A brief analysis of characteristics and cost-effectiveness of energy storage technology in the power system: a case study of Shandong province

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Abstract. This paper sorts out the working principles and technical characteristics of current mainstream energy storage technologies, forecasts the development prospects of energy storage in China, discusses the main application scenarios and profit models of energy storage in China, and conducts cost estimation for relatively mature energy storage methods such as lithium-ion battery, lead-carbon batteries, sodium-ion batteries, flow batteries compressed, air hydrogen and fuel cells. Finally, based on the actual situation of energy storage industry scale and layout in Shandong Province, suggestions are proposed for the future development direction of energy storage and related supporting policies in Shandong Province.

1 Introduction

In the context of constructing new electric power systems and with the advancement of "dual carbon" goal, large-scale grid integration of new energy, energy supply will achieve a systematic transformation from coal-fired power to new energy[1], the power system will also face a series of new challenges. In scenarios where a large number of interactive devices such as electric vehicles and distributed power sources are integrated, the power system exhibits characteristics of both a high proportion of new energy and a high level of power electronicization, known as the “double high” features. This leads to significant changes in the power system in terms of supply-demand balance, system regulation, stability, distribution network operation, control and protection, and construction costs. To address the high variability and randomness of new energy and its impact on the reliability of power systems, a series of measures need to be taken.

The development of energy storage is significant for meeting the coordination needs of the power system and promoting the growth of new energy development and consumption scale. It is also an important means to ensure the supply-demand coordination of new power systems. It is imperative to accelerate the layout of the energy storage industry, foster new business models in the energy industry, and create a new economic engine by advancing the large-scale application of advanced energy storage technologies. Therefore, it has become a necessary action to accelerate the development of the energy storage industry.

Shandong Province, as a new force in the planning, construction, operation, and application of China’s new power systems, needs to actively research and strategically plan the development of energy storage and strengthen strategic planning and system layout.

2 Analysis of the Current State of the Energy Storage Market

2.1 Main Types of Energy Storage Methods

2.1.1 Traditional energy storage

Traditional energy storage mainly refers to pumped hydro storage. This technology has lower costs and more mature applications, ensuring to some extent the effectiveness of new energy generation. However, pumped hydro storage is highly dependent on the environment and is usually built in areas such as river dams and coastlines. Affected by water resource evaporation and water pump operating efficiency, it achieves only about 70% efficiency. Moreover, it has a long construction period and high limitations.

2.1.2 New energy storage

New energy storage refers to energy storage technologies other than pumped hydro storage, primarily in the form of electricity output. It is characterized by precise control, high efficiency, quick response, flexibility, good adaptability, and the ability to adjust power flexibly in four quadrants [1]. It provides multi-timescale, full-process balancing, support, and regulation capabilities for power systems, thereby ensuring the reliability of high-proportion new energy power systems and promoting sustainable development. New energy storage can be

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divided into five categories based on the storage medium: electrochemical energy storage, chemical energy storage, mechanical energy storage, electromagnetic energy storage, and thermal energy storage[2].

2.2 Development and Technical Characteristics of Different Energy Storage Technologies

Combining the descriptions and analyses of various energy storage technologies in articles such as “Overview of large-scale energy storage technology and multi-functionapplication”[1], “Technologies and Industrial Development of New-type Energy Storage”[2], “Zhongchu International Energy: Leveraging the Advantages of Compressed Air Energy Storage Technology to Provide High Quality Energy Storage Assets for the Energy Industry”[3], “Application and Prospect of Superconducting Energy Storage in New Energy Power System”[4], “Development Report on New Energy Storage Industry (2023)”[5], the characteristics, advantages and disadvantages of each energy storage technology were summarized, and shown in Table 1.

