figure 3-2). There are also no companies in this top 20 ranking, which means that for research and development of advanced materials technologies such as storage batteries, the central research institutes of state-owned enterprises produce fewer papers than research institutes and universities.

63 . [Translator's note] A Chinese acronym for the expanded urban area consisting of Beijing, Tianjin, and Hebei, with the word "Jingjinji" composed of the common Chinese abbreviations for Beijing, Tianjin, and Hebei, respectively.

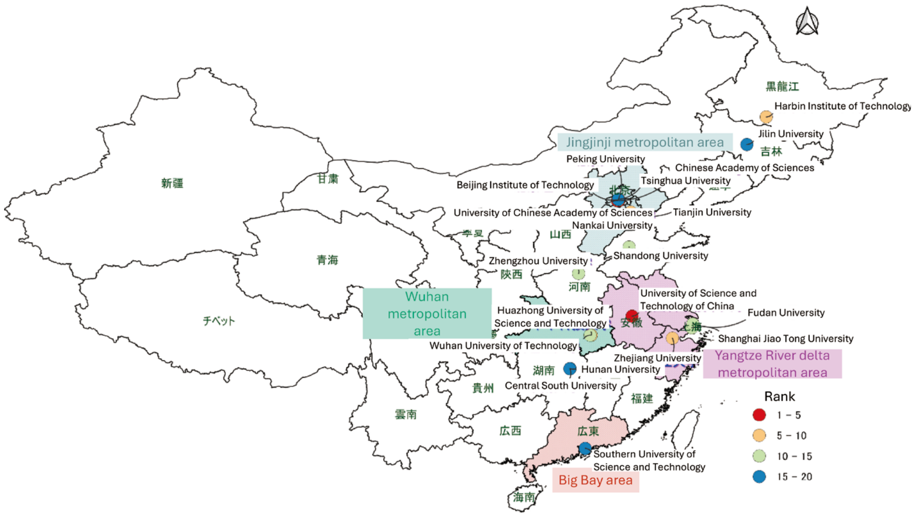
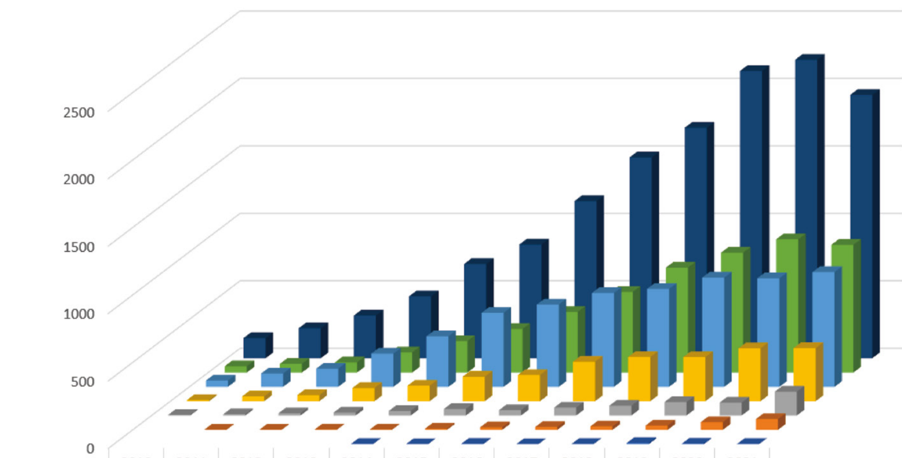



**Figure 3-2: Top 20 institutions for storage battery-related research**

## 3.1.3 Characteristics by field of storage battery technology papers from China

The flow of electrons is one-way: anion → anode → cathode → cation. In batteries, metals and other materials that are more likely to become ions dissolve, leaving electrons at the negative pole, and electrons move from the negative pole to the positive pole through conductors, where they are combined with cations. There are many types of such anions, and the numbers for related storage battery papers here are organized into seven battery-driving systems: "polyvalent ion," "anionic," "fluoride," "redox flow," "lithium-ion," "intercalation," and "conversion."




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Polyvalent | | | | | 2 | 1 | 3 | 1 | 2 | 9 | 4 | 2 |
| Anionic | | 2 | 2 | 3 | 3 | 9 | 19 | 22 | 26 | 32 | 57 | 80 |
| Fluoride | 5 | 10 | 17 | 22 | 34 | 49 | 40 | 59 | 73 | 100 | 96 | 177 |
| Redox flow | 9 | 36 | 45 | 98 | 115 | 182 | 194 | 293 | 328 | 327 | 392 | 394 |
| Lithium-ion | 47 | 99 | 135 | 247 | 375 | 549 | 610 | 696 | 726 | 810 | 805 | 851 |
| Intercalation | 47 | 65 | 76 | 150 | 233 | 323 | 449 | 598 | 778 | 889 | 988 | 947 |
| Conversion | 150 | 223 | 317 | 459 | 699 | 843 | 1165 | 1489 | 1709 | 2129 | 2212 | 1952 |

**Figure 3-3: Number of storage battery paper from China, by driving system (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

As can be seen in Figure 3-3, papers about conversion, intercalation, and lithium-ion batteries have been the mainstream of Chinese research in terms of drive systems. Papers about redox flow, fluoride, and anion batteries were less common approx. 10 years ago, but in recent years have increased significantly. Research on polyvalent batteries only started in 2014 and there are still only a few papers about it each year.

The next focus was on storage battery cathodes, and the number of papers was organized into the following fields: "lithium air," "Zn-air," and "lithium sulfur." As shown in Figure 3-4, lithium sulfur batteries are the mainstream research focus, but the number of papers about Zn-air batteries has significantly increased over the past six years. Although the number of papers related to lithium air batteries has increased to some extent, it has more or less remained flat in recent years.

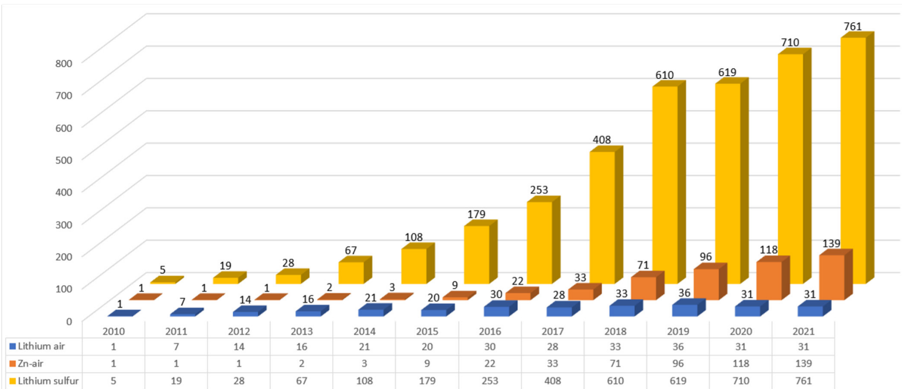



**Figure 3-4: Number of storage battery paper from China, by cathode (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

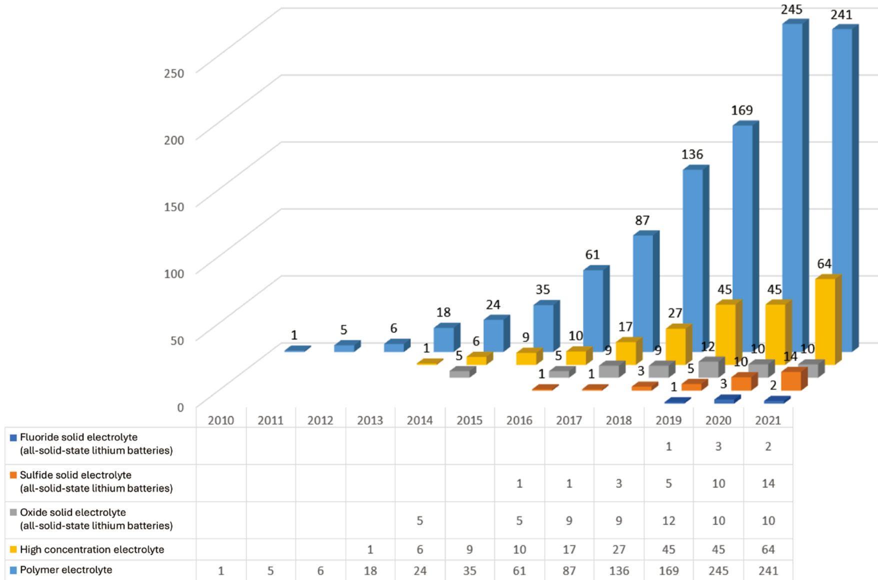
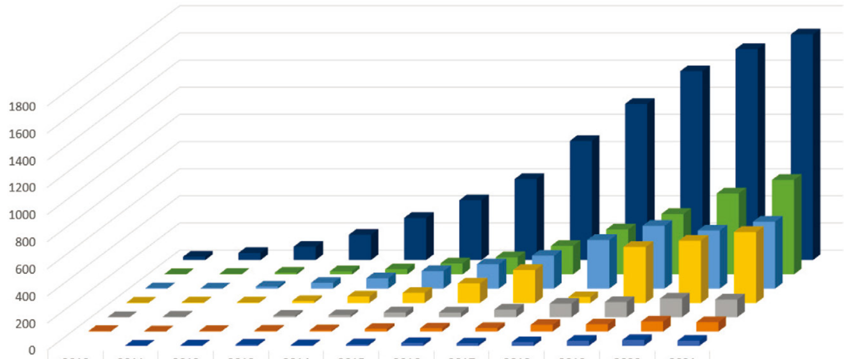



**Figure 3-5: Number of storage battery papers from China, by electrolyte (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

Focusing on electrolytes, the number of papers from China on storage batteries was organized into the following categories: “fluoride electrolyte,” “sulfide solid electrolytes (all-solid-state lithium batteries),” “oxide solid electrolyte (all-solid-state lithium batteries),” “high concentration electrolyte,” and “polymer electrolyte.” The results can be seen in Figure 3-5. In China, research on polymer electrolytes is the mainstream, while research on concentration electrolytes has increased rapidly over the past few years, with a gradually increasing trend of research on oxide solid, sulfide solid, and fluoride electrolytes.



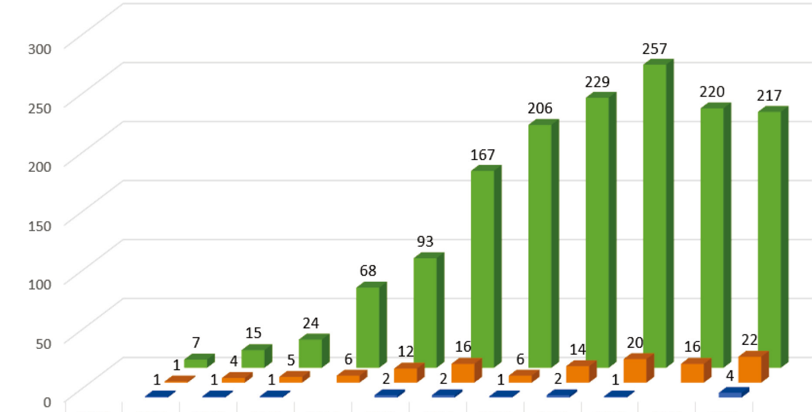

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silicon anode | | 1 | 3 | 9 | 5 | 11 | 21 | 18 | 28 | 38 | 43 | 38 |
| Magnesium | 4 | 1 | 4 | 6 | 9 | 20 | 24 | 26 | 49 | 53 | 74 | 69 |
| Graphite anode | 1 | 4 | | 11 | 16 | 36 | 35 | 57 | 100 | 112 | 138 | 131 |
| Sodium battery | 2 | 4 | 4 | 15 | 48 | 75 | 144 | 242 | 44 | 413 | 459 | 523 |
| Oxide anode | 4 | 3 | 16 | 44 | 77 | 130 | 180 | 243 | 359 | 463 | 429 | 494 |
| Metal anode | 2 | 4 | 13 | 23 | 38 | 81 | 126 | 210 | 331 | 446 | 596 | 696 |
| Lithium | 25 | 53 | 99 | 187 | 311 | 441 | 597 | 878 | 1151 | 1392 | 1555 | 1663 |

**Figure 3-6: Number of storage battery papers from China, by anode (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

Currently, a variety of anode materials are being experimented with, and lithium is the most utilized. In the second group, the number of papers related to metal, oxide, and sodium anodes has increased by approx. 500 per year. In the third group, although the number of papers related to graphite, magnesium, and silicon anodes has increased since 2010, it has remained flat in recent years (Figure 3-6).

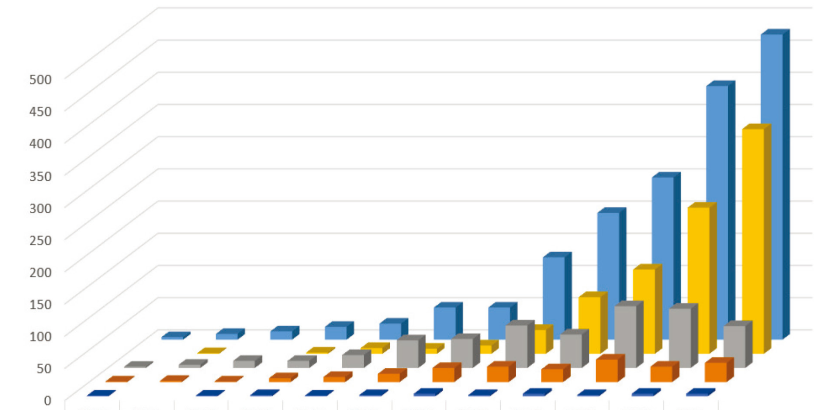
As shown in Figure 3-7, battery additives mainly include binders, conductivity additives, and dispersants. As for China’s research in these fields, the number of papers related to binders has steadily increased, but there still are not many papers about conductivity additives or dispersants.




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dispersants | | 1 | 1 | 1 | | 2 | 2 | 1 | 2 | 1 | | 4 |
| Conductive additives | | 1 | 4 | 5 | 6 | 12 | 16 | 6 | 14 | 20 | 16 | 22 |
| Binders | | 7 | 15 | 24 | 68 | 93 | 167 | 206 | 229 | 257 | 220 | 217 |

**Figure 3-7: Number of storage battery papers from China, by battery additive (2010-2021)**

Source: Created by the authors from Web of Science Core Collection




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Expansion/shrinkage | 1 | | 1 | 2 | 1 | 2 | 4 | 2 | 4 | 2 | 4 | 4 |
| Electronic conduction | 1 | 2 | 1 | 6 | 8 | 13 | 22 | 24 | 20 | 35 | 24 | 30 |
| Ionic conduction | 2 | 5 | 11 | 11 | 20 | 43 | 45 | 66 | 52 | 96 | 92 | 65 |
| Dendrite precipitation | | 1 | | 2 | 9 | 8 | 13 | 37 | 88 | 131 | 227 | 349 |
| Interfaces | 4 | 9 | 13 | 20 | 25 | 50 | 50 | 128 | 197 | 252 | 394 | 474 |

**Figure 3-8: Number of storage battery papers from China, by phenomena/structural analysis (2010-2021)**

Source: Created by the authors from Web of Science Core Collection

As shown in Figure 3-8, there has been a great deal of research on dendrite precipitation and interfaces regarding a variety of phenomena related to storage battery stability, safety, and efficiency, and so on. Although there has been much research on ionic and electronic conduction, there are still only a few papers on expansion and contraction.

# 3.2 China's storage battery-related technology as seen from patents

## 3.2.1 Characteristics of China's storage battery-related patents

Around 2010 China only had a few patents related to storage battery technologies, but as of 2021 that number has grown to 637 patent applications with 256 patents being granted. The number of related patent applications has been rapidly increasing since 2015, and the number of patents granted has been rapidly increasing since 2018 (Figure 3-9).

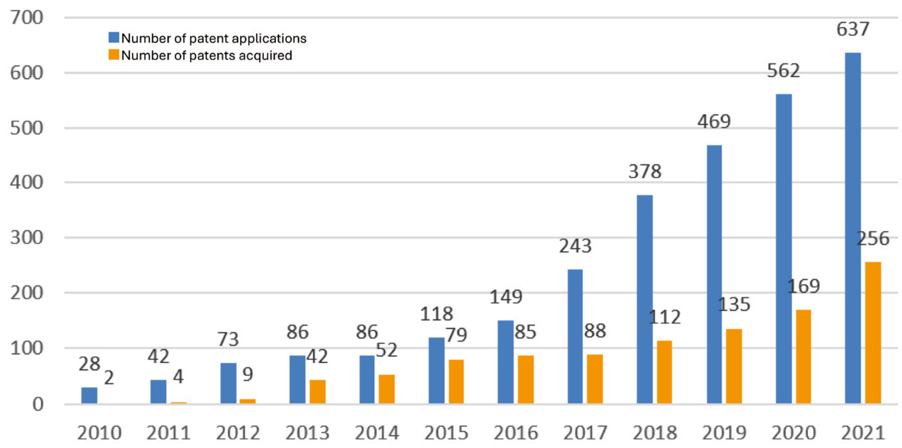



**Figure 3-9: China's storage battery-related patents (2010-2021)**

Source: Created by the authors from the CPRS[64] database

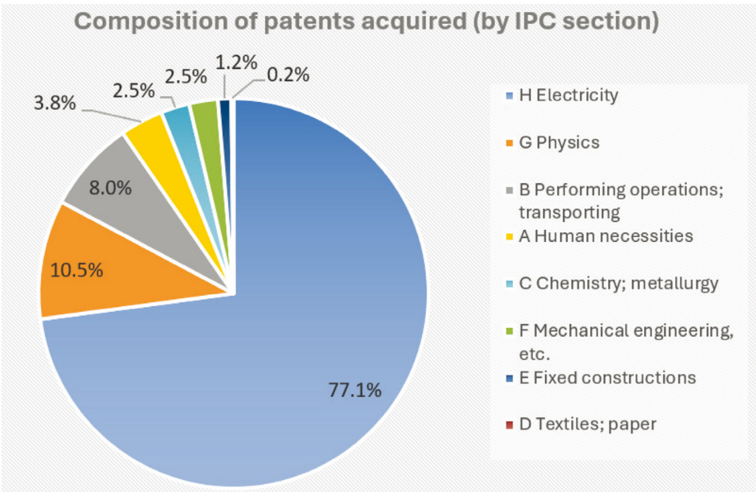



**Figure 3-10: Composition of acquired patents (by IPC section)**

Source: Created by the authors from the CPRS database

64 Chinese patent database https://cprs.patentstar.com.cn/

Looking at the fields in which China has acquired patents, electricity (77.1%), physics (10.5%), and performing operations/transportation (8%) account for more than 95% of the total (Figure 3-10).

**Table 3-2: Status of storage battery-related patent applications (Top 10)**

| Rank | Applicant | No. of patents acquired | Region |
|---|---|---|---|
| 1 | State Grid Corporation of China | 209 | Beijing |
| 2 | Wuxi Tongchun New Energy Technology | 97 | Wuxi City, Jiangsu Province |
| 3 | China Electric Power Research Institute | 61 | Beijing |
| 4 | Shanghai Power Storage Battery System Engineering Technology | 39 | Shanghai |
| 5 | Enerlution Energy | 36 | Hefei City, Anhui Province |
| 6 | Dalian Institute of Chemical Physics, Chinese Academy of Sciences | 29 | Dalian City, Liaoning Province |
| 7 | Shanghai Jiao Tong University | 26 | Shanghai |
| 8 | China Huaneng Group Clean Energy Technology Research Institute | 25 | Beijing |
| 9 | Hanergy Holding Group | 24 | Beijing |
| 10 | Shanghai Municipal Electric Power Company | 24 | Shanghai |

Source: Created by the authors from the CPRS database

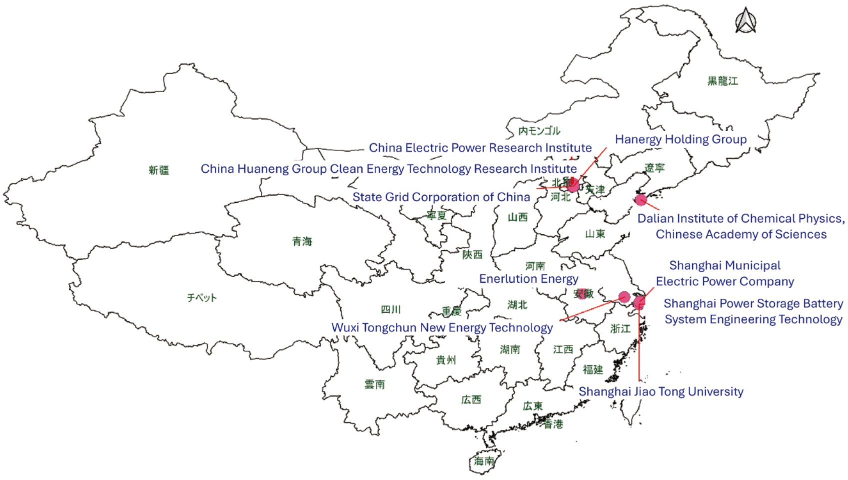



**Figure 3-11: Location of storage battery-related patent applications (Top 10)**

As shown in Table 3-2, the State Grid Corporation of China ranks first in terms of storage battery-related patent applications, with 209 applications. Including the China Electric Power Research Institute (3rd with 61 applications), which is the central research institute under the State Grid Corporation, and Shanghai Municipal Electric Power Company (10th with 24 applications), which is the Shanghai branch of the State Grid Corporation, that gives it a total of 294 storage battery-related patent applications, by far the most in China. After this, 2nd, 4th, and 5th places went to private companies. From 6th place onwards, the spots went to Dalian Institute of Chemical Physics (29 applications), Shanghai Jiao Tong University (26 applications), China Huaneng Group Clean Energy Technology Research Institute (25 applications; a state-owned company), and Hanergy Holding Group (24 applications). Figure 3-11 shows the location of each company.

### 3.2.2 Characteristics of China's storage battery-related patents by field

The state of China's technological strength in various storage battery technology-related fields was analyzed by using patent data from 2010-2021, focusing on drive method, cathode, electrolyte, anode, additive, and phenomena/structural analysis. Individual technologies that are not storage battery-related patents were analyzed based on the technology's potential by gathering statistics on patents in the battery field in general and capturing the "base" of the technology in question.

