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Review

A Review of the Development of the Energy Storage Industry in China: Challenges and Opportunities

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Abstract: As the global carbon neutrality process accelerates and energy transition continues, the energy storage industry is experiencing unprecedented growth worldwide, emerging as a key strategic sector. Focusing on China's energy storage industry, this paper systematically reviews its development trajectory and current status, examines its diverse applications across the power supply and grid, including for users, and explores influencing factors such as energy price fluctuations, policy support, and market mechanisms. Furthermore, this paper assesses the industry's profound economic and social impacts, highlighting its crucial role in advancing energy structure transformation and fostering the new energy vehicle sector. Despite challenges such as structural overcapacity, high storage costs, and an underdeveloped power market, continuous technological advancements, rapid expansion of new energy capacity, and strengthened policy support present numerous growth opportunities for the industry. This paper reviews the existing literature and offers policy recommendations that include constructing a more comprehensive policy framework, fostering the energy storage recycling market, and leveraging AI in energy storage R&D.

Keywords: energy storage industry; energy storage policy; energy transition; dual carbon goals

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1. Introduction

In response to the climate crisis, countries worldwide are developing clean energy to reduce reliance on fossil fuels and facilitate the transition to a low-carbon energy sector. Among them, the United Kingdom leads in clean energy deployment, particularly in offshore wind power. The United States is experiencing rapid growth in clean energy installations, with utility-scale solar power emerging as the primary driver of expansion. Under the "dual carbon" goals, China is prioritizing renewable energy development, particularly wind and solar power. By June 2024, China's installed capacity for renewable energy power generation reached 1.653 billion kilowatts, a year-on-year increase of 25%, comprising 53.8% of its total power generation capacity. Despite rapid expansion, the inherent intermittency and volatility of wind and solar energy pose major challenges to maintaining grid stability and ensuring a reliable power supply, potentially leading to a series of issues such as power outages and supply restrictions [1,2]. Unlike traditional fossil fuel plants, renewables generate electricity in a fluctuating manner, influenced by weather conditions, seasonal variations, and geographic constraints. This creates difficulties in balancing real-time supply and demand, leading to risks such as curtailment and power grid congestion [3]. Addressing these technical barriers is essential for China to maximize renewable energy utilization and establish a sustainable energy system.

To address these challenges, energy storage technologies have become a driving enabler of China's energy transition. They help mitigate fluctuations in renewable energy generation, facilitate grid balancing, improve peak load management, and enhance overall system flexibility [4]. By storing surplus energy during times of low demand and releasing it at peak demand, energy storage ensures efficient utilization of renewable energy sources. Furthermore, as China shifts to a market-oriented electricity system, energy storage is expected to support ancillary services, demand-side response, and decentralized energy systems, thereby accelerating the integration of renewables [5,6]. The industry encompasses various technologies, including pumped hydro storage, battery storage (lithium-ion, sodium-ion, flow batteries), hydrogen storage, and compressed-air-energy storage (CAES) [7]. Among these, lithium-ion batteries have grown rapidly due to decreasing costs and advancements in materials and efficiency. Additionally, CAES and hydrogen storage are gaining traction as viable long-term solutions. China's energy storage industry is experiencing rapid expansion and has been designated as a strategic emerging sector. Since the launch of the "dual carbon" goals, the cumulative installed capacity of new energy storage has surged from 3.81 GW in 2020 to 78.32 GW in 2024 (Figure 1).

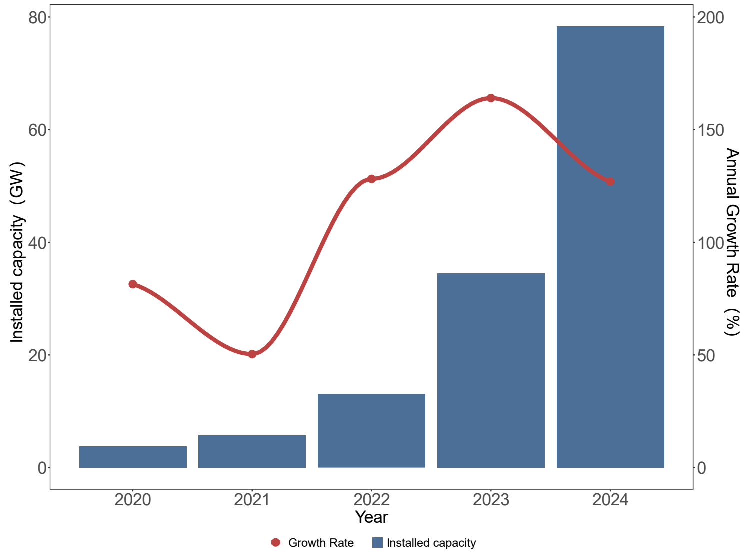

Figure 1. Cumulative installed capacity of China's new energy storage market. (Data from China Energy Storage Alliance, https://www.cnesa.org/ (accessed on 28 February 2025)).

The development of China's energy storage industry has gained strategic importance, attracting increasing policy support, technological innovation, and investment. Both central and local governments are actively advancing the development of an energy storage policy framework, encompassing energy storage planning, subsidy programs, new energy storage initiatives, and electricity pricing policies. However, despite rapid advancements, the sector faces multiple challenges, including high initial capital costs, uncertainties regarding policy and regulation, market inefficiency, and technological constraints [8]. The financial landscape for energy storage remains complex, with investment risks and revenue uncertainties hindering large-scale adoption. Furthermore, the evolving policy environment requires dynamic regulatory frameworks to support the deployment of energy storage and its integration with power markets [9]. On the technological front, improvements in storage efficiency, safety, and lifecycle costs remain areas of active research and development. Clarifying the factors influencing energy storage, understanding its economic and societal impacts, and scientifically assess the related opportunities and challenges are crucial for advancing China's energy transition and achieving its dual carbon goals.

The main contributions of this paper are as follows. First, it systematically reviews the challenges and opportunities shaping China's energy storage industry. Second, it offers a multi-dimensional analysis of the factors influencing energy storage development, encompassing economic, regulatory, and technical aspects. By integrating these perspectives, this paper highlights the complex interdependencies shaping the industry and proposes targeted strategies to overcome these challenges. Third, by synthesizing existing research and aligning it with China's energy strategy, this review aims to provide both theoretical and practical insights into the future development of energy storage.

