

Technology Review for Carbon Neutrality

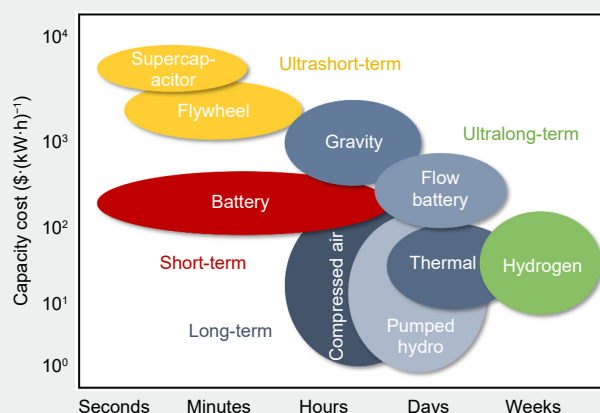
Review

The shifting technology landscape of electrical energy storage toward carbon neutrality in China

Jia-Ning Liu¹, Wen-Ze Huang¹, Cheng Tang¹, Jia-Qi Huang², Xiang Chen¹, Chen-Zi Zhao¹, Hong Li³, Haisheng Chen⁴, Zhenhua Yu⁵, Qiang Zhang^{1,*}

ABSTRACT

The strategic deployment of electrical energy storage technologies enables a new power system with higher renewable energy integration and further empowers the whole society's transition to a green, sustainable, and technologically advanced energy economy. Here we review the shifting landscape of electrical energy storage technologies in China, commenting on the technological advantages, breakthroughs, bottlenecks, and future directions of technologies from ultrashort-term options like flywheels to ultralong-term solutions like hydrogen storage. Levelized cost of those technologies are key in predicting their future deployment, while diversified local energy storage solutions are necessary to accommodate local energy resources and consumption. To promote deployment of electrical energy storage technologies, multi-sectoral policies encompassing innovation policy, regulatory policy, financial incentives, workforce training, as well as locally tailored planning are needed.



Shifting technology landscape of electrical energy storage toward carbon neutrality in China.

China's commitment to achieving carbon neutrality by 2060 necessitates a radical transformation of its energy infrastructure, with a strategic emphasis on the implementation of diverse electrical energy storage technologies. This perspective presents a detailed overview for advancing energy storage from ultrashort-term solutions to ultralong-term options, tackling the intermittency of renewable energy sources and guiding policy with cost assessments and geographic considerations.

KEYWORDS

Energy storage; carbon neutrality; green and sustainable technology; lithium-ion battery; hydrogen energy storage; energy economy

Author affiliations

1 Tsinghua Center for Green Chemical Engineering Electrification, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China

2 Advanced Research Institute of Multidisciplinary Science, Beijing Institute of Technology, Beijing 100081, China

3 Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

4 Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China

5 China Energy Storage Alliance, Beijing 100190, China

* Correspondence

Qiang Zhang,
zhang-qiang@mails.tsinghua.edu.cn

Received: 26 June 2024

Revised: 01 September 2024

Accepted: 11 December 2024

<https://doi.org/10.26599/TRCN.2025.9550004>

© The author(s) 2025.

This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, <http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As the leading emitter of greenhouse gases globally, China's pathway to carbon neutrality is a complex and ambitious endeavor, requiring concerted efforts across all sectors of the economy¹. A key change to behold is a profound transformation in power systems. According to the International Energy Agency (IEA), the share of electricity in final energy consumption is expected to jump from 20% today to over 50% by 2050², which is mainly due to accelerated electrification of end-uses. In the pursuit of carbon neutrality, it implies the imperative to generate as much electricity as possible from renewable sources. Solar and wind power, especially, are at the forefront of China's renewable energy expansion due to their scalability and increasingly favorable economics³. However, the intermittent nature of these resources induces unique challenges as wind and solar output varies with weather conditions and time of day. For instance, unlike traditional systems predominantly powered by fossil fuels where output can adjust to meet varying demands, solar and wind power lacks the flexibility to increase production on demand due to its intermittency, thus threatening grid stability and reliability⁴. The variability of renewable energy can also lead to price volatility in electricity markets. Innovative approaches are therefore needed to overcome these impediments and significantly boost the proportion of renewable sources in the power generation mix.

Current electricity system flexibility is ensured by fossil fuel plants, through enhancing the adaptability of existing generation assets⁵, fortifying transmission and distribution networks⁶, and increasing storage capabilities⁷. To replace these plants cost-effectively, alternative flexibility sources with unique profiles are required to fulfill a broad range of service demands. Energy storage, capable of enhancing the efficiency, reliability, and flexibility across various segments, serves as the key solution in modern electrical power systems. According to data from the IEA, by 2060, energy storage in the

form of batteries and pumped hydro will constitute 40% of peak capacity reserves due to their flexibility values, while dispatchable plants will primarily fulfill the longer-duration ramping needs⁸. Hence, understanding the role of energy storage is pivotal to facilitating power system transformation in China.

A growing number of studies have focused on technological and economic developments of energy storage. For instance, Zhang and co-workers⁹ developed a sequential investment decision model for energy storage projects based on real options, while Pompei et al.¹⁰ proposed systematic comparison of the current performance and costs of specific thermal energy storage. These attempts provided the initial realistic economic decision frameworks and manifest the potential of energy storage in modern power systems. Yet, currently the development of energy storage technologies faces a variety of challenges across various application scenarios, such as low utilization rates, high installation costs, inefficiencies in dispersed systems, and a lack of scientific validation for optimal configuration. A comprehensive overview of energy storage is therefore needed, in terms of its development status, economic analysis, quantitative projection, and pathways that consider the vast geographic and economic diversity across the nation. In this perspective, the multifaceted functions of energy storage as well as relevant technologies are analyzed, and a detailed pathway towards 2030 and 2060 is presented for future energy storage with time-dependent and geographical projections. Policy recommendations are also provided to support the expansion and evolution of energy storage in China. This perspective highlights the significance of energy storage and suggests pathways to support the transition to a green, sustainable, and technologically advanced energy economy.

2. Electrical energy storage: functions and types

As the power grid moves away from fossil fuel plants, a diversity of energy technologies fills in

the void to maintain secure electricity supply, of which energy storage has an important role to play (Fig. 1)¹¹. According to the IEA, by 2060 energy storage will provide 11% of ramping flexibility to meet supply or demand changes, and 29% of peak capacity to meet peak demand¹¹.

2.1 Functions of electrical energy storage

Specifically, energy storage functions distinctively on the power supply, transmission and distribution, and user sides (Fig. 2).

Power supply side

On the power supply side, energy storage is instrumental in harmonizing the supply of electricity with fluctuating demand and production levels¹². For instance, the system can provide ancillary services such as frequency regulation and peak shaving. It allows for the accumulation of excess energy generated during peak production periods, which can be discharged during times of low production or high demand. Moreover, the economic performance of traditional power plants can be enhanced by enabling what is known as "energy arbitrage".

Power transmission and distribution side

In the realm of power transmission and distribution, managing the flow of energy becomes increasingly challenging as electrical grids grow more complex and interconnected. Energy storage deployed within the transmission network can mitigate congestion, enhance line capacity during peak loads, and stabilize voltage levels across long distances¹³. This not only helps in reducing transmission losses, but also delays and negates the need for expensive infrastructure upgrades and capacity expansion¹⁴.