Table 1. Summary of Characteristics and Maturity of Different Energy Storage Technologies[1,2,3,4,5]

Energy Storage Type	Applicable Conditions	Lifespan	Advantages	Disadvantages	Technology Maturity
Pumped Hydro Storage	4-6h	40-60 years, over 10,000 cycles	① High technical maturity ② Large installed capacity ③ Long lifespan ④ High conversion efficiency	① Site limitations ② Long construction period	Large-scale application
Lithium-ion Battery	1-4h	Over 3,000 cycles	① High energy density ② Rapid response ③ Strong environmental adaptability	① Limited lithium resources ② Capacity degradation	Large-scale application
Lead Carbon Battery	Long-term storage	Under 1,000 cycles	① Mature technology ② Cost-effective ③ Easy maintenance	① Low cycle life ② High material pollution ③ Significant self-discharge	Large-scale application
Sodium-ion Battery	1-4h	2,000-4,500 cycles	① Relatively low cost ② Relative safety ③ Abundant resources	① Industry not yet mature ② Rapid life decay	Research and development stage
Flow Battery	Long-term storage	Over 6,000 cycles	① High number of cycles ② High safety	① High cost ② Energy storage heavily reliant on tank volume	Research and development stage
Hydrogen Fuel Cell	Long-term storage	About 10,000 hours	① Clean and environmentally friendly ② Long endurance	① Low conversion efficiency ② High cost	Experimental demonstration stage
Compressed Air	Long-term storage	30-50 years	① Long lifespan ② High power	① Slow response speed ② Site limitations ③ Long construction period	Experimental demonstration stage
Flywheel Storage	Short-term storage	Over 20,000 cycles	① Relatively long lifespan ② High conversion efficiency ③ Stable output	① High material requirements ② Short discharge time ③ High self-discharge rate	Research and experimental stage
Superconducting Storage	Short-term storage	Over 100,000 cycles	① Long lifespan ② High conversion efficiency ③ Fast response	① Expensive ② Complex maintenance	Research and experimental stage
Supercapacitors	Short-term storage	Over 50,000 cycles	① No significant performance degradation	① Low energy density	Research and experimental stage

Energy Storage Type	Applicable Conditions	Lifespan	Advantages	Disadvantages	Technology Maturity
			② Wide operating temperature range	② High investment cost	
Thermal/Cold Storage	Long-term storage	Generally over 10 years	① High power ② High safety	① Low conversion efficiency ② High cost	Research and experimental stage

2.3 Analysis and Forecast of Energy Storage Installed Capacity

In terms of installed capacity, by the end of 2022, China's operational electric energy storage projects had a cumulative installed capacity of 59.80 gigawatts, accounting for 25% of the global market size with an annual growth rate of 38% that marked a 51.1% increase compared to 2018. During the "14th Five-Year Plan" period, China's annual new energy installations are expected to reach approximately 100 to 120 gigawatts, posing a significant challenge to the grid integration capacity and reliability of the power system. Correspondingly, China's energy storage installation demand is no less than 30 gigawatts. It is expected that by 2025, the installed capacity will reach 65.60 gigawatts, with new energy storage accounting for 22.9%[6].

Regarding the installed capacity proportion, by the end of 2022, pumped hydro storage's share of China's operational electric energy storage projects fell below 80% for the first time, while new energy storage continued to develop rapidly with the cumulative installed capacity breaking through 10GW for the first time and reaching 13.1GW/27.1GWh[2]. As show in figure 1.

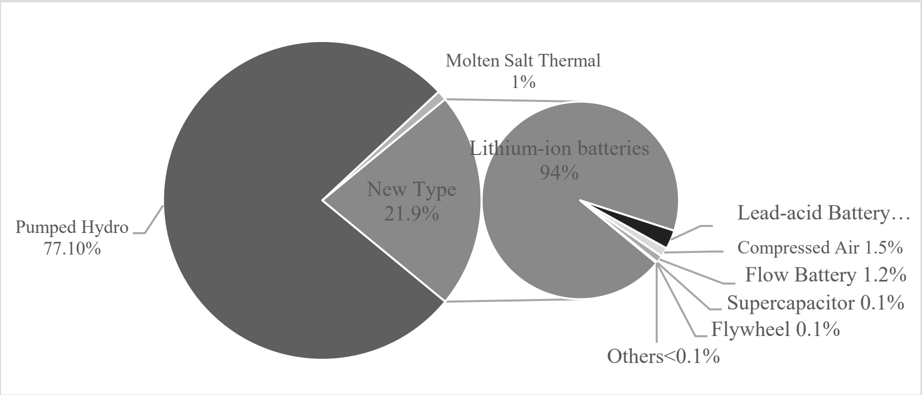

Figure 1. Breakdown of Cumulative Installed Capacity of China's Energy Storage Market in 2022

During the "14th Five-Year Plan", with the continuous advancement of energy storage technology, decreasing investment costs, and the gradual maturation of business models, combined with the current national and provincial focus on energy storage projects and the latest scientific research results while also considering the effective implementation of policies, healthy industrial development, and steady technological progress, it is forecasted that China's new energy storage cumulative scale will reach 48.51GW by 2025. As show in figure 2.