2. The Development History and Current Status of the Energy Storage Industry

2.1. Development History

As China's energy structure gradually transitions from coal-dominated to a more diversified mix, energy security and the volatility of renewable energy have become increasingly prominent concerns. Energy storage entered its initial phase around 2000, with pumped storage as the primary technology and electrochemical energy storage (such as lithium batteries) still in the laboratory and small-scale demonstration stages. The Chinese government began exploring these technologies and conducting foundational research, laying the groundwork for rapid development in subsequent years.

From 2010 to 2015, the energy storage industry entered a stage of policy guidance and commercialization. Energy storage, as a critical technology for ensuring renewable energy consumption and grid stability, gained significant attention at the policy level. In 2014, the State Council issued the Energy Development Strategic Action Plan (2014–2020), which included energy storage as one of the nine key innovation areas, marking its first inclusion in a national plan (data source: https://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm (accessed on 28 February 2025)). During this period, energy storage technologies achieved notable breakthroughs, particularly in lithium battery energy storage. Lithium battery systems began to be demonstrated and applied in grid regulation and for the integration of renewable energy. At the same time, Chinese companies such as BYD and CATL entered the energy storage market, gradually applying lithium battery solutions to homes, businesses, and grid systems.

In 2016, energy storage technology entered a phase of large-scale deployment. Its role in power regulation, renewable energy integration, and related areas became increasingly prominent, marking the industry's shift toward industrialization. The cost of lithium batteries continued to decline, and the technology gradually matured. Significant improvements in battery energy density and safety allowed new energy storage systems to be scaled up for broader application. In 2016, the Energy Technology Revolution Innovation Action Plan (2016–2030) was released, outlining goals for technological breakthroughs in energy storage and advancing the industry to a higher technological level. In 2017, the National Development and Reform Commission (NDRC), along with six other ministries, issued the Guiding Opinions on Promoting the Development of Energy Storage Industry and Technology, which was the first official document on the large-scale development and application of energy storage technologies in China (data source: https://www.gov.cn/xinwen/2017-10/12/content_5231304.htm (accessed on 28 February 2025)). The document highlighted the positive trend of diversified development in China's energy storage sector and noted that the technology had established a preliminary foundation for industrialization.

Since the introduction of the "dual carbon" goal, the demand for energy storage has grown increasingly urgent. China's energy storage industry has experienced rapid development and has become a key technology for the structural transformation of the energy sector. In 2021, the NDRC and the National Energy Administration issued China's first national-level comprehensive energy storage policy under the 14th Five-Year Plan: Guiding Opinions on Accelerating the Development of New Energy Storage (data source: https://www.gov.cn/zhengce/zhengceku/2021-07/24/content_5627088.htm (accessed on 28 February 2025)). This policy outlined specific measures to accelerate the development of energy storage and encouraged enterprises and local governments to implement demonstration projects for the application of energy storage. In 2022, the 14th Five-Year Plan for New Energy Storage Development set out the clear requirements and key tasks of China's new energy storage industry, focusing on advancing technologies such as superconducting and supercapacitor energy storage.

From a stock perspective, by the end of 2023, China's cumulative installed power energy storage capacity reached 86.5 GW, accounting for 30% of the global market, representing a 45% year-on-year increase. In terms of new additions, 2023 marked a record high, with newly installed power and energy storage reaching 21.5 GW and 46.6 GWh, respectively, which was more than triple the new capacity commissioned in 2022, representing a growth of over 150% (data from the CNESA global energy storage database, http://www.esresearch.com.cn/ (accessed on 28 February 2025)). The important policies shaping China's energy storage industry are presented in Figure 2.

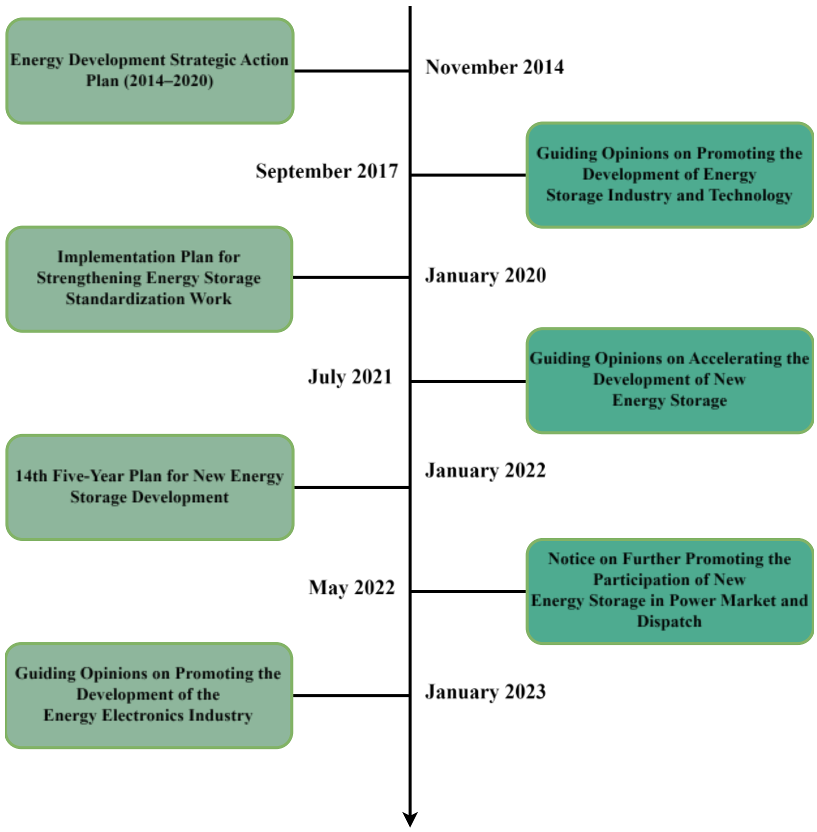

Figure 2. China's energy storage industry policies.

2.2. Industrial Chain

As a crucial driver of energy transformation and the development of new power systems, the energy storage industry has grown rapidly. China's energy storage industrial chain is now well developed, spanning upstream, midstream, and downstream sectors. This comprehensive chain encompasses various stages, including upstream materials and equipment manufacturing, integration and installation of midstream energy storage systems, and downstream application scenarios and operational services (as shown in Figure 3).

