



# The Levelized Cost of Storage of Electrochemical Energy Storage Technologies in China

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Large-scale electrochemical energy storage (EES) can contribute to renewable energy adoption and ensure the stability of electricity systems under high penetration of renewable energy. However, the commercialization of the EES industry is largely encumbered by its cost; therefore, this study studied the technical characteristics and economic analysis of EES and presents a detailed analysis of the levelized cost of storage (LCOS) for different EES technologies. The results show that in the application of energy storage peak shaving, the LCOS of lead-carbon (12 MW power and 24 MWh capacity) is 0.84 CNY/kWh, that of lithium iron phosphate (60 MW power and 240 MWh capacity) is 0.94 CNY/kWh, and that of the vanadium redox flow (200 MW power and 800 MWh capacity) is 1.21 CNY/kWh. A detailed analysis of the cost breakdown shows that the proportion of the *Capex* and charging costs of EES projects are relatively high, while the *Opex* and tax costs are comparatively low. The difference between EES projects lies in the proportion of replacement costs. Finally, a sensitivity analysis considering four factors is presented, with this study considering the impact of round-trip efficiency, storage duration, unit initial investment, and the storage application scenario on the LCOS of EES. Among them, the LCOS varies with different application scenarios. For transmission and distribution (T&D) application, the LCOS of lithium iron phosphate is the lowest, due to its long-life advantage compared to lead-carbon.

**Keywords:** electrochemical energy storage, levelized cost of storage, economy, sensitivity analysis, China

## INTRODUCTION

The contradiction between human activities and the ecological environment has become increasingly prominent since the 20th century (Yu et al., 2020). Driven by the national strategic goals of carbon peaking and carbon neutrality, the power industry in China is implementing energy transition response policies, increasing the proportion of renewable energy connected to the grid, and building a new power system with renewable energy as the mainstay. Nevertheless, the power generation capacity of renewable energy such as wind and solar is variable and intermittent, which makes it difficult to provide a stable power supply for the system. Electricity cannot be simply stored, and wind and solar curtailment is costly, which leads to insufficient renewable energy adoption. The combination of energy storage and renewable energy in power operation has significant advantages in improving the flexibility of a power system, promoting renewable energy adoption, and ensuring

the security of the power grid (Shafiullah et al., 2013; Kyriakopoulos and Arabatzis, 2016; Sakti et al., 2018; Gaudard and Madani, 2019). In the future, new power systems dominated by renewable energy will have an increasingly urgent demand for flexible power supplies, and the energy storage industry is ready to launch.

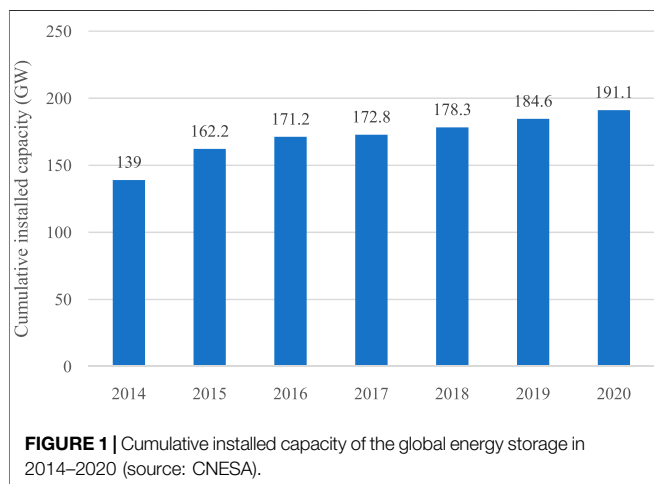
In order to achieve carbon neutrality in China by 2060, the establishment of a “near-zero emission” energy system based primarily on renewable energy will be indispensable. Energy storage is the overriding technology that can accelerate energy transition and buffer the mismatch between power demand and supply (Brandt et al., 2021; Murphy et al., 2021). The large-scale development of energy storage is a crucial technological approach to the development of low-carbon energy, the aims of which are to improve the adoption and storage capacity of renewable energy. The development of energy storage is mediated by the maturity of technology (Kousksou et al., 2014; Pierpoint, 2016), capacity allocation optimization (Ma et al., 2019; Hou et al., 2020; Jin et al., 2020; Li et al., 2020), system optimization scheduling of energy storage (Geem and Yoon, 2017; Hou et al., 2019), and energy storage policy (Ming et al., 2013; Winfield et al., 2018; McPherson et al., 2020; Varghese and Sioshansi, 2020). However, in the initial development stage, economic analysis is pivotal in the process of the technological development of energy storage (Ye et al., 2016). A reduction in the cost of energy storage technology will shorten the payback period of investment. The levelized cost of storage (LCOS) based on energy storage life cycle modeling is considered to be one of the international general energy storage cost evaluation indexes.

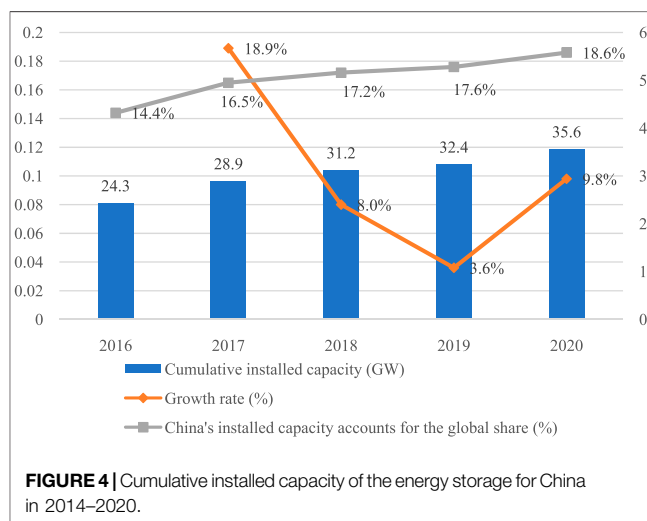
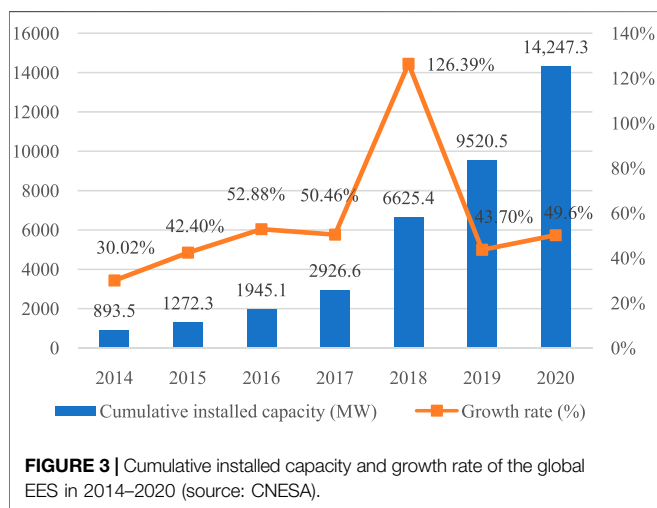
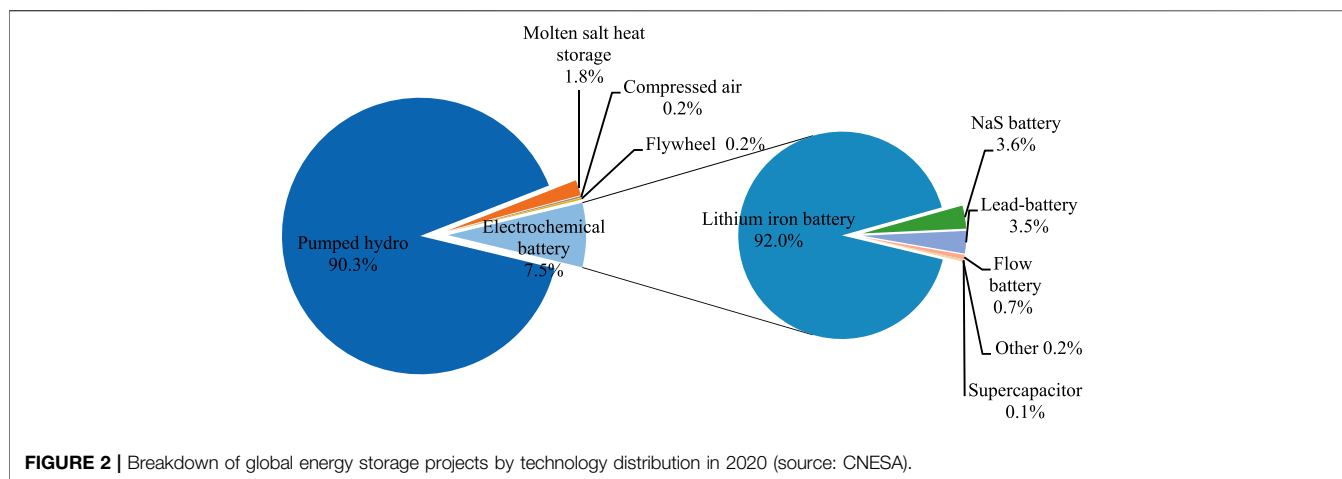
There has been a prolific number of research works employing the LCOS to analyze the economics of different storage systems. The International Renewable Energy Agency (IRENA) released the cost-of-service tool version 1.0 in 2017 to estimate the cost of energy storage in different application scenarios (Ralon et al., 2017). Lazard (2018) released a report to analyze the observed costs and revenue streams associated with commercially available energy storage technologies. Zakeri and Syri (2015) adopted an LCOS model to comprehensively analyze the economy of five types of energy storage technologies