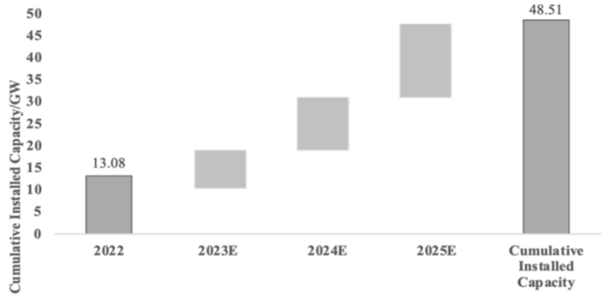

Figure 2. Forecast of New Operational Scale of China's New Energy Storage

2.4 Current State of Energy Storage Development in Shandong Province

2.4.1 Installed capacity

According to data published by the Energy Administration of Shandong Provincial in June 2023, the operational energy storage capacity in Shandong Province has reached 5.11 gigawatts, including 3.1 gigawatts of operational pumped hydro storage. In terms of electrochemical energy storage, there are 67 operational projects with a capacity of 2 gigawatts which ranks first in the country, and 17 projects under construction with a capacity of 1.8 gigawatts. In terms of compressed air energy storage, there is 1 operational project with a capacity of 0.01 gigawatts, 1 project under construction with a capacity of 0.3 gigawatts, and 2 projects planned to start within the year with a capacity of 0.95 gigawatts. By the end of 2022, Shandong Province had 58 operational new energy storage projects with a capacity of 1.55 gigawatts, ranking first in the country[7]. It is expected that by 2025, the new energy storage installed capacity in Shandong Province will reach approximately 5 gigawatts.

The statistical data show that the energy storage projects under construction are mainly new types of energy storage, fully reflecting the importance of new energy storage as a vital technology and basic equipment for constructing new power systems and as an important pillar supporting the achievement of carbon peak and carbon neutrality goals[7].

2.4.2 Industrial planning and layout

With the successive release of supporting policies such as the "Shandong Province Energy Development 14th Five-Year Plan", Shandong Province's new energy industrial system has initially formed a development pattern of "Energy Storage + Offshore New Energy" application belt, Jinan and Qingdao energy storage demonstration cities, key areas for multi-scenario energy storage applications in southwestern Shandong, key areas for compressed air energy storage in central Shandong, key areas for base-type energy storage in northern Shandong, and a highland for specialized industrial clusters, collectively forming "One Belt, Two Cities, Three Areas, N Bases". At the same time, Shandong Province is actively promoting the high-quality and large-scale development of the new energy storage industry, and the new energy storage industrial chain is becoming increasingly complete by achieving a full industry-wide chain planning and layout from material production, equipment manufacturing, system integration to operation inspection[8].

3 Study on the Cost-Effectiveness of Energy Storage Development

3.1 Analysis of Main Application Scenarios of Energy Storage

Based on the research of Yong Kang, Xiaorong Xie, Chunxing Pei, and others on energy storage application scenarios on the generation-side, grid-side, and consumer-side energy storage in "New Energy Storage Assists Energy Transformation"[9], "Functions of Energy Storage in Renewable Energy Dominated Power Systems: Review and Prospect"[10], and "Survey of application scenarios of energy storage in power system"[11], we analyze the characteristics and features of energy storage applications, as detailed below:

On the source side, the Thermal Storage Combined operating model provides secondary frequency modulation and improves AGC capability. The Renewable Energy with Storage mode reduces the curtailment of wind and solar energy, allowing for time-shifting, peak shaving, and valley filling while smoothing out the energy output[9,10,11]. For the grid side, Peak Shifting mode stores energy during low-demand periods and releases it during peak periods to relieve pressure. Frequency Regulation mode acts as a backup power source, providing emergency support and ensuring the grid's stable operation. The Alleviate Line Congestion mode improves transmission efficiency by balancing power demand with charging and discharging strategies. Delay Transmission and Distribution Expansion model avoids the need for larger-scale infrastructure upgrades[9,10,11]. On the consumer side, Capacity Charge Management model reduces peak load to lower capacity charges, while Power Quality mode enhances the reliability and quality of the power supply[9,10,11].