User side

At the user level, energy storage transforms the way that consumers interact with the grid from passive to active participation, offering increased independence and reliability while potentially lowering energy costs with electricity

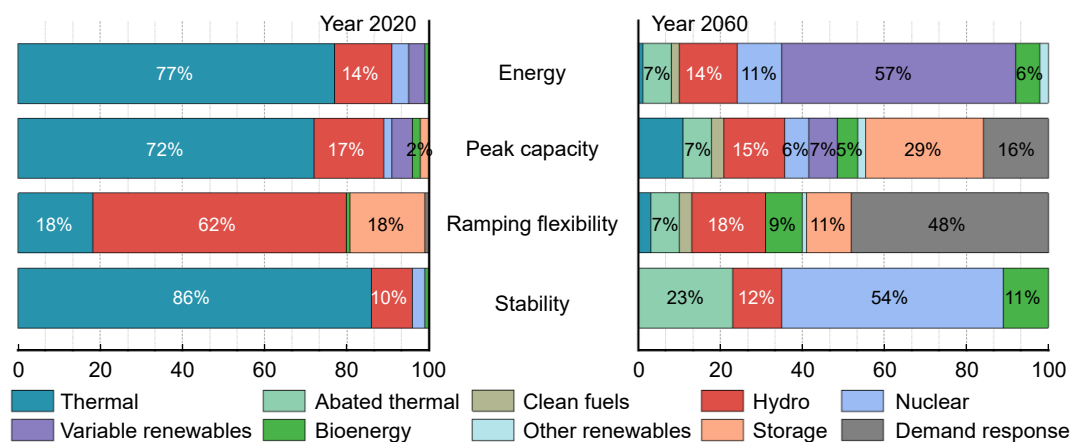


Fig. 1. Energy technologies to maintain secure electricity supply in China¹¹. Note: Energy supply, peak capacity (to meet peak demand), ramping flexibility (to respond to changes in supply or demand), and stability (to control disturbances) are provided. Produced from data released by the IEA from Ref. 11.

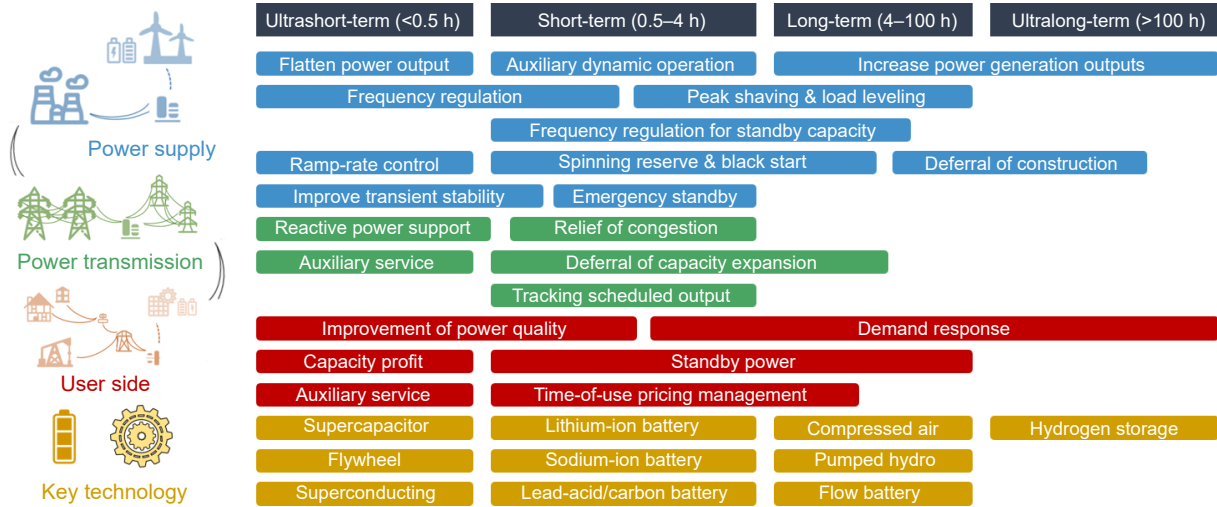


Fig. 2. Multifaceted role of energy storage in power system²⁵. Note: The blue, green, and red boxes represent functions of energy storage on the power supply side, power transmission side, and user sides, respectively. Specific energy storage technologies from ultrashort-term to ultralong-term are listed in the below yellow boxes.

trade¹⁵. Additionally, for users with installed renewable energy systems, such as rooftop solar panels, energy storage is indispensable. It allows for the storage of surplus energy generated during the day, which can then be used at night or during cloudy and windless periods, maximizing the use of generated renewable energy and reducing reliance on the grid^{16,17}. This self-sufficiency is particularly appealing for commercial entities looking to reduce their carbon footprint and for residential areas in remote locations, where grid access may be unreliable or unavailable.

2.2 Types of electrical energy storage technologies

The spectrum of energy storage technologies spans across multiple storage time scales, and they serve different functional needs within the power system (Fig. 3)¹⁸⁻²⁴. (Note: the storage time or storage duration for an energy storage

technology refers to the length of time that the system can sustain power output at its maximum discharge or output rate.)

2.2.1 Ultrashort-term technologies

At one end of the spectrum with the shortest storage time of less than half an hour are ultrashort-term energy storage technologies such as flywheels and supercapacitors²⁵. These technologies excel in providing rapid response to immediate fluctuations in the grid, offering services like frequency regulation and ramp-rate control.

Flywheel

In flywheel energy storage, motors facilitate the rapid spinning of the flywheel, converting electricity into kinetic energy for storage. When power is required, the flywheel activates a generator²⁶. The main challenges for flywheel energy storage include high manufacturing costs and issues related to material strength and

durability. Internationally, countries like the United States and Germany lead in flywheel technology, especially in high-speed systems, focusing on improving energy density and efficiency, while the research of flywheels in China began in the 1980s²⁷. In recent years, significant advancements have been achieved in China in terms of the technology breakthrough of a large-capacity magnetic levitation flywheel driven by axial-flux permanent magnet. The demonstration breakthroughs in 2024 include the 22 MW/4.5 MWh flywheel energy storage station in Ningxia, and the 100 MW/0.83 MWh flywheel storage station in Hubei^{28,29}.

Supercapacitor

In addition to flywheel energy storage, supercapacitors represent another type of ultrashort-term energy storage device. They operate based on electric double-layer adsorption, surface redox reactions, and the rapid insertion and removal of ions to store energy³⁰. Its com-

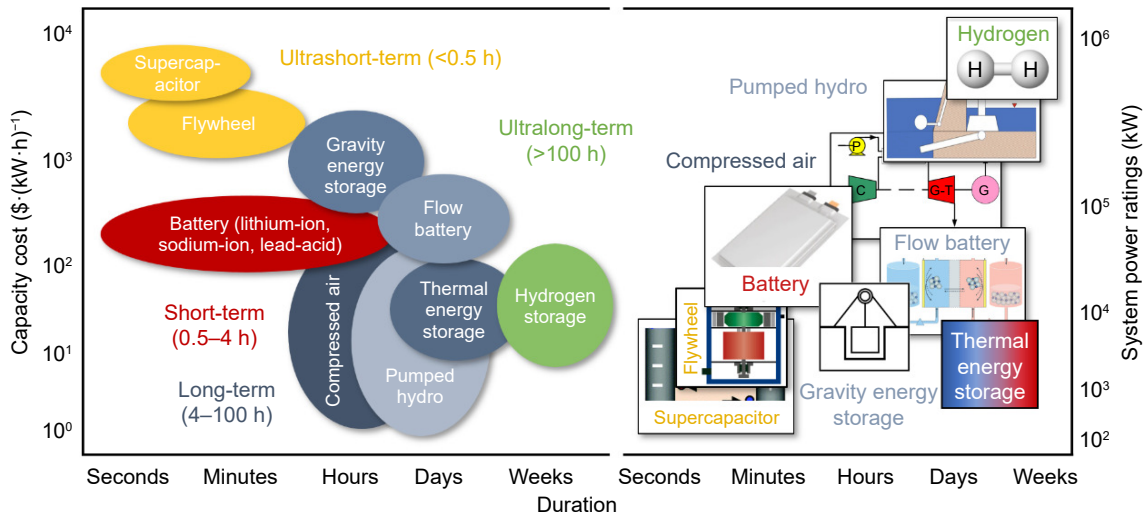


Fig. 3. Comparison of electrical energy storage technologies¹⁸⁻²⁴. Note: Duration, capacity cost, and system power ratings are listed for various energy storage technologies. The yellow, red, grey, and green oval shades on the left of the figure represent ultrashort-term, short-term, long-term, and ultralong-term energy storage technologies, respectively. Reproduced with permission from Ref. 18, © The author(s) 2014, for flywheel; Ref. 19, © the Royal Society of Chemistry 2016, for supercapacitor; Ref. 20 for battery; Ref. 21, © The author(s) 2017, for compressed air energy storage; Ref. 22, © Macmillan Publisher Limited, part of Springer Nature 2016, for flow battery; Ref. 23, © The author(s) 2022, for gravity energy storage, thermal energy storage, and hydrogen energy storage.

mercial uses in military applications and electronics are well-developed. Companies from Japan (Nichicon Corporation), the United States (Nesscap Energy Inc.), and Korea of Republic (LG Chem) are leaders in this field, currently dominating much of the global market^{31,32}.