(physical energy storage, EES, superconducting magnetic energy storage, supercapacitors, and hydrogen energy storage) in three main applications (large-capacity energy storage, transmission and distribution support services, and frequency regulation). Schmidt et al. (2017) constructed an empirical curve to predict the levelized cost of 11 electricity storage technologies using the LCOS. Schmidt et al. (2019) employed an LCOS model to determine the life costs of nine energy storage technologies in 12 power system applications from 2015 to 2050. Obi et al. (2017) discussed the variables that affect the LCOS of energy storage systems and calculated the energy storage costs of physical energy storage (pumped storage systems and compressed air systems) and chemical batteries. Pawel (2014) exhaustively examined the costs of different power storage technologies, *inter alia*, the costs of long-term storage systems (100 MW power and 70 GWh capacity), and short-term storage systems (100 MW power and 400 MWh capacity) were analyzed. Jülch (2016) conceived a new framework for calculating the cost of energy storage, which was used to calculate the LCOE of combined photovoltaic and energy storage power plants.

At present, EES is developing rapidly in China; however, the economics of EES technologies are ambiguous, which restricts further development of EES. He et al. (2019) calculated the cost per kilowatt-hour and cost per mileage of energy storage technologies and analyzed the full life cycle of energy storage in terms of the typical application scenarios of capacity and power energy storage. Xue et al. (2016) framed a general life cycle cost model to holistically calculate various costs of consumer-side energy storage, the results of which showed the average annual cost of battery energy storage on the consumer side of each category from low to high, namely, lead-acid battery < sodium sulfur battery (NaS) = lithium iron battery < vanadium redox flow battery. In summary, there is limited research analyzing the economics of large-scale EES deployment in China. Hence, it is of practical value to employ the LCOS to evaluate domestic EES projects. This study took large-scale EES projects as the research object to evaluate the average annual cost of different technologies by applying an LCOS model on lead-carbon, lithium iron phosphate, and vanadium redox flow projects.

The aims and contributions of the presented research are as follows: 1) to present the energy storage development policies over time in China and to summarize the technical characteristics of EES in China, that is, technical maturity, energy density, power density, charge/discharge cycle, roundtrip efficiency, etc.; 2) to develop an LCOS method for evaluating the levelized cost of storage by considering the technical and economic parameters and the costs, including *Capex*, *Opex*, charging cost, tax cost, replacement cost, and end-of-life cost; 3) to calculate the LCOS of three typical EES projects with different EES technologies, including lead-carbon, lithium iron phosphate, and vanadium redox flow batteries—by comparing the LCOS, the cost breakdown and its causes were analyzed; and 4) to analyze the sensitivity of four factors to the LCOS, including the round-trip efficiency, storage duration, unit initial investment, and storage application scenario, to better promote the development of EES.





The remainder of the article is organized as follows: **Section 2** presents the energy storage development status across the world and in China. **Section 3** provides the technical characteristics of EES in China. The methodology for assessing the LCOS of EES is established in **Section 4**. **Section 5** shows the results and discussion. Finally, conclusions are given in **Section 6**.

## DEVELOPMENT STATUS QUO OF ENERGY STORAGE IN INTERNATIONAL SOCIETIES AND CHINA

### The International Installed Capacity of Energy Storage and EES

The cumulative installed capacity of global energy storage in 2014–2020 is shown in **Figure 1**. According to the statistics reported by the China Energy Storage Alliance (CNESA), by the end of 2020, a total of 191.1 GW of energy storage projects had been put into operation worldwide. The breakdown of global energy storage projects in 2020 by technology

distribution is shown in **Figure 2**. The proportion of EES was 7.5%, exceeding 10 GW for the first time. Among the different types of EES, the cumulative installed capacity of lithium iron batteries was the largest, accounting for 92% of the total installed capacity of EES.

After pumped hydro, EES is the most widely used energy storage technology with great developmental potential. By the end of 2020, the cumulative installed capacity of EES had reached 14.2 GW. The cumulative installed capacity and growth rate of the global EES in 2014–2020 are shown in **Figure 3**.

### The Installed Capacity of Energy Storage and EES in China

From 2016 to 2020, the energy storage industry in China steadily expanded, with the installed capacity rising from 24.3 GW in 2016 to 35.6 GW in 2020. **Figure 4** shows the cumulative installed capacity of energy storage for China in 2016–2020. In 2020, the cumulative installed capacity in China reached 35.6 GW, a year-on-year increase of 9.8%,

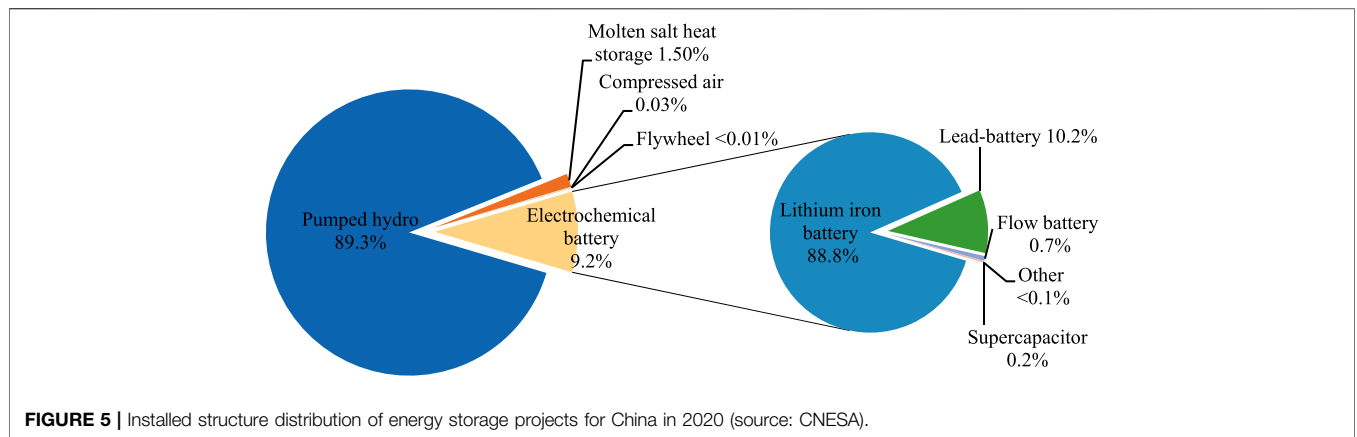


FIGURE 5 | Installed structure distribution of energy storage projects for China in 2020 (source: CNESA).