3.2 Analysis of the Main Profit Models for Energy Storage

3.2.1 Generation-side Energy Storage

Generation-side energy storage primarily serves to improve the frequency regulation performance of the power generation source and promote the consumption of new energy[9]. However, its revenue model is relatively singular, mainly consisting of increased electricity income due to new energy consumption and reduced related assessment expenditures.

3.2.2 Grid-side Energy Storage

Grid-side energy storage is mainly carried out through independent energy storage projects. The theoretical income of independent storage includes services such as ancillary services, power market arbitrage, capacity compensation income, and capacity leasing income[9]. Currently, more than 20 provinces have revised their electric power ancillary service management methods, where independent energy storage primarily plays a role in peak adjustment and frequency modulation.

In addition, China has 21 regions conducting pilot projects for the spot electricity market. Various profit models such as spot electricity trading, capacity leasing, and capacity compensation are still in the pilot stage. With the introduction of related mature policies for the spot electricity market, electricity revenue and capacity compensation are expected to become important profit models for independent energy storage enterprises, fully covering the investment cost of energy storage systems participating in the spot market for electricity generation and truly achieving "who benefits, who pays".

3.2.3 Consumer-side Energy Storage

The primary profit methods for consumer-side energy storage generally include peak shaving and valley filling, capacity charge management, and demand response. Peak shaving and valley filling achieve differential revenue by charging during low electricity price periods and discharging during high electricity price periods. Capacity charges are calculated based on the peak of the user's power demand, usually measured using a higher power demand peak as a basis.

3.2.4 Analysis of the Main Profit Models for Energy Storage in Shandong Province

Currently, energy storage projects in Shandong Province are mainly independent energy storage projects invested by power generation enterprises and third parties. The main sources of revenue include capacity leasing, capacity price compensation, and spot price arbitrage[12].

Capacity Leasing Income: Energy storage companies lease the capacity of energy storage stations to wind and photovoltaic enterprises through shared storage, allowing wind and solar enterprises to obtain grid connection indicators and profit rights. According to the requirements of “Policies and Measures to Support the Healthy and Orderly Development of New Energy Storage” in Shandong Province, the price of new energy storage capacity leasing is determined through negotiation between the parties, with the current guide price being about 260-330 yuan/kW·year.

Capacity Price Compensation: Before the operation of the capacity market in Shandong, energy storage stations calculate capacity prices based on the capacity of power generation units participating in the spot electricity market on the consumer side. Compensation is obtained through daily and monthly settlements, thereby gaining energy storage profits. However, the policy suffers from considerable uncertainty regarding the capacity compensation standards obtained by independent energy storage. Considering the duration of energy storage, the standards have been revised twice this year, now set at 1/6 of the original capacity compensation income.

Spot Market Price Difference Arbitrage: In November 2023, the Shandong Development and Reform Commission, Energy Administration of Shandong Province, and the Shandong Regulatory Office of the National Energy Administration issued “Policies and Measures to Support the Healthy and Orderly Development of New Energy Storage”, proposing to encourage new energy stations with matching storage to participate in the electricity market transactions fully. They will be cleared preferentially under safe grid operation and equal bidding conditions. New energy with matching storage will be settled jointly as one entity. Independent energy storage stations delivering electricity to the grid will not bear the transmission and distribution price and government funds and surcharges. Independent energy storage is encouraged to participate in the frequency modulation auxiliary service market according to the rules of the power market transaction and other related measures. Energy storage companies gain profits through preferential clearing of matching projects, joint settlement, and tax reduction, and cost reduction.