2.2.2 Short-term technologies

For slightly longer durations, ranging from half an hour to four hours, short-term energy storage technologies like various types of batteries (lithium-ion battery^{33,34}, sodium-ion battery³⁵, lead-acid battery³⁶, lead-carbon battery^{37,38}, and sodium-sulfur battery³⁹) become representative. These batteries are instrumental for daily load leveling, helping to bridge the gap between daytime energy generation peaks and consumption peaks, and are also critical for renewable integration where they mitigate the effects of transient clouds or reduced wind speeds on power output.

Lithium-ion battery

According to the statistics from China Energy Storage Alliance, the cumulative installed energy storage capacity reached 86.5 gigawatts (GW) by the end of 2023⁴⁰. Notably, installations of new types of energy storage, primarily represented by batteries, surpassed 30 GW for the first time, reaching 34.5 GW/74.5 GW-h. Lithium-ion batteries accounted for approximately 97.3% of this capacity. Furthermore, data released by the Ministry of Industry and Information Technology of China indicate that in 2023, the total production of lithium-ion batteries nationwide exceeded 940 GW-h, of which the application in energy storage contributed 185 GW-h.

The dominance of lithium-ion batteries in the market underscores their high efficiency, declined costs, and suitability for a range of applications, from small-scale residential to large-scale industrial uses^{41,42}. For instance, in early 2024, the National Energy Administration officially announced a list of 56 new types of energy storage demonstrations covering the main technological routes discussed above. Among these, 17 projects are related to lithium-ion battery while two projects are related to sodium-ion battery. The Three Gorges-Ulanqab next-generation grid-friendly green power station demonstration project, the first renewable energy station in China with an energy storage capacity reaching gigawatt-hour scale, is equipped with 0.55 GW of storage capacity and a duration of 2 hours with lithium-ion battery. This allows it to store the energy generated by 110 5-MW wind turbines operating at full capacity for 2 hours. However, the market's heavy reliance on lithium-ion technology highlights the need for diversifying energy storage solutions.

Alternative batteries

Alternative battery chemistries, such as sodium-ion battery, lead-acid battery, lead-

carbon battery, and sodium-sulfur battery will offer various benefits including lower costs, resource availability, or thermal stability, which are crucial for specific applications or different climatic conditions⁴³⁻⁴⁶.

2.2.3 Long-term technologies

Long-term storage technologies, including pumped hydro storage, compressed air energy storage, flow batteries, gravity energy storage, and thermal energy storage, are designed for storing energy for more than four hours. These systems are vital for balancing energy over longer periods, such as across different weather conditions and between hours when renewable energy availability may vary significantly.

Pumped hydro

Pumped hydro storage is the most established form of energy storage in China, which is used on a large scale and involves storing energy in the form of water in an elevated reservoir pumped from a lower reservoir when energy demand is low. At demand peaks, water flows back from the upper to the lower reservoir via turbines, producing electricity^{47,48}. Pumped hydro storage is capable of storing large amounts of energy economically, which makes it a backbone for load balancing over longer durations and during periods of seasonal demand variations^{49,50}. China's pumped storage industry started relatively late but has since made significant strides. After years of development, it has established a complete industrial chain and has reached advanced global standards in areas such as equipment design and power station operation.

Compressed air energy storage

In compressed air energy storage systems, air is compressed using electricity during low grid demand and stored under high pressure in locations such as abandoned mines, underwater tanks, caves, and purpose-built gas wells. During periods of peak grid demand, the compressed air is released to power steam turbines and generate electricity⁵¹. China's research into compressed air energy storage systems commenced comparatively late, with foundational studies launching in 2003⁵². In the years since, the nation has aggressively championed the advancement of compressed air energy storage technology, enacting a suite of policies designed to foster innovation⁵³⁻⁵⁵. Key demonstrations showcasing compressed air energy storage in China include the validation platform in Guizhou that manifest its industrial potential for load leveling, the national demonstration situated in the salt caverns of Jiangsu that highlights the localization of corresponding equipment and the initial attempt to utilizing salt caverns for energy storage, and the national demonstration in Shandong that set a significant milestone with the highest efficiency, the largest capacity, and the lowest construction cost⁵⁶. These initiatives

are pivotal in demonstrating the practical applications and potential of compressed air energy storage technology, setting industry standards, and providing critical data and insights that will guide the future trajectory of long-term energy storage solutions across China.

Flow battery

Flow batteries represent another crucial long-term energy storage technology, operating on the principle of electrochemical conversion. They store energy in liquid electrolyte solutions housed in external tanks, which flow through an electrochemical cell that converts the stored energy into electricity⁵⁷. Flow batteries are especially advantageous for their scalability and the ability to quickly ramp up their output or recharge⁵⁸. In 2022, with the technical expertise of the Dalian Institute of Chemical Physics, Chinese Academy of Sciences, the world's largest flow battery energy storage power station was officially connected to the grid and began operation, which is the world's largest both in capacity and power output and capable of generating hundreds of megawatts.

Gravity energy storage

In addition to the above two emerging technologies, gravity energy storage is another innovative technology that leverages the potential energy of heavy objects to store and release energy⁵⁹. The basic principle involves using excess electricity during periods of low demand to lift heavy weights, such as large concrete blocks or steel containers, to a higher elevation. When energy demand increases, the weights are lowered, and the gravitational potential energy is converted back into electricity through generators^{60,61}. A key demonstration in China is the Energy Vault gravity energy storage system in Jiangsu. The main structure of the system, the gravity tower, measures 122 meters in length, 110 meters in width, and 148 meters in height. It utilizes 12,600 individual gravity blocks, each weighing 25 tons. The combined weight of the tower and the gravity blocks exceeds 800,000 tons, approaching the weight of China's tallest building, the Shanghai Tower. Once completed, the system will have an energy storage capacity of 100 MW-h and 25 MW, representing the world's first commercial, utility-scale, non-pumped hydro gravity energy storage system. However, gravity energy storage faces challenges such as the need for large-scale infrastructure, which can be expensive and requires significant space. Additionally, the efficiency of energy conversion and the wear and tear on mechanical components over time are areas that need ongoing research and development.

Thermal energy storage

In addition to storing energy in the form of electricity, thermal energy storage stores excess

energy by converting it into heat, which can be stored in various materials such as molten salts, rocks, or water, and later converted back into electricity or used for direct heating^{62,63}. A prominent demonstration is the Dunhuang molten salt tower thermal energy storage project in Gansu. This project utilizes concentrated solar power technology, where mirrors focus sunlight onto a central tower to heat molten salt to high temperatures. The Dunhuang project has a storage capacity of 100 MW, providing a continuous power supply for up to 11 hours, significantly enhancing the reliability of solar power.

Likewise, cool thermal energy storage is a similar method for storing thermal energy in the form of cold⁶⁴. This technology is primarily used to manage cooling demands in buildings and industrial processes by shifting energy consumption to off-peak hours, thus enhancing energy efficiency and reducing costs⁶⁵. One notable demonstration is the Suzhou Industrial Park cool thermal energy storage system. This large-scale chilled water storage system is designed to meet the cooling demands of the extensive industrial and commercial facilities in the park. Such a system has a storage capacity of 150 MWh, offering substantial energy savings and operational efficiency and serves as a model for other large-scale applications of cool thermal energy storage technology.

2.2.4 Ultralong-term technologies

At the other end of the energy storage technology spectrum are ultralong-term storage technologies like hydrogen storage. Hydrogen can be produced during periods of excess renewable energy via electrolysis, stored indefinitely, and then used either to regenerate electricity or as a fuel for various applications^{66,67}. This technology is particularly promising for its potential to handle seasonal storage needs with the time scale of more than 100 hours, effectively decoupling the time of energy production from its use and facilitating a transition to a fully renewable energy grid.