**Table 3-3: Number of China-acquired battery-related patents, by drive method**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Polyvalent (general batteries) | 0 (2) | - | - | - | - | - | - | - | - | - | (1) | (1) | - |
| Anionic (general batteries) | 0 (5) | - | - | (3) | - | - | - | - | - | - | - | (2) | - |
| Fluoride (general batteries) | 0 (4) | - | - | (1) | - | - | - | - | - | - | (1) | (1) | (1) |
| Redox flow (general batteries) | 155 | - | 2 | 5 | 8 | 4 | 5 | 15 | 17 | 15 | 27 | 19 | 38 |
| Redox flow (storage batteries | 12 | - | - | - | 3 | 1 | 1 | 1 | 1 | 0 | 2 | - | 3 |
| Lithium-ion (general batteries) | 11,908 | 95 | 119 | 201 | 279 | 450 | 830 | 1,234 | 1,132 | 1,193 | 1,419 | 2,148 | 2,808 |
| Lithium-ion (storage batteries) | 47 | - | - | 1 | 5 | - | 5 | 6 | 3 | 8 | 6 | 5 | 8 |
| Sodium (general batteries) | 944 | 0 | 0 | 0 | 0 | 4 | 17 | 20 | 72 | 102 | 161 | 260 | 308 |
| Sodium (storage batteries) | 54 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 6 | 10 | 14 | 19 |
| Intercalation (general batteries) | 3 | - | - | - | - | - | - | - | - | 1 | - | 1 | 1 |
| Conversion (general batteries) | 0 | - | - | - | - | - | - | - | - | - | - | - | - |

*Numbers in parenthesis () denote the numbers of patent applications
Source: Created by the authors from the CPRS database

As shown in Table 3-3, between 2010 and 2021, China has accumulated a large number of lithium-ion and sodium-ion battery technologies, and has obtained numerous storage battery-related patents. On the other hand, China has not yet been granted any storage battery-related patents for polyvalent, anionic, fluoride, or conversion batteries, although it has filed applications for general battery-related patents in these areas. As previously mentioned, there are few research papers related to these technologies, there is limited accumulation of technologies in this field, and there is also limited accumulation of redox flow technologies.

**Table 3-4: Number of China-acquired battery-related patents, by cathode (2010-2021)**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lithium air (general batteries) | 232 | - | 1 | 3 | 2 | 10 | 17 | 37 | 25 | 21 | 32 | 36 | 48 |
| Lithium air (storage batteries) | 2 | - | - | - | - | - | - | - | - | - | - | 1 | 1 |
| Zn-air (general batteries) | 90 | - | - | - | - | - | 5 | 3 | 5 | 11 | 13 | 19 | 34 |
| Zn-air (storage batteries) | 4 | - | - | - | - | - | - | - | - | 1 | 1 | - | 2 |
| Lithium sulfur (general batteries) | 1,115 | 2 | 2 | 7 | 8 | 11 | 38 | 56 | 81 | 96 | 166 | 267 | 381 |
| Lithium sulfur (storage batteries) | 58 | -- | -- | -- | 1 | 3 | 3 | - | 10 | 3 | 9 | 11 | 18 |

Source: Created by the authors from the CPRS database

As shown in table 3-4, China has a large number of patents related to lithium-ion batteries, and a large number of storage battery-related patents. In recent years, China has had a gradually increasing number of patents related to lithium air and zinc air batteries.

**Table 3-5: Number of China-acquired battery-related patents, by electrolyte (2010-2021)**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fluoride solid electrolyte (all-solid-state lithium batteries; general batteries) | 0 | - | - | - | - | - | - | - | - | - | - | - | - |
| Sulfide solid electrolyte (all-solid-state lithium batteries; general batteries) | 2(3) | - | - | - | - | - | - | (1) | - | (2) | 1 | - | 1 |
| Oxide solid electrolyte (all-solid-state lithium batteries; general batteries) | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| High concentration electrolyte (general batteries) | 11 | - | - | 1 | - | - | 1 | 1 | 2 | 2 | 2 | 1 | 1 |
| High concentration electrolyte (storage batteries) | 0(1) | - | - | - | - | - | - | - | - | - | - | - | (1) |
| Polymer electrolyte (general batteries) | 634 | 13 | 14 | 16 | 19 | 31 | 30 | 67 | 47 | 51 | 86 | 100 | 160 |
| Polymer electrolyte (storage batteries) | 17 | - | - | - | 1 | - | 1 | 1 | 2 | 2 | 3 | 5 | 2 |

*Numbers in parenthesis () denote the numbers of patent applications
Source: Created by the authors from the CPRS database

As shown in Table 3-5, for electrolytes in all-solid-state lithium batteries, a handful of all-solid-state battery patents have been obtained for sulfide and oxide electrolytes, but no storage battery-related patents. China has applied for and been granted zero patents for fluoride electrolyte all-solid-state lithium batteries. In terms of electrolytes, China has the most patents for polymer electrolytes, including 17 storage battery-related patents. China only has a small number of high concentration electrolyte patents; for storage batteries China has applied for only one patent and so far has not been granted any.

**Table 3-6: Number of China-acquired battery-related patents, by anode (2010-2021)**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silicon anode (general batteries) | 94 | - | - | 2 | 1 | - | 1 | 7 | 2 | 6 | 14 | 14 | 47 |
| Silicon anode (storage batteries) | 2 | - | - | - | - | - | - | 1 | - | - | - | 1 | - |
| Magnesium (general batteries) | 15 | - | - | - | 1 | - | 2 | 1 | 1 | - | 2 | 2 | 6 |
| Magnesium (storage batteries) | 2 | - | - | - | - | - | - | - | - | 1 | - | 1 | - |
| Graphite anode (general batteries) | 245 | 3 | - | 1 | 3 | 16 | 17 | 23 | 27 | 25 | 25 | 39 | 66 |
| Graphite anode (storage batteries) | 8 | - | - | - | - | - | - | 1 | - | 2 | - | 3 | 2 |
| Sodium battery (general batteries) | 3 | - | - | - | - | - | - | - | - | - | - | 1 | 2 |
| Sodium battery (storage batteries) | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - |
| Oxide anode (general batteries) | 44 | - | 1 | - | 2 | 1 | 2 | 6 | 8 | 5 | 7 | 9 | 3 |
| Oxide anode (storage batteries) | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - |
| Metal anode (general batteries) | 159 | 1 | - | - | - | 2 | 3 | 7 | 7 | 1 | 13 | 39 | 86 |
| Metal anode (storage batteries) | 10 | - | - | - | - | - | - | - | 1 | 1 | - | 2 | 6 |
| Lithium (general batteries) | 85 | - | - | - | - | - | - | - | - | 2 | 8 | 18 | 57 |
| Lithium (storage batteries) | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - |

Source: Created by the authors from the CPRS database

As shown in Table 3-6, in recent years China has seen a rapid increase in graphite anode and metal anode-related patents, with about 10 of them being related to storage batteries. There has also been a gradual increase in silicon anode, magnesium anode, oxide anode, and lithium battery-related patents, but only a few storage battery-related patents have been obtained.

**Table 3-7: Number of China-acquired battery-related patents, by additives (2010-2021)**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dispersants (general batteries) | 1,121 | 6 | 14 | 20 | 27 | 51 | 85 | 113 | 123 | 109 | 117 | 214 | 242 |
| Dispersants (storage batteries) | 31 | - | - | - | 1 | 1 | - | 1 | 2 | 4 | 9 | 6 | 7 |
| Conductive additives (general batteries) | 99 | - | - | 1 | 1 | 2 | 5 | 11 | 15 | 17 | 11 | 17 | 19 |
| Binders (general batteries) | 2,751 | 20 | 23 | 43 | 59 | 82 | 166 | 234 | 298 | 239 | 320 | 531 | 736 |
| Binders (storage batteries) | 123 | - | - | - | 4 | 3 | 10 | 12 | 15 | 10 | 13 | 23 | 33 |

Source: Created by the authors from the CPRS database

As shown in Table 3-7, when it comes to battery additives, China has accumulated a large number of patents related to binders and dispersants, of which many of those are storage battery-related patents. However, China has been granted only a small number of patents for conductive additives. Interestingly, the majority of Chinese patents for conductivity additives have been obtained by local subsidiaries of Japanese companies (Nissan, Semiconductor Energy Laboratory, and Toyota as examples of the top three companies).

**Table 3-8: Number of China-acquired battery-related patents, by phenomena/structural analysis (2010-2021)**

| Type | Total | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Expansion/shrinkage | 46 | - | - | 2 | 3 | 2 | 4 | 2 | 7 | 5 | 4 | 5 | 12 |
| Electronic conduction (general batteries) | 225 | 2 | 2 | 1 | 7 | 9 | 12 | 20 | 13 | 22 | 23 | 56 | 58 |
| Electronic conduction (storage batteries) | 20 | - | - | - | 2 | 1 | 1 | 3 | 2 | - | 1 | 5 | 5 |
| Ionic conduction (general batteries) | 347 | 6 | 5 | 6 | 15 | 15 | 26 | 27 | 31 | 29 | 38 | 56 | 93 |
| Ionic conduction (storage batteries) | 14 | - | - | 1 | 1 | 1 | 2 | 1 | 1 | 2 | - | 2 | 3 |
| Dendrite precipitation (general batteries) | 672 | 10 | 6 | 15 | 11 | 16 | 14 | 27 | 41 | 43 | 73 | 137 | 279 |
| Dendrite precipitation (storage batteries) | 28 | - | - | - | - | - | 1 | 2 | 3 | 1 | 3 | 7 | 11 |
| Interfaces (general batteries) | 63 | - | - | - | - | - | 3 | 7 | 6 | 5 | 12 | 12 | 18 |
| Interfaces (storage batteries) | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - |

Source: Created by the authors from the CPRS database

In the analysis of various phenomena related to battery stability, safety, and efficiency, including those related to storage batteries, as shown in Table 3-8, China's largest number of granted patents are for dendrite precipitation, of which some are related to storage batteries. Although China has accumulated a certain amount of patents related to electronic and ionic conduction all-solid-state batteries, it only has about 20 storage battery-related patents in these fields. The number of patents granted for battery expansion/shrinkage is still low.

Additionally, for the above 30 elemental technology areas, ones in which China has accumulated more than 25 patents (such as for lithium-ion batteries, sodium-ion batteries, lithium sulfur batteries, binders, dispersants, and dendrite precipitation), information about the patent applications was extracted and organized.

**Table 3-9: Patent applications for lithium-ion battery patents (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Shanghai Power Storage Battery System Engineering Technology | Private enterprise | 9 |
| 2 | Shanghai Institute of Space Power-Sources | State-owned enterprise | 6 |
| 3 | BTR New Material Group | Private enterprise | 4 |
| 4 | PowerSmooth | Private enterprise | 3 |
| 5 | Thunder Sky Winston Battery | Private enterprise | 2 |
| 6 | Nankai University | University | 2 |
| 7 | State Grid Corporation of China | State-owned enterprise | 2 |
| 8 | Wuxi Tongchun New Energy Technology | Private enterprise | 2 |
| 9 | Zhejiang Narada Power Source | Private enterprise | 2 |
| 10 | Shanghai University | University | 1 |

Source: Created by the authors from the CPRS database

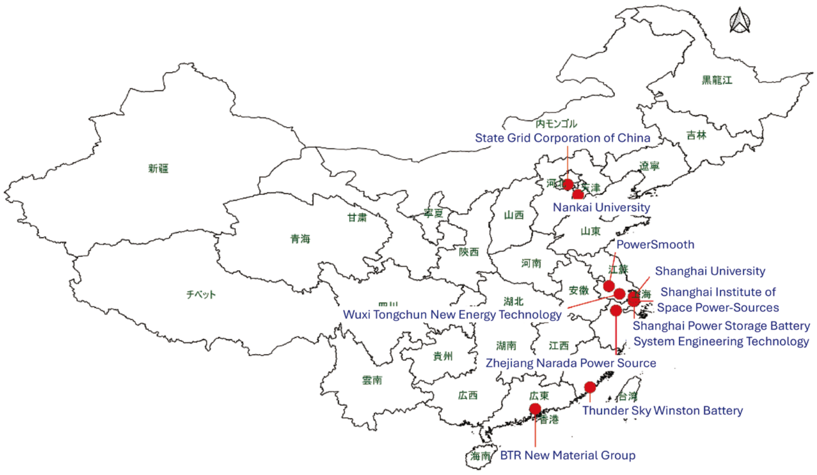



**Figure 3-12: Location of patent applications for lithium-ion battery patents (top 10)**

As shown in Table 3-9, lithium-ion battery-related patents for storage batteries are primarily owned by private enterprises. Shanghai Institute of Space Power-Sources, which ranks second, is affiliated with China Aerospace Science and Technology Corporation (a state-owned enterprise), and began by researching and developing batteries for satellites. Although the State Grid Corporation of China, ranked seventh, has a strong presence in storage batteries overall, the number of lithium-ion battery patents that it has obtained is still small. Their locations are shown in Figure 3-12.

**Table 3-10: Patent applications for sodium-ion battery patents (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Central South University | University | 6 |
| 2 | Huazhong University of Science and Technology | University | 3 |
| 3 | Shaanxi University of Science and Technology | University | 3 |
| 4 | Shanghai Jiao Tong University | University | 2 |
| 5 | Shanghai Zijian Chemical Science and Technology | Private enterprise | 2 |
| 6 | Institute of Chemistry, Chinese Academy of Sciences | State research institution | 2 |
| 7 | Beijing University of Chemical Technology | University | 2 |
| 8 | Beijing Institute of Technology | University | 2 |
| 9 | Nankai University | University | 2 |
| 10 | Lu Yiyuan | Individual | 2 |

As shown in Table 3-10, China's sodium-ion battery patents for storage batteries are primarily owned by universities and research institutes, with the exception of the fifth ranked entity, which is a private enterprise. Their locations are shown in Figure 3-13.

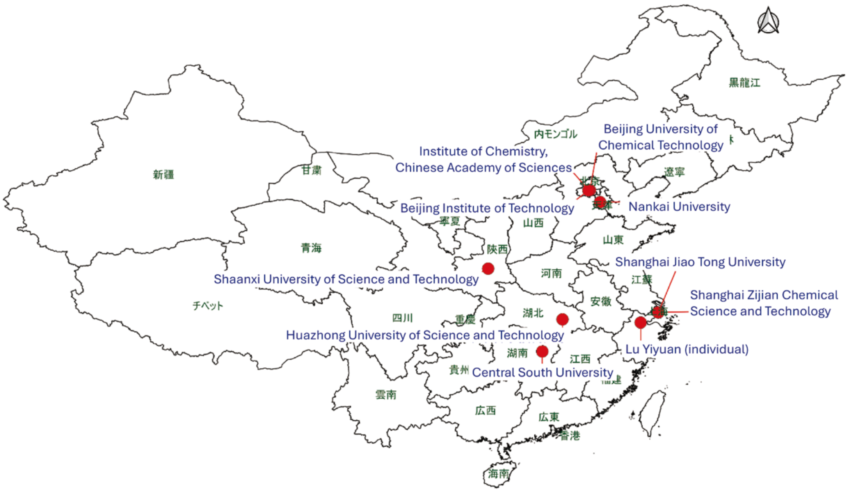



**Figure 3-13: Location of patent applications for sodium-ion battery patents (top 10)**

**Table 3-11: Patent applications for lithium-sulfur battery patents (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Beijing Institute of Technology | University | 8 |
| 2 | South China Normal University | University | 3 |
| 3 | Dalian University of Technology | University | 3 |
| 4 | Zhejiang Sci-tech University | University | 3 |
| 5 | Central South University | University | 2 |
| 6 | Institute of Metal Research, Chinese Academy of Sciences | State research institution | 2 |
| 7 | Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences | State research institution | 2 |
| 8 | Sun Yat-sen University | University | 2 |
| 9 | Hefei Guoxuan High-Tech Power Energy | Private enterprise | 2 |
| 10 | Shaanxi University of Science and Technology | University | 2 |

Source: Created by the authors from the CPRS database

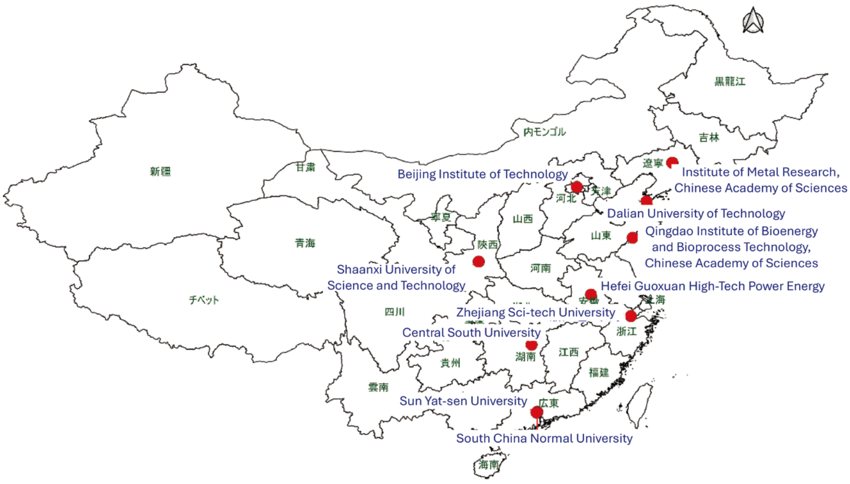



**Figure 3-14: Location of patent applications for lithium-sulfur battery patents (top 10)**

As shown in Table 3-11 and Figure 3-14, in China the development of lithium-sulfur batteries for storage battery use is primarily conducted at universities and national research institutes.

On the other hand, as shown in Tables 3-12, 13, and 14, patents related to storage battery binders, dispersants, and dendrite precipitation are owned by private enterprises, for the most part. Their locations are shown in Figure 3-15, 16, and 17, respectively.

**Table 3-12: Patent applications for binders in storage batteries (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Ningxia Hanyao Graphene Energy Storage Material Technology | Private enterprise | 8 |
| 2 | Nankai University | University | 5 |
| 3 | Ningbo CRRC New Energy Technology | State-owned enterprise | 5 |
| 4 | Ningxia Hanghan Graphene Technology Research Institute | Private enterprise | 4 |
| 5 | CATL | Private enterprise | 4 |
| 6 | Dalian Institute of Chemical Physics, Chinese Academy of Sciences | State research institution | 3 |
| 7 | Beijing University of Chemical Technology | University | 3 |
| 8 | Beijing Hawaga Power Storage Technology Company | Private enterprise | 3 |
| 9 | Beijing Institute of Technology | University | 3 |
| 10 | Tianmu Lake Institute of Advanced Energy Storage Technologies | Private enterprise | 3 |

Source: Created by the authors from the CPRS database

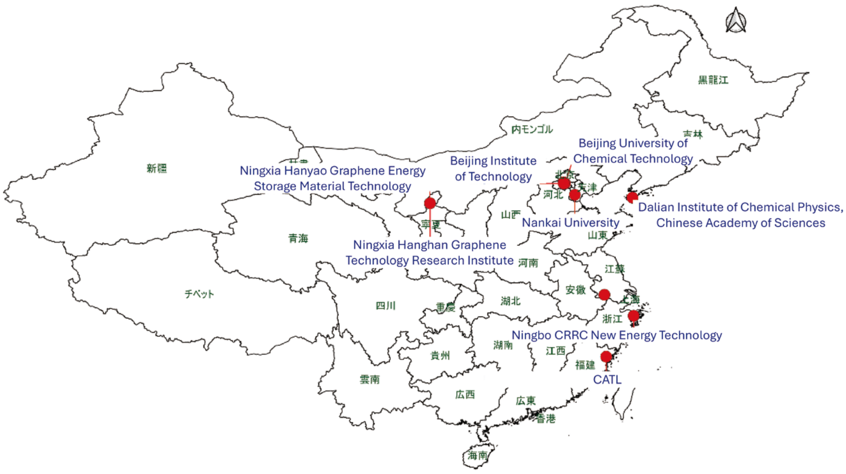



**Figure 3-15: Location of patent applications for binders in storage battery patents (top 10)**

**Table 3-13: Patent applications for dispersants in storage batteries (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Jilin Province Kaiyu Electrochemical Energy Storage Technology Development | Private enterprise | 3 |
| 2 | Ningxia Hanyao Graphene Energy Storage Material Technology | Private enterprise | 3 |
| 3 | Central South University | University | 2 |
| 4 | Shanghai University | University | 1 |
| 5 | Shanghai University of Engineering Science | University | 1 |
| 6 | Shanghai Jiuyin Electronic Technology | Private enterprise | 1 |
| 7 | CITIC Guoan MGL Power Technology | State-owned enterprise | 1 |
| 8 | Research Center of Laser Fusion, China Academy of Engineering Physics | State-owned enterprise | 1 |
| 9 | Shenzhen National Engineering Research Center of Advanced Energy Storage Materials | State-owned enterprise | 1 |
| 10 | GCL System Integration Technology | Private enterprise | 1 |

Source: Created by the authors from the CPRS database

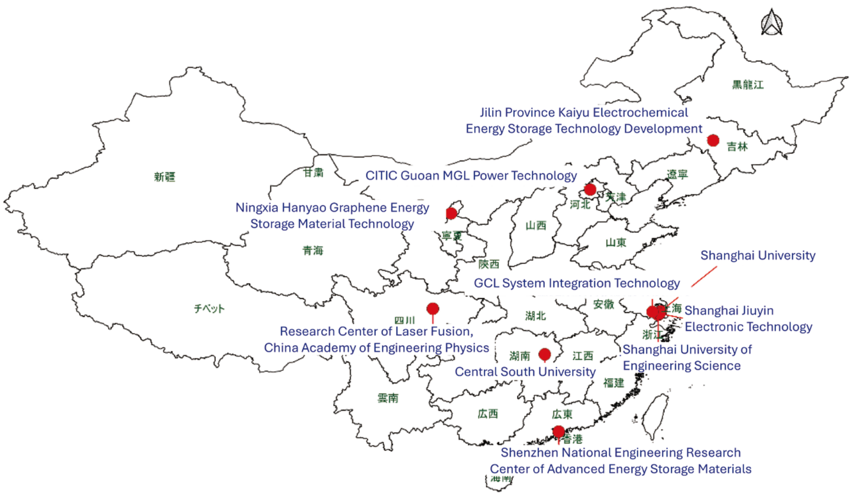



**Figure 3-16: Location of patent applications for dispersants in storage battery patents (top10)**

**Table 3-14: Patent applications for dendrite precipitation in storage batteries (top 10)**

| Rank | Patent applicant | Organization type | No. of patents obtained |
|---|---|---|---|
| 1 | Beijing Hawaga Power Storage Technology Company | Private enterprise | 6 |
| 2 | Ocean's King Lighting Science & Technology | Private enterprise | 2 |
| 3 | Shenzhen Ocean King Zhongwang Lighting Engineering Co. | Private enterprise | 2 |
| 4 | Shenzhen Ocean King Lighting Technology Co. | Private enterprise | 2 |
| 5 | Central South University | University | 2 |
| 6 | Institute of Physics, Chinese Academy of Sciences | State research institution | 1 |
| 7 | Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences | State research institution | 1 |
| 8 | Huazhong Agricultural University | University | 1 |
| 9 | South China University of Technology | University | 1 |
| 10 | Synergy Energy (Beijing) Energy Storage Technology | State research institution | 1 |

Source: Created by the authors from the CPRS database

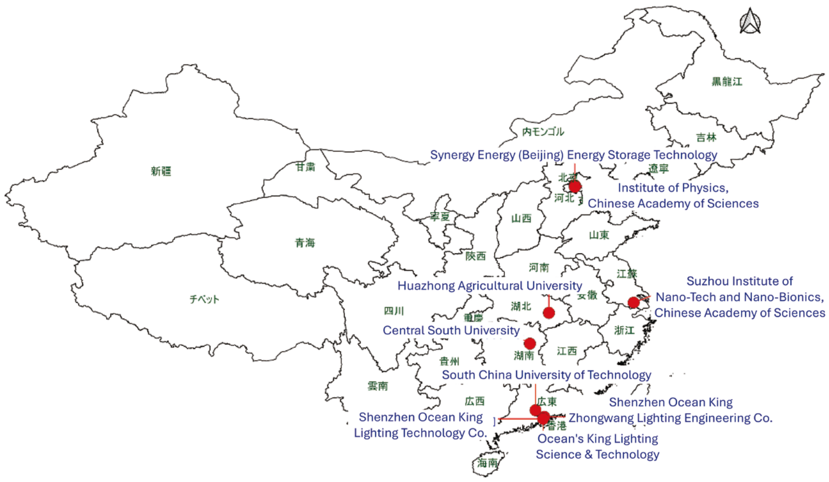



**Figure 3-17: Location of patent applications for dendrite precipitation in storage battery patents (top 10)**

# 3.3 Research support in China for storage battery technology

## 3.3.1 Research grant programs centered around research institutions

As mentioned above, China is actively conducting storage battery-related research and development, and, from 2010 to 2021, 25,204 research papers from China were submitted. Of these, most were from universities and research institutions such as the Chinese Academy of Sciences. These studies are promoted by research grant programs as shown in Table 3-15 below.