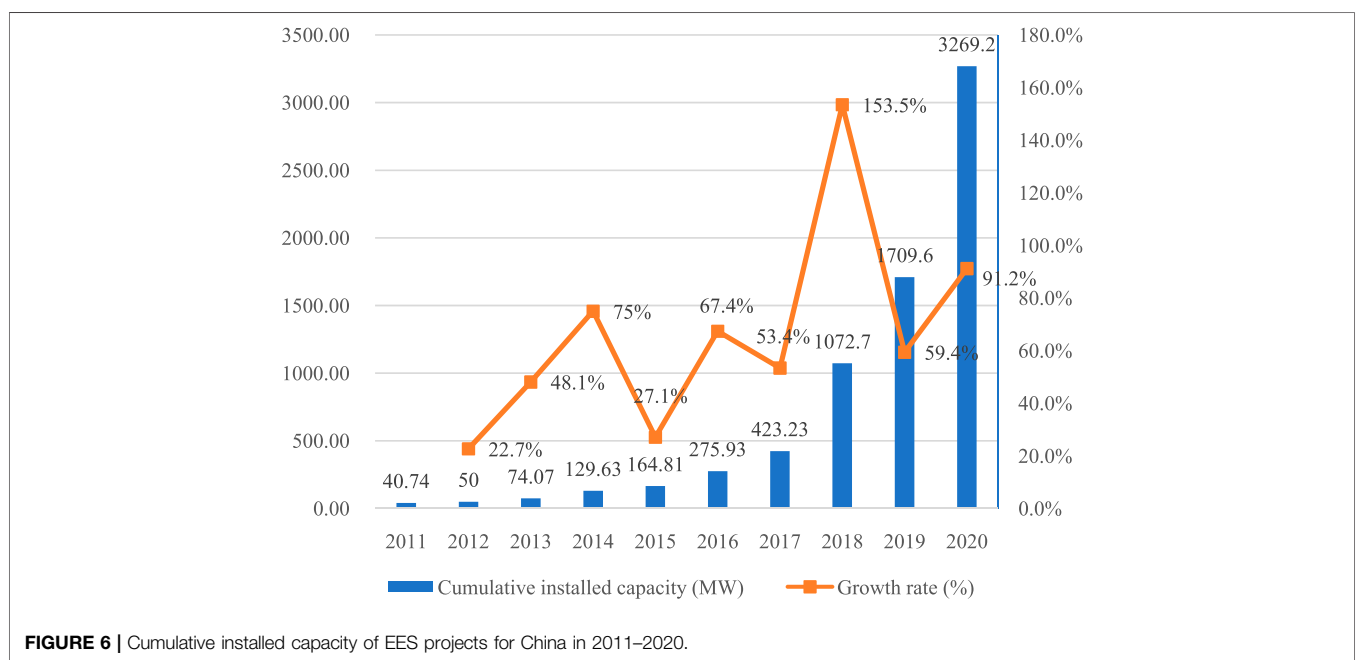


FIGURE 6 | Cumulative installed capacity of EES projects for China in 2011–2020.

accounting for 18.6% of the global total installed capacity. Pumped hydro accounted for 89.30%, followed by EES with a cumulative installed capacity of 3.27 GW, accounting for 9.2%. Among all types of EES, the cumulative installed capacity of lithium iron batteries was the largest, accounting for 88.8%, with an installed capacity of 2.90 GW. The installed structure distribution of energy storage projects for China in 2020 is shown in **Figure 5**.

By the end of 2020, the cumulative installed capacity of EES in China was 3269.2 MW, with a year-on-year growth of 91.2%. The cumulative installed capacity of newly added EES reached 1.56 GW, transcending 1 GW for the first time. In 2018, with the explosive growth in EES, the newly installed capacity of EES was as high as 612.8 MW compared to the newly added 147.3 MW in 2017, a year-on-year increase of 316%. **Figure 6** shows the cumulative installed capacity and growth rate of EES in China from 2011 to 2020.

## Policy Review Early Stage (2005–2010)

In 2005, the “Guiding Catalogue for the Development of Renewable Energy Industry,” which was issued by the National Development and Reform Commission (NDRC), began to involve the strategic layout of the energy storage industry. With the continuous expansion of market demand for the renewable energy industry, energy storage development was written into the bill for the first time in 2010. In the “Renewable Energy Law Amendment,” it was stipulated that power grid enterprises should develop and apply smart grid and energy storage technology.

## The 12th Five-Year Plan Stage (2011–2015)

At the end of the 12th Five-Year Plan, policies on energy storage began to be issued frequently. The “Energy Development Strategy Action Plan (2014–2020)” mentioned that energy storage should be used to solve the problem of renewable energy adoption and should

**TABLE 1** | Policy of the energy storage industry in China.

Period	Document	Issuer	Year	Objectives	References
Early stage	“Guiding Catalogue for the Development of Renewable Energy Industry” “Renewable Energy Law Amendment”	NDRC	2005	To lay out the beginning of the energy storage industry in China	NDRC, (2005)
		National People’s Congress (NPC)	2010	To write energy storage development into the proposed law for the first time	NPC, (2010)
12th Five-Year Plan	“Energy Development Strategy Action Plan (2014–2020)”	State Council (SC)	2014	To utilize energy storage to solve the problem of grid connection and adoption and to promote reformation of the power system	State Council, (2014)
	“Several Opinions on Further Deepening the Reform of the Power System”	SC	2015	To proactively develop advanced energy storage technology	State Council, (2015)
	“Guiding Opinions on Promoting the Construction of Renewable Energy Microgrid Demonstration Projects”	National Energy Administration (NEA)	2015	To use the energy storage system as the key construction object of the renewable energy microgrid	NEA, (2015b)
13th Five-Year Plan	“Outline of the 13th Five-Year Plan for the National Economic and Social Development of the People’s Republic of China”	NPC	2016	To include the development of energy storage and distributed energy in 100 major projects, for which implementation in the next 5 years was planned	NPC, (2016)
	“13th Five-Year Plan for Renewable Energy Development”	NDRC	2016	To carry out demonstration applications of energy storage in the field of renewable energy and to improve the technical and economic efficiency of energy storage	NDRC, (2016)
	“Guiding Opinions on Promoting the Development of Energy Storage Technology and Industry”	NDRC	2017	To deploy the development stage goals and key development directions of energy storage	NDRC, (2017)
	“Opinions on Innovating and Improving the Price Mechanism for Promoting Green Development”	NDRC	2018	To promote energy storage facilities to participate in grid peak reduction, to fill valleys, and to increase subsidies	NDRC, (2018)
	“Implement the “Guiding Opinions on Promoting the Development of Energy Storage Technology and Industry” Action Plan for 2019–2020”	NDRC	2019	To establish requirements for technology research, intelligent manufacturing, energy storage industrial policies, exemplary projects, and the standardization of energy storage	NDRC, (2019)
14th Five-Year Plan	“The 14th Five-Year Plan for the National Economic and Social Development of the People’s Republic of China and the Long-term Target Plan for 2035”	NPC	2021	To incubate and implement industries in the frontier scientific and technological fields, such as hydrogen energy and energy storage	NPC, (2021)
	“Guiding Opinions on Accelerating the Development of Renewable Energy Storage (Draft for Solicitation of Comments)”	NDRC, NEA	2021	To articulate the development goal of 30 GW of energy storage and realize the leap-forward development of energy storage	NDRC and NEA, (2021)

promote reformation of the power system. At the same time, in the “Several Opinions on Further Deepening the Reform of the Power System,” it was pointed out that the Chinese energy sector should actively develop microgrid and smart grid technology that integrates advanced energy storage technology and information technology to improve the system energy consumption capacity and energy utilization efficiency. The reform of the power system and a series of supporting documents created a more flexible and market-oriented environment and widened the application space of energy storage in the power system.