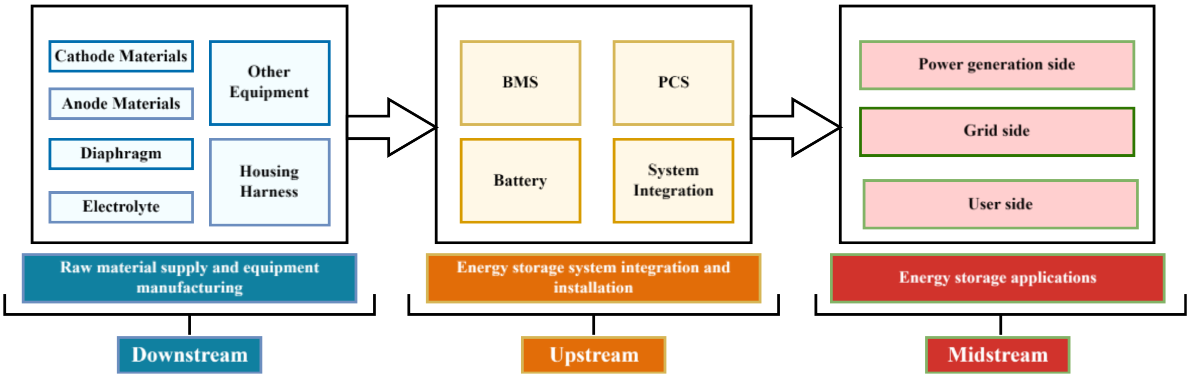

Figure 3. Energy Storage Industrial Chain.

Upstream manufacturing of energy storage system equipment forms the foundation of the industry chain, primarily involving research, development, and the production of raw materials, energy storage devices, and core battery components. The core of energy storage technology is in the storage batteries, whose performance and cost are directly shaped by the upstream materials' quality and the supply capacity [10]. Raw materials for batteries include cathode materials, anode materials, electrolytes, and separators. Key cathode materials include lithium iron phosphate, ternary compounds, and sodium ion. Lithium iron phosphate batteries have been widely adopted for energy storage due to their high safety, long cycle life, and low cost [11]. Energy storage equipment and components also include battery management systems, energy management systems, storage converters, and inverters. Among these, energy storage converters are critical for enabling bidirectional energy conversion, controlling the charging and discharging processes, and they are increasingly attracting attention from investors [12]. Competition in the upstream energy storage battery sector is intense. Currently, China's energy storage battery industry holds a strong competitive advantage, with major battery manufacturers such as CATL and BYD occupying significant positions in the global market.

The midstream is the core link of the energy storage industry chain, primarily involving the integration, installation, and commissioning of energy storage systems. Energy storage system integrators combine upstream components such as batteries, BMS, and PCS to create complete energy storage solutions [13]. Integration of energy storage systems is typically a diversified project, with battery selection, system control, and management system construction tailored to specific application scenarios. In general, compared with battery systems for electric vehicles, integration of energy storage systems is more complex and precise, addressing various factors like battery management, thermal safety, and intelligent monitoring. System integrators are responsible for optimizing and integrating various energy storage equipment and management systems in the midstream, to meet the needs of different applications [14].

The downstream sector primarily focuses on energy storage system operations, covering different application scenarios and related services. As energy storage technology matures and costs decrease, its applications continue to expand across power generation, transmission, distribution, and consumption. In the power systems, energy storage is typically categorized into three primary application scenarios: power generation, grid, and user [15]. The user side is further divided into industrial and commercial distributed storage and household storage. By the end of 2022, the total energy storage capacity across the power supply, grid, and users accounted for 48.4%, 38.72%, and 12.88%, respectively (data from the CHINA ELECTRICITY COUNCIL, https://cec.org.cn/ (accessed on 28 February 2025)). Electrochemical energy storage varies across these application scenarios. Energy storage on the power generation side is primarily managed by state-owned enterprises such as Huaneng, Huadian, Datang, and State Energy Group, while grid-side integration is led by power companies. Operational services for energy storage include managing energy storage power stations, energy management services, and power market transactions. Energy storage operations require a professional team to monitor, maintain, and optimize systems in real time to ensure efficient operation. Additionally, these teams must participate in energy transactions and manage market operations to maximize both economic benefits and the system's flexibility.

2.3. Current Status Under Dual Carbon Goals

In 2023, China ranked first globally in terms of the numbers of SCI papers published, patent applications, and installed capacity in the energy storage sector, further solidifying its global leadership. Among the related technologies, pumped hydro energy storage (PHES), compressed-air-energy storage (CAES), flywheel storage (FES), lithium-ion batteries, flow batteries, and supercapacitors have received considerable attention due to their technological maturity and scalability. A comparative analysis of these technologies reveals differences in efficiency, energy density, cycle life, and response time, which influence their suitability for different applications (Table 1).

Table 1. Comparison between major energy storage technologies.

Technology	Power Station Power Level	Response Time Level	Energy Density (W·h/kg)	Operating Life/Number of Cycles	Construction Costs (RMB/KW)
PHES	Gigawatt	Minute	0.5–1.5	≥50 (year)	About 7500
CAES	100 Megawatt	Minute	3–60	30–50 (year)	5000–6000
FES	Megawatt	Millisecond	10–30	≥20 (year)	10,000–15,000
Lithium-ion	100 Megawatt	Millisecond	75–300	3000–10,000 (times)	About 2000
Flow	100 Megawatt	100 Millisecond	12–80	6000–15,000 (times)	2000–4000
Supercapacitors	Megawatt	Millisecond	0.05–15.00	≥50,000 (times)	2000–15,000

Pumped storage is currently the most mature of these technologies, while battery storage is advancing rapidly. Some other energy storage technologies are developing more slowly, with some still in the demonstration phase. Pumped storage relies on height difference and gravity, using water to store and release energy [16]. It is characterized by mature technology, low cost, and a long lifespan, though it requires high initial investment and has a long development cycle. Lithium-ion battery storage, on the other hand, offers greater flexibility in terms of site selection and construction, making it more compatible with large-scale deployment alongside wind and solar power. Local governments have increasingly focused on integrating battery energy storage solutions. At present, pumped storage remains dominant, with lithium battery energy storage serving as a complementary solution under specific conditions (data source: The Energy Storage Industry Research White Paper 2024, http://www.esresearch.com.cn/report/?category_id=26 (accessed on 28 February 2025)). In the future, lithium battery energy storage is expected to surpass pumped storage, with the focus of power system demand shifting toward long-duration energy storage, particularly in the area of flow batteries.