**Table 3-15: Storage battery-related research grant programs in China**

| Grant program | No. of papers | Share |
|---|---|---|
| National Natural Science Foundation of China (NSFC) | 17,947 | 70.6% |
| National University Scientific Research Grant | 3,068 | 12.1% |
| National Priority Research and Development Plan | 2,094 | 8.2% |
| National Basic Research Program of China (973 Program) | 1,737 | 6.8 |
| China Postdoctoral Science Foundation | 1,728 | 6.8% |
| Natural Science Foundation of Jiangsu Province | 873 | 3.4% |
| Chinese Academy of Sciences | 789 | 3.1% |
| National Study-Abroad Fund (Ministry of Education) | 678 | 2.7% |
| Ministry of Education 111 Project | 606 | 2.4% |

Source: Created by the authors from Web of Science Core Collection

Of these, the National Natural Science Foundation of China (NSFC) (which corresponds to grant-in-aid for scientific research from the Japan Society for the Promotion of Science), supports 70% of this research. Other support comes from related programs by the Ministry of Education and the Ministry of Science and Technology, local natural science foundations, and the Chinese Academy of Sciences.

### 3.3.2 Research grant programs centered around companies

In recent years China has set a goal of reaching carbon neutrality, and as such, under the National Priority Research and Development Plan (a strategic research program aimed at creating innovation) it has been providing subsidies for storage battery-related technology. This priority plan, which has been implemented since 2021, provides a total of approx. 30 million CNY (approx. 600 million JPY) in support for each project over 3 to 4 years. Support eligibility is mainly for companies, as shown in Table 3-16 and Figure 3-18.

**Table 3-16: National Priority Research and Development Plan (grants for storage battery-related technologies)**

| Project Number | Research theme | Research Institute | Period |
|---|---|---|---|
| 2021YFB2400100 | Gigawatt class lithium storage battery systems | CATL | 4 years |
| 2021YFB2400200 | Gigawatt class lithium all-solid-state storage battery systems | RiseSun MGL | 4 years |
| 2021YFB2400300 | Safe metal sulfide storage batteries | Shanghai Jiao Tong University | 4 years |
| 2021YFB2401500 | Dry DC capacitor electrolyte membrane materials | Tsinghua University | 4 years |
| 2021YFB2401800 | Storage battery aging analysis and life prediction technologies | China Electric Power Research Institute | 4 years |
| 2021YFB2401900 | Lithium-ion battery sensing | Beijing Institute of Technology | 4 years |
| 2021YFB2402100 | Lithium-ion storage battery system life cycle safety technologies | China Southern Power Grid Nanfang Peak Adjustment Frequency Generation | 3 years |

Source:Created by the authors based on websites related to the National Priority Research and Development Plan

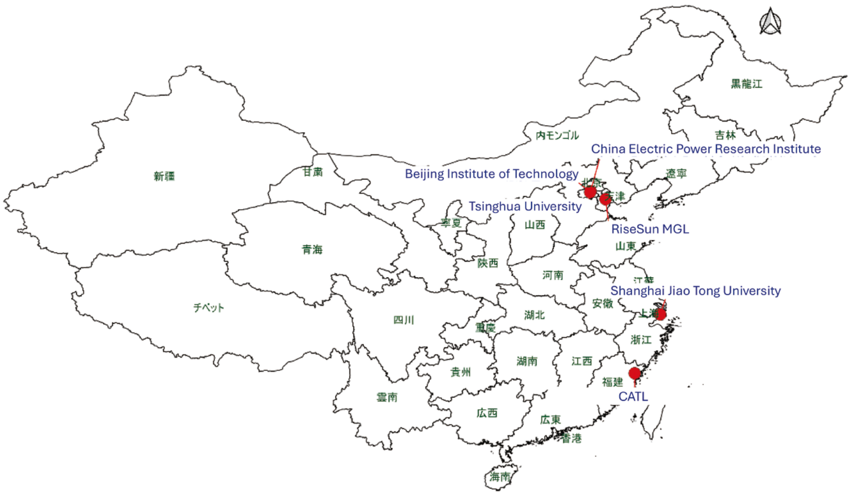



**Figure 3-18: National Priority Research and Development Plan grant recipient locations (grants for storage battery-related technologies)**

# 3.4 Summary

This chapter presented a quantitative analysis of the R&D status of storage battery-related technologies in China, based on data for papers and patents during the 2010-2021 time period. The rapid increase in the number of papers from China is largely due to the influence of a number of national research grant programs, as shown in Table 3-14.

Top universities and institutions, such as the Chinese Academy of Sciences, Nankai University, Beijing Institute of Technology, and Shanghai Jiao Tong University, have a large number of papers and patents in specific fields, and there is active technology transfer and startups through industry-academia collaborations. Looking at the number of patents in related technology areas, state-owned companies and private companies are competing for the top spots in various storage battery systems. China's universities also have strong development capabilities in advanced materials fields such as lithium-sulfur batteries.

China is expected to create an enormous market for battery storage as it vigorously promotes the spread of renewable energy to achieve its goal of reaching carbon neutrality by 2060. Although it is not yet clear which type of storage battery will eventually become the mainstream, China's development trends are bound to have a major impact on the world.

# Reference materials and literature

National Priority Research and Development Plan energy storage and smart grid technology subsidy list
http://www.cnqingdan.com/index.php?m=information&a=fileview&id=6326&infoid=6050&cate=2

# 4 Research and development trends in China for next-generation sodium-ion battery technology

## 4.1 Overview of sodium-ion batteries

### 4.1.1 Overview of sodium-ion batteries

At the end of the 1970s, research on sodium-ion battery technology was already underway at the same time as research on lithium batteries. Sodium-ion batteries, like lithium-ion batteries, consist of an electrolyte, cathode and anode materials, and a separator. They have similar ion insertion/desorption mechanisms, and, in the process of charging/discharging, sodium ions move back and forth between the cathode/anode like a rocking chair while electrons move through the external circuit, thereby achieving mutual conversion between chemical and electrical energy. Although the energy density of sodium-ion batteries is not yet comparable to that of lithium-ion batteries, they have the advantages of abundant reserves of sodium and low cost, which will greatly facilitate the development of large-scale energy storage. Above all, in addition to their resource reserves and cost advantages, sodium-ion batteries are superior to lithium-ion batteries in the following ways.

#### 1. Current collector material

Lithium and aluminum undergo alloying reactions at low potentials, so copper is the only choice for a current collection in lithium-ion batteries. However, sodium and aluminum do not have allying reactions at low potentials, so sodium-ion batteries can use inexpensive aluminum as the current collector, thereby reducing the overall cost[1].

#### 2. Interface ion diffusion ability

Because the solvation free energy of sodium ions is lower than that of lithium ions, at the interface the ions have better diffusion ability.

#### 3. Ionic conductivity

Since the Stokes radius of sodium ions is smaller than that of lithium ions, a sodium electrolyte of the same concentration has a higher ionic conductivity than a lithium salt electrolyte.

#### 4. High and low temperature characteristics

According to current basic high-temperature test results, the high-temperature characteristics of sodium-ion batteries are superior to lithium-ion batteries.

#### 5. Safety

Although the internal resistance of sodium-ion batteries is slightly higher than that of lithium-ion batteries, they are safer because they generate less instantaneous heat and cause a smaller temperature rise in the event of a short circuit.

Sodium-ion batteries also have other essential advantages over other batteries. Because the structure and operating principles of sodium-ion batteries are similar to those of lithium-ion batteries, the mature manufacturing technologies for lithium-ion batteries can be utilized to accelerate the development and application of sodium-ion batteries. Sodium-ion batteries can also fully complement the related fields of lithium-ion batteries. In particular, sodium-ion batteries are expected to show strengths in fields such as medium- and low-speed electric vehicles and large-scale energy storage (civil communication base stations, data centers, backup power sources, home energy storage on the user side, and large-scale energy storage on the power grid side).

In recent years, China has made rapid progress in researching and developing sodium-ion batteries, and there is increasing enthusiasm for participation from academia and industry. In academia, research on sodium-ion batteries has been revisited since 2010, and the number of sodium-ion battery-related papers that have been published is rapidly increasing. There are two main reasons for this. First, research on lithium-ion battery materials is becoming more mature day by day (Figure 4-1). Research at the time was mainly focused on the application and improvement of materials and advanced analysis of electrochemical processes, and the difficulty of developing new materials was clearly increasing. As a result, many researchers have turned to searching for materials for sodium-ion batteries. Second, there are concerns about a global shortage of lithium resources and the need for new large-scale energy storage applications. These factors have also prompted researchers to develop new battery systems. Based on the abundant research and development results accumulated in the lithium-ion battery field, sodium-ion batteries have been rapidly progressing in recent years, with various cathode/anode materials and electrolytes being successively reported.

Cathode materials that have been reported include layered/tunneled transition metal oxides, polyanionic compounds, Prussian blue analogues (PBA), and organic materials. Examples of anode materials include carbon materials, alloys, phosphides, and organic carboxylates. In addition to research into new materials, research and development is also being conducted on sodium-ion batteries themselves to reduce costs and put them into practical use.

In 2011, Komaba et al. [2] reported on the performance of the world's first hard carbon || $NaNi_{0.5}Mn_{0.5}O_2$ fuel call (all battery). As a result of this achievement, Faradion was established that year in the UK as the world's first sodium-ion battery company. In 2013, the American company Goodenough [3] launched a cathode material using Prussian white, which has excellent high voltage and rate characteristics. In 2014, Hu Yongsheng et al. [4] first discovered the electrochemical activity of the $Cu^{3+}/Cu^{2+}$ redox couple in layered oxides, and then designed and formulated/prepared a low-cost Cu-based cathode material [5]. Then again in 2016, Hu et al. [6] presented an amorphous carbon material for sodium-ion battery anodes, which was formulated/prepared with inexpensive anthracite coal. Based on these research and development results for key materials like the cathode and anode, in 2017 HiNa Battery was established as China's first company doing research, development, and manufacturing of sodium-ion batteries, and they subsequently announced the world's first low-speed electric vehicle equipped with sodium-ion batteries and a 1MWh energy storage power plant using sodium-ion batteries [7]. At the same time, the company is also concurrently conducting research and development to improve the safety of sodium-ion batteries for large energy storage systems. In addition, aqueous sodium-ion batteries and solid-state sodium-ion batteries, which use aqueous electrolyte and solid electrolyte instead of organic electrolyte, respectively, are under development.

In China, new energy storage technology is an important technology and basic equipment for building its new type of power system, and is also an important support for realizing China's twin goals of achieving peak $CO_2$ emissions and carbon neutrality. In the 13th Five-Year Plan for Energy Storage Direction of the Smart Grid Key Special Project, China's Ministry of Science and Technology designated sodium-ion batteries as the most important item under "basic science and future technology research for new energy storage devices."[65] In July 2021, the National Development and Reform Commission and the National Energy Administration promulgated the "Guiding Opinion on Accelerating the Promotion of New Energy Storage Development,"[66] which aimed to improve science, technology, and innovation capabilities, such as by strengthening the energy storage industry system and accelerating large-scale model trials of sodium-ion battery technology.

Since the 13th Five-Year Plan, China's new energy storage industry has been in the process of transitioning from a research and development model to the early stages of commercialization, with substantial progress having been made in research and development of technological equipment, construction of model projects, exploration of business models, and establishment of policy systems. The application market scale for new energy storage has steadily expanded, and it has begun to play a role in supporting the energy transition. New energy storage development implementation plans in the 14th Five-Year Plan were previously mentioned, and in them, in order to eliminate bottlenecks in core technology and equipment for new energy storage, sodium-ion batteries are being considered as one of the important directions during the 14th Five-Year Plan period, with the policy requiring model trials of new energy storage technology using sodium-ion batteries. This shows that sodium-ion battery technology has already become an important strategic demand for China's national development.

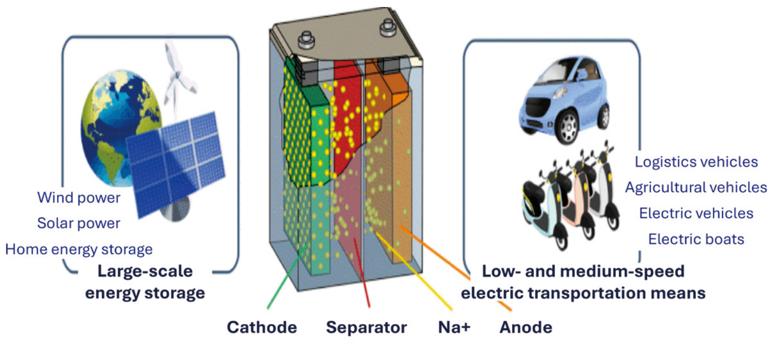



**Figure 4-1: Structure and main application fields for sodium-ion batteries**

Source: Created by the authors with some modifications based on the website of HiNa Battery[67]

## 4.1.2 Major sodium-ion battery systems

Currently, there are relatively many sodium-ion battery systems with industrialization potential, and much research is underway in China, with many different materials being advanced in parallel. Cathode materials are mainly layered oxides [8-10], polyanionic compounds [11], Prussian blue-white analogues [12], etc., while typical layered oxides are

65 http://www.gov.cn/zhengce/content/2016-08/08/content_5098072.htm

66 https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202107/t20210723_1291321.html

67 https://www.hinabattery.com/index.php?catid=12

mainly ternary materials such as copper-iron-manganese, nickel-iron-manganese, and nickel-titanium-manganese. Polyanionic compounds include sodium vanadium phosphate, sodium vanadium fluorophosphate, sodium complex iron-phosphate, and sodium-iron-sulfate, while Prussian blue-white analogues are mainly composed of iron and manganese. The main anode materials are hard carbon, soft carbon, and composite amorphous carbon materials [13-15]. On the other hand, solvent and additives components for the electrolyte material are similar to those of lithium-ion batteries, but the compatible electrolyte solvent differs depending on the electrode material. Solute types include $NaClO_4$, $NaPF_6$, NaFSI, and NaTFSI, with $NaPF_6$ being the most commonly used [16-17].

## 4.2 Industrial status of sodium-ion battery technology

### 4.2.1 Industrialization status of sodium-ion batteries

Sodium ion batteries are gradually moving from basic research to the application stage. More than 20 companies around the world have already implemented plans to industrialize sodium-ion batteries, and are making dramatic progress. The world's leading companies and institutions in sodium-ion batteries are represented by Faradion of the United Kingdom, Tiamat of France, Kishida Chemical of Japan, and, in China, HiNa Battery, Natrium Energy, Contemporary Amperex Technology (CATL), the Chinese Academy of Sciences (CAS), and Dalian Institute of Chemical Physics [18]. The type of material used differs depending on the company, but in general three types of cathode materials are used: oxides, Prussian blue, and polyanionic compounds.

Faradion has developed a prototype 10 Ah soft pack battery based on a Ni-Mn-Ti layered oxide. The specific energy exceeds 140 Wh/kg, and the predicted life exceeds 1,000 cycles based on cycle tests with an 80% depth of discharge (DOD). HiNa Battery, with the backing of the CAS Institute of Physics, has developed a series of sodium-ion battery products based on layered oxides. The specific energy exceeds 140 Wh/kg and has applications in low-speed electric vehicles, 100 kWh energy storage power plants, and 1 MWh solar energy storage smart microgrid systems. Natrium Energy has formulated/prepared sodium-ion soft pack batteries utilizing a $Na[Ni_{1/3}Fe_{1/3}Mn_{1/3}]O_2$ layered oxide, which have a specific energy of 100-120 Wh/kg and a capacity retention rate after 1,000 cycles that exceeds 92%. CATL announced in July 2021 that they had reached a specific energy of 160 Wh/kg with Prussian white-based cells. Tiamat has developed a sodium vanadium fluoride phosphate-based cell that can be quickly recharged in 5 minutes. The specific power reaches 2-5 kW/kg, but the specific energy is rather low at 90 Wh/kg. In the past few years, the CAS Dalian Institute of Chemical Physics, based on a phosphate polyanion compound cathode, has successively developed a sodium vanadium phosphate soft pack battery with a specific energy of approximately 127Wh/kg, as well as a sodium vanadium fluorine phosphate soft pack battery with a specific energy of over 143Wh/kg and which can be rapidly charged in 6 minutes. Furthermore, they have constructed an energy storage system using a 48V/10Ah sodium phosphate ion battery, and have successfully applied it to the battery of a low-speed electric vehicle.

What is particularly noteworthy is that the aforementioned research and development team led by Hu Yong-Sheng from the CAS Institute of Physics is now on par with the world's top leaders in both basic research and in the industrialization of sodium-ion batteries. Over the past few years, they have made great strides with a series of their studies, and, in 2020 in particular, they achieved a major breakthrough in theoretical research on sodium-ion battery cathode materials. By setting a variable parameter called the cation potential (Φ cation), they were able to understand the competitive interrelationship between the O3 and P2 structures, and created a phase diagram that allowed them to distinguish between these two structures. This is a new way to hypothesize and design layered oxide cathode materials, and provides a rationale for developing low-cost, high-performance cathode materials. The research results were published in the journal *Science* under the title "Rational design of layered oxide materials for sodium-ion batteries."[68] After more than 100 years of being in print, the publication of *Science*'s first paper on the field of sodium-ion batteries is a testament not only to the importance placed on this technological breakthrough by the world's mainstream scientific community, but also to the state-of-the-art of sodium-ion batteries, and also means that sodium-ion battery advanced research and technology have reached the world's top level (Figure 4-2).

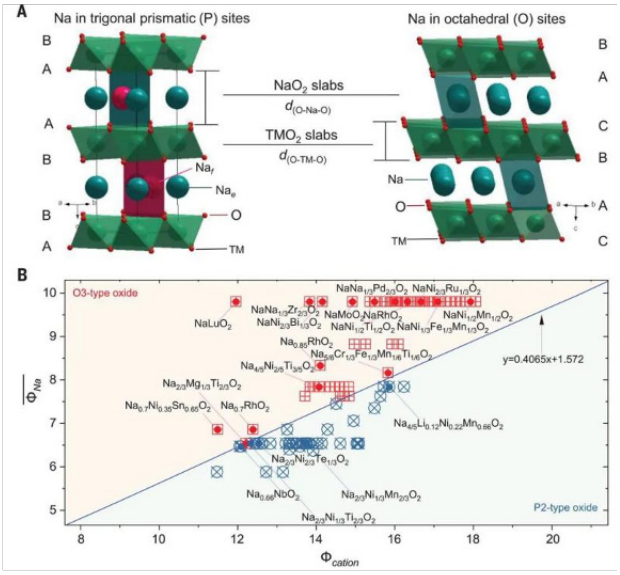



**Figure 4-2: Cation potential and its application in sodium-ion layered oxides[69]**

Based on the layered oxide cathode material, anthracite anode material, and sodium-ion battery technologies developed so far, on June 28, 2021, Hu's research team completed a 1MWh solar energy storage smart microgrid system using sodium-ion batteries and officially started operation at the Shanxi Transformation and Comprehensive Reform Demonstration Zone in Taiyuan City, Shanxi Province (Figure 4-3).[70] This system places sodium-ion batteries, originally developed by the CAS Institute of Physics, at the core of energy storage, and combines commercial power sources, photovoltaic power generation, and charging facilities to form a microgrid, establishing self-control, maintenance, and management. It has a flexible operating model and dispatch capability, and can be integrated into a large-scale power grid or operated independently. This shows that China is starting to take the lead in the world in industrializing sodium-ion battery technology, and at the same time further promotes the commercial application of sodium-ion batteries.

68 https://www.science.org/doi/10.1126/science.aay9972

69 Zhao et al., (2020): Rational design of layered oxide materials for sodium-ion batteries, SCIENCE, Vol.370, Issue 6517, pp.708-711.

70 http://www.iop.cas.cn/xwzx/snxw/202106/t20210628_6118350.html

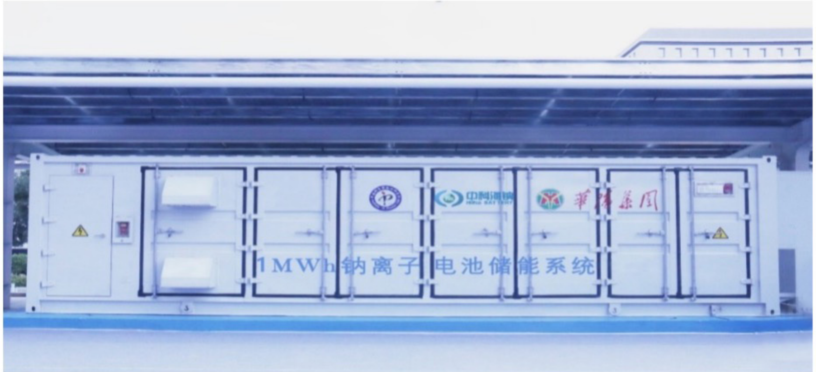



**Figure 4-3: World's first 1 MWh sodium-ion battery energy storage system[71]**

## 4.2.2 Sodium-ion battery industry chain companies

As a new battery technology route, the sodium-ion battery industry chain consists of resource development companies and battery material/cell manufacturers. The specific companies/institutions are shown below (Figure 4-4).