### The 13th Five-Year Plan Stage (2016–2020)

During the 13th Five-Year Plan period, the energy storage strategy occupied a more important position. In 2016, in the “Outline of the 13th Five-Year Plan for the National Economic and Social Development of the People’s Republic of China,” the development of energy storage and distributed energy was included in the 100 major projects that China plans to implement in the next 5 years, and energy storage officially entered the national development plan for the first time, laying a good foundation for the introduction of energy storage policies in the future. At the same time, at the end of

the 13th Five-Year Plan, the NDRC made it clear that it was necessary to promote energy storage to participate in power market transactions, which provided a guarantee for further promoting the development of energy storage.

### The 14th Five-Year Plan Stage (2021–2025)

Entering the new stage of the 14th Five-Year Plan, the energy storage industry has matured, and the key position of energy storage in the construction of China’s energy system in the future is becoming more and more prominent. The energy storage industry has ushered in rapid development, and the speed of policy introduction has been significantly accelerated. Driven by the policies, energy storage is changing from “optional” in the past to “mandatory” in the future power system. **Table 1** summarizes the policies of China’s energy storage industry.

## TECHNICAL CHARACTERISTICS OF EES IN CHINA

Energy storage is the process of storing energy through media or equipment and releasing it when needed (Hua, 2019). Energy

**TABLE 2** | Characteristics of the EES technology in China.

	Lead acid battery		Lithium iron battery			NaS	Flow battery		Supercapacitor
	Traditional lead acid	Lead-carbon	Lithium iron phosphate	Lithium titanate	Nickel-cobalt-manganate lithium		Vanadium redox flow	Zinc bromide flow	
Technical maturity	Commercialization	Demonstration	Commercialization	Demonstration	Commercialization	Commercialization	Demonstration	Demonstration	Demonstration
Energy density (W.h/kg)	30–50	25–50	150	110	220	150	15–25	65	10–15
Power density (W/kg)	<150	500–600	1500–2000	3000	3000	22	50–100	200	5000–10,000
Round-trip efficiency (%)	70–85	90	90–95	>95	>95	87	75–85	75–80	>90
Self-discharge rate (%/month)	1	1	2	2	2	0	Low	10	<10
Battery lifetime (year)	2–3	4–5	8	10	8	8–10	15	10	15
Charge/discharge cycle	200–800	2000–3000	3000–5000	≥10,000	5000–6000	4500	>10,000	5000	>100,000
Response speed (ms)	<10	<10	Milliseconds	Milliseconds	Milliseconds	Milliseconds	Milliseconds	Milliseconds	Milliseconds
Power cost (CNY/kW)	500–1000	6400–10,400	3200–5800	9000	4000–5000	13,200–13,800	17,500–19,500	12,500–15,000	400–500
Energy cost (CNY/kWh)	500–1000	800–1300	1600–2900	4500	2000–2500	2200–2300	3000–3500	2500–3000	9500–13,500
Operation and maintenance cost (CNY/kW)	15–50	192–520	96–290	270–450	120–250	390–690	175–585	375–750	12–25
Security	High	High	Medium	Medium	Medium	Low	High	High	Medium
Depth of discharge (%)	60%	80%	80%	80%	80%	90%	100%	100%	100%
Working temperature	–40 to 50	–30 to 60	300–350	0–40	15–50	–40 to 70	–	–	–
Advantages	Low investment	High performance cost and good consistency	High energy density and little pollution			High energy density	Large capacity and long lifetime		Long lifetime and high efficiency
Disadvantages	Short lifetime	Low energy density	High cost			High cost and complex O&M	Low energy density	Corrosivity and volatility of raw materials	Low energy density
References	(CNESA, 2019; Schmidt et al., 2019)		(Lai et al., 2017a; CNESA, 2019; Schmidt et al., 2019)			(CNESA, 2019; Schmidt et al., 2019)	(Lai et al., 2017a; CNESA, 2019; Schmidt et al., 2019)		(CNESA, 2019; Schmidt et al., 2019)

storage enables the temporal and spatial transfer of electric energy, which can effectively isolate the production and utilization of electric power. It also eliminates the peak valley difference of day and night power consumption, improves resource utilization efficiency, and ensures the large-scale grid connection of renewable energy (Shafiullah et al., 2013; Taylor et al., 2013). Meanwhile, energy storage devices can improve the peak shaving and frequency modulation capacity of the system; they reduce the investment in the construction of peak-shaving power stations, reserve capacity, and expansion of power transmission and distribution (CNESA, 2019; Giarola et al., 2021).

EES technology has broad application prospects in the field of power systems due to its characteristics of high-energy density, high specific power, fast response, high reliability, long life, flexible installation, etc. EES is a popular research topic and key developmental direction in different countries around the world (Wang et al., 2020). At present, the main EES technologies in China include lead, lithium iron, flow batteries, NaS, and supercapacitors. **Table 2** summarizes the main characteristics of the EES technology in China.

## METHODOLOGY AND DATA

### The LCOS Model

In order to evaluate the cost of energy storage technologies, it is necessary to establish a cost analysis model suitable for various energy storage technologies. The LCOS model is a tool for comparing the unit costs of different energy storage technologies. It can be described as the total lifetime cost of energy storage technology divided by its cumulative delivered electricity using the discount rate  $i$  (Schmidt et al., 2019).

Despite the increasing research on the LCOS, there is no unified understanding of the calculation method of energy storage costs. While some studies have ignored economic parameters such as replacement or charging costs, others have excluded technical parameters such as  $\eta$  and the self-discharge rate ( $O_u$ ) (Lai and McCulloch, 2017a; Obi et al., 2017).

In this study, the LCOS considers all technical and economic parameters affecting the lifetime cost. EES costs include *Capex*, *Opex*, *charging cost*, *tax cost*, *replacement cost*, and *end-of-life cost*. The LCOS quantifies the discounted cost per unit of discharged electricity for a specific storage technology. The calculation method of the LCOS is similar to the LCOE of power generation technology, so it is a comparable and suitable tool for comparing the cost of power storage technology (Kousksou et al., 2014; Zakeri and Syri, 2015; Jülch, 2016; Lai et al., 2017b, 2019; Lai and McCulloch, 2017b; Schmidt et al., 2017, 2019).

Stakeholders can use the LCOS model to calculate the cost of different energy storage technologies, compare the results, and analyze the competitiveness of each energy storage technology, so as to make better decisions and promote the development of the energy storage industry. For example, market participants can choose lower-cost energy storage technology to maximize their benefits. For system operators, they can select a more appropriate

energy storage technology to solve the problems of limited power grid consumption capacity and insufficient peak shaving capacity. Additionally, by analyzing the costs of different energy storage technologies, policymakers can help guide the development policies of the energy storage industry, such as the subsidy policy, in order to provide reference for the development planning and sustainable development operation of the energy storage industry against the background of large-scale grid connection of renewable energy in China.

$$LCOS = \frac{Capex + \sum_{n=1}^N \frac{Opex_n}{(1+r)^n} + \sum_{n=1}^N \frac{Tax_n}{(1+r)^n} + \sum_{n=1}^N \frac{Charging_n}{(1+r)^n} + C_{rep} + C_{rec}}{\sum_{n=1}^N \frac{E_{Discharge}}{(1+r)^n}} \quad (1)$$

where *Capex* is the value of the initial investment cost, *Opex<sub>n</sub>* is the annual value of the operation and maintenance costs, *Tax<sub>n</sub>* is the annual tax amount of a power plant, *Charging<sub>n</sub>* is the annual value of the charging costs, *C<sub>rep</sub>* is the discounted value of the replacement cost of batteries, *C<sub>rec</sub>* is the discounted residual value of a power station, *E<sub>Discharge</sub>* is the discharge of the energy storage system, and *N* is the service lifetime of the plant.

### Variables and Factors

This study calculated the LCOS by evaluating the discharged electricity and various costs from construction and operations. The following variables were the principal inputs for calculating the LCOS.

**Capital expenditure (*Capex*):** The initial investment cost includes the energy storage system cost, the power conversion cost, and the civil construction cost. Among them, the system cost is mainly composed of equipment installation costs (including battery costs) and construction costs (excluding land costs). The energy storage equipment includes energy storage batteries, battery management systems, energy storage inverters, and power distribution systems. The construction costs mainly include construction engineering fees, installation engineering fees, and equipment and facility design and commissioning expenses.