China's energy storage has achieved significant advancements in basic research, key technologies, and integrated demonstration projects. For physical energy storage, pumped storage is the dominant technology for large-scale energy storage, having evolved toward high-altitude, large-capacity, variable-speed systems. Key breakthroughs have been achieved in technologies such as large-diameter inclined-shaft tunneling and variable-speed pumped storage units. Compressed-air-energy storage has advanced from a single 100 MW system to the 300 MW level, significantly improving system efficiency, with multiple demonstration projects successfully connected to the grid. In the context of chemical energy storage, lithium-ion batteries continue to experience rapid growth, with advancements in large-capacity battery cells and long-life battery technologies, along with the mainstream adoption of liquid cooling systems. Flow batteries have made notable progress in terms of ion conduction membranes and stack design, with widespread implementation of all-vanadium flow batteries. Supercapacitors for electromagnetic energy storage have undergone continuous innovation in terms of their electrode materials, electrolytes, and device design, with their applications expanding to smart grids and rail transit.

Despite these advancements, several challenges remain. First, technologies such as variable-speed pumped storage, flywheel energy storage, and supercapacitors still lag behind the international advanced level, requiring further improvements in performance and cost reduction. Second, the safety and reliability of energy storage systems need strengthening, particularly for large-scale applications, where thermal runaway and fire risks remain significant challenges. Additionally, the economic and market-driven mechanisms for energy storage are still underdeveloped, necessitating further policy support and market optimization.

From the perspective of application scenarios, China's energy storage market is showing a clear trend of differentiation; demand for large-scale energy storage (large storage) is rising rapidly, while household storage continues to grow steadily. Large-scale storage, primarily used on the grid and for power generation, remains the main driver of China's energy storage market. Its demand is fueled by policy support, the rapid expansion of renewable energy, and the increasing need for flexible resources in the power system. Notably, China's cumulative wind power capacity increased from 163.67 million kilowatts in 2017 to 441.34 million kilowatts in 2023, with an annual compound growth rate of 15.22% (data source: China Energy Storage Industry Development Status Research and Investment Prospect Analysis Report, https://www.chinabaogao.com/detail/731312.html (accessed on 28 February 2025)). Meanwhile, newly installed photovoltaic capacity reached 216.88 GW in 2023, a year-on-year increase of 148%, setting a historical record (data source: China Energy Network, www.cnenergynews.cn (accessed on 28 February 2025)). The intermittent spatiotemporal distribution and unpredictable nature of wind and photovoltaic power make it difficult for them to directly meet the stable power supply needs of the grid, resulting in significant energy curtailment. Energy storage systems effectively address this challenge by storing excess electricity and releasing it when needed, enhancing grid stability and increasing renewable energy absorption capacity. With the rapid growth of renewable energy sources, the demand for energy storage has surged. Additionally, household energy storage, primarily used by residential and small industrial or commercial users, has also seen steady growth [17]. This growth is mainly influenced by electricity price policies, user awareness, and technological advancements.

3. Factors Affecting the Development of the Energy Storage Industry

The development of China's energy storage industry is influenced by multiple factors, including technological advancements, the fluctuating prices of raw materials and electricity, market demand, and government policies. Understanding these factors is essential for grasping the broader trends, as each plays a key role in shaping the industry's trajectory. The following analysis explores how technology, pricing dynamics, market demand, and policy impact the evolution of energy storage technologies (as shown in Table 2).

Table 2. Factors affecting the energy storage industry.

Influencing Factors	Mechanism of Action	References
Technological advancements	Technological progress in lithium-ion batteries, compressed-air storage, and hydrogen energy storage improves efficiency, reduces costs, and enhances integration with renewable energy sources.	Tong et al., 2021 [18]; Huang and Li, 2022 [19]; Matos et al., 2022 [20]; Zhang et al., 2023 [21]
Raw material costs	Fluctuations in the prices of critical materials like lithium, cobalt, and nickel impact the overall cost of energy storage systems, driving research into alternative battery chemistries.	Yu and Manthiram, 2021 [22]; Klopčič et al., 2023 [23]; Zhao et al., 2023 [24]
Electricity prices	Energy storage systems benefit from electricity price fluctuations, storing energy when prices are low and discharging when they are high, making arbitrage strategies economically viable.	Wu and Lin., 2018 [25]; Topalović et al., 2023 [26];
Market demand and applications	Rising adoption of renewable energy and electric vehicles increases demand for storage solutions to stabilize the grid and ensure reliability, promoting further innovation and expansion of capacity.	Elio et al., 2021 [27]; Zhu et al., 2022 [28]
Macroeconomic policies	Government policies, including subsidies, tax incentives, and regulatory frameworks, play a crucial role in market development, cost reduction, and commercialization of technology.	McIlwaine et al., 2021 [29]; Geng et al., 2022 [30]

3.1. Technological Advancements

Technological advancements are crucial for the growth of the energy storage industry. Among the various technologies, lithium-ion batteries, CAES, and hydrogen energy storage are gaining significant attention [18,31]. Lithium-ion batteries have become the industry cornerstone due to their high efficiency, long life cycle, and ability to provide reliable grid services [32]. Additionally, advancements in hydrogen production [33,34] have enabled large-scale hydrogen energy manufacturing, driving greater demand for hydrogen storage solutions.

In China, significant research has focused on improving the efficiency and reducing the costs of energy storage technologies. For instance, CAES, which stores energy as compressed air, has proven effective for large-scale applications. It is especially notable for its capacity to store energy during periods of low demand and releasing it when demand is high, making it an ideal complement to intermittent renewable energy sources like wind and solar. Similarly, advancements in hydrogen storage technologies are enhancing the large-scale storage and transport of energy, further strengthening the case for integrating renewable energy into the power grid [35]. If successfully scaled and commercialized, these technologies could significantly lower the cost of energy storage and enhance the efficiency of power systems, making integration of renewable energy sources more feasible and reliable.

3.2. Raw Material Costs

Another significant factor influencing the development of the energy storage industry in China is the cost of raw materials. Energy storage technologies, especially lithium-ion batteries, are heavily dependent on materials such as lithium, cobalt, and nickel. The cost of lithium iron phosphate (LFP) materials accounts for approximately 40% of the total cost of LFP battery cell materials, creating a noticeable disparity compared with other materials costs. With the continuous expansion of global lithium mining, the price of lithium carbonate has also experienced considerable volatility, exhibiting an overall downward trend. The price of battery-grade lithium carbonate has declined sharply from its peak of RMB 585,500/ton in 2022 to RMB 75,500/ton in March 2025, a decrease of over 87% (data source https://www.mysteel.com/mmlc (accessed on 28 February 2025)). These price fluctuations have significantly impacted upstream mining companies while also exerting considerable pressure on downstream industry players. Performance reports from numerous companies highlight that fluctuations in raw material prices have had a substantial effect on their financial results.