1. Companies developing technology for sodium-ion batteries: CATL, HiNa Battery (Beijing), Natrium Energy (Zhejiang), Star Sodium, GuangZhou Great Power Energy & Technology, Dynavolt Tech, Shandong Sacred Sun Power Sources, Wuhan Sunmoon Battery, and Sunwoda, etc.
2. Holding / investment companies for sodium-ion battery companies: Shan Xi Hua Yang Group New Energy, Zhejiang Medicine, and Chengdu Xinzhu Road & Bridge Machinery, etc.
3. Companies developing and manufacturing technology for sodium-ion battery materials: Anode manufacturers: Shenzhen XFH Technology; cathode manufacturers: Ningbo Ronbay Lithium Battery Material; aluminum manufacturers: Jiangsu Dingsheng New Energy Materials, Shandong Nanshan Aluminium, Henan Mingtai Al. Industrial, and Shantou Wanshun New Material Group, etc.
4. Companies developing sodium resources:
   CNSIG Inner Mongolia Chemical Industry, Nafine Chemical Industry Group, Lily Group, etc.

71 https://www.hinabattery.com/index.php?id=181

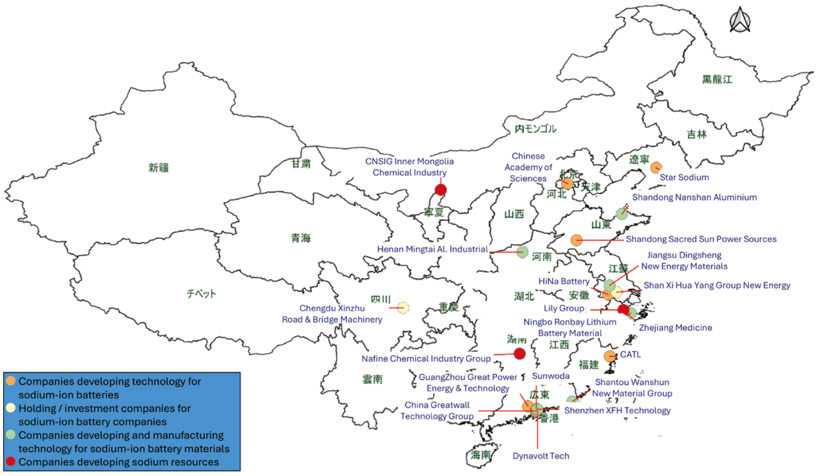



**Figure 4-4: Location of companies in the sodium-ion battery industrial chain**

### 4.2.3 Target application market for sodium-ion batteries

Sodium ion batteries are expected to have a wide range of applications in situations where energy density requirements are not very high. In particular, if sodium-ion batteries are commercialized on a large scale, then they will occupy a corner of the market, particularly in usage scenarios where current lithium-iron-phosphate batteries have an advantage (such as electric two-wheel vehicles (electric bicycles and electric motorcycles, etc.), low-speed electric vehicles, energy storage/power plants, and home energy storage products).

Energy storage, electric two-wheel vehicles, and A00-class automobiles three promising areas for the application of sodium-ion batteries, and the combined battery demand in China in 2025 for these three major areas is expected to reach 123 GWh. Sodium-ion battery demand in 2020 was approx. 17GWh, 32GWh, and 7GWh for the installed energy storage capacity, electric two-wheel vehicles, and drive battery capacity for A00 class automobiles, respectively, but it is estimated that by 2025 they will reach 48GWh, 41GWh, and 34GWh, respectively. Assuming that lithium-iron-phosphate batteries are used in these three major fields, the market size from 2021 to 2025 will be CNY40.8 billion, CNY51 billion, CNY54.5 billion, CNY53.2 billion, and CNY53.7 billion, respectively (approx. 1,000 billion JPY).[72]

Considering the current technological maturity and manufacturing scale of sodium ion-batteries, it seems that the best application market to start with would be low-speed electric vehicles. Subsequently, with improvements to product technological maturity and further industry standardization/normalization, the applications for and industrialization of sodium-ion batteries will enter a period of rapid development, and will then gradually enter the energy storage application market. Additionally, due to factors such as an incomplete industrial chain and high manufacturing costs, the actual production cost of sodium-ion batteries is currently more than 1 RMB/Wh. Once industrialization progresses smoothly and production capacity reaches the GWh level, because the capital investments for sodium-ion batteries can be deprecated, sodium-ion batteries' inherent advantages of lower material costs will become apparent (due to their price advantages for cathode and anode current collector materials, the material cost of sodium-ion batteries is approximately 30% lower than that of lithium-iron-phosphate batteries). Sodium-ion batteries are expected

72 http://www.dzzq.com.cn/bond/44627521.html

to replace lithium-iron-phosphate batteries in fields such as energy storage, electric two-wheel vehicles, and A00 class automobiles.

### 4.2.4 Challenges facing the development of sodium ion-batteries

Because the structure and operating principles of sodium-ion batteries are similar to those of lithium-ion batteries, the manufacturing processes for lithium-ion batteries can be used as a reference in scaling up and industrialization. As such, it can be said that there is just a short period of time until entering the industrialization stage. However, there are many differences between the two types of batteries. For example, there are major differences in the types of electrode materials, such as the use of aluminum foil current collectors for the anode material of sodium-ion batteries. There are also still many problems and challenges in the process of industrializing sodium-ion batteries.

1. Sodium-ion batteries have a problem in that a final unified standard for cathode/anode materials has not yet been determined. There are three main types of cathode materials: oxides, polyanionic compounds, and Prussian blue, and there are many types of cathodes that belong to each type. These various materials also have problems that need to be resolved as soon as possible. For example, oxides have the problem of somewhat poor storage stability in the atmosphere, and Prussian blue is prone to defects and problems with bound water during the synthesis process, both of which have an impact on battery performance. The hard and soft carbon materials often used in anodes have very low product performance indicators in China, so, compared to the amorphous carbon materials developed in countries such as Japan and France, the initial use effect and specific energy of the battery are extremely low. Research and development capabilities for anode materials must be further strengthened.

   As for electrolytes, although the constituent elements of solvents and additives are similar to those of lithium-ion batteries, considering that the electrolytes that match each material are different, there is still the problem of a lack of standard design guidance principles. In particular, from the perspective of solvation structure, there is a lack of understanding in terms of the electrochemical reactions of each electrolyte at the battery interface, the structure-activity relationship (SAR) between the desolvation process, and battery performance.
2. The electrode materials and related auxiliary materials used in sodium-ion batteries do not necessarily all match the materials used in lithium-ion batteries, so there are some differences in the process of single cell integration and system integration for both. As such, there is a need for further system integration research.
3. Promoting and accelerating the industrialization of sodium-ion batteries requires the construction of a well-organized industrial chain. However, at present, there is still only a low and insufficient level of scale up for stages related to electrolytes and carbon-based anodes.
4. The positioning of sodium-ion batteries in the applied market needs to be further segmented. Furthermore, there is an urgent need to test various energy storage system application models and to verify the reliability of sodium-ion batteries.

### 4.2.5 Direction of research and development for sodium-ion batteries

With regard to the problems and issues mentioned above the priority directions for the development of sodium-ion battery technology are as follows.

1. Strengthen research and development capabilities for core materials (cathode/anode, electrolyte, etc.), core devices, and system integration technologies for sodium-ion batteries. Achieve breakthroughs in various types of technology such as: synthesis technology and scale expansion technology for core materials that improve specific energy, specific output, long life, and safety; high-integrity, high-reliability, and large-capacity cell assembly technology; system integration and smart control technology for highly energy efficient and highly reliable 100kWh to 100MWh class energy storage systems, etc.
2. Accelerate verification by applying sodium-ion batteries using various electrode materials to energy storage systems. Apply various technological routes to appropriate fields and compare their cost performance and reliability. Screening of cathode/anode electrode materials and electrolytes suitable for the application field of sodium-ion batteries.
3. Increase the scale of sodium-ion battery cathodes/anodes, electrolytes, and related auxiliary materials. Respond to the needs of energy storage application models for sodium-ion batteries in new energy fields.
4. Establish standards for sodium-ion battery technology. Focus on standardizing the industry and market, improving product quality, and promoting market penetration. Promote and accelerate the industrialization of sodium-ion batteries.

## 4.3 Trends and prospects for standardizing sodium-ion batteries

### 4.3.1 Necessity of establishing standards

Sodium and lithium ions have similar insertion and desorption mechanisms in battery systems. If the research and development of sodium ion batteries advances and they become a substitute for lithium-ion batteries, then situations where the development of new energy batteries is limited by the lack of lithium resources can be alleviated. At present, although sodium-ion batteries still have differences with lithium-ion batteries in terms of energy density and other aspects, cost and lifespan are more important indicators than energy density for applications in low-speed electric vehicles and large-scale energy storage. Therefore, it can be concluded that sodium-ion batteries have a greater competitive advantage over lithium-ion batteries in the market for applications such as low-speed electric vehicles, large-scale energy storage, 5G communication base stations, and data centers. In recent years, these application fields have been experiencing high growth, and the unique advantages of sodium-ion batteries have created unprecedented opportunities for their research and industrialization. Sodium ion batteries have been successfully applied in a number of model applications in various target fields, related products have gradually entered the market, and related industries are gaining momentum. As such, given these circumstances, it is clear that it is important to establish standards for sodium-ion batteries.

However, while sodium-ion batteries are a completely new chemical power system, when being introduced into markets there are still no current product standards and norms, a problem that is not just in China, but worldwide. This is a major hindrance to the advancement of sodium-ion battery technology and to the development of the industry. As such, it is necessary to establish industry standards (or de facto standards) and the countries that they apply to; standardize inspections of sodium-ion battery products; standardize quality; and optimize market orders to promote progress in sodium-ion battery technology.

### 4.3.2 Development of and prospects for standardization of sodium-ion batteries

At the end of December 2021, the first industry standard for sodium-ion batteries, the “Common Specification for Sodium-Ion Secondary Batteries,”[73] was officially promulgated. The standard was proposed by the Institute of Physics, Chinese Academy of Sciences (CAS), and then drafted after review by the China Energy Storage Alliance standards committee. With the CAS Institute of Physics as the lead drafting organization, the following companies/institutions participated in the drafting: HiNa Battery, Shanghai Jiao Tong University, Natrium Energy, CAS Dalian Institute of Chemical Physics, State Grid Corporation Beijing Electric Power Company China Electric Power Research Institute, Huawei, CATL, Faenlaite, Li-Fun Technology, and China Southern Power Grid Technology. This standard stipulates common requirements for sodium-ion batteries, including model nomenclature, technical requirements, test methods, inspection rules and indicators, packaging, transportation and storage. The proposal standardized industry terminology, thereby allowing companies to share common concepts and awareness, achieve cost reductions through scaling up, and fulfilling the role of leading the industry by meeting market needs.

Going forward, there must be a more complete standardization system for sodium-ion batteries, including standards for material products, battery products, testing and inspection methods, maintenance, reliability evaluations, safety, and recovery. In particular, safety standards are an important criterion for controlling product quality and an important means of optimizing the market order and promoting technological progress. In the past few years, there have been many reports of electric vehicle accidents caused by lithium-ion battery technology, and safety has become one of the most important indicators to consider when entering the lithium-ion battery market. Furthermore, as sodium ion batteries are expected to become more popular in the field of medium- and low-speed electric vehicles in the future, demands for sodium-ion battery safety are increasing even further. As such, it is particularly important to establish relevant standards and to ensure the quality and appropriateness of sodium-ion battery products that are distributed in the market.

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# 5 Research and development trends in China for next-generation lithium battery electrolyte technology

## 5.1 Overview of lithium battery electrolytes

Lithium-ion batteries are composed of an electrolyte, cathode and anode materials, and a separator, with the electrolyte functioning as the lithium-ion battery's "blood." By transporting ions and blocking electrons between the cathode and anode, and forming a current path between the cathode and anode, the battery can smoothly charge and discharge. The electrolyte plays a decisive role in the mechanism of battery operating reactions, directly influencing the battery's specific capacity, rate characteristics, cycle stability, and safety [1]. The electrolytes in lithium-ion batteries can be broadly divided into three types: liquid electrolytes (organic liquids and ionic liquids), gel polymer electrolytes, and solid-state electrolytes (solid polymers and inorganic solids). The ideal electrolyte for lithium-ion batteries has the following characteristics [2-4].

1. Excellent chemical stability and essentially does not react with the battery's cathode/anode materials, current collectors, or separators, etc.
2. Electrochemically stable over a wide potential window, allowing the battery to successfully operate over a wide voltage range without electrolysis
3. High ionic conductivity over a wide temperature range, extremely high lithium-ion mobility, and low viscosity
4. Excellent film-forming properties and thermal stability
5. High flash point and ignition point, excellent safety
6. Low toxicity and environmentally friendly

Of the different types of electrolytes, organic liquid electrolytes, which have been studied for a long time, are the most advanced. Solid and gel electrolytes have drawbacks such as low ionic conductivity and poor rate characteristics, so most current lithium-ion batteries in the Chinese market use organic liquid electrolytes.

## 5.2 Electrolyte components and characteristics

The organic liquid electrolytes in Chinese lithium-ion batteries generally consists of a lithium salt, an organic solvent, and additives. The most commonly used lithium salt is lithium hexafluorophosphate ($LiPF_6$). Organic solvents are mainly divided into carbonate esters, ethers, and carboxylic esters. Additives are classified into many types according to their functions, such as conductive aids, film-forming aids, overcharge inhibitors, and flame retardants.

### 5.2.1 Electrolyte: Lithium salts

The lithium salt in the electrolyte has a large effect on battery performance. Lithium salts for lithium-ion batteries for practical applications must meet the following requirements [5].

1. High conductivity and wide potential window
2. Excellent chemical and thermal stability
3. High solubility and degree of dissociation in organic solvents, and excellent solubility
4. High affinity with the environment, and relatively small impact on the decomposition of other products in the environment
5. Easy formulation/preparation and purification, and low production costs

$LiPF_6$ is currently the most widely used lithium salt in the lithium-ion battery field in China. Pure $LiPF_6$ is a white crystal, and has the advantages of good compatibility with cathode/anode materials, does not corrode aluminum foil, has moderate solubility in organic solvents and high conductivity, and is low cost. However, it has the disadvantage of slightly inferior thermal stability, and is easily decomposed by heat to produce phosphorus pentafluoride ($PF_5$). $PF_5$ reacts with carbonate ester solvents to form $CO_2$, which destroys the SEI film and seriously affects the battery's cycle stability. It also reacts instantaneously with impurities in organic solvents, such as trace amounts of water, to produce highly poisonous gases such as $POF_3$ and HF [6].

As such, the development of new lithium salts is an important future direction in the research and development of electrolytes for high-performance lithium-ion batteries. Organic lithium salts, which have high oxidation resistance and thermal stability, are attracting widespread attention from Chinese researchers. Table 5-1 is a comparison of the advantages and disadvantages between $LiPF_6$ and novel organic lithium salts such as lithium bis(oxalate) borate (LiBOB), lithium difluoro(oxalate)borate (LidFOB), lithium bis(fluorosulfonyl)imide (LiFSI), lithium bis(trifluoromethanesulfonyl)imide (LiTFSI)), and lithium bis(pentafluoroethylsulfonyl)imide (LiBETI), etc.

**Table 5-1: Comparison of advantages and disadvantages of $LiPF_6$ and new organic lithium salts**

| Organic lithium salt | Thermal decomposition temperature (℃) | Conductivity (mS/cm) | Advantage | Disadvantage |
|---|---|---|---|---|
| Lithium hexafluorophosphate ($LiPF_6$) | 125 | 10.8 | High conductivity, relatively good solubility, low production costs | Easily decomposed by heat and water |
| Lithium bis(oxalate) borate (LiBOB) | 275 | 14.9 | High conductivity, good thermal stability and film-forming properties | Slightly low solubility |
| Lithium difluoro(oxalate)borate (LiDFOB) | 200 | 8.58 | Wide potential window, good film forming properties and high/ low temperature cycle characteristics | High production costs |
| Lithium bis(fluorosulfonyl) imide (LiFSI) | 200 | 9.73 | High conductivity, good thermal stability, wide potential window | Slightly low corrosion potential with aluminum foil (4.2V) |
| Lithium bis(trifluoromethanesulfonyl) imide (LiTFSI) | 360 | 9 | High conductivity, high solubility, good thermal stability, not easy to hydrolyze | Low corrosion potential with aluminum foil (3.7V) |
| Lithium bis(pentafluoroethylsulfonyl) imide (LiBETI) | 250 | 11.1 | High conductivity, good thermal stability and film-forming properties | High production costs |

## 5.2.2 Electrolyte: Organic solvent

Organic carbonate esters are often used as organic solvents. Their parameters (such as melting point, dielectric constant, and viscosity) greatly affect the battery's operating temperature, and their redox potential is an extremely important factor for the battery's operating voltage. Their boiling and flash points also have a serious impact on the electrolyte's safety. As such, when choosing a solvent, the following conditions must be considered [7-8].

1. A high dielectric constant increases the electrolyte's conductivity
2. Relatively low viscosity and melting point
3. Do not chemically react with each other or with lithium salts
4. Strongly heat-resistant
5. Non-toxic, environmentally friendly, and low cost

The physiochemical properties of commonly used organic carbonate ester solvents are shown in Table 5-2.

**Table 5-2: Physiochemical properties of common organic carbonate ester solvents (25°C)**

| Solvent | Freezing point (°C) | Flash point (°C) | Density ($g/cm^3$) | Dielectric constant $C^2/(N \cdot M^2)$ | Viscosity (mPa·s) |
|---|---|---|---|---|---|
| Ethylene carbonate (EC) | 36.4 | 152 | 1.321 | 89.78 | 1.85 |
| Propylene carbonate (PC) | -48.8 | 132 | 1.206 | 64.92 | 2.53 |
| Ethyl methyl carbonate (EMC) | -55 | 23 | 1.006 | 2.958 | 0.65 |
| Dimethyl carbonate (DMC) | 4.6 | 65 | 1.069 | 3.107 | 0.65 |
| Diethyl carbonate (DEC) | -74.3 | 25 | 0.975 | 2.805 | 0.75 |
| Ethyl acetate (EA) | -83.6 | -4 | 0.90 | 6 | 0.426 |
| Methyl butyrate (MB) | -84 | 53 | 0.898 | 5.5 | 0.6 |
| Ethyl butyrate (EB) | -93 | 19.4 | 0.886 | 5.2 | 0.71 |
| Fluoroethylene carbonate (FEC) | 18 | 120 | 1.454 | - | - |

There are two classes of carbonate esters: cyclic carbonic esters (such as propylene carbonate (PC) and ethylene carbonate (EC)) and chain carbonic esters (such as dimethyl carbonate (DMC), diethyl carbonate (DEC), and ethyl methyl carbonate (EMC)). Cyclic carbonic esters have the advantages of large polarity and high dielectric constant, and are often used as the primary solvent in an electrolyte. However, due to their drawbacks of high viscosity and strong intermolecular forces, the movement speed of lithium ions is somewhat slow when they are used as a single solvent, which ultimately leads to a decrease in the battery's rate characteristics and low-temperature characteristics [4]. On the other hand, although chain carbonic ester-based organic solvents have a low dielectric constant and a weak ability to dissolve lithium salts, they have low viscosity and excellent fluidity, which promote movement speed for lithium ions. However, their reduction product (alkyl carboxylic acid ester) during charging and discharging is not stable, which makes it impossible for them to form a highly stable SEI film on the electrode surface [9].

Ether-based organic solvents include chain ethers (such as 2,2-dimethoxypropane (DMP), dimethoxymethane (DMM), and ethylene glycol dimethyl ether (DME)) and cyclic ethers (such as tetrahydrofuran (THF) and 2-methyltetrahydrofuran (2-Me -THF)) [2]. For ether solvents, the longer the carbon chain, the better the chemical stability, but it also causes viscosity to rise and the transfer rate of lithium ions to fall. Ethylene glycol dimethyl ether (DME) reacts with lithium hexafluorophosphate (LiPF6) to form a relatively stable LiPF6-DME chelate complex, which has strong dissolving power for lithium salts and brings high conductivity to the electrolyte. However, because of its slightly inferior chemical stability, it is not possible for it to form a highly stable passive film on the surface of the anode material.

In terms of using a single solvent, organic solvents do not meet the high conductivity standards required for electrolytes. Therefore, in order to meet the needs for high-performance electrolytes, a method of mixing multiple solvents is typically adopted. This improves the overall performance of the electrolyte in terms of reducing the solvent's flammability and volatility, while also inhibiting solvent decomposition.

### 5.2.3 Electrolyte: Additives

Producing a noticeable effect with a small amount of additive is an economical and practical way to improve the performance of lithium-ion batteries. Adding small amounts of additives to a lithium-ion battery's electrolyte improves battery performance (including reversible capacity), electrode/electrolyte compatibility, cycle characteristics, rate characteristics, and safety. Additives play a very important role in lithium-ion batteries. The ideal additives for lithium-ion battery electrolytes have the following characteristics [10].

1. High solubility in organic solvents
2. Adding a small amount significantly improves one or more of the solvent's properties
3. Does not cause harmful side reactions with other components of the battery and does not affect its characteristics
4. Low cost and non-toxic or low toxicity [11]

Additives are classified by function into conductivity aids, overcharge inhibitors, flame retardants, film formation aids, cathode protectants, $LiPF_6$ stabilizers, and other functional additives [12].

#### (1) Conductivity aids

Conductivity aids have the effect of promoting dissolution and ionization of lithium salts and reducing the solvation radius of lithium ions by coordinating additive molecules with electrolyte ions [13]. Depending on how these ligand additives interact with electrolyte ions in the electrolyte, they can be classified as cationic, anionic, or neutral ligands [14].

Cationic ligands primarily enable preferential solvation of $Li^+$ and reduction of the $Li^+$ solvation radius. Cationic ligands include small amine, crown ether, and cryptand types. In general, their donor number is relatively large and exerts a strong chelating effect with lithium ions, which greatly improves the mobility of solvated lithium ions and significantly increases the conductivity of the electrolyte over a wide range [15].

Anionic ligands are compounds called anion receptors, which mainly form complexes with lithium salt anions, reduce $Li^+$/anion interactions, increase the number of Li+ transfers, reduce anion mobility and electrochemical activity, and control anion oxidation and reduction at the electrode interface. Neutral ligands are compounds formed by an electron-rich group bond and an electron-poor N or B atom, and include azaether and alkylboron compounds [16]. These enhance the conductivity of cations and anions in the electrolyte solution through their cooperative action with electrolyte ions, and as a result, significantly improve the electrical conductivity of the electrolyte solution.