**Operation and maintenance costs (*Opex*):** The operation and maintenance costs are those costs needed to maintain the energy storage power station in a good standby state. These costs include maintenance costs (*C<sub>m</sub>*), labor costs (*C<sub>l</sub>*), insurance costs (*C<sub>i</sub>*), power station management costs (*C<sub>psm</sub>*), and other fixed costs (*C<sub>oth</sub>*).

**Financial costs:** These include the own capital ratio (*P*), loan interest rate (*R*) and load period (*P<sub>l</sub>*), after-tax internal return rate (*IRR*), service lifetime (*P<sub>s</sub>*), and depreciation rate (*q*).

**Tax costs:** These include income tax (*T<sub>i</sub>*), value-added tax (*VAT*), land use tax (*T<sub>l</sub>*), urban maintenance and construction tax (*T<sub>u</sub>*), and education surcharges (*T<sub>e</sub>*).

**Charging costs:** Electricity price and  $\eta$  are two important indicators that determine the unit charging costs.

**Replacement costs:** These include the percentage of annual reduction in the battery installation costs, battery replacement times, battery lifetime, etc.

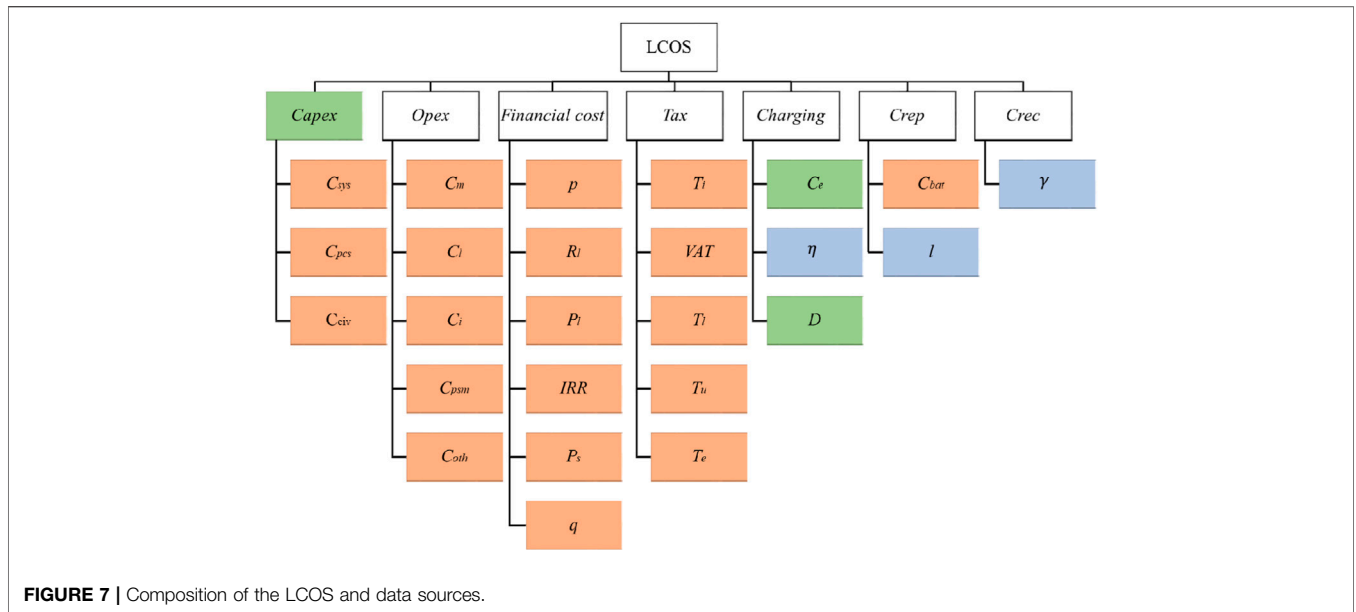


FIGURE 7 | Composition of the LCOS and data sources.

End-of-life cost: These include asset evaluation fees, clean-up fees, dismantling and transportation fees, recycling and regeneration treatment fees, and recycling value.

Figure 7 clearly shows the cost structure of the LCOS.

### Parameterization and Assumptions

In the aforementioned EES technologies, lead acid, lithium iron, flow, and NaS batteries can be employed in large-scale EES projects. In China, the use of NaS batteries started late. The current demonstration project is a 100 kw/800 kwh NaS energy storage system developed by the Institute of Silicate, Chinese Academy of Sciences, in cooperation with Shanghai Electric Power Company; there is no megawatt-level application demonstration case yet. Therefore, this study selected typical large-scale EES projects in China (the Huzhou 10 kV Bingchen 12 MW/24 MWh lead-carbon energy storage project, the Gansu Jiuquan Zhongneng brunji 60 MW/240 MWh energy storage project, and the Dalian liquid flow battery 200 MW/800 MWh energy storage project) to study the LCOS of lead-carbon, lithium iron phosphate, and vanadium redox flow batteries. Their application scenario is energy storage peak shaving, which is designed to charge at night and discharge during the day. Thus, these systems are assumed to charge and discharge once during each 24-h period at full charge/discharge depth. The power capacity, energy capacity, total initial investment, etc., are set according to the design value of the actual project. The battery and energy storage system costs are determined in proportion to the initial investment. The battery life, recycling coefficient ( $\gamma$ ),  $\eta$ , and  $O_u$  are set according to the technical characteristics of different types of EES.

#### (1) Capital expenditure (Capex)

The whole life cycle of an EES project is divided into a construction period and an operation period. The Capex

occurs in the construction period of the project, which refers to the fixed asset investment. It mainly includes the energy storage system cost ( $C_{sys}$ ), power conversion cost ( $C_{pcs}$ ), and civil construction cost ( $C_{civ}$ ). The  $C_{sys}$  accounts for a large portion of the Capex. For lithium iron battery energy storage, the system cost accounts for 80–85%, of which the battery cell cost ( $C_{bat}$ ) accounts for 50%, the system components account for 20%, the management systems account for 15%, and other equipment accounts for 15%. In the cost structure of battery cells, the material cost usually accounts for more than 50% of the  $C_{bat}$ . For EES technology, the power conversion cost in the power usage scenario is 500,000–800,000 CNY/MW, while that in the energy usage scenario is determined by the ratio of the nominal power capacity of the energy storage system to the nominal energy capacity. The  $C_{civ}$  mainly includes the planning, survey, design, construction land fee, and project management fee of the power station in the early stage, accounting for 3–10% of the Capex (He et al., 2019).

$$Capex = C_{sys} + C_{pcs} + C_{civ} \tag{2}$$

$$C_{bat} = C_E \times (E_{nom}/\eta_{bat}) = C_E \times [(P_{nom}t)/\eta_{bat}] \tag{3}$$

where  $C_E$  is the unit energy cost of the battery (CNY/kWh),  $E_{nom}$  is the nominal energy capacity (kWh),  $P_{nom}$  is the nominal power capacity (kW),  $\eta_{bat}$  is the conversion efficiency (%), and  $t$  is the nominal discharge time (h).

$$C_{pcs-e} = \lambda_{P/E} C_{pcs-p} \tag{4}$$

where  $C_{pcs-e}$  is the unit power conversion cost in the energy-usage scenario (CNY/kWh),  $C_{pcs-p}$  is the unit power conversion cost in the power-usage scenario (CNY/kW), and  $\lambda_{P/E}$  is the ratio of the nominal power capacity of the energy storage system to the nominal energy capacity.

This study calculated the cost of three EES technologies in the energy-usage scenario.



$$C_{pcs} = C_{pcs-e} \times E_{nom} \tag{5}$$

where  $C_{pcs}$  is the power conversion cost in the energy-usage scenario (CNY/kWh).

$$C_{civ} = C_c \times E_{nom} \tag{6}$$

where  $C_c$  is the unit cost of civil construction per installed capacity (CNY/kWh).