As China continues its relentless pursuit of a carbon-neutral future, it is crucial to under-

stand and deploy these diverse energy storage technologies in a strategic, coordinated manner. Each technology offers unique benefits and is suited to specific tasks within the broader energy system, from immediate grid stabilization to seasonal energy management (Table 1). Also, the integration and optimization of these diverse technologies within the national grid are paramount. This requires not only technological innovation but also regulatory, financial, and policy frameworks that promote the adoption and integration of energy storage.

3. Electrical energy storage roadmap: techno-economics and temporal-spatial distribution

As China ambitiously steers towards its carbon neutrality goal by 2060, the roadmap for energy storage becomes critical. Central to this roadmap are two main trends that will shape the evolution of energy storage: the competition and selection of energy storage technologies based on techno-economics, and the temporal-spatial distribution of energy storage capacity.

3.1 Techno-economics of technologies

The levelized cost of energy storage (LCOS) is an important tool and frequently used to assess the market share of different electrical energy storage technologies, which measures the discounted cost per unit of discharged electricity for a specific storage technology and application.

In a pioneering study that examines grid energy storage across durations and frequencies, Schmidt and co-workers⁶⁸ calculated the LCOS projections for seven technologies across twelve power system applications from 2015 to 2050, including supercapacitor, flywheel, battery, flow battery, pumped hydro, compressed air, and hydrogen (Fig. 4)^{68,69}. They found that: a) flywheel, battery, flow battery, and hydrogen energy storage are able to meet diversified storage demands; b) the LCOS will decrease by one-third by 2030 and by half by 2050 across the applications; and c) lithium-ion batteries are expected to be the

most cost-effective for almost all stationary applications from 2030. The study indicates that investing in alternative technologies could be unproductive unless they achieve significant performance enhancements to remain competitive with lithium-ion batteries.

Another study by Li et al.⁷⁰ found that the electrochemical technology (primarily, batteries) and hydrogen storage technology display cost-effectiveness in short-term storage and long-term storage, respectively. Specifically, by 2025, lithium-ion batteries will hold a competitive edge in most scenarios where the duration is under 4 hours, whereas hydrogen will be cost-effective in scenarios exceeding 100 hours. While pumped hydro is expected to dominate the electrical energy storage market for durations ranging from 4 to 48 hours, by 2035 the cost benefits of lithium-ion batteries and hydrogen storage are projected to extend to durations of 10 hours and 48 hours, respectively, due to rapid advancements in battery and hydrogen technologies.

The above progress emphasizes the importance of LCOS in predicting market shifts and directing policy and investment of various technologies. It indicates that with cost reduction, lithium-ion batteries are extending their dominance into short-term durations while hydrogen and flywheel emerge as viable options for ultralong-term and ultrashort-term storage.

3.2 Temporal-spatial distribution of electrical energy storage

The temporal and spatial distribution of energy storage capacity are important considerations for planning of the energy storage roadmap, as they would affect policy-making for different time and different locales.

3.2.1 Temporal distribution of electrical energy storage

Several reports have offered different estimates of energy storage capacity from 2020 to 2060. In terms of total capacity (Fig. 5(a)^{40,71-77}), during the carbon peaking period up to 2030, energy storage capacity is expected to reach 410 GW to

Table 1. Comparison of response, duration, efficiency, and lifetime for various electrical energy storage technologies.

	Technology	Response	Duration	Efficiency (%)	Lifetime (year)
Ultrashort-term	Flywheel	ms–min	ms–min	93–95	>15
	Supercapacitor	ms	ms–min	90–95	>20
Short-term	Lead battery	ms–min	<4 h	75–90	5–10
	Sodium-ion battery	min	<4 h	90–95	5–15
	Lithium-ion battery	min	<4 h	95–98	5–15
Long-term	Pumped hydro	min	4–100 h	75–85	40–60
	Compressed air	min	4–100 h	70–85	20–40
	Thermal	min	4–100 h	50–60	20–30
	Gravity	min	4–100 h	80–90	20–30
	Flow battery	min	4–100 h	60–85	5–10
Ultralong-term	Hydrogen storage	ms–min	>100 h	/	10–20

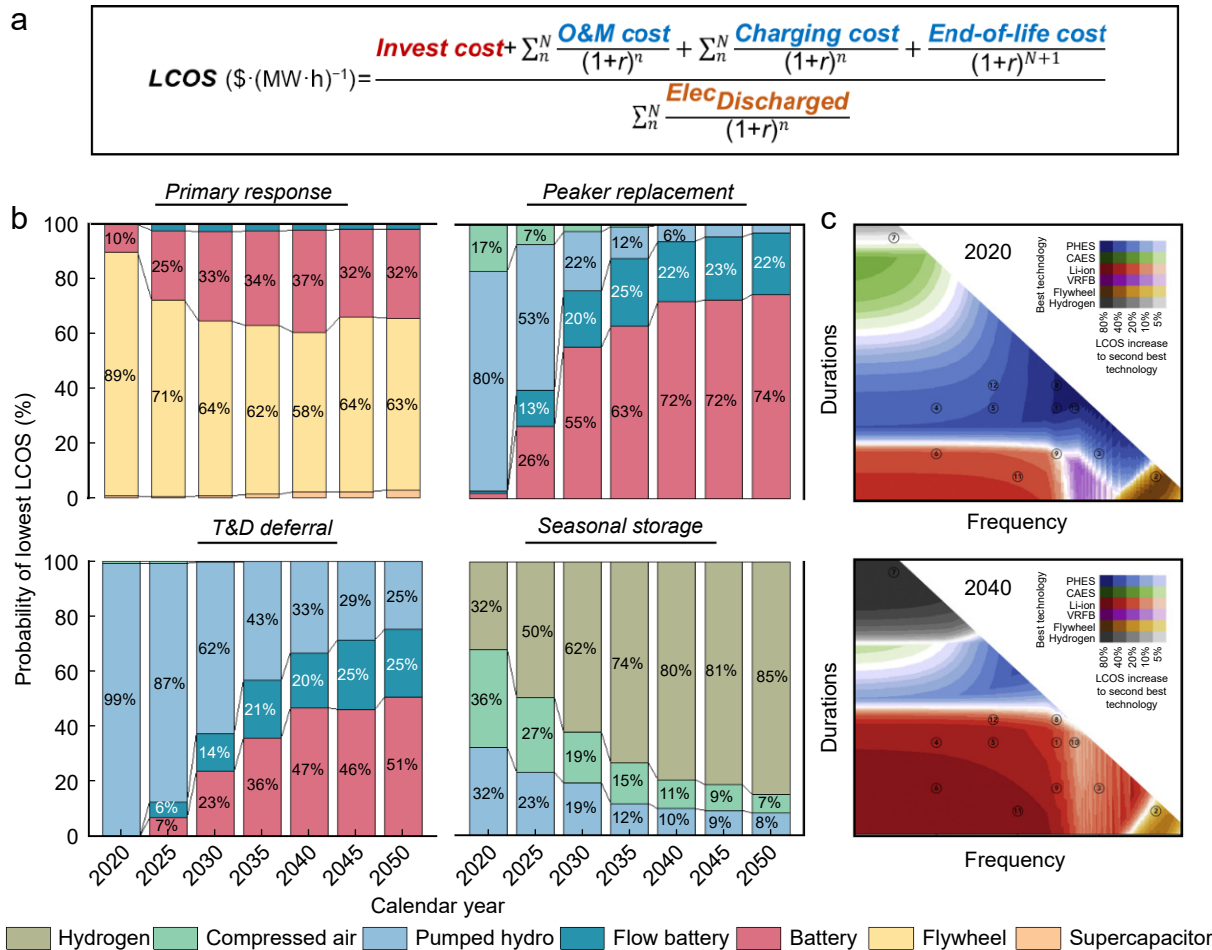


Fig. 4. Levelized cost of energy storage for diverse energy storage technologies⁶⁸⁻⁶⁹. (a) Equation definition of LCOS. Note: It calculates the total lifetime cost of an electricity storage technologies, including investment cost, operation and maintenance (O&M) cost, charging cost, and end-of-life cost, divided by the electricity discharged over the investment period. Note that costs for grids and infrastructure linking the storage facilities to generation or end use sites are included in the investment cost. It considers anticipated reductions in investment costs and existing performance parameters. It assumes that all investment costs are incurred in the first year, with ongoing costs summed each year (n) up to the system's lifetime (N), and discounted by the discount rate (r). Reproduced with permission from Ref. 68, © Elsevier Inc. 2018. (b) The LCOS projections of supercapacitor, flywheel, battery, flow battery, pumped hydro, compressed air, and hydrogen energy storage under typical energy storage scenarios in power grid from 2020 to 2050. Reproduced with permission from Ref. 68, © Elsevier Inc. 2018 and Ref. 69, © Author(s) 2018. (c) Most cost-efficient technologies relative to discharge duration and annual cycle requirements. Reproduced with permission from Ref. 68, © Elsevier Inc. 2018.