#### (2) Film formation aids

During a lithium-ion battery's initial charging and discharging, the electrolyte undergoes an electrochemical reaction on the electrode surface, and the reaction products are deposited on the electrode surface to form a passive film. This film is called a "Solid Electrolyte Interphase," or "SEI film" [9, 17], and has the characteristics of a solid-state electrolyte, allowing lithium ions to be smoothly desorbed and blocking the passage of electrons. The chemical composition and structural stability of the SEI film are the keys to determining the stability of lithium-ion batteries. Optimizing the properties of SEI films is one of the important directions in the development of lithium-ion batteries, improving electrolyte/electrode compatibility and realizing an expanded variety of electrolyte types [17, 18].

Film formation aids are classified into the following types, depending on their functional mechanism: electrochemical reduction, chemical reaction, and SEI film modification. Electrochemical reduction additives have a higher reduction potential than the organic solvent in the electrolyte, and electrochemical reduction reactions occur preferentially on the electrode surface, thereby forming an SEI film with excellent properties. Electrochemical reduction additives include vinylene carbonate (VC), acrylic nitrile, $SO_2$, $CS_2$, and polysulfides ($S_x^{2-}$) [19]. On the other hand, chemical reaction additives bond through radical reactions with intermediates of organic solvent reduction products or chemical reactions with final products during charging and discharging, which produces a more stable SEI film.

## (3) Overcharge inhibitors

Overcharging is an important battery safety issue. When a lithium-ion battery is overcharged, the polarization of the battery continues to increase, causing irreversible changes in the cathode/anode active material. At the same time, the voltage on the cathode surface gradually increases, causing severe oxidative decomposition of the electrolyte, instantaneously generating a large amount of gas and heat. As a result, the pressure and temperature inside the battery rapidly rise, potentially causing the battery to burn or even to explode in the worst-case scenario [7]. A common solution to this problem is to control the external circuit or to add an overcharge inhibitor. Overcharge inhibitors are broadly divided into two types, depending on their functional mechanism: redox (oxidation-reduction) pairs and electrolytic polymerization.

1. Redox pair additives

Under normal charging conditions, redox pairs stably exist in the electrolyte without any chemical reactions. However, when the voltage reaches the cutoff voltage (a specified value), the redox pairs are oxidized/reduced at the cathode/anode and then diffuse to the counter electrode for further oxidation/reduction. By doing so, the battery's voltage is kept within the cutoff voltage range. Commonly used redox pairs are aromatic compounds, metallocene compounds, and polypyridine complexes.

2. Electrolytic polymerization additives

When a polymer monomer is added within the battery and the battery is then charged to a certain voltage, the monomer undergoes a polymerization reaction on the surface of the cathode, which forms a conductive polymer film. When this conductive polymer film makes fixed-point contact with the anode, it creates micro short circuits within the battery, which slowly returns the battery to a safe state. Additives prevalent in the Chinese market are mainly biphenyls, thiophenes, furans, and their derivatives.

## (4) Flame retardants

Alkyl carbonate-based organic compounds are often used as solvents for electrolytes in lithium-ion batteries, but they generally have low flash points and are highly combustible. Lithium-ion batteries are susceptible to accelerated radical chain reactions under conditions such as short-circuiting, overcharging and discharging, and long-term high current discharge, which can result in combustion or explosion [20]. Safety issues have already become an important issue for lithium-ion batteries in China, and more advanced and modern lithium-ion batteries are required, especially for electric automobiles.

By adding a flame retardant, the organic electrolyte changes from flammable to flame retardant or non-flammable, the battery's heat generation amount and self-heating rate are reduced, and the battery's thermal stability itself is improved. This avoids combustion and explosion of overheated batteries [21]. Flame retardants have two primary functional mechanisms. The first is creating a barrier layer between the gas phase and the agglomerated phase, and preventing combustion of the gas phase and the agglomerated phase. The second is to capture radicals during the combustion reaction, stopping the radical chain reaction and preventing combustion reactions between gas phases. Types of flame retardants include phosphorus, halogen, and composite flame retardants.

## 5.3 Progress in electrolyte research in China

### 5.3.1 Low-temperature electrolytes

Although lithium batteries have large capacity and outstanding cycle stability at room temperature, at low temperatures they have very large capacity loss and significantly lower discharge voltage [22]. This low-temperature characteristic inevitably and greatly limits their applications. In China, researchers have conducted numerous studies over the past few years to try and improve the low-temperature properties of lithium-ion batteries, and have made some progress.

For example, according to Li et al. [23], a quaternary electrolyte using a 1M $LiPF_6$ EC/PC/EMC/FEC system is being investigated.

According to the research results, for batteries using FEC-based electrolytes at -40℃, battery capacity is equivalent to 5% of room temperature capacity, and for half cells using MCMB/Li electrolytes at -40℃, the discharge capacity reached 91% of room temperature capacity. Incidentally, for conventional electrolytes ($LiPF_6$/EC+DMC (1:1, v/v)), the discharge capacity at -40℃ is close to zero. On the other hand, Liao et al. [24] showed that additives also improve the low-temperature properties of batteries. The main purpose of the additive is to change the solvent composition so that the electrolyte ensures better mobility and conductivity of lithium ions even at low temperatures.

In addition to changing the composition and ratio of solvents, there are other ways to improve the low-temperature properties of batteries. Lithium salts, which supply lithium ions to lithium-ion batteries, and their anions also cause changes in the physical and chemical properties of the electrolyte [25]. The lithium salt used in commercial electrolytes in China is $LiPF_6$, but at low temperatures the electrolyte's conductivity drops significantly, slowing the movement of ions. To resolve this problem, Zhang et al. [26] optimized battery performance by using a mixture of LiBOB and $LiBF_4$ lithium salts, using their respective strengths to compensate for deficiencies. As a result, for an electrolyte containing 0.9M LiBF4 + 0.1M LiBOB, the battery can discharge 30% of the discharge voltage at -50℃ compared to room temperature, but, as the LiBOB content increases, the discharge voltage drops significantly. In addition, when using lithium nickel oxide for the cathode and lithium sheet for the anode in an electrolyte containing 0.98M $LiBF_4$ + 0.02M LiBOB, at -30℃ discharge voltage was 85% of room temperature voltage and at -40℃ discharge voltage was 65% of room temperature voltage. From these results, it is clear that the low-temperature characteristics of batteries are improving.

### 5.3.2 High voltage electrolytes

The development of high-voltage electrolytes is an effective approach to improving the safety and energy density of lithium-ion batteries. The electrolyte used in China's current commercial lithium-ion batteries consists of an organic solvent in which LiPF6 electrolyte has been dissolved. Under normal voltages, the electrolyte reliably guarantees the transport of lithium ions between the electrodes. However, at operating voltages above 4.3V, commonly used organic carbonate-based electrolytes undergo severe oxidative decomposition, which increases the interfacial resistance between the electrode/electrolyte interface, resulting in a serious deterioration of battery performance [27].

In order to solve this problem, a series of studies on novel high voltage-resistant electrolytes are being conducted by numerous researchers. At present, there are two main technological approaches. The first is to replace some or all of the existing carbonate ester solvents [28] with new solvents that have high oxidation resistance (nitrile, sulfonic, and fluorinated solvents, room temperature ionic liquids, etc.). The other approach is to add a small amount of a high-voltage additive to the electrolyte to promote the action of passive film formation at the cathode interface.

### (1) Nitrile solvents

Nitrile solvents with high oxidation potential inhibit oxidative decomposition of the electrolyte by concentrating and reducing the contact between the electrolyte and the cathode on the cathode surface. However, because of their somewhat poor compatibility with low-potential anodes such as graphite and lithium metal, polymerization reactions are extremely likely to occur on the anode surface, and the products of these reactions prevent the desorption of $Li^+$.

According to Wang et al. [29], 3-methoxypropionitrile reduces the interfacial reaction between solvent/electrode and accelerates the desolvation of $Li^+$ ions, thereby improving the charge transfer process at the electrode/electrolyte interface. Additionally, adiponitrile (ADN) forms a highly stable and effective protective film on the surface of the cathode/anode, which is advantageous in maintaining capacity [30]. On the other hand, Li et al. [31] selected the LiDFOB-DEC/EC/AND system as the high-voltage electrolyte in order to meet the needs of cathode materials compatible with 5V high voltage, and analyzed the results of XPS and theoretical calculations. Their results showed that ADN can improve high-voltage characteristics by preventing the progress of decomposition of the electrolyte through surface modification of the cathode material, and by forming a passive film with excellent protection.

### (2) Sulfonic solvents

Sulfonic solvents with wide potential windows (>5.8V *vs.* $Li^+/Li$) can be used as additives in functional electrolytes. Most of them exist as solids at room temperature and must be mixed with other solvents to form electrolytes. Although sulfonic solvents have a rather low affinity with anodes, when used in combination with other additives, such as VC, they produce highly stable SEI films on graphite surfaces. By using additives, the compatibility between the sulfonic electrolyte and the graphite anode can be increased, thereby improving the battery's cycle characteristics.

According to Huang et al [32], the addition of tetramethylene sulfoxide (TMS) improved the solubility and ionic conductivity of lithium salts, as well as the compatibility of the ionic liquid (PP14-TFSI) with the electrode. As a result, the compatibility between the 0.5M LiDFOB/(60%) PP14-TFSI/(40%) TMS mixed electrolyte and $Li_{1.2}Ni_{0.2}Mn_{0.6}O_2$ cathode was improved and the battery's cycle characteristics were enhanced. However, sulfones have low stability against graphite anodes, as well as high viscosity, which has a negative effect on the low-temperature characteristics and high-rate characteristics of lithium batteries. As such, there is only limited use of sulfonic solvents.

### (3) Fluorinated solvents

Due to the high electronegativity and weak polarity of fluorine atoms, fluorinated solvents have excellent electrochemical stability. Currently, many fluorinated solvents are used as cosolvents or as additives in the liquid electrolytes of lithium-ion batteries. Traditionally, China's development of fluorinated solvents has focused on fluorinated carbonate esters, fluorinated carboxylic acid esters, and fluorinated ethers.

Zhang et al. [33] conducted a series of studies on fluorinated organic carbonate solvents and found that the introduction of fluorine into organic solvents significantly improved their oxidation potential and cycle characteristics. For example, the oxidation potential of fluoroethylene carbonate (FEC) and ethyl-2,2,2-trifluoroethyl carbonate (ETFEC) is much higher than that of non-fluorinated ethylene carbonate (EC) and diethyl carbonate (DEC) [34]. However, there is a disadvantage: as the number of hydrogen atoms replaced by fluorine atoms increases, there is a significant decrease of the solvent's solubility towards $LiPF_6$. In China FEC has already been commercialized and is being produced on a large scale. FEC has a high flash point, and, when added to an electrolyte as a co-solvent, it significantly reduces the flammability of the electrolyte, making it widely used in research on safer electrolytes.

## (4) Ionic liquids

Ionic liquids (RTILs), also called "room temperature molten salts," are typically composed of organic cations and organic/inorganic anions (anions) [35]. Cations in ionic liquids include pyrrole salt ions, quaternary ammonium salt ions, piperidine salt ions, and imidazolium salt ions, while anions in ionic liquids include halogens, $FSI^-$, $PF_6^-$, and $BF_4^-$. These cations and anions are relatively large in volume and weak in interaction, so they become liquid and can freely move at room temperature. Amongst ionic liquids, those composed of piperidine salt-based ions or pyrrole-based ions as cations have a wide potential window, are electrochemically stable, and are suitable as solvents for high-voltage electrolytes.

The advantages of ionic liquids are that they have excellent thermal stability, low volatility, flame retardancy, and a wide potential window [36]. On the other hand, their disadvantages are high viscosity and low conductivity. This will become a bottleneck for the future development of ionic liquids. Furthermore, they also have other issues, such as a high reduction potential (~1.5V *vs.* $Li^+/Li$) and low affinity with anodes, so they cannot be used with graphite anode materials, and they are also quite expensive, which makes them difficult to use in large-scale applications. Therefore, for mainstream lithium-ion batteries in China, ionic liquids alone are not used as solvents, but instead are generally used in combination with conventional organic carbonate ester solvents.

## (5) Additives

The main function of additives in high-voltage electrolytes is to form a protective film by oxidizing on the cathode surface in preference to carbonate ester solvents. This protective film reduces contact between the cathode surface and the solvent, thereby suppressing oxidative decomposition of the electrolyte and improving the battery's coulombic efficiency and cycling characteristics. Presently, commonly used additives are classified as boron-containing, sulfur-containing, fluorine-containing, or nitrogen-containing. According to Hu et al. [37], when LiDFOB was used as an additive, the $LiCoPO_4$ cathodes exhibited very good cycling properties. XPS and FTIR (ATR method) analysis results show that LiDFOB has a positive effect not only on the formation of interphase films, but also on the deactivation of the cathode surface, thereby suppressing electrolyte degradation to a certain extent.

On the other hand, Zhu et al. [38] announced Diethyl (thiophen-2-ylmethyl) phosphonate (DTYP) as a new additive for electrolytes. Their results showed that DTYP significantly improved the high voltage cycling stability of $LiNi_{0.5}Mn_{1.5}O_4$ cathodes, with a capacity retention of 85% (18% without the addition of DTYP) for lithium-ion batteries after 280 cycles at an ambient temperature of 60°C and a 1C rate. Similarly, Huang et al. [32] used 4-(trifluoromethyl)-benzylnitrile (4-TB) as a new additive, which remarkably improved the cycling properties of $LiNi_{0.5}Mn_{1.5}O_4$ cathodes. Furthermore, 4-TB is preferentially oxidized on $LiNi_{0.5}Mn_{1.5}O_4$ cathode surfaces to form a low-resistance protective film that prevents oxidative degradation of the electrolyte.

### 5.3.3 High concentration electrolytes

As lithium salt concentrations increase, cation-anion/solvent interactions intensify, and the content of free solvent molecules decreases. As shown in Figure 5-1, when the lithium salt concentration exceeds a threshold (typically >3-5 M, depending on salt/solvent type), free solvent molecules disappear and there is an increase in anions joining the solvation sheath around $Li^+$. This leads to the formation of a new electrolyte with a special three-dimensional solution structure, called a “high concentration electrolyte” [39, 40].

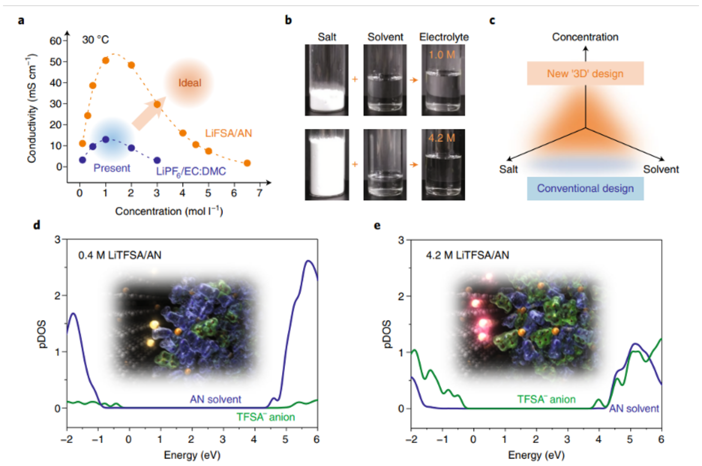


**Figure 5-1: General comparison of standard electrolytes and high concentration electrolytes:[74]**

(a) Correlation curve between concentration and ion conduction
(b) Electrolytes at different concentrations
(c) Three-dimensional electrolyte design of lithium salt, solvent, and concentration
(d) (e) Electronic structures in electrolytes at different concentrations [40]

Due to the strong solvent/lithium salt interactions, high concentration electrolytes have the following unique properties:

(1) Good thermodynamic stability and reversible insertion/desorption reactions of Li+ on graphite electrodes

(2) Enhanced reduction stability and reversible reactions with low-potential anodes [41], widened potential window for electrochemical stability, effective suppression of oxidative degradation of high-potential electrolytes, and improved battery safety

(3) Solutions that do not contain free solvents reduce corrosion and dissolution of electrodes, and increase the

[74] http://m.cbea.com/djy/201903/885296.html

oxidation stability of Al current collectors [42]

(4) SEI films are formed via anionic induction, primarily of inorganic components, ionophore (ion-permeable carriers) density is relatively high, increased number of lithium ion transfers, and uniform/high-speed transport of Li+ at the interface are enabled [43]. At the same time, growth of lithium dendrites is suppressed.

High concentration electrolytes will have huge advantages in next-generation high-performance lithium batteries (Figure 5-2). For example, Hu et al. [44] mixed acetamide and LiTFSI lithium salt at a molar ratio of 4:1 to produce room temperature molten salts with a minimum eutectic point of -67 ℃. The ionic conductivity at room temperature exceeded $10^{-3}$S/cm, and the potential window was 0.7 to 4.4V (*vs.* $Li^+$/Li), which were significant improvements to the low-temperature and high-voltage resistance of lithium batteries.

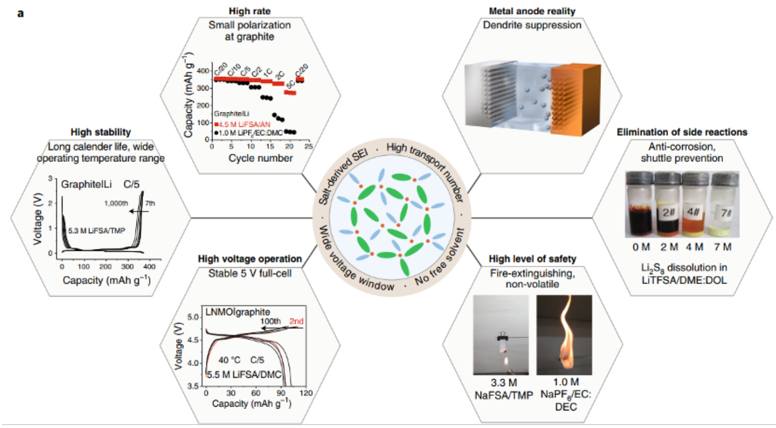


**Figure 5-2: Outstanding characteristics of high concentration electrolytes:**[75]

High rate characteristics [40], high stability [45], wide potential window [44, 46], highly safe [45, 47], reduced dendrites and side reactions [48]

However, high concentration electrolytes often face problems such as high viscosity, low permeability, low ionic conductivity, and high cost, which makes large-scale commercialization, popularization, and application extremely difficult. In response to this, in recent years, Zheng et al. [49] (a project team led by Ji-Guang Zhang) have proposed a new concept of localized high concentration electrolytes. This refers to the introduction of a low polarity diluent that does not dissolve lithium salt into a high concentration electrolyte so as to locally create a high concentration state. In doing so, it is possible to lower the solvent's viscosity and improve its infiltrability without changing the solvation structure [50]. With this method, it is possible to further reduce costs while also guaranteeing the properties of high concentration electrolytes. As such, localized high concentration electrolytes quickly gained widespread attention in the lithium battery research field. Perez Beltran [51] also achieved stability during high voltage operation of lithium metal batteries by using a localized high concentration electrolyte composed of LiFSI as a lithium salt, dimethyl carbonate (DMC) as a solvent, and 2,2,2-trifluoroethyl ether (BTFE) as a diluent. Zhang and Xu Wu, et al. [52] further

[75] http://m.cbea.com/djy/201903/885296.html

reported that LiFSI; ethylene glycol dimethyl ether (DME); and 1,1,2,2-tetrafluoroethyl-2,2,3,3-tetrafluoropropyl ether (TTE) was used to formulate/prepare a localized high concentration electrolyte (LHCE). The LHCE forms a highly protective cathode-electrolyte interface (CEI) that uniformly contains a large amount of LiF on the surface of an ultra-high nickel cathode made of $LiNi_{0.94}Co_{0.06}O_2$ (NC).

Chen et al. [53] designed an electrolyte with a localized high salt concentration state that guaranteed stable operation, which they did by using LiFSI as the lithium salt, low viscosity DMC as the solvent, and bis(2,2,2-trifluoroethyl) ether (BTFE) as the diluent. Jiang et al. [54] also presented a localized high concentration electrolyte composed of LiFSI, bis(2,2,2-trifluoroethyl) ether (BTFE), and ethylene glycol dimethyl ether (DME). Through preferential decomposition of anions, a uniform and strong SEI film is formed on the graphite surface, which greatly suppresses the co-insertion reaction of ether-based solvents and enables highly reversible and fast Li+ insertion and desorption. Accordingly, graphite/Li batteries have a promising future with high-speed charging potential (4C rate, 220mAh $g^{-1}$), outstanding cycle stability (85.5% initial capacity retention after approximately 200 cycles at 4C rate), and excellent low-temperature characteristics.

## 5.3.4 Solid-state electrolytes

Reliability and safety are of paramount importance in the development of next-generation lithium-ion battery systems. All-solid-state lithium-ion batteries with inorganic solid-state electrolytes are considered to be one of the ultimate goals for future electric vehicles and various energy storage systems [55]. All-solid-state lithium-ion batteries, in which the electrolyte and separator are replaced by a solid-state electrolyte, will dramatically improve safety and, at the same time, increase the energy density of the battery by being compatible with high-voltage cathode materials.

Lithium-ion solid-state electrolytes are mainly divided into organic polymer electrolytes and inorganic solid-state electrolytes (glass ceramic electrolytes). Polymer solid-state electrolytes [55-58] are lithium-ion solid-state electrolytes composed of organic polymers (PEO, PVDF, etc.) and lithium salts (LiTFSI, $LiClO_4$, $LiPF_6$), and due to the properties of the polymer, they have unique and good extensibility and flexibility. The most widely studied polymer electrolyte is polyethylene oxide (PEO), which forms coordination structures with various lithium salts (such as LiTFSI) and enables high-speed conduction of lithium ions. In addition, when a small amount of inorganic material ($SiO_2$, $Al_2O_3$, MgO, zeolite, montmorillonite, etc.) is introduced into a polymer solid-state electrolyte, its ionic conductivity at room temperature is increased ($10^{-4}$-$10^{-5}$ S/cm) through the hybrid structure formed by inorganic fillers and polymers. Moreover, the inorganic filler itself also increases the working voltage range and mechanical strength of the composite to a certain extent [59, 60].

On the other hand, inorganic solid-state electrolytes can be categorized into two types: crystalline and amorphous [61]. Crystalline solid-state electrolytes have three major crystal structures: NASICON, perovskite, and garnet. A glass state, which is a type of amorphous state, is formed when multiple types of substances that are melted at high temperatures and evenly mixed are then rapidly cooled beyond the crystallization temperature. The electrochemical properties change depending on the substance's composition, and, although it greatly varies depending on the electrochemical system, ionic conductivity at room temperature is generally lower than that of crystalline solid-state electrolytes. Types of glassy lithium ion electrolytes mainly include oxides, sulfides, and nitrogen oxides.