(2) Operation and maintenance cost (*Opex*)

During the life cycle of an EES project, in order to ensure its normal operation, the power station needs to be maintained every year. The *Opex* mainly includes the insurance, transportation, maintenance, wages, and welfare. Insurances and repair charges are given in the form of rates, which are 0.5 and 2% of the plant's fixed assets per year, respectively (Hahn et al., 2017). According to the actual survey data, it is estimated that the annual employee salary in the power station is 80,000 CNY. The welfare labor insurance coefficient is set at 60% of the total salary, and the employee wage growth rate is 6%.

$$Opex = C_{om} \times E_{nom} \tag{7}$$

where  $C_{om}$  is the unit energy cost of the *Opex* (CNY/kWh).

(3) Financial cost

The construction cost of the project is relatively high, and most of the investment comes from bank loans. According to the "Notice of the State Council on Strengthening the Capital Management of Fixed Asset Investment Projects," this study set the capital proportion to 20%, with the other funds financed by bank loans (State Council, 2019). Considering the time value of the funds, a discount rate of 8% is adopted to discount the funds in the whole life period of the project (Schmidt et al., 2019). Since October 2015, the People's Bank of China has adjusted the long-term loan interest rate to 4.9% (Monetary Policy Department, 2015). The loan period is 15 years, the design lifetime of the power station is 20 years, and the depreciation period is 15 years (NEA, 2015a; Hahn et al., 2017). According to the standard of the power industry, the internal rate of return (IRR) of an EES project is set at 8%.

(4) Tax cost

The tax basis for tax purposes is different and needs to be determined according to the situation. Under the implementation of the policy of "Replacing Business Tax with Value-added Tax," the operating tax of an EES project is not calculated. According to "Enterprise income tax law of the people's Republic of China," the enterprise income tax is levied at a tax rate of 15% on enterprises (STA, 2019a). According to the "Regulations on the Implementation of the Enterprise Income Tax Law of the People's Republic of China," from the tax year of the first production and the operation income of the project, the enterprise income tax is exempted from the first to the third

year and is reduced by half from the fourth to the sixth year (STA, 2019b). Value-added tax has become one of the most important taxes in China. The NEA issued "The Notice on Reducing the Tax Burdened on Enterprises in the Field of Renewable Energy" and implemented a VAT rate of 6.5% (China Power Grid, 2017; STA, 2019c). Land use tax is levied on the land within the scope of cities, counties, organizational towns, and industrial and mining areas, and the actual occupied land area is the basis for tax calculation. The land use tax is levied at 2 CNY/m<sup>2</sup> (Yuan et al., 2016). According to the relevant regulations on property tax, the tax rate is 1.2% and the property tax deduction ratio is 30% (TCPGPRC, 2005a). In addition, urban maintenance and construction tax and education surcharges are based on value-added tax, which are 4 and 3%, respectively (TCPGPRC, 2005b; TCPGPRC, 2020).

(5) Charging cost

According to Obi et al. (2017), this study adopted off-peak electricity prices. The charging cost can be expressed as follows:

$$Charging = C_e \times E_{nom} \tag{8}$$

where  $C_e$  is the charging electricity price (CNY/kWh).

(6) Replacement cost

In an EES system, the battery has capacity degradation, a decrease in performance, and a limited usage time. If the battery's lifetime is shorter than the project's, the replacement cost needs to be considered. As battery technology matures and expands, battery costs will drop year on year. Therefore, it is necessary to consider the proportion of battery cost reductions when determining battery replacement costs. During the project cycle, the replacement cost of a battery each time can be expressed as follows:

$$C_{bat-r} = (1 - \alpha)^{kl} C_{bat} \tag{9}$$

where  $\alpha$  is the percentage of annual reduction in battery installation costs,  $k$  is the battery replacement time, and  $l$  is the battery lifetime.

Therefore, the discounted value of replacement cost of the battery can be expressed as follows:

$$C_{rep} = \sum_{\beta=1}^k [C_{bat} (1 - \alpha)^{\beta l} / (1 + i)^{\beta l}] \tag{10}$$

where  $\beta$  is the  $\beta_{th}$  time to replace the battery.

(7) End-of-life cost

After the end of the service life of the energy storage power station, the assets of the power station need to be disposed of, and the end-of-life costs mainly include asset evaluation fees, clean-up fees, dismantling and transportation fees, and recycling and regeneration treatment fees. The metal materials and some components in the power plant can be recovered. Therefore,

**TABLE 3** | Common parameters of EES projects.

Parameters	Value	Parameters	Value
Unit life (year)	20	Discount rate (%)	8%
Years of bank loan (year)	15	Premium rate (%)	0.5%
Capital ratio (%)	20%	Major repair rate (%)	2%
Annual interest rate (%)	4.9%	Urban maintenance and construction tax (%)	5%
IRR (%)	8%	Education surcharges (%)	3%
Income tax (%)	15%	Property tax (%)	1.2%
VAT (%)	6.5%	Land use tax (CNY/m <sup>2</sup> )	2
D (day)	330	$\alpha$ (%)	8%
C <sub>e</sub> (CNY/kWh)	0.25	Construction time (year)	1

**TABLE 4** | Specific parameters for the three different types of EES projects.

Types	Lead-carbon	Lithium iron phosphate	Vanadium redox flow
Power capacity (MW)	12	60	200
Storage duration (h)	2	4	4
Energy capacity (MWh)	24	240	800
Total initial investment (Million CNY)	31	400	3500
Unit initial investment (CNY/kWh)	1282	1667	4375
System cost (CNY/kWh)	1089	1417	3719
Battery cost (CNY/kWh)	600	730	2500
Battery life (year)	5	8	15
$\gamma$ (%)	20%	0	40%
$\eta$ (%)	90%	95%	85%
Self-discharge rate (%/month)	1%	2%	0.5%

Their application scenario is energy storage peak shaving. The sources are: Zakeri and Syri, 2015; Berrada and Loudiyi, 2016; Sepulveda et al., 2021; Nan, 2015; Gan, 2020; Pai, 2016; Lazard, 2015; and survey data.

the residual value of an energy storage power station is defined as the residual value at the end of the life of the power station, excluding the disposal cost. If the disposal fee is greater than the recycling value of the power station, it is the cost; otherwise, it is the income.  $\gamma$  is related to the type of battery technology. At present, it seems that the recovery value of lead and vanadium liquid flow batteries is higher, approximately 20–40%. The diversity of materials and the variety of shapes and sizes make recycling systems for lithium-ion batteries lag far behind (Huang et al., 2018). The cost of recycling lithium-ion batteries is higher than the cost of their regeneration; therefore, lithium iron phosphate batteries are not recycled, and the residual value is set to 0 (He et al., 2019). The end-of-life cost is determined by  $\gamma$  and the *Capex*.

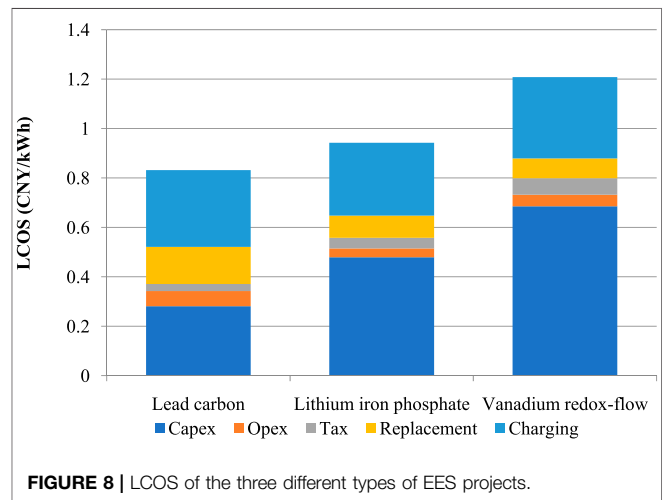
Therefore, the discounted value of the end-of-life cost of can be expressed as follows:

$$C_{rec} = (End - of - life\ cost) / (1 + r)^{N+1} = \gamma Capex / (1 + r)^{N+1} \tag{11}$$

Where  $\gamma$  is the recycling coefficient; in the project cycle, it is assumed as the ratio of the residual value of the energy storage power station to the *Capex*.