The rising costs of raw materials pose a challenge for energy storage developers in China, as they directly affect the production costs of storage technologies. To mitigate these effects, efforts are underway to develop alternative battery chemistries that use more affordable materials, and also to improve recycling rates. Technological advancements such as progress in solid-state and sodium-ion batteries hold promise for reducing dependence on costly materials like lithium and cobalt [24]. However, the widespread adoption of these technologies will require significant investment in research and development. Therefore, fluctuations in the prices of raw materials and ongoing efforts to reduce material dependency through innovation and recycling will be crucial in determining the long-term economic sustainability of China's energy storage industry.

3.3. Electricity Prices

Electricity prices are a key factor influencing the economic viability of energy storage systems. The sector capitalizes on price fluctuations by storing energy when prices are low and discharging it when prices increase. This arbitrage model offers significant profit potential, especially in China, where electricity prices fluctuate according to supply conditions, seasonal demand, and the growing integration of renewable energy sources [36]. The Chinese electricity market features a dual-tiered pricing system—a basic price set administratively and a market-driven price for peak-load electricity. This price volatility creates opportunities for energy storage to stabilize the grid by balancing supply and demand.

However, the profitability of energy storage is heavily influenced by the regulatory environment. For example, if the government imposes strict pricing caps or reduces variability in pricing, the incentives for deploying large-scale storage systems may diminish. Additionally, energy storage systems are most beneficial in markets with highly volatile prices [37]. As the penetration of renewable energy increases in China, the variability in electricity prices is expected to grow, providing more opportunities for energy storage to thrive. Policies such as time-of-use pricing and demand response mechanisms can further enhance the economic attractiveness of energy storage by offering higher prices for energy during peak demand periods. Therefore, the dynamics of electricity prices, coupled with regulatory support, will play a critical role in shaping the development of China's energy storage sector [25].

3.4. Market Demand and Applications

The growing demand for renewable energy and electric vehicles (EVs) is significantly boosting the energy storage market in China. As the country strives to reduce its carbon footprint, the use of renewable energy sources like solar and wind has surged. However, their intermittent nature requires efficient energy storage systems to ensure a stable and reliable power supply [28]. Additionally, the rising EV market also drives dual demand for energy storage—both for grid stabilization and vehicle battery charging. With the increasing adoption of EVs, the demand for energy storage systems will continue to grow, fostering innovation in battery technologies [38].

3.5. Macroeconomic Policies

The Chinese government has actively promoted energy storage technologies to reduce reliance on fossil fuels. Several initiatives and policy frameworks have been introduced to accelerate the deployment of energy storage systems. For instance, the 14th Five-Year Plan for New Energy Storage Development highlights the critical role of energy storage in ensuring grid stability and enhancing the integration of renewable energy. The plan sets ambitious targets for advancing new energy storage technologies, emphasizing the need to scale up manufacturing, improve efficiency, and lower costs. Additionally, the government has provided financial support through subsidies, tax incentives, and favorable financing conditions, encouraging both domestic and foreign investment in the sector. The establishment of national standards and regulations has also created a more predictable and transparent market environment, essential for long-term growth.

Local policies also play a crucial role in promoting the development of the energy storage industry, primarily through various measures such as electricity pricing mechanisms, capacity compensation, fiscal incentives, and ancillary service markets to enhance the competitiveness of energy storage projects. Local electricity pricing mechanisms guide the charging and discharging behavior of energy storage equipment through price signals, thereby improving the overall efficiency of the power system. Compared with fixed electricity prices, peak–valley electricity pricing can enhance the return on investment of energy storage projects, achieving both economic and environmental benefits [39]. Moreover, local governments have addressed the high fixed-investment costs of new energy storage technologies such as lithium-ion batteries by establishing capacity compensation mechanisms, thereby improving the financial feasibility of energy storage projects. This mechanism is particularly suitable for independent energy storage projects. Some scholars have reported that capacity compensation mechanisms help independent energy storage projects recover investment costs by providing economic incentives and enhancing their market value [40].

The success of energy storage technologies in China is heavily reliant on sustained government support [29,41]. The government's ability to set clear policy objectives, provide financial incentives, and create a supportive regulatory framework will determine the speed at which energy storage is adopted. Thus, the growth of the energy storage sector in China is influenced not only by market forces but also by government intervention, which can either accelerate or hinder progress [42,43].

4. Impact of Energy Storage on Economy and Society

Energy storage plays a vital role in economic and social transformation by enhancing the stability and flexibility of energy systems. As the world transitions to sustainable energy, storage balances the intermittent supply of renewables, strengthens energy security by providing backup during disruptions, and contributes to economic growth by optimizing energy use, reducing costs, and enabling the integration of clean energy. This paper examines the impact of energy storage on energy transition, security, and economic development.

4.1. Accelerating Energy Transition

Energy storage technologies are essential for advancing a low-carbon energy system. They address a number of challenges associated with renewable energy integration, particularly variability and intermittency, ensuring a more stable grid. This paper examines how energy storage contributes to the future of energy, focusing on integration of renewable energy and grid stability.

4.1.1. Promoting Integration of Renewable Energy

The variability of wind and solar energy presents a major challenge for grid integration, as electricity generation depends on the weather, time of day, and seasonal changes, often causing supply–demand mismatches [2]. As a result, regions with high penetration by renewables often experience a substantial reduction in or waste of excess energy because demand is insufficient to absorb the surplus. This phenomenon is known as "curtailment"; it not only lowers the efficiency of renewable energy systems but also leads to economic losses and missed environmental benefits.

Energy storage systems address this issue by acting as a buffer between supply and demand. When renewable generation exceeds demand, energy storage systems can absorb the excess power, storing it for later use. Conversely, when renewable generation is low, the energy storage system can release stored electricity back into the grid to meet demand. This functionality mitigates curtailment and ensures a higher utilization rate of renewable resources. By reducing curtailment, energy storage enhances the economic viability of renewable energy projects and supports the achievement of climate and energy goals [44]. Furthermore, the ability to store excess renewable energy helps maintain grid stability. It enables a more flexible response to sudden drops or increases in renewable generation, which becomes particularly important as renewable energy provides a larger share of the energy mix. Thus, energy storage contributes directly to overcoming the challenges of intermittency and curtailment, providing a pathway to integrate renewables at scale without compromising the reliability of the power grid [45].