Solid-state electrolytes have the following advantages [57, 60-62].

#### (1) Highly safe

Current commercial organic electrolytes have the risk of leakage during use and polarization due to expansion. Therefore, for power batteries (driving batteries) that have relatively large capacity and volume, the electrolyte can pose serious safety problems. On the other hand, all-solid-state batteries that do not use an electrolyte are significantly safer.

#### (2) High energy density

Solid-state electrolytes' relatively wide operation voltage range (up to 6V) is well matched with the high-voltage cathode materials of batteries, which increases energy density. When compared to liquid batteries, all-solid-state batteries also have fewer protection systems against electrolyte decomposition, so the battery structure is simpler and easier to assemble. Simple superposition enables large currents and high voltages, thereby improving mass and volumetric energy density.

#### (3) Long service life

The presence or absence of electrolyte side reactions is an important factor in determining cycle life. Solid electrolytes do not have side reactions such as oxidative decomposition of the electrolyte.

#### (4) Wide operating temperature range

Inorganic solid-state electrolytes can withstand high temperatures of over 300℃. The high-temperature characteristics of large-capacity all-solid-state lithium-ion batteries are comparatively excellent, and there is room for improvement in low-temperature characteristics if interface problems are resolved.

#### (5) Flexible and wearable

Creating foldable polymer electrolytes and flexible sulfides is relatively simple and safe. As such, depending on product needs, all-solid-state batteries can be used to manufacture thin-film batteries and flexible batteries of various shapes. They can also provide power for specialized needs, such as implantable medical devices and smart wearables.

#### (6) Recovery convenience

Dry pulverization can be used to directly process and recover solid-state electrolyte from all-solid-state lithium-ion batteries, which is significantly easier than processing the electrolyte via separation methods.

## 5.4 Development of and prospects for the electrolyte industry in China

### 5.4.1 Current market situation

According to statistics from the China Research Institute of Economy, Trade and Industry,[76] electrolytes generally

76 https://www.huaon.com/about/index.html

account for approx. 7-12% of battery costs. Formulation/preparation of electrolytes can be broadly split into three steps: solvent synthesis, material mixing, and post-treatment. Of these, the technological barrier is in the composition at the material mixing stage, with the electrolyte composition differing slightly for each type of battery. Electrolyte formulations are essentially led by the downstream lithium battery companies, but, for electrolytes in some segmented high-end consumer products and in nickel power products, lithium battery companies and electrolyte companies usually conduct joint research and development.

Prior to 2010, $LiPF_6$ production capacity was mainly concentrated in Japanese companies such as Stella Chemifa, Kanto Denka Kogyo, and Morita Chemical Industries and in Korean companies such as Hyosung Chemical. As of 2011, Chinese companies accounted for less than 15% of $LiPF_6$ production capacity, but since 2011 companies such as Tinci Materials, Capchem, and Goutai-Huarong made successive technological breakthroughs and began to significantly expand production. In 2020, Chinese companies' market share had increased to more than 80%.

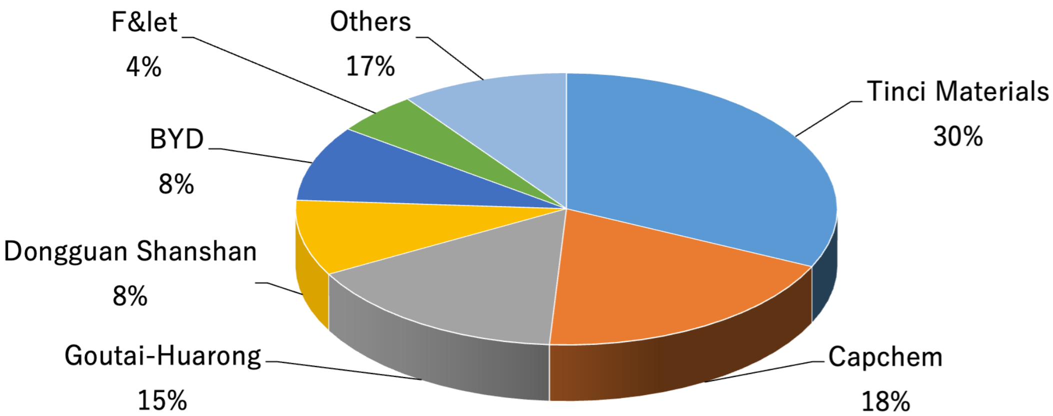


**Figure 5-3: Electrolyte market share in China (2020)**

Source: Created based on "2021 China Electrolyte Industry Market Competition Situation Analysis" by the Qianzhan Industry Research Institute[77]

According to research statistics from Gaogong Industry Institute (GGII),[78] the shipment volume for China's electrolyte market in 2020 was 250,000 tons, an increase of 38% from the previous year. Additionally, according to forecasts by Sealand Securities, the global demand for lithium batteries will reach approx. 1,200 GWh by 2025, and the corresponding demand for electrolytes will reach approx. 1.32 million tons, with a compound annual growth rate (CAGR) during this period of 35%. As such, there is still significant room for development in the electrolyte market.

## 5.4.2 Distribution of companies in the lithium battery electrolyte field, and ownership of intellectual property rights

The distribution of intellectual patent rights ownership provides some insight into the research status and

77 https://www.qianzhan.com/analyst/detail/220/210520-90603b27.html

78 https://www.gg-lb.com/research.html

technological level of companies in the lithium battery electrolyte field. This reflects the positioning of competitors in the technological field, the level of scientific research, and technological expertise.

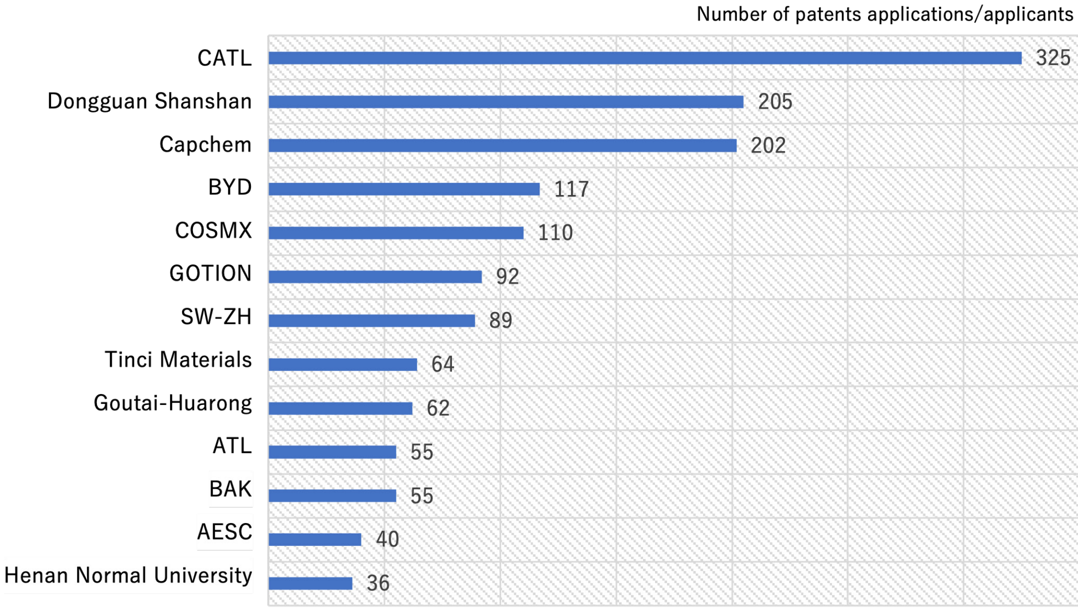


**Figure 5-4: Main patent applicants for patents related to electrolytes for lithium batteries**

Source: Patsnap[79]

Looking at a ranking of patent applicants (patent holders) based on statistics from the number of patent applications (Figure 5-4), the companies that have accumulated the most innovation results in the field of electrolytes for lithium batteries are CATL, Dongguan Shanshan, Capchem, BYD, COSMX, GOTION, SW-ZH, Tinci Materials, and Goutai-Huarong. On the other hand, the research and development capabilities of research institutions affiliated with Chinese universities, such as South China Normal University, are relatively weak. This shows that China's theoretical research on lithium battery electrolytes has already reached a sufficient level, and that actual applied research is being led by companies.

### 5.4.3 Future development trends

Future directions for the development of lithium battery electrolytes include the development of electrolytes that are compatible with high-voltage cathodes; compatibility with silicon/carbon-based high-capacity anodes; and the problem of avoiding excessive electrolyte consumption due to repeated rupture and regeneration of SEI films as caused by the volumetric expansion of silicon anodes during the cycling process. Additives that significantly affect the electrolyte's infiltrability, flame retardance, and film-formation properties, etc. are the core value in electrolytes and will be the key to developing high-performance electrolytes.

The development path and goals for electrolyte material technology are as follows:

79 https://analytics.zhihuiya.com/

(1) 2025: Use of fluorinated solvents and small amounts of ionic liquids. Substitution of single $LiPF_6$ to composite lithium salts. Exploring multifunctional additives. Development of a new electrolyte with high voltage (>5V), high conductivity ($\geq 10^{-2}$ S/m), low flammability, and high safety.

(2) 2030: Simultaneous research and development of high-performance organic liquid electrolytes, all-solid-state inorganic solid-state electrolytes, and solid-state polymer electrolytes. Focus on developing solid-state electrolyte materials with high voltage (>6V), high conductivity ($\geq 10^{-2}$ S/m), long life, and no potential safety issues.

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# 6 Research and development trends in China for next-generation all-solid-state lithium battery technology

## Introduction

All-solid-state lithium batteries are becoming the mainstream direction for the development of next-generation battery technology due to their high safety and energy density advantages, and scientific research institutions and companies around the world are conducting intensive research, development, industrialization of them. According to the "China Solid State Battery Industry Market Outlook and Investment Strategy Plan Analysis Report,"[80] there are currently more than 50 companies worldwide engaged in research and development of all-solid-state lithium batteries. Among them, major global companies such as Japan's Toyota Motor Corporation and South Korea's Samsung Electronics are actively conducting research and development on solid-state electrolytes and on all-solid-state lithium batteries. In China, research has been conducted since 1978 under the guidance of Chen Liquan, an academician at the Chinese Academy of Engineering, and after more than 40 years of unremitting efforts, a solid foundation has been established for the dramatic development of China's solid-state lithium battery field. has been built up.

As a powerhouse in terms of both automobiles and energy, China is now promoting the development of all-solid-state lithium battery technology via the dual driving forces of 1) its "double carbon" strategy (that is, peak carbon emissions and becoming carbon neutral), and 2) a belief in aiming to shift from an "automotive powerhouse" into an "automotive great power." In the 13th Five-Year Plan there is enormous support for basic science research and key technology development related to all-solid-state lithium batteries via special projects such for new energy vehicles, smart grid technology and equipment, nanotechnology, and key technology/support platforms for material genomic engineering. Additionally, the 14th Five-Year Plan continues support for the development of all-solid-state lithium batteries via special priority projects such as energy storage/smart grid technologies.

The "New Energy Automobile Industry Development Plan (2021-2035)"[81] that was established by the Ministry of Industry and Information Technology clearly calls for "accelerating research, development, and industrialization of solid-state power battery technology." With all-solid-state lithium batteries as a "challenging core technology project for new energy vehicles," China is aiming to reach an internationally advanced level in the all-solid-state lithium battery technology field. The plan also sets a goal to transition China's liquid electrolytes to solid-state electrolytes by 2030, raising the issue of solid-state battery development to the national level for the first time. As a result, provinces and cities such as Beijing, Tianjin, Anhui, and Shandong have clarified the goal of focusing on the development of solid-state batteries, and advanced solid-state battery technology has is increasingly being moved from the research and development stage to the industrialization stage.

80 https://bg.qianzhan.com/report/keys/9b4cb24b.html

81 http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm

Based on published papers, patents, and company reports, this chapter focuses on progress in basic scientific research by Chinese scientific research institutes and universities, as well as development trends of companies in the field of all-solid-state lithium batteries. As for the various problems that are serving as a bottleneck for all-solid-state lithium batteries, with a focus on the various types of solid-state electrolytes and their potential commercialization value, this chapter also summarizes the progress of research and development by scientific research teams in China and analyzes the development plans of relevant companies in China's solid-state battery industry.

This chapter will provide a useful reference for the next phase of China's development plans for all-solid-state lithium batteries, and for the rest of the world to review the development process of China's all-solid-state lithium batteries sector.

## 6.1 Research trends in basic materials for sulfide-based solid-state electrolytes

### 6.1.1 Institute of Physics, Chinese Academy of Sciences

For sulfide-based solid-state electrolytes, the Institute of Physics has developed an advanced one-step gas-phase synthesis method suitable for large-scale formulation/preparation in atmospheric conditions, and has applied the method to a formulation/preparation of sulfide-based solid-state electrolytes ($Li_{4-x}Sn_{1-x}M_xS_4$) which are stable in the atmosphere. The Institute of Physics also demonstrated that the super hydrophobicity of fluorinated polysiloxane promotes lithium-ion conduction and improves the atmospheric stability of sulfide-based $Li_6PS_5Cl$ solid-state electrolytes [1, 2].

In terms of industrialization, lot formulation/preparation of silver sulfide germanium ore sulfide solid-state electrolytes on a kilogram scale has already been conducted. Formulation/preparation technologies have been established for large-area sulfide-based solid-state electrolyte membranes utilizing wet coatings; prototype production of single-layer and multi-layer laminated sheet-type sulfide-based all-solid-state laminate batteries (pouch cells) has been completed, and small-volume production lines for sulfide-based all-solid-state batteries are currently being built.

### 6.1.2 Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences

Qingdao Institute of Bioenergy and Bioprocess Technology has conducted research on sulfide-based solid-state lithium battery deterioration mechanisms and performance improvements. Utilizing in-situ scanning transmission electron microscopy (in-situ STEM) and differential phase contrast (DPC) imaging, they achieved in-situ visualization of charge distribution and changes at the $LiCoO_2|Li_6PS_5Cl$ interface. By forming a discontinuous ferroelectric modification layer, the institute solved the space charge layer problem that occurs at the interface, improved the dynamics of interfacial lithium-ion movement, and improved the rate characteristics of $LiCoO_2$|In-Li all-solid-state lithium batteries [3]. By forming a lithium zirconium phosphate $Li_xZr_2(PO_4)_3$ modification layer with high electrochemical affinity and low lithium ion migration barrier on the $LiCoO_2$ surface, the initial capacity of 4.5V $LiCoO_2$|In-Li all-solid-state lithium batteries was 143.3mAh $g^{-1}$ and the capacity retention rate after 100 cycles was 95.5% [4]. By combining various characterization techniques (such as synchrotron emission X-ray tomography

(SRX-rayμCT); time-of-flight secondary ion mass spectrometry (TOF-SIMS); and finite element analysis (FEA) modeling methods), the institute clarified the fusion mechanism for electrical, chemical, and mechanical energy in $Li_{10}SnP_2S_{12}$all-solid-state lithium batteries [5].

Currently, there are already formulation/preparation capabilities for kilogram-scale sulfide electrolytes and formulation/preparation capabilities for the mass production of sulfide/polymer composite electrolytes, with work being done on prototypes for the practical use of all-solid-state batteries with a sulfide-based composite electrolyte.

### 6.1.3 Ningbo Institute of Materials Technology & Engineering, Chinese Academy of Sciences

The Ningbo Institute of Materials Technology & Engineering has utilized dense $Li_6PS_5Cl$ thin film sheets prepared via pressurized high temperature sintering to achieve room temperature ionic conductivity of 6.11 mS $cm^{-1}$ and critical current density of 1.05 mA $cm^{-2}$ [6]. With lithium dilute and chlorine-rich sulfide-based solid-state electrolyte $Li_{6-x}PS_{5-x}Cl_{1+x}$ ($0 \leq x \leq 0.8$) (which were formulated/prepared via wet polishing and pressurized high temperature sintering using anhydrous acetonitrile), they achieved room temperature ionic conductivity of 6.18 mS $cm^{-1}$ [7]. The institute has also developed a low-temperature phase $Li_7P_2S_8I$ with excellent stability to metallic lithium and a room temperature ionic conductivity of 1.57 mS $cm^{-1}$ [8].

For forming large-area films of sulfide-based solid-state electrolytes, the institute increased the sophistication of film-forming technologies such as via direct pressure forming using cooling rolls and via ball milling/heating roll pressure forming, which resulted in film thicknesses of 35 μm and 30 μm, respectively, and room temperature ionic conductivities of 0.2 mS $cm^{-1}$ and 8.4 mS $cm^{-1}$ [9, 10].

### 6.1.4 Tsinghua University

Ce-Wen Nan's team formulated/prepared a free-standing sulfide-based solid-state electrolyte membrane with a film thickness of 120 μm via a liquid phase method (using toluene or ethyl acetate as a solvent) and then separately added lithium salt LiTFSI. In doing so, they found that the ionic conductivity of sulfide-based solid-state electrolyte membranes increases [11]. The team has conducted research on the influence $75Li_2S$ $25P_2S_5$ crystallinity on the performance of all-solid-state lithium batteries [12]; developed all-solid-state lithium batteries with $Li_6PS_5Cl_{0.5}Br_{0.5}$/ multi-walled carbon nanotubes as a composite cathode (amorphous active material formed in-situ), $Li_6PS_5Cl_{0.5}Br_{0.5}$ as a solid-state electrolyte, and InLi as an anode; and achieved a capacity retention rate of 94% and a capacity of 1.24 mwah $cm^{-2}$ after 1,000 cycles at room temperature [13].

Xing Zhang's team used a wet method to formulate/prepare a free-standing solid-state electrolyte composite membrane with a thickness of 65 μm, and studied dendrite growth conditions of Li-In anodes under high current density (3.8 mA $cm^{-2}$) and high load (4 mAh $cm^{-2}$) conditions.

Qiang Zhang's team injected $Li_6PS_5Cl$ into a cellulose film and formulated/prepared a free-standing solid-state electrolyte membrane with a thickness of 60μm, which let them achieve room temperature conductivity of 6.3 mS $cm^{-1}$. The team also studied electrochemical redox mechanisms at the interface of $Li_7P_3S_{11}$ solid-state electrolytes under rapid charging [16, 17].

### 6.1.5 Other scientific research institutions

#### (1) Beijing Institute of Technology

Controlled crystallinity of $Li_7P_3S_{11}$ via dopants, which resulted in highly crystalline $Li_7P_{2.9}Ce_{0.2}S_{10.9}Cl_{0.3}$ (3.2 mS $cm^{-1}$) and atmospherically stable $Li_{6.95}Zr_{0.05}P_{2.9}S_{10.8}O_{0.1}I_{0.4}$ (3.2 mS $cm^{-1}$), and applied it to an all-solid-state lithium-sulfur battery using $Li_2S$ cathode [18, 19].

#### (2) Yanshan University

In-situ electron microscopy (EM) revealed that the chemical and mechanical degradation of $Li_{10}GeP_2S_{12}$ solid-state electrolytes is closely related to the size of the solid-state electrolyte particles, with cracking and powdering of the particles occurring at subcritical sizes and causing degradation [20].

#### (3) Xiamen University

Compared the electrochemical and mechanical coupling effects of single-crystalline and polycrystalline high nickel-based cathodes on the complete microstructure of high nickel-based cathodes in solid-state batteries, with the results showing that single crystals have superior mechanical stability [21].

#### (4) Institute of Chemistry, Chinese Academy of Sciences

Used in-situ electrochemical atomic force microscopy (EC-AFM) to reveal the dynamic lithium insertion/withdrawal processes of Li, Li-In, and In anodes in $Li_{10}GeP_2S_{12}$ all-solid-state lithium batteries and the changes in SEI films, respectively. Showed that SEI films, which form uniform and flexible wrinkle structures on Li-In secondary alloys and In electrodes, are effective in protecting anodes and controlling the degree of Li adaptation [22].

## 6.2 Research trends in basic materials for oxide-based solid-state electrolytes

### 6.2.1 Institute of Physics, Chinese Academy of Sciences

Utilized an adiabatic accelerated rate calorimeter to investigate thermal affinity between various oxide solid-state electrolytes and metallic lithium, finding that thermal stability increases in the following order: $Li_{1.5}Al_{0.5}Ge_{1.5}(PO_4)_3$ < $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ < $Li_{3x}La_{2/3-x}TiO_3$ < $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$. The thermal runaway mechanism was clarified as follows: after the oxide solid-state electrolyte comes into contact with metallic lithium, heat is generated by a chemical reaction that occurs at the interface at high temperature, which decomposes the oxide solid-state electrolyte to generate oxygen, and then undergoes a violent reaction with metallic lithium, causing further heat generation [23]. Utilizing an in-situ tabletop scanning electron microscope (SEM), made the first successful observations of the microscopic processes of the microscopic processes of lithium dendrite growth and electrolyte crack propagation in a Li|$Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$|Ti all-solid-state battery system. Also conducted a quantitative study of the deposition behavior of metallic lithium in a three-dimensional structured electrode by using in-situ neutron depth profiling (NDP) [24].

### 6.2.2 Qingdao University

In terms of basic research, by forming a lithium polyacrylate layer between metallic lithium and a lithium lanthanum zirconium oxide electrolyte, through which electronic insulating ions conduct, it suppressed the growth of lithium dendrites in the solid-state electrolyte and enabled 400 stable charge/discharge cycles at room temperature and at a current density of 1 mA $cm^{-2}$ (area capacity of 1 mAh $cm^{-2}$) [25]. Between metallic lithium and $Li_7La_3Zr_2O_{12}$, the growth of lithium dendrites was suppressed by forming a $Li_{56}La_{24}Zr_{15}TiO_{96}$ or $Li_3N$-Cu layer that conducts ions and electrons and by controlling localized overvoltage [26, 27]. Coating $Li_7La_3Zr_2O_{12}$ with dopamine improved atmospheric stability and solved the problem of $Li_7La_3Zr_2O_{12}$ powder's tendency to agglomerate [28].

In terms of industrial development, Qingdao University has enabled the formulation/preparation of oxide solid-state electrolyte powders suitable for various scales (µm to nm), and has conducted mass formulation/preparation of a cubic garnet-type electrolyte with a room temperature ionic conductivity of 1 mS $cm^{-1}$ or more. The university has also installed a processing line for highly densified oxide ceramic solid-state electrolytes, which lets them process large quantities of oxide ceramic solid-state electrolytes of various types/standards according to customer needs, such as garnet-type electrolytes, NASICON-type electrolytes, perovskite-type electrolytes, and sodium-ion conductors.