3.3 Cost Calculation of Major New Types of Energy Storage

Since energy storage projects primarily focus on the national strategy for the construction of new electric power systems and are planned and developed accordingly, many rely on new energy storage technologies. This study mainly uses the Levelized Cost of Storage (LCOS) to measure the unit cost of new energy storage projects. The specific calculation formula is as follows[13]:

$$\mathrm{LCOS} = C_{SUM} \,/\, E_{SUM} = C_{SUM} \,/\, \mathrm{nDOD}\eta\zeta \qquad (1)$$

Where C_{SUM} refers to the total lifecycle cost of the energy storage station, including the cost of the energy storage system, power conversion cost, civil engineering cost, operation and maintenance cost, residual value of the power station, and other costs. E_{SUM} refers to the total electricity processed over the lifespan of the energy storage station, n is the cycle life, DOD is the depth of discharge, η is system efficiency, and ζ is the efficiency retention rate. Generally, the efficiency retention rate of physical energy storage remains constant, hence set to 1. The efficiency retention rate formula for chemical energy storage is[13]:

$$\zeta = \frac{\int_1^n [1 - (N - 1)\frac{1 - \varepsilon}{n} dN}{n} \qquad (2)$$

Where ε is the final capacity retention rate. For convenience of calculation, this paper assumes the final capacity retention rate of various types of chemical energy storage as 70% for estimation.

3.3.1 Lithium-ion Battery

Inserting the core assumptions for calculating the lifecycle levelized cost of storage (LCOS) for lithium-ion batteries, based on different assumptions of investment costs and cycle life, when the energy storage life reaches 4900 cycles and the initial cost drops to 1.3 yuan/Wh, the LCOS can be reduced to 0.48 yuan/Wh. When the cycle life of the energy storage system reaches 10,000 cycles and the energy efficiency reaches 98%, the levelized cost of lithium-ion batteries will be competitive with pumped hydro storage power stations[13,14].

3.3.2 Lead-Carbon Batteries

Incorporating the core assumptions for the lifecycle levelized cost of storage (LCOS) calculation for lead-carbon batteries, based on different assumptions of investment costs and cycle life, when the number of annual cycles exceeds 500, and the initial investment cost is between 0.8 to 1 yuan/Wh, the cost of energy storage per kilowatt-hour for lead-carbon batteries is between 0.52 to 0.747 yuan/kWh[15].

3.3.3 Sodium-ion Batteries

Incorporating the core assumptions for the lifecycle levelized cost of storage (LCOS) calculation for sodium-ion batteries[13,14], since the industry has not yet applied it, the data are simulated figures derived after synthesizing various specialized research reports. Through calculation, the cost per kilowatt-hour of sodium-ion batteries is comparable to that of lithium iron phosphate batteries. If commercialized, and if the investment cost of sodium-ion batteries can be controlled below 1.1 yuan/Wh, and the cycle life exceeds 3000 times, then the cost per kWh can be controlled between 0.270 to 0.662 yuan, making sodium-ion batteries economically superior to lithium iron phosphate batteries[15].

3.3.4 Flow Batteries

Incorporating the core assumptions for the lifecycle levelized cost of storage (LCOS) calculation for flow batteries[14], initial investment and utilization hours greatly influence the cost per kWh. As technology progresses, there is still room for a decrease in initial investment. Utilization hours primarily depend on the station's utilization rate in actual operation; the higher the number of charges and discharges per day, the lower the cost. In a 100MW/400MWh system, when the initial investment is between 11 to 13 yuan/W and the number of annual cycles exceeds 600, the cost of energy storage per kWh ranges from 0.44 to 0.69 yuan.

3.3.5 Compressed Air

Incorporating the core assumptions for the lifecycle levelized cost of storage (LCOS) calculation for compressed air energy storage[3,14], the commercial development of compressed air energy storage depends on the steady improvement of system efficiency and the effective reduction of generation costs. Based on current completed and under-construction projects, the system efficiency of megawatt-level systems can reach 52.1%, 10-megawatt systems can reach 60.2%, and systems above the hundred-megawatt level can achieve an efficiency of 70%. Advanced compressed air energy storage systems are approaching an efficiency of 75%. As the system scale increases, the unit investment cost continues to decrease, with a unit cost reduction of about 30% for each order of magnitude increase in system size [15].

Similar to flow batteries, the cost per kilowatt-hour (kWh) of compressed air energy storage also heavily depends on initial investment and usage hours. In a system of 100MW/400MWh, with initial investments of 5-6 yuan/W and annual cycle numbers reaching 450-600 times, the cost per kWh ranges between 0.252 to 0.413 yuan.