4.1.2. Ensuring Stable Power Supply

As global energy systems shift away from fossil fuels and towards renewable sources, maintaining a stable and reliable power supply becomes increasingly complex. Renewable energy sources, while essential for decarbonization, introduce variability and unpredictability into energy systems. This variability can cause power supply disruptions if not properly managed. Energy storage systems can play a critical role in stabilizing the grid, particularly as the share of renewable energy in the mix continues to grow [46].

Energy storage can act as a quick-response resource during sudden spikes in demand. For example, during heatwaves or cold snaps, when electricity demand surges due to increased use of air conditioning or heating, storage systems can discharge power rapidly to meet the increased load. Grid overloads and power outages lead to severe economic losses, which can be prevented by using mobile energy storage systems to ensure continuous power supply during disruptions [47]. The ability of storage systems to respond swiftly ensures that the grid can maintain a stable supply even during times of peak demand. Another challenge is managing the daily and seasonal fluctuations in energy consumption and production. Solar power generation, for instance, peaks during midday hours, while electricity demand is typically highest in the evening. Similarly, seasonal changes affect both renewable generation and consumption patterns, with winter months often seeing higher energy demand and lower generation via renewables. Energy storage systems mitigate fluctuations by storing surplus energy during periods of low demand or high generation and releasing it during peak demand or at times of low renewable-sourced output. This approach flattens the load curve and reduces the need for peaking power plants [48].

In addition to managing daily and seasonal variability, energy storage systems also offer backup power during emergencies or system failures. In the event of grid disruption caused by equipment malfunction or extreme weather events, energy storage systems can provide instant power to critical infrastructure and help stabilize the grid until normal operations are restored. Energy storage serves as an insurance policy against grid instability, contributing to overall energy security [49].

4.2. Ensuring Energy Security

Another important benefit of energy storage is the shift from a centralized energy system to a distributed energy system where power generation and consumption are performed locally [50]. Distributed energy resources (DERs), including local battery storage, rooftop solar panels, and small-scale wind turbines, are increasingly deployed to reduce dependence on large centralized grids. DERs enable consumers to generate, store, and consume their own energy, enhancing the network's flexibility.

Energy storage plays a pivotal role in this transition by enabling the storage and use of locally generated power as needed. For instance, excess solar energy produced during the day can be stored in batteries and utilized during the evening when demand peaks. This helps reduce grid dependence by increasing self-sufficiency, enabling users to rely more on their renewable energy sources rather than external grid power [51]. Moreover, energy storage can help alleviate the pressure on transmission infrastructure, as localized storage reduces the need for long-distance power transmission. DERs make the entire energy system more flexible and less vulnerable to external shocks.

Additionally, DERs contribute to improved energy security. By diversifying energy sources and enabling local control over energy resources, energy storage enhances national and regional energy resilience. In remote or off-grid areas, energy storage can provide a stable energy supply without the need for extensive transmission infrastructure, reducing the vulnerability of these areas to grid disruptions. These microgrids also align with broader goals of energy independence and sustainability, allowing communities to reduce their reliance on fossil fuels and large-scale, centralized power generation [52].

4.3. Boosting Economic Development

4.3.1. Driving Growth in Related Industries

The energy storage industry has catalyzed growth across several related industries, including the battery manufacturing, smart grid technologies, and energy management systems sectors [53]. As the demand for energy storage solutions grows, the need for advanced materials and manufacturing techniques for energy storage devices increases; examples include lithium-ion batteries, flow batteries, and hydrogen storage. This has led to the creation of new industries and job opportunities, particularly in the fields of research, engineering, and production.

Furthermore, energy storage is closely linked to the growth of the electric vehicle market. Advances in energy storage technology have led to improvements in electric vehicles' range, efficiency, and affordability [54]. This interconnection between energy storage and electric vehicles has created a symbiotic relationship, where developments in one field fuel progress in the other. As a result, energy storage technologies have become a critical enabler of the broader clean transportation revolution, providing both environmental and economic benefits. The growing energy storage market also promotes innovation in other areas, such as energy management systems that can help optimize energy use in homes, businesses, and industries [55]. This creates fertile ground for collaboration across sectors, leading to enhanced technological capabilities and increased efficiency in energy production, distribution, and consumption.

4.3.2. Reducing Energy Costs

Energy storage can significantly lower the costs of energy production and distribution. By storing energy during low-demand periods and discharging it during peak demand, energy storage systems reduce the need for costly peaking power plants, which are typically inefficient and expensive to operate [56]. This reduction in costs is passed on to consumers in the form of lower electricity prices during peak periods. In addition to reducing peak generation costs, energy storage also lowers the costs associated with transmitting and distributing electricity.

Energy storage systems (ESSs) integrated into virtual power plants (VPPs) reduce the need for extensive transmission infrastructure, thereby alleviating the strain on long-distance power transmission [57]. This leads to a more cost-effective energy system overall, as utilities can avoid the high capital expenditures associated with grid expansion.

5. Challenges and Opportunities in the Energy Storage Industry

The energy storage industry stands at a critical juncture, with the demand for advanced storage solutions rising alongside substantial challenges. The global shift toward renewable energy, driven by increasing shares of wind and solar power, has intensified the need for efficient and reliable storage technologies. In 2021, China accounted for over 50% of the world's new renewable energy installations, particularly in wind and solar power [58]. Despite this rapid expansion, the country faces significant constraints on energy storage, such as imbalance between supply and demand, the high costs of energy storage, and so on. This section details the key challenges and opportunities in China's energy storage industry (as shown in Table 3).

Table 3. Challenges and Opportunities in the Energy Storage Industry.