### 6.2.3 Shanghai Institute of Ceramics, Chinese Academy of Sciences

The LiF-LiCl modification layer for $Li_7La_3Zr_2O_{12}$ has a ternary cross-linked structure with both lithium affinity and electronic insulation properties. By doping it with Ta, lithium metal and solid-state electrolyte wetting is promoted via capillary attraction, and $Li_7La_3Zr_2O_{12}$ builds a uniform and solid interface. Utilizing the property of Ga to spontaneously form $Ga_2O_3$ in an atmospheric environment, when the surface of the garnet-type oxide solid-state electrolyte $Li_{6.5}La_3Zr_{1.5}Ta_{0.5}O_{12}$ is coated with liquid metal Ga, a uniform lithium affinity layer is formed on the surface. The contact resistivity to the lithium interface was reduced to 5Ω $cm^2$, and stable cycle characteristics were demonstrated for more than 9,930 hours under conditions of a current density of 0.2mA $cm^{-2}$ and an ultra-low polarization voltage value (±10mV) [30]. The institute also discovered that a lithium-sodium eutectic alloy buffer layer improves the infiltration of metallic lithium with Ta-doped $Li_7La_3Zr_2O_{12}$ solid-state electrolyte, and successfully constructed Li-Na|Ta-$Li_7La_3Zr_2O_{12}$|$FeF_3$ all-solid-state lithium batteries with excellent cycle stability [31].

On the other hand, the institute developed a film-forming technology for ceramic solid-state electrolyte membranes that allows continuous formulation/preparation based on the casting method. The film's thickness was adjustable in the range of 20–200 µm, had a density of 98.0–99.9%, and an ionic conductivity of greater than 1 mS $cm^{-1}$.

### 6.2.4 Institute of Chemistry, Chinese Academy of Sciences

In a medium temperature environment (<180 ℃), $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ solid-state electrolyte was reacted with $NH_4F$, and LiOH and $Li_2CO_3$ on the surface reacted with NH4F to generate LiF. In doing so, this improved atmospheric stability and suppressed the growth of lithium dendrites [32]. An-Min Cao's project team reduced the impedance at the interface with Li by forming an $Al_2O_3$ nano-thin film on the surface of $Li_{6.5}La_3Zr_{1.5}Ta_{0.5}O_{12}$. The $LiNi_{0.83}Co_{0.07}Mn_{0.1}O_2$|Li all-solid-state battery using this solid-state electrolyte has a reversible specific capacity of 201.5mAh $g^{-1}$ under a load of 4.8 mg $cm^{-2}$, and a capacity retention rate of 90.2% after 100 cycles [33].

The surface of $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ solid-state electrolyte particles is uniformly coated with a polyacrylonitrile layer to produce powder containing an ultra-solid electrolyte (94.3wt.%), and ultra-thin (film thickness formulation/ preparation of solid-state electrolyte membranes (<10 μm) [34].

# 6.3 Research trends in basic materials for halide solid-state electrolytes

## 6.3.1 China Automotive Battery Research Institute (Glabat)

The room temperature ionic conductivity of high-purity rare earth halide solid-state electrolytes $Li_3YCl_6$, $Li_3YBr_6$, $Li_3ErCl_6$, and $Li_3ScCl_6$ synthesized via a wet chemical method reached 1 mS $cm^{-1}$.

Additionally, the room temperature ionic conductivity of the synthesized halide-based solid-state electrolyte $Li_{2.556}Yb_{0.492}Zr_{0.492}Cl_6$ reached 1.58 mS $cm^{-1}$, and, by utilizing this, 4.3V $LiNi_{0.83}Co_{0.12}Mn_{0.05}O_2$|Li all-solid-state lithium batteries at a 0.1C rate had an initial specific capacity of 209.8mAh $g^{-1}$, a coulombic efficiency at the first cycle of 91.5%, and a capacity retention rate after 100 cycles at a 0.3C rate of 78% [35]. In solving the bottleneck of high reaction activity that occurs between halide-based solid-state electrolytes and metallic lithium, the institute synthesized $Li_3YBr_{5.7}F_{0.3}$, a fluorohalide-based solid-state electrolyte with high ionic conductivity (1.8 mS $cm^{-1}$) that can be used in direct contact with lithium anodes [36].

## 6.3.2 University of Science and Technology of China

In designing and synthesizing $Li_2ZrCl_6$, a new low-cost and stable chloride-based solid-state electrolyte, no changes in ionic conductivity or crystal structure were observed in an atmosphere with a maximum relative humidity of 5%. Compared to chloride- and sulfide-based solid-state electrolytes, which are sensitive to moisture, $Li_2ZrCl_6$ is expected to enable much easier mass formulation/preparation. The specific capacity of all-solid-state lithium batteries consisting of $Li_2ZrCl_6$ solid-state electrolyte, single-crystal $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ cathode, and Li-In anode was 150 mAh after 200 cycles at a high current density of 200 mA $g^{-1}$, and showed almost no attenuation [37].

## 6.3.3 Shanghai Institute of Ceramics, Chinese Academy of Sciences

The institute succeeded in the formulation/preparation of $Li_3GaF_6$ and $Li_3AlF_6$ nanocomposite-structured lithium-rich fluoride solid-state electrolytes by utilizing a synthetic method with low energy loss using fluorination of low-temperature ionic liquids. Their characteristics included highly open ion channels within the structure and that their grain boundaries are modified via an ionic liquid. The optimized $Li_3GaF_6$ achieved the highest ionic conductivity record in a fluorine-based solid-state electrolyte (nearly reaching $10^{-4}$ S $cm^{-1}$ at room temperature), and a Li|$LiFePO_4$ solid-state battery built on this basis has successfully operated at a high rate of 1C for more than 150 cycles [38].

## 6.4 Research trends in basic materials for organic-inorganic composite solid-state electrolytes

### 6.4.1 Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences

In terms of basic research, polyethylene glycol methyl ether monomers were injected into a self-supporting three-dimensional porous inorganic solid-state electrolyte structure ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ and $Li_6PS_5Cl$) and then solidified via in-situ solidification technology, which enabled the design of a composite solid electrolyte with a three-phase seepage flow structure with integrated solid/solid interfaces. Through a combination method of solid nuclear magnetism and a $^6Li$ isotope tracer, the institute investigated the transport behavior of $Li^+$ in this three-phase osmotic flow composite electrolyte and clarified the tri-phase co-transport mechanism of Li+ in the interfacial phase/organic phase/inorganic phase. The outstanding affinity between the two types of three-phase permeate composite solid electrolytes and the electrode interface enabled room-temperature operation of $LiCoO_2$|Li and $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$|Li all-solid-state batteries under high voltage [39, 40].

The institute achieved a series of advances in the field of interfacial fusion technology through in-situ solidification of high-safety, high-specific-energy polymer solid-state lithium batteries, and have also succeeded in industrializing solid-state batteries. Energy density has reached a maximum of 350Wh $kg^{-1}$, and a 1000km driving test was conducted with a new energy vehicle. Currently, lithium metal anodes are being used to optimize solid-state batteries with a single cell energy density of 520Wh $kg^{-1}$.

### 6.4.2 Institute of Physics, Chinese Academy of Sciences

The institute investigated the mechanism of interfacial degradation that occurs between LiTFSI-PEO polymer solid-state electrolyte and $LiCoO_2$. PEO begins to oxidatively degrade at 3.9 V, and the lattice oxygen ions of $LiCoO_2$ oxidize PEO at 4.2 V, which accelerates the degradation. However, it was found that coating $LiCoO_2$ with $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ could suppress the PEO decomposition under high voltage [41, 42].

The institute also developed an ultra-thin composite solid electrolyte membrane that is easy to mass formulate/ preparate. When a polyethylene separator coated with $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ is used as a substrate and a PEO/LiTFSI solution is filled into the voids of the separator of the substrate, a continuous lithium ion transport channel is formed after drying. The capacity of the assembled $LiFePO_4$|Li all-solid-state battery reached 60mAh $g^{-1}$ even after 200 cycles under the conditions of 60℃ environment and at a 0.2C rate [43].

### 6.4.3 Qingdao University

Qingdao University designed a two-layer organic/inorganic composite solid-state electrolyte membrane. The first layer is polyacrylonitrile (PAN)-$Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ film, which corresponds to $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$, and the second layer consists of a PEO-$Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ film that matches metallic lithium [44]. A laminated organic/inorganic composite solid-state electrolyte membrane was formed by using a layer/layer coating method on a cathode support layer. The specific method is to first apply a layer of composite solid electrolyte (10% $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ content in

PAN) to the cathode, and then to further reapply the composite solid-state electrolyte (40% $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ content in PEO). The assembled $LiFePO_4$|Li (high load 15.2 mg $cm^{-2}$) all-solid-state battery achieved an initial capacity of 129 mAh $g^{-1}$ at 0.1 C rate and a capacity retention rate of 80.6% after 150 cycles at room temperature [45].

Meanwhile, in situ polymerization of ethoxylated trimethylolpropane triacrylate was applied to large-area $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ solid electrolyte sheets to construct flexible solid-state lithium batteries with high-performance interfaces [46].

### 6.4.4 Tsinghua Shenzhen International Graduate School (Tsinghua SIGS)

Tsinghua SIGS achieved room temperature ionic conductivity of $3.1\times10^{-4}$S $cm^{-1}$ by formulating/preparing a new polymer solid electrolyte from polyvinylidene fluoride-co-trifluoroethylene-co-chlorotrifluoroethylene and LiTFSI, which are ultra-high dielectric constant and relaxed ferroelectric polymer materials. The assembled $LiFePO_4$|Li and $LiNi_{0.8}Co_{0.1}Mo_{0.1}O_2$|Li solid-state batteries have stable cycling characteristics under a room temperature environment [47]. Recently, $La_2Zr_2O_7$ nanowires and PEO were used to form an efficient and variable lithium-ion transport channel that combines “solid/polymer/solid” in a cathode. Although its ionic conductivity is as low as $4.56\times10^{-6}$S $cm^{-1}$, the assembled $LiFePO_4$|Li all-solid-state battery had a stable charge-discharge for 1,400 cycles at room temperature, while the $LiNi_{0.8}Co_{0.1}Mo_{0.1}O_2$|Li all-solid-state battery using PVDF reached 2,880 cycles [48].

### 6.4.5 University of Science and Technology Beijing (USTB)

Using a composite solid electrolyte membrane formulated/prepared via a solvent-free method, polytetrafluoroethylene and $Li_{6.75}La_3Zr_{1.75}Ta_{0.25}O_{12}$ were directly pressure-formed into a three-dimensional structure membrane (with nylon mesh as a base material) using a roll press, and then filled with a succinonitrile-LiTFSI eutectic mixture. The room temperature ionic conductivity of the flame-retardant composite solid electrolyte as formulated/prepared is $1.2\times10^{-4}$S $cm^{-1}$, which is applicable to $LiFePO_4$|Li and $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$|Li all-solid-state batteries [49]. A novel and simple synthesis scheme for $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ porous ion transport structures was successfully developed by using ordinary and inexpensive NaCl powder as a sacrificial template. PEO-LiTFSI is injected into this to formulate/preparate the composite solid-state electrolyte [50].

### 6.4.6 Other research institutions

#### (1) Institute of Process Engineering, Chinese Academy of Sciences

Using the commercially available silane coupling agent (3-chloropropyl) trimethoxysilane as a “bridge,” after chemically bonding $Li_{10}GeP_2S_{12}$ and polyethylene glycol to form a high-speed transport channel for lithium ions, PEO and LiTFSI are added to formulate/prepare a composite solid-state electrolyte. The room temperature ionic conductivity of this composite solid-state electrolyte was recorded as 9.83 × 10−4 S cm−1, which is 10 times higher than that of conventional PEO [51].

#### (2) Ningbo Institute of Materials Technology & Engineering, Chinese Academy of Sciences

The institute presented a solid polymer electrolyte with ultra-thin thickness (10 μm), high tensile strength (103 MPa), and good compatibility with interfaces, and then applied it to flexible all-solid-state lithium metal batteries. Of these, a 7 μm polyethylene separator was selected as a support, and a porous polymethyl methacrylate/polystyrene interface layer was adhered to both sides of the separator via a reverse phase method. Using solvent-free polyethylene glycol methyl ether acrylate and LiTFSI as fillers, they were filled inside a modified polyethylene separator using an in-situ thermal curing method to form a fast and continuous lithium ion transport channel [52].

# 6.5 Development of start-up companies in the solid-state battery industry

## 6.5.1 ProLogium Technology

ProLogium Technology (PLG), a relatively fast-growing company in the solid-state battery field, has already successfully manufactured a solid-state battery prototype. The anode is completely made of lithium metal, has a mass energy density of 383Wh $kg^{-1}$, a volumetric energy density of 1,025Wh $L^{-1}$, and 500 charge/discharge cycles.

In July 2020, the company established its China headquarters in Hangzhou and invested in a project to build an overseas manufacturing facility, which included a project to industrialize solid-state lithium ceramic battery cells. To ensure the successful implementation of the project, the company completed a D-round financing of approximately $100 million in April 2021. So far, the company has received continuous investment from SoftBank China Venture Capital (SBCVC) and dGav Capital.

Additionally, in 2019, in Taoyuan City, Taiwan, the company signed a strategic partnership agreement with Shanghai automobile company NIO. The two companies have jointly manufactured a prototype vehicle equipped with a PLG MAB solid-state battery pack, but the specific structure of this solid-state battery has not been made public.

## 6.5.2 Beijing WELION New Energy Technology

Beijing WELION New Energy Technology (WELION New Energy), a high-tech company led by the team of Chen Liquan (an academician at the Chinese Academy of Engineering), has announced a material system for solid-state batteries that is primarily based on modified high-nickel ternary materials and silicon-based anode materials, with the addition of solid electrolytes and ion conductive films. This belongs to a solid-liquid mixed battery that combines an oxide-based solid electrolyte and in-situ solidification technology.

Currently, a large-scale production line for 2 GWh solid-liquid mixed solid-state power batteries is under construction and will primarily be used to produce 350-360 Wh $kg^{-1}$ new energy automotive power batteries. In the automotive power battery field, the company has already completed the design and development of a 300 Wh $kg^{-1}$ or more hybrid solid-state battery using high nickel ternary cathodes, and it has also passed abuse tests such as penetration (by nails), crushing, overcharging, and short circuiting.

## 6.5.3 QingTao (KunShan) Energy Development

QingTao (KunShan) Energy Development (QingTao Development) is a high-tech company led by the team of Ce-Wen Nan, a Chinese Academy of Sciences academician. Their solid-state power batteries, with a measured value of 368

Wh $kg^{-1}$, have already obtained mandatory national certifications such as the “Electric vehicles traction battery safety requirements” (GB/T 38031-2020). In July, the company completed E+ round financing. SAIC Capital is the lead investor, with co-investments from Kunshan GuoChuang Investment and Huai’an Elites Investments. Around the same time, the first phase of the Yishun solid-state lithium-ion battery project, in which QingTao Development invested a total of CNY5.5 billion, began. The project, which began construction in August 2019, plans to build a manufacturing base for all-solid-state lithium-ion batteries with an annual production capacity of 10 GWh. The investment for its first phase is CNY0.55 billion, with an annual production capacity of 1 GWh of solid-state power lithium batteries. The second phase will have an investment of 4.95 billion yuan, with a new production capacity of 9 GWh.

According to the official announcement, QingTao Development is focusing on lithium lanthanum zirconium oxygen, a garnet-type oxide-based electrolyte, has solved technical difficulties in the mass production of solid electrolytes, and has already started large-scale mass production. At the same time, the company also does surface coating of cathode materials and has set up a line dedicated to coating solid electrolytes for high nickel-based materials. Meanwhile, in partnership with automobile manufacturer BAIC BluePark, in 2020, a prototype pure electric vehicle (BEV) equipped with QingTao Development’s first-generation solid-state battery system was completed, and successfully went off the production line after testing and adjustment. The company also partnered with Hozon Auto to conduct joint research/development and performance testing of the Neta U (哪吒U) electric vehicle (EV) for about two years. The plan is to mass-product 500 units of the Neta U with solid-state batteries by the end of 2021.

### 6.5.4 Ganfeng LiEnergy

Since 2017, Ganfeng LiEnergy has been moving forward with the deployment of solid-state batteries, playing to its strengths in the battery industry chain. Ganfeng LiEnergy’s solid-state batteries employ thick oxide-based films to produce solid-liquid mixed batteries. Currently, their test line for the first generation 2GWh solid-state batteries is running smoothly. Battery products of the first generation solid-liquid mixed electrolyte with energy density reaching 235-280 Wh $kg^{-1}$ have already passed safety tests and customer sample tests by several third-party inspection agencies. In terms of cooperation with automakers, Dongfeng Technology Center of Dongfeng Motor and Ganfeng Lithium have officially signed an agreement to discuss joint operation of solid-state battery models and agreed on a promotion agreement for solid-state battery models to be used in Dongfeng Motor’s E70.

Ganfeng LiEnergy has announced two oxide-based solid electrolyte products that use NASICON-type titanium aluminum lithium phosphate and garnet-type lithium lanthanum zirconium oxygen. Of these, submicron-grade NASICON-type titanium aluminum phosphate with ionic conductivity of 0.8 mS $cm^{-1}$ is available in powder, slurry, or dense ceramic sheet forms, depending on customer needs. By utilizing a multi-element co-doping technology, the company has successfully developed a second-generation garnet-type lithium-lanthanum zirconate material with a high ionic conductivity of 1.1 mS $cm^{-1}$ at room temperature.

### 6.5.5 China National Machinery Industry Corporation – Guilin Electrical Equipment Scientific Research Institute

Guilin Electrical Equipment Scientific Research Institute (GLESI) has developed a sulfide-based solid electrolyte powder with a kilogram-scale mass, and its lithium-ion conductivity exceeds 3.0mS $cm^{-1}$. The company has also led the establishment of the "Measurement Method for Thin Film Ionic Conductivity in Power Batteries" (NB/T 10827-2021), which became China's first evaluation standard for lithium-ion conductivity of sulfide-based solid electrolytes.

Finally, the locations of the institutions in sections 6.1 to 6.5 are shown in Figure 6-1.

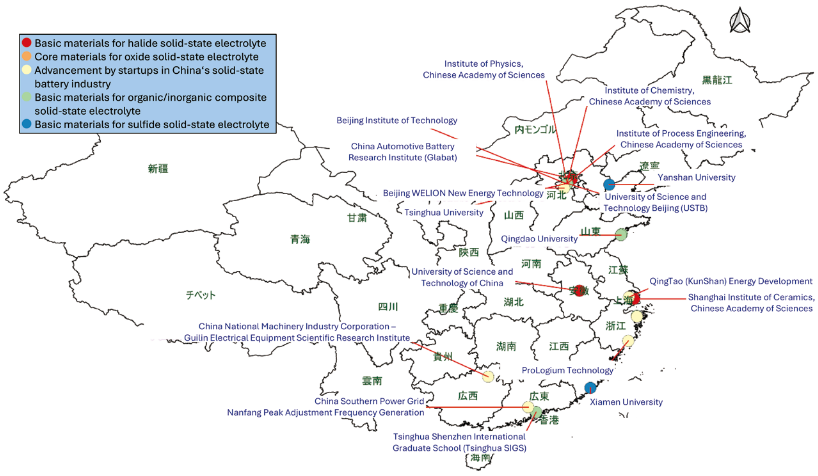


**Figure 6-1: Location of research institutes for next-generation all-solid-state lithium local technology**

# 6.6 Challenges and prospects for next-generation all-solid-state lithium battery technology in China

Although the outlook for the development of all-solid-state lithium batteries is bright, there are many bottlenecks that have not yet been completely resolved. Considering the current state of costs and technological maturity, the technological paths announced by companies are primarily focused on solid-liquid mixed batteries. In order to improve energy density, rate characteristics, and cycle life for all-solid-state lithium batteries, scientific research institutes and important companies are not only focusing on basic science aspects (such as the development of new electrolyte materials, interface modification, and battery degradation mechanisms), but are also increasingly placing emphasis on key technologies for practical application (such as mass production technology for electrolyte materials with high atmospheric stability, continuous formulation/preparation technology for large-area and ultra-thin solid electrolytes, and integrated manufacturing technology for all-solid-state lithium batteries). Against the backdrop of China's strategic "double carbon" goal and breakthroughs in key technologies, the cooperative model between Chinese battery companies and automakers will evolve to an even deeper level, and a new cooperative model will surely emerge in the new energy vehicle field.

Given its progress on the path of lithium battery technology, various nation plans, and companies' solid-state battery deployment plans, the development of China's solid-state battery industry is solidly on track. In the future, solid-state battery technology will continue to advance, and the energy density, safety, and cost of solid-state batteries themselves will further improve, so it will not be long until solid-state batteries see mass production and commercialization.

China's solid-state battery industry is riding a wave of commercial opportunity, but for automakers, power battery manufacturers, and start-ups, it is a new, highly competitive challenge, albeit one with ample potential. According to Liquan Chen, “If the development of solid-state batteries accelerates, then it will drive forward ’electric China’ (China’s electrification). I believe that with strong government interest and the support of social capital, an era of rapidly developing solid-state batteries will arrive sooner rather than later.”

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# 7 Development trends and prospects in China for next-generation storage batteries

## 7.1 Current trends around carbon neutrality and storage batteries

### 7.1.1 Global energy storage market trends

The conclusion of the November 2021 COP26 Summit was for governments to support the transition to green energy by taking steps to encourage the electrification of the manufacturing and transport sectors so as to meet their national emissions reduction targets. In response to this trend towards electrification, 24 countries (incl. the UK, Canada, and the Netherlands), 11 automakers/organizations (incl. GM, Ford, and Mercedes-Benz), as well as financial institutions and investors, signed and announced a joint statement to ensure that all new cars, including EVs, are zero-emissions in major markets by 2035 and globally by 2040.[82]

One of the challenges in energy electrification is the difficulty of storing electrical energy. Electricity cannot be easily stored like fossil fuels such as oil, so it must be stored in a different form of energy, such as in storage batteries. In response to these trends, in forecasts for global the global energy storage equipment market it is reported that, over the next 10 years (2020-2030), installed energy storage capacity will be more than 20 times the 17 GW / 34 GWh in 2020 (345 GW / 999 GWh in 2030), and that the related investment amount will be more than 262 billion USD.[83] The forecast also noted that the United States and China would be the two largest market, accounting for half of the world's energy storage facilities by 2030, while also mentioning other major markets such as India, Australia, Germany, Britian, and Japan. 55% of the installed energy storage capacity will be provided for the shift to renewable energy (green power storage applications).