(8) Discharged electricity

Energy capacity, self-discharge, and  $\eta$  are all important factors influencing the annual storage capacity (annual delivery capacity)



**FIGURE 8** | LCOS of the three different types of EES projects.

of an energy storage system.  $\eta$  refers to the ratio of discharge to charge of the storage system. It determines the energy that the storage system buys from the outside. During the working process of the battery, an internal irreversible reaction occurs, causing the storage capacity to gradually decrease. The reduced capacity ratio is called  $O_u$ . Due to different working principles, the  $\eta$  and  $O_u$  of EES technologies are also different.

$$E_{Discharge} = E_{nom} \times D \times DoD \times \eta \times (1 - o_u) \tag{12}$$

where  $DoD$  is the depth of discharge,  $\eta$  is the round-trip efficiency,  $D$  is the annual operating days, and  $o_u$  is the self-discharge rate. Table 3 shows the common parameters of EES projects, while Table 4 shows the specific parameters for the three different types of EES projects.

## RESULTS AND DISCUSSION

### The LCOS for the Three Technologies in EES Projects

In Figure 8, the results show that the LCOS of lead-carbon is 0.84 CNY/kWh, that of lithium iron phosphate is 0.94 CNY/kWh, and that of vanadium redox flow is 1.21 CNY/kWh.

Lead-carbon batteries are a new generation of lead acid batteries, in which carbon is added into the negative active material of traditional lead acid batteries. China has prolific lead resources, which can be simply processed with raw material of a lower cost. Additionally, the lead-carbon battery recycling system is relatively mature, as it is easier to recycle active materials from used batteries. This type of battery is easy to recycle because the residual value is quite high and the *Capex* is significantly lower than those of the other two types of battery. This is why the value of the LCOS of lead-carbon batteries is the smallest.

Lithium iron phosphate batteries have a long life cycle, with a 95% round-trip efficiency and a low charging cost. However, this type of energy storage project still faces many adversities. For instance, during the disposal of recycled batteries, the recycling cost is high, *inter alia*, the end-of-life cost of the lithium element is five times that of original lithium batteries. The positive and negative electrode materials of the batteries, the material side reactions of the electrolyte, the internal short circuit of the battery cores, and so on cause a high  $O_u$  of lithium iron phosphate batteries, as well as a power loss. Taking the above factors into consideration, the LCOS value of the lithium iron phosphate in EES projects is slightly higher than that of lead-carbon.

At present, lithium iron phosphate batteries are more widely used than lead-carbon batteries. However, regarding the repeated occurrence of safety incidents in lithium battery storage power stations around the world, lead-carbon batteries have become another development direction of EES projects due to the safety of lead-carbon batteries (Yang, 2021; CIEIN, 2022). Lead-carbon batteries currently have a good development momentum in China. Due to their low initial investment, high residual value, and easy recycling, the LCOS of lead-carbon batteries is the lowest.

Vanadium ions are the sole electrolyte ions of vanadium redox flow batteries. Changes in the valence state in vanadium ions occur during charging and discharging without the phase changes that other batteries commonly have. After long-term utilization, fast charge and discharge responses can still be maintained. When a battery's life ends, the electrolyte solution can be recycled, the cost of which accounts for more than 50% of the total cost of the energy storage system, so the residual value is extremely high after the energy storage system is scrapped. The life cycle of vanadium redox flow batteries is much longer than those of lead-carbon and

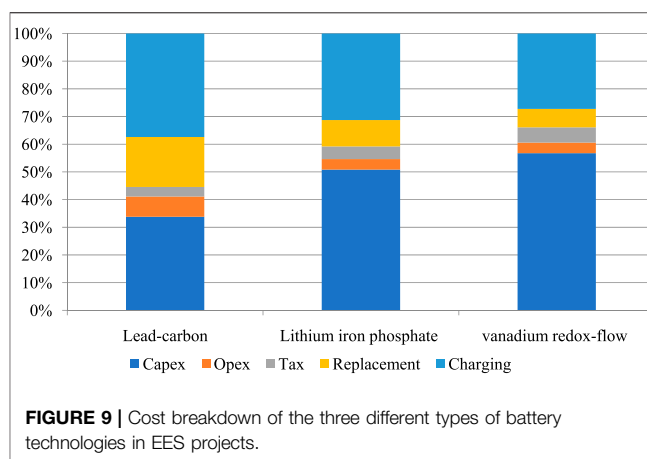


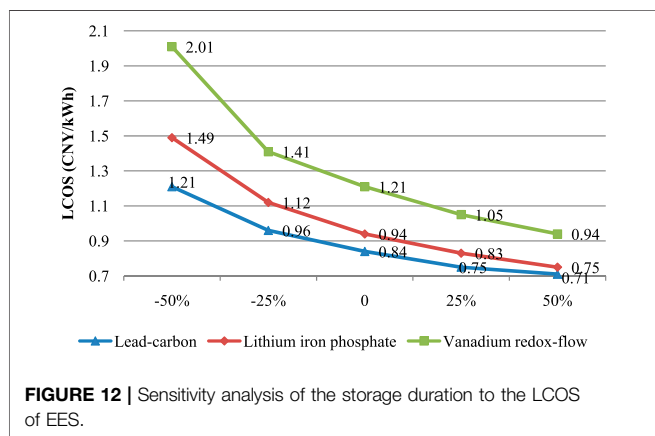
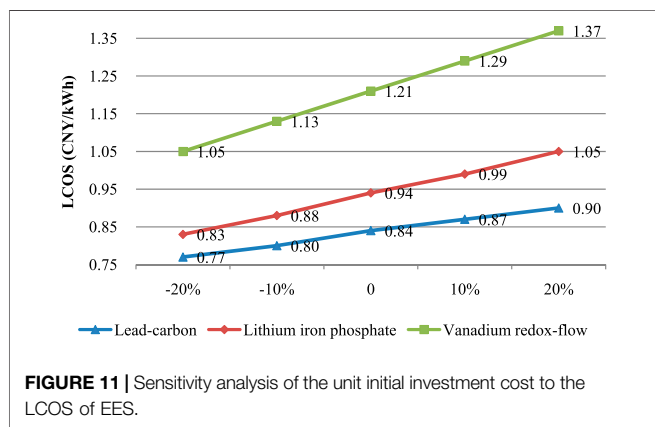
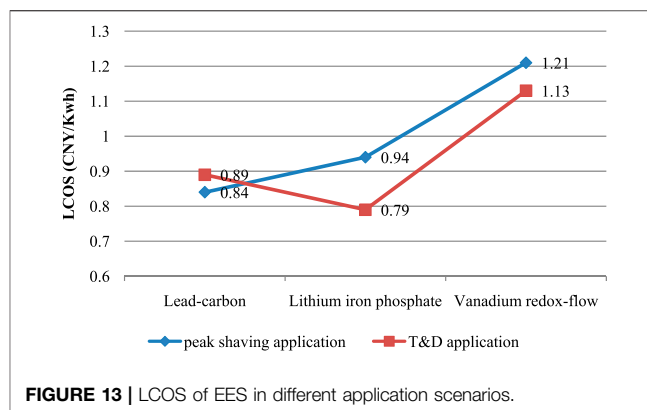
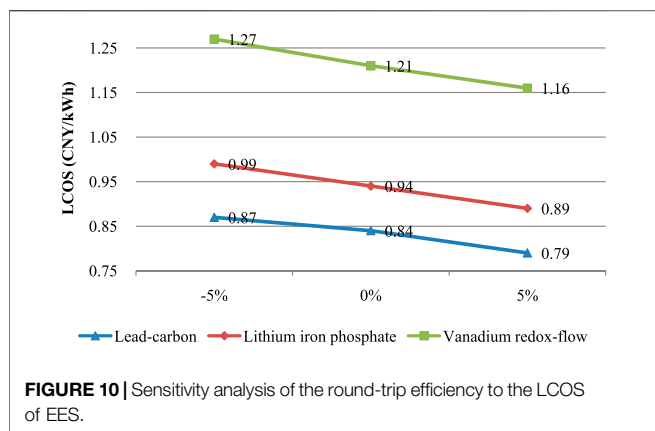
FIGURE 9 | Cost breakdown of the three different types of battery technologies in EES projects.

lithium iron phosphate batteries. The former batteries only need to be replaced once during the lifetime of the energy storage project, so the replacement cost is relatively low. The positive and negative electrolytes of the batteries are stored separately, and the  $O_u$  is very low when the batteries are in standby mode. However, the shortcomings are evident. First of all, such projects require independent storage tanks, reaction tanks, and facilities such as pumps and different types of pipelines, which take up more space and result in a higher *Capex*. Second, this type of EES project is still in its initial stage, with immature technology and a lower  $\eta$ , which affects the charging price and discharged electricity. The shortcomings mentioned above contribute to the high LCOS value of vanadium redox flow in EES projects.