Category	Specific Category	Description	References
Challenge	Structural imbalance between supply and demand	Low-cost, short-duration storage solutions dominate the market, while high-end storage remains underdeveloped.	Ganzer et al., 2022 [58]
	High costs of energy storage systems	Energy storage technologies, particularly lithium-ion batteries, remain expensive due to raw materials costs, manufacturing complexities, and operational expenses.	Tong et al., 2022 [59]; Song et al., 2023 [60]
	Lack of guarantee of market players	Regulatory frameworks and market mechanisms do not adequately value energy storage, limiting its economic viability and integration into the energy market.	Ganzer et al., 2022 [58]
Opportunity	Growing demand for energy storage	As renewable energy continues to penetrate, the need for effective storage solutions grows, to balance fluctuations in supply and demand.	Topalović et al., 2023 [26]
	Strong government support and policy incentives	China's policy initiatives, including subsidies and mandatory storage integration with renewables, are fostering rapid growth in the energy storage sector.	Zhao and Zhang, 2025 [61]; Liu et al., 2023 [62]
	Technological advancements	Advances in battery chemistry, AI-driven optimization, and so on.	Ai et al., 2022 [63]; Entezari et al., 2023 [64]
	Energy security enhancement	Energy storage enhances energy security by reducing dependence on imported fossil fuels and enabling strategic energy reserves.	Odoi-Yorke et al., 2023 [65]; Thaler et al., 2022 [66]

5.1. Challenges

5.1.1. Structural Imbalance Between Supply and Demand

One of the challenges facing the energy storage industry is structural imbalance; low-end storage solutions dominate the market, while advanced technologies remain scarce. Low-cost options such as small-scale lead-acid batteries have expanded rapidly due to their cost-effectiveness for short-term applications. However, these systems are insufficient for the large-scale, long-duration storage required to integrate high levels of intermittent renewable energy sources like wind and solar. In contrast, advanced storage solutions such as long-duration batteries, flow batteries, and power-to-gas systems are essential for ensuring grid stability and reducing curtailment of renewable energy, but these methods remain underdeveloped.

The shortage of high-end technologies hinders the scaling of storage systems capable of addressing seasonal and inter-annual fluctuations in renewable energy production [67]. Despite the rapid expansion of renewable energy infrastructure, the lack of efficient long-term storage systems has resulted in significant inefficiencies and wastage of renewable energy during periods of high generation and low demand [58].

5.1.2. High Costs of Energy Storage Systems

The cost of energy storage remains a major barrier to the sector's growth. Energy storage technologies, particularly batteries, are costly to develop, manufacture, and deploy at scale. For instance, the lithium-ion batteries that dominate the market continue to incur high capital costs. Key cost drivers include raw materials like lithium, cobalt, and nickel, which are often sourced from unstable regions, as well as manufacturing processes that demand significant energy input. Consequently, the price of these systems remains prohibitive for large-scale deployment, particularly in grid-scale storage applications [68]. In addition, the operational costs of energy storage systems, including maintenance, energy losses during charging and discharging, and periodic replacements, further increase the overall cost burden. Power-to-gas and long-duration storage systems suffer from high capital expenditure and relatively low round-trip efficiency; with the need for seasonal energy balancing, high levelized costs of storage are incurred [69]. In a typical electrochemical energy storage system, battery pack costs comprise up to 67% of the total, followed by energy storage inverters at 10%, while the battery management system (BMS) and energy management system (EMS) account for 9% and 2%, respectively (data source: https://www.ccedia.com/storage_detail/8260.html (accessed on 28 February 2025)). These high costs undermine the economic viability of energy storage, limiting its competitiveness against more established energy generation technologies.

5.1.3. Lack of Guarantee of Market Players

Energy storage systems are still struggling to find a stable position within electricity markets, particularly in China. The regulatory environment often fails to adequately value energy storage's role in ensuring grid stability, such as in balancing intermittent renewable energy sources, and its capacity to respond quickly to demand peaks. In many Chinese regions, energy storage is classified merely as an ancillary service, limiting its market participation rights compared with conventional generation sources like coal or gas-fired plants. This lack of market integration hinders energy storage from achieving stable and predictable revenue streams, making it a less attractive investment [60].

Although energy storage is increasingly recognized as essential for integrating renewable energy, the market remains dominated by state-owned power companies that control generation and grid operations. These companies have been slow to embrace storage solutions, due to the entrenched role of conventional generation in providing energy. Furthermore, the regulatory framework does not fully incentivize energy storage deployment, with policies that often favor short-term cost savings over long-term system flexibility. As a result, energy storage solutions remain underutilized, leading to inefficiencies and missed opportunities to enhance grid stability [58].

5.2. Opportunities

5.2.1. Growing Demand for Energy Storage

As countries worldwide accelerate efforts to achieve carbon neutrality goals, demand is surging for renewable energy sources, particularly wind and solar power. China aims to reach carbon neutrality by 2060, with wind and solar energy becoming important sources of electricity generation in the coming decades. As the installed capacity grows, the need for energy storage solutions increases accordingly, and these are crucial for integrating the variable and intermittent sources of renewable energy.

The intermittency of wind and solar energy leads to a mismatch between generation and consumption. This disparity necessitates large-scale energy storage systems to capture surplus energy during periods of high generation and release it when demand peaks, ensuring a balance of supply and demand [58]. Without adequate storage capacity, a considerable share of renewable energy would be curtailed, wasting resources and limiting its potential to replace fossil fuels.

Despite the rising demand, deployment of energy storage has lagged behind the expansion of renewable energy. The energy storage sector, particularly for long-duration and large-scale applications, remains underdeveloped compared with technologies in the renewables sector. Advanced storage solutions such as long-duration batteries, compressed-air-energy storage, and flywheel energy storage are still in the early stages of development and deployment. Consequently, a significant gap persists between growing renewable capacity and the storage required for full grid integration [70]. Closing this gap is crucial for achieving a fully decarbonized energy system.

5.2.2. Strong Government Support and Policy Incentives

The Chinese government has launched multiple initiatives to advance energy storage technologies. The 14th Five-Year Plan for energy development, covering the period from 2021 to 2025, is a critical policy framework that emphasizes large-scale investments in energy storage to achieve carbon neutrality by 2060. Specifically, this plan outlines a roadmap for increasing energy storage capacity, particularly in conjunction with integrating renewable energy and enhancing grid flexibility. Furthermore, development of energy storage aligns with China's broader goal of decarbonizing its power sector and reducing reliance on fossil fuels.

China's energy storage sector also benefits from financial incentives, subsidies, and regulatory reforms. Policies aimed at reducing capital costs and fostering innovation include subsidies for battery manufacturing and installation, as well as tax incentives for grid-scale storage deployment [70]. For example, local governments in provinces such as Qinghai and Guangdong have introduced specific policies mandating the integration of energy storage systems with renewable energy projects. These initiatives are crucial for addressing the financial risks and cost uncertainties associated with large-scale energy storage deployment. Given the sector's challenges, including high capital expenditure and relatively low round-trip efficiencies, the support of both central and local government is essential for driving technological progress and market adoption.