82 https://ukcop26.org/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans/

83 https://about.bnef.com/blog/global-energy-storage-market-set-to-hit-one-terawatt-hour-by-2030/

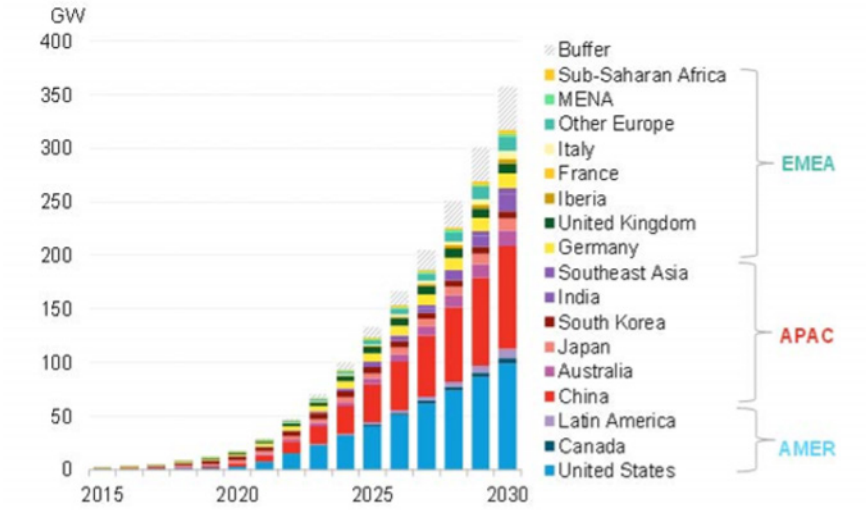


**Figure 7-1: Forecast for global energy storage equipment**

Note: MENA = Middle East & North Africa. Buffer represents markets and use-cases that we are unable to forecast due to lack of visibility.

Source: BloombergNEF (BNEF)[84]

Renewable energy such as solar power and wind power generation are increasing due to efforts to realize carbon neutrality, but have variable output due to weather conditions. As such, these types of power storage equipment will be important for facilities to control this kind of variable output and also to realize a stable power supply (adjustment of supply and demand). As shown in Table 7-1, there are several types of electrical energy storage facilities, including storage batteries, pumped storage hydroelectric power, and power to gas (pumped storage hydroelectric power is not included in this BloombergNEF forecast).[85]

According to the US Department of Energy, approx. 158 GWh of energy storage has been installed worldwide (approx. 28 GWh in Japan), and while pumped storage hydroelectric power continues to be a powerful energy storage method, with more new installations expected in the future.[86]

84 https://about.bnef.com/blog/global-energy-storage-market-set-to-hit-one-terawatt-hour-by-2030/

85 https://www.nedo.go.jp/content/100866310.pdf

86 https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Market%20Report%202020_0.pdf

**Table 7-1: Types of energy storage equipment**

| | |
|---|---|
| Storage batteries<br>・Sodium sulfur battery<br>・Redox flow battery<br>・Nickel-Metal Hydride Batteries<br>・Lithium-ion batteries<br>・Lead-acid batteries | CAES (Compressed Air Energy Storage)<br>LAES (Liquid Air Energy Storage)<br>Flywheel |
| Pumped storage hydroelectric | SMES (Superconducting Magnetic Energy Storage) |
| Power to gas | EDLC (Electric Double Layer Capacitor) |

Source: NEDO Technology Strategy Center Report, TSC Foresight[87]

Table 7-2 is a quantitative comparison of facility costs and cycle efficiency for energy storage systems when they are used to output their stored electricity. Facility costs vary widely by method, and, even within the same method, there is a wide range depending on the facility's scale and installation environment, which makes comparisons difficult. On the other hand, in the future storage batteries are expected to be utilized more than pumped storage hydroelectric energy storage. BNEF predicts that storage batteries will drive the energy storage market in the future, and that they will see rapid progress in technological development, practical application, and cost reduction. The advantage of storage batteries is that they can be widely used on both the demand and generation sides because of flexible configurability, such as being able to accommodate outputs from several kW to several hundred MW.

87 https://www.nedo.go.jp/content/100866310.pdf

**Table 7-2: Types of energy storage facilities**

| Method | Unit capacity | | | | | Facility cost (1,000 JPY/ kWh) | Facility cost (1,000 JPY / KW) | Energy density (Wh/L) | Cycle efficiency (%) | Supply & demand adjustment range | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100 kWh | MWh | 10 MWh | 100 MWh | GWh | | | | | Minutes | Hours | Days | Months |
| Storage batteries | ● | ● | ● | ● | | 32-682 | 33-385 | 20-400 | 75-95 | ● | ● | ● | |
| Pumped storage hydroelectric | | | | ● | ● | 28-47 | 55-506 | 0.1-0.2 | 50-85 | ● | ● | ● | |
| Power to gas | | | ● | ● | ● | 48-96<br>Conversion only | 55-83 | 600<br>(200 bar compressed hydrogen) | 22-50 | | ● | ● | ● |
| CAES<br>*Local | | | ● | ● | ● | 7-14 | 55-165 | 2-6 | 27-70 | ● | ● | ● | |
| LAES | | | ● | ● | ● | 29-58 | 99-209 | — | 55-85 | ● | ● | ● | |
| Flywheel | ● | | | | | 858-968 | 14-55 | 20-80 | 90-95 | ● | | | |
| SMES | ● | ● | | | | 77,000 | 14-57 | 6 | 90-95 | ● | | | |
| ELDC | ● | | | | | 1,100 | 14-57 | 10-20 | 90-95 | ● | | | |

Source: NEDO Technology Strategy Center Report, TSC Foresight

## 7.1.2 Storage battery applications: transport sector

As mentioned above, due to efforts towards carbon neutrality, there are increasing expectations for the role of storage batteries. The primary uses for storage batteries include (1) the transportation sector, (2) energy storage equipment in the power sector, and (3) portable power sources. Of these, the transportation sector is expected to be the largest market in 2030, accounting for more than 80% of total demand.[88]

Looking at global automobile shipment forecasts (November 2021), the average annual growth rate from 2020 to 2030 is expected to be around 3%, and from around 2027 shipments are expected to increase by more than 100 million cars a year. In terms of composition ratio, the shipment ratio of environmentally friendly vehicles, including EVs, is increasing, and the shipment ratio of environmentally friendly vehicles is expected to exceed 50% by 2030.[89] According to the International Energy Agency (IEA), demand for EV batteries is likely to surge by approx. 20 times to a maximum of 3,200 GWh in 2030, compared to 155 GWh in 2020.[90] Accelerating factors include the environmental regulations and policies in each country (such as Europe's 95g/km $CO_2$ emissions regulation in 2021 and tightened regulations in 2030).

88 https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

89 https://response.jp/article/2021/09/28/349845.html

90 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf

### 7.1.3 Storage battery applications: Energy storage facilities in the power sector

In this way the storage battery market towards 2030 is expected to expand mainly via automotive batteries, but, after 2030, energy storage equipment usage is expected to expand as a means of smoothing output fluctuations due to the large-scale introduction of renewable energy. It is expected that lithium-iron-phosphate (LFP) batteries, which are particularly cost-effective and safe, will be widely used as energy storage batteries around the world in the future, and that they will play an important role in energy storage facilities until 2030, along with competing sodium-ion (NMC) batteries.[91] Since the spring of 2021, global lithium-ion battery manufacturers have announced a series of plans to invest trillions of yen to significantly increase production. It is said that the transport sector will generate large amounts of used storage batteries after 2030, and trends in the reuse of these storage batteries in the power sector are also attracting attention.

Furthermore, electric energy storage systems are not composed solely of storage batteries, and costs for ancillary equipment (such as power conditioners (PCS) that control charging and discharging) costs for distribution cannot be ignored. Figure 7-2 shows the price level of commercial and industrial power storage systems in Japan in 2019, and approximately 47% of the total system price is non-battery costs such as PCS and distribution. PCS in particular have an impact not only on costs, but also on power losses (energy efficiency) associated with charging and discharging, so in the future it will be necessary to pay close attention to system level competitiveness, including such ancillary equipment.

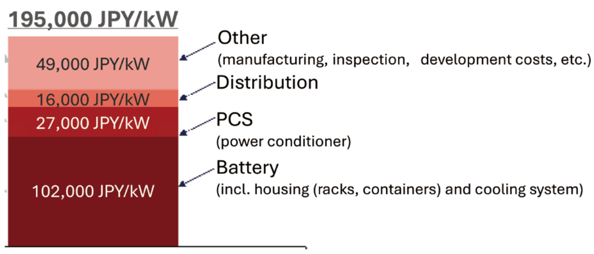


**Figure 7-2: Japan's commercial/industrial energy storage system prices**

Source:Ministry of Economy, Trade and Industry; materials from the 4th meeting of the Study Committee on Expanding and Spreading Stationary Energy Storage Systems[92]

91 https://about.bnef.com/blog/global-energy-storage-market-set-to-hit-one-terawatt-hour-by-2030/

92 https://www.meti.go.jp/shingikai/energy_environment/storage_system/pdf/004_04_00.pdf

## 7.2 Development trends in China for next-generation storage batteries

### 7.2.1 Storage battery trends in the transportation sector in China

China continues to lead the world in EV sales, with monthly sales reaching a new record of 427,000 units in November 2021. Total global sales of EVs in 2021 will be 6.5 million units,[93] of which 3.52 million units[94] will be sold in the Chinese market, meaning that more than 50% of the world's demand already originates from the Chinese market.

Against this backdrop, China has recently been gaining the upper hand in EV batteries. Leading EV manufacturers such as Tesla, VW, Ford, and Daimler, have successively decided to adopt LFP batteries, the majority of which are supplied by Chinese companies. Key patents related to LFP battery production are managed by a consortium of Chinese universities and research institutes and are provided to battery manufacturers in the country on a license-free basis. This is part of China's competitive advantage. Of course, the Chinese government also provides support. For example, on December 10, 2021, the government lowered the energy density limit regulations for automotive LFP batteries from 180 Wh/kg to 160 Wh/kg, a change that, amid rising battery material costs (cathode materials), was intended to promote the use of price competitive LFPs in EVs.

Liquid lithium-ion batteries include NMC/ternary, NCA/lithium nickelate, and LFP/lithium iron phosphate, depending on the cathode material. Of these, Chinese manufacturers focus on LFP, while Japanese manufacturers have taken a strategy of focusing on NMC and NCA manufacturing. LFP batteries are less flammable than the other two, and as such are safer, as well as having cost advantages. The cathode materials are rare metals, which are estimated to account for half of the total battery cost. Cobalt in particular is expensive, but LFP batteries do not contain cobalt and are generally a quarter of the cost of NMC batteries. On the other hand, one disadvantage of LFP batteries is their low energy density. This was an issue for EVs, where space in the vehicle is limited and batteries with higher energy density are required. However, this issue is being resolved with advances in cell-to-pack technology, and the fact that driving ranges in excess of 500 km are leading to their adoption.

In June 2021, Tesla, not wanting to see battery material costs rise, announced that it would extend its contract with a Chinese LFP manufacturer until the end of 2025, and in October 2021 announced that worldwide it would shift its automotive batteries to LFP batteries. Tesla CEO Elon Musk has his intention to eventually have LFP make up two-thirds of Tesla's batteries, with the rest being NCA. Tesla will also use LFP batteries in its energy storage facilities. This trend can also be seen in other companies that are installing similar energy storage facilities. Battery trends in China, which accounts for the majority of the world's EV demand, are affecting not only automotive applications but also energy storage facilities, which are expected to see global increases due to renewable energy demand.

### 7.2.2 Storage battery trends in the power sector in China

As previously mentioned, according to the China Energy Storage Alliance (CNESA), the cumulative capacity of

93 https://36kr.jp/174702/

94 https://www.nikkei.com/article/DGKKZO58913440Y2A300C2EA2000/

energy storage equipment in operation as of the end of 2020 was 35.6GW, which accounted for approx. 20% of the total global market size. The main focus is on pumped storage hydroelectric power generation. In 2019 installed capacity for pumped storage was approx. 30 GWh, which is projected to reach 120 GWh in 2035 and 170 GWh in 2060.

In 2021, under China's guidance for its "double carbon" development goal, the energy storage industry has continued to be a focus of attention. In the short-term, lithium-iron-phosphate and pumped storage are promising technologies; but in the long-term, the picture will have various technologies (such as sodium-ion batteries, compressed air, and hydrogen energy) that complement existing systems. With such a variety of storage technologies under consideration, it will be interesting to see whether China can create energy storage technologies and systems that guarantee safety, and how used storage batteries from the transportation sector will be utilized in power storage sector.

### 7.2.3 Trends amongst storage battery companies in China

Against the backdrop of the China's expanding EV market that was mentioned above, Chinese battery manufacturers are establishing their position as leading global manufacturers. As previously stated, Contemporary Amperex Technology (CATL) had a 50% share of the world's production capacity in 2020, and a 48% share of the domestic Chinese market. In August 2021, the company announced a capital increase of up to CNY58.2 billion (approx. 1 trillion JPY). Of this amount, CNY41.9 billion will be used for the construction of five new battery factories in Fujian, Guangdong, and Jiangsu provinces, and the remaining CNY16.3 billion will be used to develop advanced new energy-related technologies and for working capital (investments in battery supply chain-related companies). Through these aggressive investments, CATL is planning to expand its sales in Japan, Europe, and other global markets.

Following CATL, China's BYD has a 15% share of global production capacity. Currently, BYD sells the majority of its batteries internally to the electric vehicle industry, but it is planning to expand its external sales from 2022 onwards, and is said to be planning to partner with Dongfeng Motors, Changan Automobile, Ford, and Toyota to supply batteries. Some companies specialize in LFP batteries and are rapidly expanding their sales. In September 2021, CALB announced its new "One-Stop Battery," which reduces the weight of storage battery structural components by 40% and reduces the number of components by 25%, thereby increasing production efficiency. Above all, the company has rapidly grown in just three years, from 715.8 MWh in 2018 to 6.42 GWh in October 2021, and has gained a 6% share of the Chinese automotive battery market, giving it the third largest share position after BYD.

New leading companies are also being born through industry-government collaborations. In March 2022, Huawei invested in two sodium-ion battery startups from the Chinese Academy of Sciences. One of the companies, HiNa Battery, has developed rapidly. In 2018 it demonstrated the world's first sodium-ion battery for low-speed electric vehicles, and in 2019 it completed the world's first 100kWh sodium-ion battery energy storage power plant. WELION, the other company, currently has a valuation that has grown to more than CNY15 billion. Xiaomi has also completed an investment in the company. The presence of risk money is essential for the creation of new industries. For China's startup ecosystem to function and create new industries, there has always been the presence of venture capitalists (VCs) who provide this risk money. In the storage battery industry, which is expected to grow by more than 25% over the next 10 years, VCs are giving birth to new unicorn companies.

Competition in the Chinese storage battery industry will essentially come down to production scale and cost, which will be the competitive factors among manufacturers until game-changing innovations such as all solid-state batteries are commercialized. At this stage, CATL is strong both in terms of cost and in terms of customer stickiness. In August 2021, the company increased its capital by CNY58.2 billion (about 1.06 trillion JPY) to increase its production capacity for lithium-ion batteries to 137 GWh per year and its production capacity for storage battery storage equipment to 30 GWh per year. On the other hand, emerging companies are also increasing their competitiveness through new investments. In September 2021 CALB announced that it plans to raise CNY12 billion (approx. 220 billion JPY) and achieve an annual production capacity of over 500 GWh in 2023. The company is also aiming to be listed on the Hong Kong Stock Exchange. SVOLT Energy Technology, a storage battery manufacturer affiliated with Great Wall Motor, also plans to raise a total of CNY16 billion in 2021, and is aiming to achieve an annual production capacity of 600 GWh by 2025. Emerging companies are also trying to win out over the competition by allocating funds obtained from new fundraising and IPOs to expanding their production capacity.[95]

### 7.2.4 Trends in the battery supply chain in China

As mentioned above, in terms of storage battery applications, Chinese companies are in an advantageous position to capture the rapid growth from the transportation sector market and the subsequent storage battery demand for energy storage facility applications from the power sector. Not only that, but with the support of the Chinese government, Chinese companies and China-related organizations are also working upstream in the supply chain to secure resources for raw materials, and are making steady progress in establishing their own domestic supply chains, including downstream. In addition, because current battery supply chains are concentrated around the manufacturing and development bases of automobile OEMs, in addition to the various publicly available subsidies, local governments are also developing policies to attract new battery companies through tailored, company-specific policies.

In addition to China, the US and Europe are also stepping up policies to protect their own battery industries. Battery supply chains are a major value-added portion of the game-changing shift from gasoline-powered vehicles to environmentally friendly vehicles, and the US and Europe are also aiming to bring these supply chains into their own economic spheres. In the US, a February 2021 presidential degree has, from the perspective of economic security, accelerated the movement to secure large-capacity battery supply chains within the US. Chinese capital is finding it difficult to make investments, and, in addition to Tesla and Panasonic battery factories, Korean companies LG and SK are taking the initiative in expanding production capacity by teaming up with GM and Ford. Europe is aiming to build a capacity base of 400 GWh (equivalent to 8 million vehicles; 10 times the capacity of Tesla's Gigafactory in the US) by 2030. In addition to Korean companies such as LG, SK, and Samsung, China's CATL and OEM companies (VW, Renault, Stellantis) are also expanding their production capacity while forming JVs. Additionally, in Europe, the movement toward local production for local consumption is also expanding from the perspective of promoting employment and economic security.

95 https://36kr.jp/

## 7.3 Future prospects for next-generation storage batteries in China

The medium- to long-term issues surrounding storage batteries point to the need to (1) reduce costs, (2) achieve life cycle decarbonization, and (3) fundamentally improve energy density.

For (1), it has been pointed out that current battery costs must be reduced by half in order to achieve cost competitiveness with internal combustion engine vehicles. For (2), EV manufacturing processes are expected to emit approx. twice as much $CO_2$ as international combustion engine vehicles, so the manufacturing processes must be improved. For (3), next-generation battery technologies must be established, their costs must be reduced, and they must be mass produced.

As pointed out in Chapter 1, safety issues in the energy storage industry attracted a great deal of attention in China in 2021. This is a potential risk factor for storage batteries, not only in China, and the safety of energy storage systems is an issue that must be taken seriously by all industry stakeholders. It is expected that those involved in China's storage battery industry will lead the world in addressing these issues.

There is an ample market in China, and, by leveraging that market, exports of price-competitive products to outside of China will likely progress in the medium- to long-term. In this case, there is potential for collaboration with next-generation batteries, where Japan is leading in basic research to solve the afore-mentioned issues, and with Japan's environmental technologies.

# Conclusion

Energy is essential for humankind's survival and development, and the demand for energy continues to increase as populations grow and societies develop. The world's fossil fuel supply and environmental situation are becoming increasingly perilous, with conventional fossil fuels becoming ever more depleted and the use of fossil fuels causing serious environmental pollution problems. In 2015, Xi Jinping advocated that China will "establish a global energy Internet to facilitate efforts to meet the global power demand with clean and green alternatives." At the 75th UN General Assembly held in September 2020, he announced to the international community that "We aim to have $CO_2$ emissions peak before 2030 and achieve carbon neutrality before 2060." By 2030, China will also increase the share of non-fossil fuels in its primary energy consumption to approx. 25%, and will increase the total installed capacity for wind and solar power generation to more than 1.2 billion kW.

Renewable energy is intermittent, variable, and distributed, and as such it requires the construction of an "energy internet," that is, an energy network that collects, stores, and utilizes renewable energy on site. The energy internet has five characteristics: (1) All of the energy used is renewable; (2) the energy is distributed; (3) it is interconnected, so entities must be connected to the network to use it; (4) with an open network, entities can sell excess energy and buy as much energy as they need; (5) it is a completely smart network via smart control. The cornerstone of the energy Internet is energy storage, and the key to this energy storage is secondary batteries, especially solid-state lithium and sodium-ion batteries.

Based on China's abundance of coal but scarcity of oil and gas, it is actively and steadily promoting the goals of reducing peak carbon emissions and achieving carbon neutrality while also striving to realize "electric China" (China's electrification). In order to do so, the first step is to electrify transportation, and significant progress must still be made in electric vehicles (EVs), electric ships (EV ships), and electric aircraft. At the same time, it is also necessary to make smart facilities, smart cities, smart rural villages, and smart mines that must all be built in parallel. Lithium-ion and sodium-ion batteries are required for all of these, and their rapid advancement will be essential.

China's lithium-ion batteries have already captured the lion's share of the global market. However, there are two serious problems: energy density is close to the limit of 300 Wh/kg, and combustion/explosion accidents occasionally occur. The development of solid-state lithium batteries will be essential in solving these problems. Because all-solid-state lithium-ion batteries utilize metallic lithium anodes, they have a capacity that is 10 times higher than existing lithium-ion batteries that use graphite anodes. Existing inexpensive cathode materials are used for the cathode, and solid materials with excellent thermal stability are used for the electrolyte. In order to fully utilize existing lithium-ion battery technologies and manufacturing facilities, in-situ solidification technology will be used to increase the energy density to over 300 Wh/kg, thereby creating batteries with safe and reliable power and energy storage capacity.

Lithium-ion batteries have now become such a hot product that countries around the world are competing to be the first to manufacture them. However, lithium resources are limited. Lithium is found in only 0.0065% of the earth's crust, while sodium is relatively abundant at 2.75%. If all of the world's cars were powered by lithium-ion batteries and if all of the world's electricity were stored in lithium-ion batteries, then lithium resources would soon run out. Therefore, the next generation of batteries must be considered, and sodium-ion batteries are the leading candidate. Sodium resources are widely distributed and inexpensive. In addition, sodium-ion batteries have stable high-temperature characteristics, long cycle life, and an energy density that is almost the same as that of lithium-iron-phosphate batteries.

The CAS Institute of Physics has been researching sodium-ion batteries since 2009 and has a first-mover advantage because it owns the core technology for and independent intellectual property rights to sodium ion batteries. In 2017, HiNa Battery was established to focus on researching, developing, and manufacturing sodium-ion batteries. The company then realized a low-speed electric vehicle powered by sodium-ion batteries and a 1 MWh energy storage system utilizing sodium-ion batteries. Although current sodium-ion batteries are still in the early stages of industrialization, they have many similarities to lithium-ion batteries, and as such sodium-ion battery development speed will likely far exceed expectations.

We would like to thank the experts in various fields from China and Japan for writing the "R&D Trends in Next-Generation Batteries from the Perspective of Leading Chinese Researchers" report for this research activity. We hope that this report will be useful for the research and development of solid-state and sodium-ion batteries in China and that it will promote the development of the electric vehicle and energy storage industries in China and Japan, as well as international exchanges and cooperation. Above all, we hope to work together with all of you to achieve the "double carbon" goals.

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[Research planning]

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