700 GW; by 2050, storage capacity is expected to reach 1,090 GW to 1,830 GW; by 2060 as carbon neutrality is achieved, storage capacity may rise to 1,250 GW to 2,000 GW.

In terms of energy storage capacity of different technologies (Fig. 5(b)⁷¹), ultrashort-term energy storage technologies, primarily comprising flywheel and supercapacitor, occupy a smaller proportion of the market and are expected to grow from 21 GW in 2030 to 62 GW by 2060, mainly serving applications like auxiliary frequency regulation with thermal plants. Short-term energy storage technologies, dominated by batteries and especially lithium-ion batteries, are used extensively for peak shaving and are projected to expand significantly, from 138 GW in 2030 to 950 GW by 2060. Long-term energy storage technologies, catering to extended periods of energy retention, will see accelerated growth especially in emerging technologies such as compressed air and flow batteries, growing from 373 GW in

2030 to 481 GW by 2060 in aggregate. Ultralong-term energy storage technologies, crucial for smoothing seasonal power fluctuations and enhancing renewable energy output and mainly involving chemical storage solutions like green hydrogen, are anticipated to increase from 21 GW in 2030 to 130 GW by 2060.

3.2.2 Spatial distribution of electrical energy storage

The spatial distribution of future energy storage is affected by local endowments of renewable energy sources and local economic characteristics (Fig. 5(c))^{71,78-81}.

Northeast China region

In the Northeast region, including major provinces like Heilongjiang, Jilin, and Liaoning, cogeneration energy storage systems are suitable. The colder average temperature and extended winter hinder the operation of electrochemical battery systems but create a significant demand for thermal energy, making

cogeneration storage system a flexible energy supply solution and a small increment in ultralong-term energy storage.

North China region

The North China region serves as the economic hub of the north, including Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia. This area has a high energy demand, hence a significant need for energy storage, particularly in frequency regulation. Inner Mongolia, with its substantial energy reserves and potential for wind and solar power, is poised to see increased demand for energy storage on the power supply and transmission sides, and therefore the hydrogen storage is typically selected with increased capacity.

Central China region

Central China, with its well-developed hydro network including provinces like Henan, Hubei, and Hunan, benefits from the abundant hydropower resources of the Yellow and

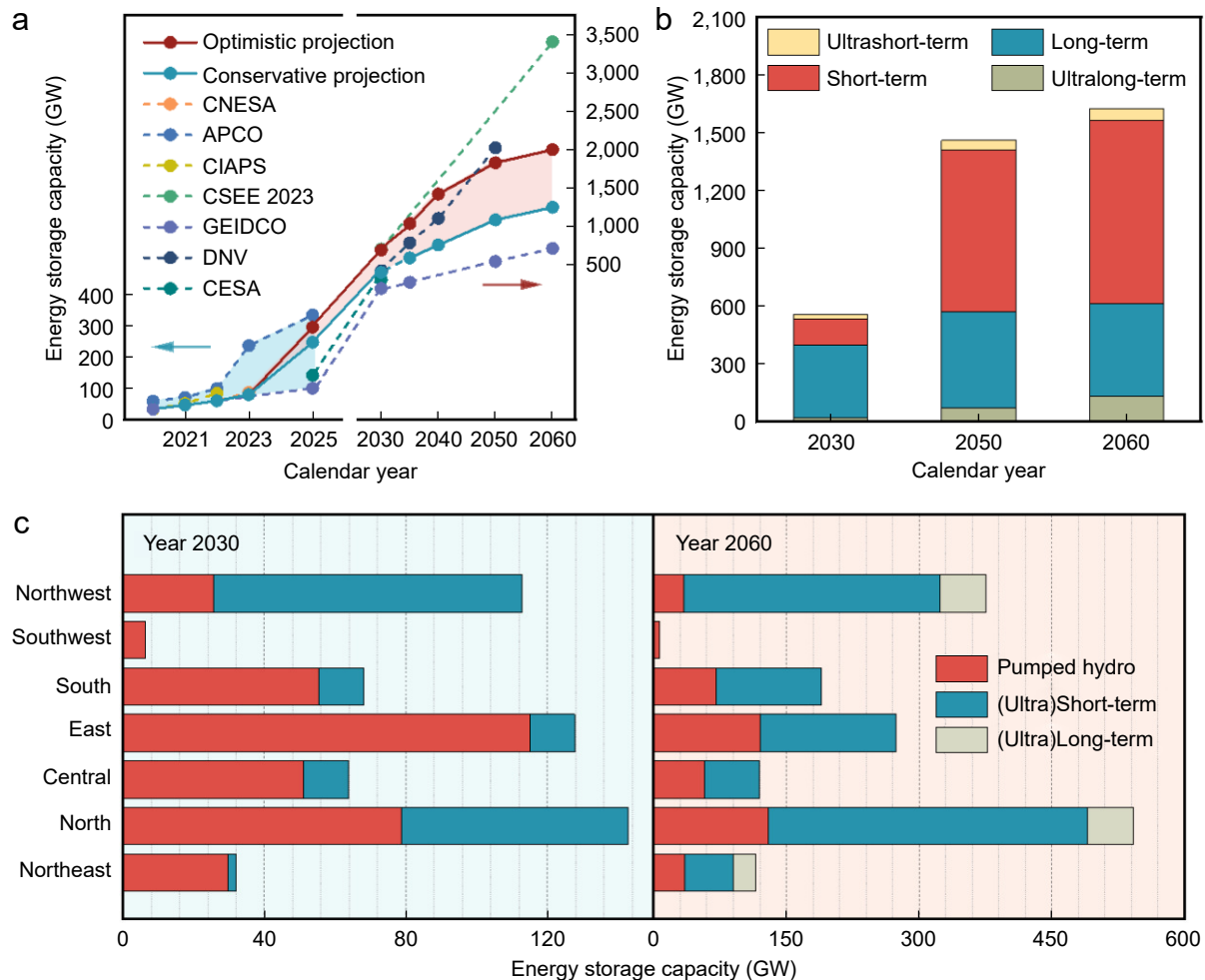


Fig. 5. Projections for energy storage capacity toward 2030 and 2060^{40,71-77}. (a) Optimistic (red) and conservative (blue) projections for energy storage capacity in 2030, 2040, 2050, and 2060 according to the listed reports (the red coloured zone)^{40,71-77}. The projections are made based on the estimated capacity of renewable energy sources and the cost as well as durations of future energy storage. (b) Projections for ultrashort-term, short-term, long-term, and ultralong-term energy storage in 2030, 2050, and 2060⁷¹. (c) Geographical energy storage distribution in 2030 and 2060. Seven typical districts, including northeast, north, central, east, south, southwest, and northwest of the nation are projected⁷¹.

Yangtze River basins. Energy storage via pumped hydro is feasible herein, and the strong capability on the power supply side can adequately meet the hydroelectric needs of North and Central China, thereby reducing the demand for other types of power storage.

East China region

East China, another economic center including Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, and Taiwan, experiences high electricity demand and load, necessitating substantial transmission-side and (ultra)short-term energy storage. The economic prosperity also spells vast potential for user-side energy storage, providing major regulation capabilities for the grid.

South China region

The South region includes Guangdong, Guangxi, Hainan, and the Hong Kong and Macao areas. Economically advanced areas exhibit high electricity demands, while the electrochemical battery industry in Guangdong provides economic advantages, promoting the

adoption of batteries and (ultra)short-term energy storage technologies.