5.2.3. Technological Development

Technological advancements in energy storage offer significant opportunities to enhance efficiency and reduce costs. Lithium-ion batteries currently dominate the market due to their cost-effectiveness and high efficiency in short-duration applications. However, as demand for long-duration storage grows, innovations are needed to expand storage capacity without excessive costs. Research into solid-state batteries and advanced flow battery chemistries is progressing rapidly, promising reduced costs and higher energy density [69]. These advancements are expected to lower the levelized cost of storage, which is a key factor for large-scale adoption, especially in regions with high penetration by renewable energy.

AI is also playing a pivotal role in optimizing the design, integration, and operation of energy storage systems. AI-driven algorithms enable more accurate forecasting of energy production from renewable sources, which is critical for storage management. Additionally, AI is advancing material selection and facilitating seamless integration with smart grids, reducing system costs while maximizing efficiency [71]. By dynamically responding to fluctuations in supply and demand, AI-enabled storage enhances grid resilience and operational stability.

5.2.4. Enhanced Energy Security

The growing volatility of global energy markets, driven by geopolitical tensions and the push for energy independence, presents a crucial opportunity for the energy storage industry to strengthen national energy security. As a key element of diversified energy strategy, storage reduces reliance on fossil fuel imports, stabilizes the energy supply, and enhances energy sovereignty. As countries strive to diversify their energy mix and decrease reliance on imported fossil fuels, energy storage will play a central role in maintaining the resilience and stability of national energy infrastructure.

In particular, hydrogen storage is emerging as a promising technology contributing to both decarbonization and energy security. By converting surplus renewable electricity into hydrogen through electrolysis, it can be stored and later converted back into electricity when needed. This "power-to-gas" technology enables long-term energy storage, providing a reliable backup for renewable energy generation during periods of low production. Hydrogen storage also offers a strategic advantage for balancing seasonal variations in energy supply, especially in countries with significant potential for the use of renewable energy but high seasonal variability.

6. Conclusions and Policy Implications

China's energy storage industry has experienced rapid growth, emerging as a dominant force in the global market. By 2023, China accounted for 47% of new energy storage projects worldwide (data from the Energy Storage Industry Research White Paper 2024 released by CNESA). As renewable energy penetration increases, energy storage plays an increasingly vital role in maintaining grid stability and improving energy efficiency. This paper summarizes the key factors influencing the industry, its economic and social impacts, major challenges, and future opportunities. The main research conclusions are as follows:

China's energy storage growth is determined by a combination of technological advancements, material costs, electricity price dynamics, market demand, and policy interventions. Technological innovations in lithium-ion batteries, compressed-air-energy storage, and hydrogen storage have significantly improved efficiency and scalability, yet cost and resource dependency issues remain. Fluctuations in raw material prices, particularly for lithium, cobalt, and nickel, pose economic challenges, while electricity market structures and pricing mechanisms affect the profitability of storage investments. The increasing adoption of renewable energy and electric vehicles is driving market demand, but supply–demand mismatches hinder large-scale implementation. Policy support plays a pivotal role in fostering industrial development, including subsidies, regulatory frameworks, electricity pricing mechanisms, capacity compensation, and so on.

As a key driver of China's transition toward a low-carbon economy, energy storage has an important impact on China's economy and society. By enhancing renewable energy integration, storage systems reduce reliance on fossil fuels and mitigate grid instability through intermittent generation of power. The industry also contributes to economic growth through the creation of new industrial chains, job opportunities, and increased energy efficiency. Additionally, energy storage improves energy security by enabling better peak-load management and reducing transmission losses.

Despite energy storage potential, the industry faces several challenges. High initial investment costs hinder large-scale deployment, especially in grid-scale applications. The lack of a well-defined revenue model and limited participation in electricity markets reduce profitability for storage operators. Policy uncertainties and regulatory inconsistencies further complicate investment decisions. Moreover, safety concerns, especially in battery technologies, necessitate robust standards and continuous technological improvements. Overcoming these challenges requires coordinated efforts from the government, industry stakeholders, and financial institutions.

Multiple opportunities exist to accelerate energy storage development in China. The rapid expansion of renewable energy sources, particularly wind and solar, creates a strong demand for storage solutions. Technological advancements, such as AI-driven energy management and new battery chemistries, hold promise for improving efficiency. Additionally, the rise of the electric vehicle sector provides a secondary market for energy storage applications, including vehicle-to-grid integration.

In view of the above research conclusions, the policy implications of this article are as follows:

1. A more comprehensive policy framework should be constructed. A well-structured and adaptive policy system is essential for fostering the development of energy storage. The government can refine fiscal support mechanisms, such as targeted subsidies and tax incentives, to reduce capital costs and stimulate private-sector investment. Additionally, it is crucial to establish comprehensive industry safety standards to ensure long-term system reliability and public confidence. Enhancing subsidies for energy storage applications in both large-scale grid infrastructure and distributed power generation can further stabilize the market and accelerate technological deployment. By refining regulatory mechanisms and ensuring policy consistency, China can create a more predictable business environment, which is vital for sustained investment in energy storage.
2. The energy storage recycling market should be developed. With the rapid expansion of the energy storage sector, the need for a structured and incentivized recycling system has become increasingly evident. Despite the growing volume of retired storage units from electric vehicles and grid applications, the recycling market remains underdeveloped. Establishing clear policies and financial incentives for battery recycling will reduce dependence on raw materials, lower production costs, and mitigate environmental impact. Investing in second-life battery applications, such as repurposing EV batteries for stationary storage, can create additional revenue streams and improve utilization of resources. Given that this remains an emerging market, proactive government intervention and collaboration with industry can position China as a global leader in sustainable energy storage solutions.
3. Technological innovation should be enhanced through AI. AI-driven predictive modeling can optimize material selection, enhance battery performance, and reduce system inefficiencies. Automation and machine learning technologies can significantly

shorten research and development cycles, enabling quicker commercialization of advanced storage solutions. Furthermore, integrating smart grids powered by AI can improve the efficiency of energy dispatch and alleviate grid congestion, making energy storage more viable for managing variable power supplies. Leveraging AI and automation can enhance cost-effectiveness and long-term sustainability, ultimately strengthening China's global leadership in the energy transition.

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Abbreviations

The following abbreviations are used in this manuscript:

CAES	Compressed-air-energy storage
EV	Electric vehicle
DERs	Distributed energy resources
ESS	Energy storage systems
CATL	Contemporary Amperex Technology Co., Ltd.
BYD	BYD Company Limited
VPPs	Virtual power plants
NDRC	National Development and Reform Commission

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