3.3.6 Hydrogen Fuel Cells

Combining the analysis of hydrogen energy storage by Zhang Zhen in "Economics Analysis and Prospect of Hydrogen Energy Storage"[16], incorporating the core assumptions for the lifecycle levelized cost of storage (LCOS) calculation for hydrogen fuel cells[16], the cost per kWh of hydrogen fuel cells depends not only on the initial investment size and the system's charge-discharge efficiency but also on the hydrogen production and storage systems. Currently, hydrogen fuel cells have not yet been applied on a large commercial scale. The core assumptions for this calculation mainly refer to data from the Zhangjiakou 200MW/800MWh hydrogen energy storage power generation project.

Calculations show that the cost per kWh of hydrogen energy storage cells remains high. However, a comprehensive analysis of various literature data indicates that in scenarios of increased capacity, the cost increase of hydrogen storage is much lower than that of various electrochemical energy storage systems. Thus, hydrogen storage is more suitable for large-scale energy storage scenarios[16]. With future technological advancements and further cost reductions, hydrogen storage has significant development space and economic potential[17].

4 Recommendations for the Development of Energy Storage in Shandong

4.1 Promote the Implementation of Energy Storage Projects Tailored to Local Conditions

Based on the analysis of the strengths and weaknesses of energy storage technologies and in conjunction with the "14th Five-Year Plan for Energy Development in Shandong Province", it is recommended to vigorously promote the construction of lithium-ion battery projects on the foundation of solid pumped hydro storage applications. Projects for sodium-ion batteries should be dynamically carried out according to their research and application status, and pilot projects for compressed air energy storage should be initiated in the central region of Shandong.

4.2 High-Quality Advancement of Energy Storage Construction Planning and Technological Breakthroughs

As a leader in energy storage development in China, Shandong province is at the forefront of the country in terms of construction scale and planning layout. However, there is still a significant gap compared to the "14th Five-Year Plan" and the national requirements for high-quality development. It is advised to rely on the existing industrial layout, actively carry out industry-university-research cooperation with power companies, universities, and scientific research institutions, promote the establishment of key laboratories for energy storage and other industry-university-research platforms, and focus on addressing issues such as insufficient lifespans and high cell costs of lithium-ion and sodium-ion batteries, as well as the high cost and low conversion rate of hydrogen storage. Additionally, it is recommended to utilize Shandong's abundant natural resources like salt caverns and abandoned coal and gypsum mines in the southwest of Shandong, develop advanced compressed air technologies, focus on energy conversion efficiency, and push compressed air energy storage towards commercialization.

4.3 Policy Support to Promote Cost Reduction and Efficiency Increase in Energy Storage

4.3.1 Guide incentive policies to enhance revenue

It is recommended to actively guide new energy stations to allocate new energy storage in a market-oriented manner. For new energy projects that build new energy storage as required or implement new energy storage in a shared mode, it is suggested to provide certain policy support at the beginning of the project, such as tax incentives and energy price subsidies. During the project's progression, it is recommended to appropriately arrange grid connection times for energy storage projects or adopt priority dispatch strategies to ensure the utilization hours of energy storage projects, stabilize market revenue, and promote the healthy and orderly development of the "new energy + storage" model.

4.3.2 Improve market trading rules to standardize costs and prices

It is also suggested to establish a trading mechanism for energy storage and new energy to jointly participate in the market, promptly introduce detailed rules for independent energy storage to participate in spot market trading, gradually relax entry conditions, and allow market entities to transition from price takers to bid-quantity bidders. It is recommended that regions timely establish new auxiliary service trading products such as reserve, ramping, rotational inertia, reactive power balance services, and promptly introduce or improve rules for different forms such as energy storage + thermal power, energy storage + new energy, and independent energy storage to participate in the auxiliary service market.

4.3.3 Expand energy storage trading channels to increase value acquisition

It is advised to allow energy storage to participate flexibly in multiple segmented markets in various ways (energy storage + new energy, energy storage + thermal power, independent energy storage), such as spot + frequency regulation, peak shaving + frequency regulation, etc., enabling it to trade flexibly across various markets and fully leverage its flexibility and systemic value.

5 Conclusions

In summary, the energy storage market has a vast scale and broad prospects, and it is a necessary safeguard to achieve the "dual carbon" goals. However, the current development of energy storage still faces issues such as insufficient profit models, imperfect management systems, and unclear industry standards. Shandong province should combine its existing industrial advantages and scale benefits to play an active role in technological innovation, cost reduction, policy formulation, and business model development within the energy storage industry, promoting the healthy and stable development of the energy storage industry.

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