Southwest China region

The Southwest region, mainly including Sichuan, Chongqing, Guizhou, Yunnan, and Xizang, has rich potential for hydropower generation and storage with the high terrain, which diminishes the demand for other types of energy storage.

Northwest China region

The Northwest region, comprising Xinjiang, Qinghai, Gansu, Ningxia, and Shaanxi, is rich in wind and solar resources, necessitating substantial energy storage installations to balance both power supply and transmission sides. This area is also a major domestic lithium resource region, which supports the establishment of electrochemical storage industries to enhance both (ultra)short-term and (ultra)long-term energy storage.

Such diverse geographic and climatic conditions across the regions necessitate tailored approaches to energy storage that

consider both local renewable energy potentials and specific economic needs. As illustrated in the above assessments and forecast, the demand for energy storage will significantly increase by 2060, including in both (ultra)short-term and (ultra)long-term storage capacities. These projections align with the goals of enhancing grid stability, integrating a higher share of renewable energy, and providing reliable power supply across varied demand scenarios. Furthermore, the development of regional energy storage solutions, such as the adaptation of cogeneration systems in colder climates and the exploitation of hydropower in mountainous areas, underscores the importance of a nuanced approach that leverages local strengths. The integration of advanced technologies like lithium-ion batteries and green hydrogen not only supports the energy transition but also catalyzes regional economic development, thus forming a cornerstone of China's strategy to balance energy security, economic stability, and environmental sustainability.

4. Multi-sectoral policy recommendations

Looking towards 2060, electrical energy storage in China will embark upon profound changes to support the country's ambitious carbon neutrality goals. These changes will encompass a wide array of technologies and applications, each playing a strategic role in the power grid's evolution. As renewable energy sources like solar and wind continue to scale up, the demand for innovative energy storage solutions to address their intermittency will significantly increase. Based on the comprehensive analysis presented in the previous sections, which outlines the challenges and opportunities of the energy storage technology landscape, the following policy recommendations are proposed to bolster the development and implementation of energy storage solutions. These recommendations aim to address the technical, economic, and regulatory aspects that will support the expansion and evolution of the energy storage toward carbon neutrality.

a) Incentivize research and development in emerging technologies. Given the critical role of electrical energy storage in achieving carbon neutrality, the government should provide robust funding and incentives for research and development in cutting-edge storage technologies, including but not limited to lithium-based batteries, hydrogen storage, flow batteries, and compressed air energy storage systems. Such support should aim to reduce the cost of these technologies and improve their efficiency and scalability. Collaboration between academia, industry, and government research institutions should be encouraged to foster innovation and accelerate the transition from laboratory to market. Additionally, establishing dedicated innovation hubs and technology parks can facilitate knowledge sharing and attract relevant investment.

b) Implement regulatory frameworks to support grid integration. Currently, regulatory inconsistencies still exist, especially with regard to compensation mechanisms for stored energy, which may discourage investment in storage technologies. A comprehensive regulatory framework that specifically addresses the integration of various energy storage technologies into the national grid is essential. This framework should include guidelines for grid interconnection, standards for safety and performance, and protocols for energy trading, particularly for stored energy. It should also promote the decentralization of energy storage by supporting installations in both urban and rural areas, thereby enhancing grid resilience and reducing transmission losses. Policies that mandate a certain percentage of energy storage capacity for new renewable installations can also ensure that the growth in renewable energy capacity is matched by adequate storage infrastructure.

c) Establish financial incentives for electrical energy storage deployment. Financial mechanisms such as tax credits, subsidies, and low-interest loans can be instrumental in promoting the adoption of energy storage systems across residential, commercial, and industrial sectors. For example, the government can introduce feed-in tariffs for the energy discharged from storage systems during peak demand periods, which will make energy storage investments more attractive. Additionally, public-private partnerships can be leveraged to fund large-scale storage projects, particularly in regions where energy security is critical or where grid stability needs significant reinforcement.

d) Enhance technical training and workforce development. As energy storage technologies become more prevalent, there will be a growing need for skilled professionals who can install, maintain, and manage these systems. In China, several provinces have already launched training programs in partnership with universities and research institutes to cultivate expertise in battery technology and energy management. However, there is still a need for more standardized and comprehensive training initiatives to address the regional skill gaps and support the rapid expansion of the sector. The government should invest in technical training programs at universities, vocational schools, and through online platforms to educate and certify workers in the energy storage sector. This initiative should also focus on current energy sector employees, providing them with the necessary skills to transition to roles in the energy storage industry. This will not only ensure the availability of a skilled workforce but also support job creation in the new energy economy.

e) Promote regional energy storage solutions. Recognizing the geographical and climatic diversity of China, policies should encourage the development of region-specific energy storage solutions that align with local energy needs and renewable energy availability. For instance, regions with abundant hydro resources could benefit from pumped hydro storage, while areas with geothermal activity might focus on thermal energy storage systems. Local governments should be empowered through grants and technical support to develop and implement these tailored solutions. This localized approach will ensure that energy storage systems are optimally designed and utilized, maximizing their impact on both regional and national energy stability and sustainability.

5. Conclusion

In conclusion, this perspective presents a comprehensive overview of the technologies that will drive the future of electrical energy storage in China, analyzing their importance,

types and functions, techno-economics, and temporal-spatial distribution projections, which are tailored to meet the dynamic needs of evolving energy infrastructure. Targeted policy recommendations are also provided to foster the expansion and evolution of electrical energy storage capabilities. These recommendations aim to refine regulatory frameworks, stimulate investment in new technologies, and facilitate the integration of energy storage solutions across sectors. This perspective highlights the pivotal role of electrical energy storage in supporting China's transition toward a green, sustainable, and technologically sophisticated energy economy.

Acknowledgements

This work was supported by National Natural Science Foundation of China (T2322015, 22109086, 22108151, 22109084, and 22309101), National Key Research and Development Program (2021YFB2500300, and 2022YFB2404402), Beijing Municipal Natural Science Foundation (Z200011), Tsinghua-Jiangyin Innovation Special Fund (2022JYTH0101), Ordos-Tsinghua Innovative & Collaborative Research Program in Carbon Neutrality, Tsinghua University Initiative Scientific Research Program, and the "Shuimu Tsinghua Scholar Program of Tsinghua University".

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

REFERENCES

- Lei, Y. D., Wang Z. L., Wang, D. Y., Zhang, X. Y., Che, H. Z., Yue, X., Tian, C. G., Zhong, J. T., Guo, L. F., Li, L., et al. (2023). Co-benefits of carbon neutrality in enhancing and stabilizing solar and wind energy. *Nature Climate Change*, 13: 693–700.
- International Energy Agency. (2023). Tracking clean energy progress. Paris.
- Zhang, S., Chen, W. Y. (2022). Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nature Communication*, 13: 87.
- Olabi, A. G., Ali Abdelkareem, M. (2022). Renewable energy and climate change. *Renewable and Sustainable Energy Reviews*, 158: 112111.
- Ali, S. M. H., Lenzen, M., Sack, F., Yousefzadeh, M. (2020). Electricity generation and demand flexibility in wastewater treatment plants: Benefits for 100% renewable electricity grids. *Applied Energy*, 268: 114960.
- Cao, Y. P., Zhou, B., Chung, C. Y., Shuai, Z. K., Hua, Z. H., Sun, Y. X. (2023). Dynamic modelling and mutual coordination of electricity and watershed networks for spatio-temporal operational flexibility enhancement under rainy climates. *IEEE Transactions on Smart Grid*, 14: 3450–3464.

7. Li, X., Li, W. M., Zhang, R. F., Jiang, T., Chen, H. H., Li, G. Q. (2020). Collaborative scheduling and flexibility assessment of integrated electricity and district heating systems utilizing thermal inertia of district heating network and aggregated buildings. *Applied Energy*, 258: 114021.
8. International Energy Agency. (2021). An energy sector roadmap to carbon neutrality in China. Paris.
9. Sun, B., Zhang, Y., Fan, B., Xie, P. (2024). An optimal sequential investment decision model for generation-side energy storage projects in China considering policy uncertainty. *Journal of Energy Storage*, 83: 110748.
10. Pompei, L., Nardecchia, F., Miliozzi, A. (2023). Current, projected performance and costs of thermal energy storage. *Processes*, 11: 729.
11. International Energy Agency. (2022). Energy transitions require innovation in power system planning. Paris.
12. Zhao, P., Gou, F. F., Xu, W. P., Wang, J. F., Dai, Y. P. (2022). Multi-objective optimization of a renewable power supply system with underwater compressed air energy storage for seawater reverse osmosis under two different operation schemes. *Renewable Energy*, 181: 71–90.
13. Pulazza, G., Zhang, N., Kang, C. Q., Nucci, C. A. (2021). Transmission planning with battery-based energy storage transportation for power systems with high penetration of renewable energy. *IEEE Transactions on Power Systems*, 36(6): 4928–4940.
14. Moradi-Sepahvand, M., Amraee, T. (2021). Integrated expansion planning of electric energy generation, transmission, and storage for handling high shares of wind and solar power generation. *Applied Energy*, 298: 117137.
15. Ding, Y. X., Xu, Q. S., Huang, Y. (2020). Optimal sizing of user-side energy storage considering demand management and scheduling cycle. *Electric Power Systems Research*, 184: 106284.
16. Liu, Y. S., Liu, Q. Q., Guan, H. M., Li, X., Bi, D. Q., Guo, Y. J., Sun, H. X. (2022). Optimization strategy of configuration and scheduling for user-side energy storage. *Electronics*, 11: 120.
17. Xia, Y. X., Xu, Q. S., Zhao, J., Yuan, X. D. (2020). Two-stage robust optimisation of user-side cloud energy storage configuration considering load fluctuation and energy storage loss. *IET Generation, Transmission & Distribution*, 14: 3278–3287.
18. Luo, X., Wang, J. H., Dooner, M., Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137: 511–536.
19. Wang, Y. G., Song, Y. F., Xia, Y. Y. (2016). Electrochemical capacitors: mechanism, materials, systems, characterization and applications. *Chemical Society Reviews*, 45(21): 5925–5950.
20. Liu, J., Bao, Z., Cui, Y., Dufek, E. J., Goodenough, J., Khalifah, P., Li, Q., Liaw, B., Liu, P., Manthiram, A., et al. (2019). Pathways for practical high-energy long-cycling lithium metal batteries. *Nature Energy*, 4: 180–186.
21. Wang, J., Lu, K., Ma, L., Wang, J., Dooner, M., Miao, S., Li, J., Wang, D. (2017). Overview of compressed air energy storage and technology development. *Energies*, 10: 991.
22. Park, M., Ryu, J., Wang, W., Cho, J. (2017). Material design and engineering of next-generation flow-battery technologies. *Nature Reviews Materials*, 2: 16080.
23. Alnaqbi, S., Alasad, S., Aljaghoub, H., Alami, A., Abdelkareem, M., Olabi, A. (2022). Applicability of hydropower generation and pumped hydro energy storage in the middle east and North Africa. *Energies*, 15: 2412.
24. Chen, H. S., Liu, C., Xu, Y. J., Yue, F., Liu, W., Yu, Z. H. (2021) The strategic position and role of energy storage under the goal of carbon peak and carbon neutrality. *Energy Storage Science and Technology*, 10, 1477–1485. (In Chinese)
25. Li, H., Zhang, Q. (2022). A review of energy storage science and technology projects supported by national key R&D program. *Energy Storage Science and Technology*, 11: 2691–2701. (In Chinese)
26. Choudhury, S. (2021). Flywheel energy storage systems: A critical review on technologies, applications, and future prospects. *International Transactions on Electrical Energy Systems*, 31: e13024.
27. Li, X., Palazzolo, A. (2022). A review of flywheel energy storage systems: State of the art and opportunities. *Journal of Energy Storage*, 46: 103576.
28. Sun, M. X., Xu, Y. L. (2024). Research on the axial stability of large-capacity magnetic levitation flywheel driven by axial-flux permanent magnet machine based on Runge-Kutta method. *IEEE Access*, 12: 22315–22330.
29. Olabi, A. G., Wilberforce, T., Ali Abdelkareem, M., Ramadan, M. (2021). Critical review of flywheel energy storage system. *Energies*, 14: 2159.
30. Kundu, M., Mondal, D., Mondal, I., Baral, A., Halder, P., Biswas, S., Paul, B. K., Bose, N., Basu, R., Das, S. (2023). A rational preparation strategy of phase tuned MoO₃ nanostructures for high-performance all-solid asymmetric supercapacitor. *Journal of Energy Chemistry*, 87: 192–206.
31. Iqbal, M. Z., Aziz, U. (2022). Supercapattery: Merging of battery-supercapacitor electrodes for hybrid energy storage devices. *Journal of Energy Storage*, 46: 103823.
32. Saikia, B. K., Benoy, S. M., Bora, M., Tamuly, J., Pandey, M., Bhattacharya, D. (2020). A brief review on supercapacitor energy storage devices and utilization of natural carbon resources as their electrode materials. *Fuel*, 282: 118796.
33. Yue, X. Y., Yao, Y. X., Zhang, J., Yang, S. Y., Li, Z. H., Yan, C., Zhang, Q. (2022). Unblocked electron channels enable efficient contact prelithiation for lithium-ion batteries. *Advanced Materials*, 34(15): 2110337.
34. Shen, X., Zhang, X. Q., Ding, F., Huang, J. Q., Xu, R., Chen, X., Yan, C., Su, F. Y., Chen, C. M., Liu, X. J., et al. (2021). Advanced electrode materials in lithium batteries: Retrospect and prospect. *Energy Material Advances*, 2021: 1205324.
35. Chang, X., Yang, Z., Liu, Y., Chen, J., Wu, M., Li, L., Chou, S., Qiao, Y. (2024). The guarantee of large-scale energy storage: Non-flammable organic liquid electrolytes for high-safety sodium ion batteries. *Energy Storage Materials*, 69: 103407.
36. Esparcia, E. A. Jr, Castro, M. T., Odulio, C. M. F., Ocon, J. D. (2022). A stochastic techno-economic comparison of generation-integrated long duration flywheel, lithium-ion battery, and lead-acid battery energy storage technologies for isolated microgrid applications. *Journal of Energy Storage*, 52: 104681.
37. Li, X. N., Geng, G. C., Jiang, Q. Y., Ma, J. C., Ni, Q. L., Guo, K. J. (2022). Case study of power allocation strategy for a grid-side lead-carbon battery energy storage system. *IET Renewable Power Generation*, 16: 435–446.
38. Wang, Z. D., Tuo, X. P., Zhou, J. Q., Xiao, G. (2022). Performance study of large capacity industrial lead-carbon battery for energy storage. *Journal of Energy Storage*, 55: 105398.
39. Zhang, C. Y., Lu, X., Han, X., Yu, J., Zhang, C. Q., Huang, C., Balcells, L., Manjon, A. G., Biendicho, J. J., Li, J. S., et al. (2023). Identifying the role of the cationic geometric configuration in spinel catalysts for polysulfide conversion in sodium-sulfur batteries. *Journal of the American Chemical Society*, 145: 18992–19004.
40. China Energy Storage Alliance. (2024). Energy storage industrial research white paper 2024. Beijing.
41. Chen, X. R., Qin, Y. D., Shen, X., Yan, C., Diao, R., Zhu, H. Z., Tang, C., Ouyang, M. G., Zhang, Q. (2023). Lithium-ion batteries participating in frequency regulation through low-destructive bidirectional pulsed current operation. *Advanced Energy Materials*, 13: 2300500.
42. Cheng, X. B., Liu, H., Yuan, H., Peng, H. J., Tang, C., Huang, J. Q., Zhang, Q. (2021). A perspective on sustainable energy materials for lithium batteries. *SusMat*, 1: 38.
43. He, J. R., Bhargava, A., Su, L. S., Charalambous, H., Manthiram, A. (2023). Intercalation-type catalyst for non-aqueous room temperature sodium-sulfur batteries. *Nature Communications*, 14: 6568.
44. Qin, Y. D., Chen, X. R., Tomaszewska, A., Chen, H., Wei, Y. F., Zhu, H. Z., Li, Y. L., Cui, Z. H., Huang, J. H. Du, J. Y., et al. (2022). Lithium-ion batteries under pulsed current operation to stabilize future grids. *Cell Reports Physical Science*, 3: 100708.
45. Huang, Y. L., Cao, B. W., Geng, Z., Li, H. (2024). Advanced electrolytes for rechargeable lithium metal batteries with high safety and cycling stability. *Accounts of Materials Research*, 5: 184–193.
46. Li, A., Qian, C., Mao, G., Liu, Z., Li, Z., Zhang, Y., Yin, L., Shen, L., Li, H. (2024). One-step

- multifunctional surface modification strategy enhancing cycling performance of Li-rich cathodes for lithium-ion batteries. *Journal of Power Sources*, 599: 234245.
47. Javed M. S., Zhong, D., Ma, T., Song, A. T., Ahmed, S. (2020). Hybrid pumped hydro and battery storage for renewable energy based power supply system. *Applied Energy*, 257: 114026.
48. Yang, Y. S., Li, Z. M., Mandapaka, P. V., Lo, E. Y. M. (2023). Risk-averse restoration of coupled power and water systems with small pumped-hydro storage and stochastic rooftop renewables. *Applied Energy*, 339: 120953.
49. Li, J. L., Zhao, Z. W., Xu, D., Li, P. Q., Liu, Y., Mahmud, M. A., Chen, D. Y. (2023). The potential assessment of pump hydro energy storage to reduce renewable curtailment and CO₂ emissions in Northwest China. *Renewable Energy*, 212: 82–96.
50. Mahfoud, R. J., Alkayem, N. F., Zhang, Y. Q., Zheng, Y., Sun, Y. H., Alhelou, H. H. (2023). Optimal operation of pumped hydro storage-based energy systems: A compendium of current challenges and future perspectives. *Renewable and Sustainable Energy Reviews*, 178: 113267.
51. Khalafian, F., Iliiae, N., Diakina, E., Parsa, P., Alhaider, M. M., Masali, M. H., Pirouzi, S., Zhu, M. (2024). Capabilities of compressed air energy storage in the economic design of renewable off-grid system to supply electricity and heat costumers and smart charging-based electric vehicles. *Journal of Energy Storage*, 78: 109888.
52. Karaca, A. E., Dincer, I., Nitefor, M. (2023). A new renewable energy system integrated with compressed air energy storage and multistage desalination. *Energy*, 268: 126723.
53. Guo D. Z., Zhou X. Z., Zhang, X. J. Xu, Y. J., Yin, Z., Liu, C. C., Fu, W. X., Chen, H. S. (2024). Operation characteristics study of fiber reinforced composite air storage vessel for compressed air energy storage system. *Journal of Energy Storage*, 86: 111148.
54. Liu, C., Su, X., Yin, Z., Sheng, Y., Zhou, X., Xu, Y., Wang, X., Chen, H. (2024). Experimental study on the feasibility of isobaric compressed air energy storage as wind power side energy storage. *Applied Energy*, 364: 123129.
55. Pan, X., Zhu, Y., Wang, X., Xiong, J., Guan, Y., Chen, H. (2024). Numerical investigation on the influence of axial thermal expansion in axial turbine for compressed air energy storage system. *Journal of Energy Storage*, 84: 110595.
56. Tong, Z. M., Cheng, Z. W. Tong, S. G. (2021). A review on the development of compressed air energy storage in China: Technical and economic challenges to commercialization. *Renewable and Sustainable Energy Reviews*, 135: 110178.
57. Carrington M. E., Sokolowski, K., Jonsson, E., Zhao, E. W., Graf, A. M., Temprano, I., McCune, J. A., Grey, C. P., Scherman, O. A. (2023). Associative pyridinium electrolytes for air-tolerant redox flow batteries. *Nature*, 623: 949–955.
58. Lv, X. L., Sullivan, P. T., Li, W. J., Fu, H. C., Jacobs, R., Chen, C. J., Morgan, D., Jin, S., Feng, D. W. (2023). Modular dimerization of organic radicals for stable and dense flow battery catholyte. *Nature Energy*, 8: 1109–1118.
59. Hunt, J. D., Zakeri, B., Jurasz, J., Tong, W. X., Dabek, P. B., Brandao, R., Patro, E. R., Durin, B., Leal, W., Wada, Y., et al. (2023). Underground gravity energy storage: A solution for long-term energy storage. *Energies*, 16: 825.
60. Tong, W. X., Lu, Z. A., Chen, W. J., Han, M. X., Zhao, G. L., Wang, X. F., Deng, Z. F. (2022). Solid gravity energy storage: A review. *Journal of Energy Storage*, 53: 105226.
61. Tong, W. X., Lu Z. A., Hunt, J. D., Zhao, H. S., Han, M. X., Zhao, G. L. (2023). The structure and control strategies of hybrid solid gravity energy storage system. *Journal of Energy Storage*, 74: 109283.
62. Lawag, R. A., Ali, H. M. (2022). Phase change materials for thermal management and energy storage: A review. *Journal of Energy Storage*, 55: 105602.
63. Sadeghi, G. (2022). Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. *Energy Storage Materials*, 46: 192.
64. Sathishkumar, A., Cheralathan, M. (2023). Charging and discharging processes of low capacity nano-PCM based cool thermal energy storage system: An experimental study. *Energy*, 263: 125700.
65. Tang, H., Yu, J., Geng, Y., Liu, X., Lin, B. (2023). Optimization of operational strategy for ice thermal energy storage in a district cooling system based on model predictive control. *Journal of Energy Storage*, 62: 106872.
66. Krevor, S., de Coninck, H., Gasda, S. E., Ghaleigh, N. S., de Gooyert, V., Hajibeygi, H., Juanes, R., Neufeld, J., Roberts J. J., Swennenhuis, F. (2023). Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. *Nature Reviews Earth & Environment*, 4: 102.
67. Thomas, J. M., Edwards, P. P., Dobson, P. J., Owen, G. P. (2020). Decarbonising energy: The developing international activity in hydrogen technologies and fuel cells. *Journal of Energy Chemistry*, 51: 405–415.
68. Schmidt, O., Melchior, S., Hawkes, A., Staffell, I. (2019). Projecting the future levelized cost of electricity storage technologies. *Joule*, 3: 81–100.
69. Schmidt, O., Melchior, S., Hawkes, A. D., Staffell, I. (2018). Figshare. DOI: 10.6084/m9.figshare.7330931.v1.
70. Li, Y. L., Wei, Y. F., Zhu, F. Q., Du, J. Y., Zhao, Z. M., Ouyang, M. G. (2023). The path enabling storage of renewable energy toward carbon neutralization in China. *eTransportation*, 16: 100226.
71. Global Energy Interconnection Development and Cooperation Organization. (2023). Energy storage requirements and development pathways for new power system. Beijing.
72. Ouyang, M. G. (2023). Full-cycle energy storage technology for flexible power systems. In Proceedings of the CSEE Annual Meeting 2023. Nanjing. (In Chinese)
73. Peking University. (2023). The connotation and prospects of new power system. Beijing.
74. China Industrial Association of Power Sources. (2023). White paper on China household energy storage industry development 2023. Beijing.
75. APCO Worldwide. (2023). China's booming energy storage: A policy-driven and highly concentrated market. Beijing.
76. DNV. (2024). China's energy transition outlook 2024. Oslo.
77. China Energy Storage Alliance. (2024). Energy storage application branch of China industrial association of power sources. In: China Energy Storage Industry White Paper 2024. Beijing.
78. Jurasz, J., Canales, F. A., Kies, A., Guezgouz, M., Beluco, A. (2020). A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. *Solar Energy*, 195: 703–724.
79. Li, M. H., Hamawandy, N. M., Wahid, F., Rjoub, H., Bao, Z. K. (2021). Renewable energy resources investment and green finance: Evidence from China. *Resources Policy*, 74: 102402.
80. Ren, G. R. Wan, J., Liu, J. F., Yu, D. R. (2019). Yu Spatial and temporal assessments of complementarity for renewable energy resources in China. *Energy*, 177: 262–275.
81. Yin X. B., Yang R. G., Tan, G., Fan, S. H. (2020). Terrestrial radiative cooling: Using the cold universe as a renewable and sustainable energy source. *Science*, 370: 786–791.