The charging cost of an EES project is a significant part of the LCOS. It is in direct proportion to the electricity price and is inversely proportional to the  $\eta$ . The three projects adopt the same electricity price and  $\eta$ ; Lithium iron phosphate > lead-carbon > vanadium redox flow, so the charging cost is as follows: vanadium redox flow > lead-carbon > lithium iron phosphate. However, there is not much difference in the charging costs among the three projects; hence, the charging cost is not the major reason for the discrepancy between the three projects in the LCOS.

### Cost Breakdown for the Three Technologies in EES Projects

The cost breakdown of the three different types of battery technologies in EES projects is shown in Figure 9. The common point that the three projects have is that the *Capex* and charging cost account for a large proportion, while the *Opex* and tax cost account for the smallest proportion. The costs of lithium iron phosphate and vanadium redox flow in each category are basically the same; the *Capex* and charging cost account for the largest proportion, with the replacement cost being the second largest. The proportion of the *Capex* of lead-carbon drops significantly compared to the other two; instead, the proportion of replacement cost increases for lead-carbon batteries, which have a short life cycle and require three replacements during the lifetime of an energy storage project. The replacement cost is much higher than that for the other two



types of batteries, but the raw material reserves for lead-carbon technology are prolific, the battery cost is low, and the recycling value is high; therefore, the *Capex* is less.

### Sensitivity Analysis

According to Schmidt et al. (2017), the experience rates (based on the production price) of lead-carbon, lithium ion, and vanadium redox flow are 4, 12, and 11%, respectively, and are based on the works of Obi et al. (2017) and Jülch (2016). This study selected

four factors, namely, round-trip efficiency ( $\pm 5\%$ ), storage duration ( $\pm 50\%$ ), unit initial investment ( $\pm 20\%$ ), and storage application scenario, to explore the impact of technology learning on the LCOS of EES. The results are shown in Figures 10–13.

In Figure 10, the LCOS of the three types of EES decreases with the increase in round-trip efficiency, and the decrease pattern is basically similar.

In Figure 11, the LCOS of the three types of EES increases with the increase in the unit initial investment cost. The rate of vanadium redox flow is the fastest, followed by lithium iron phosphate, while lead-carbon is the slowest. Therefore, vanadium redox flow is the most sensitive to unit initial investment cost, followed by lithium iron phosphate, while lead-carbon is the least sensitive. The experience rate (based on production price) of lead-carbon batteries is much lower than that of the other batteries (Schmidt et al., 2017). Therefore, compared to lead-carbon, the initial investment cost of lithium iron phosphate and vanadium redox flow has a higher declining slope, resulting in a faster decline of the LCOS.

In Figure 12, the LCOS of the three types of EES decreases with the increase in storage duration. The decreasing rate of vanadium redox flow is the fastest, followed by lithium iron phosphate, while lead-carbon is the slowest. This means that vanadium redox flow is the most sensitive to storage duration, followed by lithium iron phosphate, while lead-carbon is the least sensitive. The technical advantage of vanadium redox flow is the medium- to long-term energy storage range of 4–10 h. When the vanadium redox flow increases by 50% (6 h), the LCOS is 0.94 CNY/kWh, which decreases by 29%. With the decrease in the initial investment cost of the battery and the extension of storage duration (which is its unique technical advantage), the vanadium redox flow is expected to compete with other technologies.

For transmission and distribution (T&D) application, storage systems charge/discharge twice during each 24-h period. In Figure 13, the results show that the LCOS of lead-carbon is 0.89 CNY/kWh, that of lithium iron phosphate is 0.79 CNY/kWh, and that of vanadium redox-flow is 1.13 CNY/kWh in T&D application.

In this scenario, the battery capacity is not fully utilized and the battery life increases. Lithium iron phosphate takes advantage of its long life. It only needs to be replaced once during the lifetime of the EES project, and the amortized value of the

replacement cost over the whole lifecycle is 0.05 CNY/kWh, while that of lead-carbon battery is 0.21 CNY/kWh. This is the main reason why the LCOS of lithium iron phosphate is the smallest. Therefore, investors should give full play to the advantages of different technology types to maximize the income when arranging EES.

In China, the cumulative installed capacity of lithium-ion batteries accounted for 88.8% of the EES in 2020. Lithium iron phosphate batteries are the predominant EES technology, as they are the most widely used and commercialized at present in China. Lead-carbon batteries have the highest safety due to their lack of combustibles during operation. They have also become an option for large-scale EES technology. The cost of vanadium redox flow is high in the initial stage of development, but with the development of technology and industry, the cost will be greatly lowered. Moreover, the scale design of this type of battery is very flexible. The energy storage capacity depends on the electrolyte capacity and concentration. As long as the volume of the electrolyte is increased, the energy storage capacity can be enhanced. Therefore, vanadium redox flow will be the most promising large-scale EES technology in the future.

## CONCLUSION

As a high-quality flexible resource, energy storage can play an important regulatory role in a high proportion of renewable energy power systems. With the increasing proportion of renewable energy in power generation, energy storage technology has great potential in energy systems. In recent years, the demand for EES in China has greatly increased, the installed capacity of EES on the power supply and grid sides continues to rise, and large-scale energy storage presents a rapid developmental trend.

This study combed the development process of energy storage policy and summarized the characteristics of EES technology in China and then analyzed the leveled cost of storage of three different types of EES power stations based on the LCOS model. The costs consisted of *Capex*, *Opex*, charging cost, tax cost, replacement cost, and end-of-life cost. This study calculated the LCOS by evaluating the discharged electricity and various costs related to construction and operation. Finally, the round-trip efficiency, storage duration, unit initial investment, and storage application scenario were selected as sensitivity factors, and sensitivity analysis of the four factors to the LCOS of EES was employed.

From the results, in the application scenario of energy storage peak shaving, due to the abundant lead resources and mature lead-carbon battery recycling system, the initial investment cost of lead-carbon batteries is significantly lower than that of the other two; the LCOS of lead-carbon is 0.84 CNY/kWh, which is the smallest. Due to the long life cycle but high end-of-life cost, the LCOS of lithium iron phosphate batteries is 0.94 CNY/kWh, which is in the middle. Due to the high recycling value and high investment cost, vanadium redox flow technology is still

immature, with an LCOS of 1.21 CNY/kWh, which is the highest.

From the cost breakdown, it is indicated that the proportion of *Capex* and charging cost is the largest, while the proportion of tax cost and *Opex* is the smallest. The difference among the three projects lies in the fact that lead-carbon has a short life cycle with many replacements, which results in a large cost. The distinction of costs in each part was presented in this article.

From the sensitivity analysis, with an increase in the round-trip efficiency factor, the LCOS of the three types of EES decreases linearly with similar trends. With a decrease in the unit initial investment cost factor, the LCOS values of the three types of EES all show a downward trend, with that of vanadium redox flow being the most sensitive. With an increase in the storage duration factor, the LCOS of vanadium redox flow decreases the fastest, followed by that of lithium iron phosphate, while that of lead-carbon is the slowest. The LCOS varies with different application scenarios. For T&D application, LCOS is the lowest because the lithium iron phosphate batteries only need to be replaced once, taking advantage of their long life. In summary, stakeholders should minimize the cost of EES by improving round-trip efficiency and storage duration, reducing the unit initial investment cost, and giving full play to the advantages of different technology types when laying out EES.

The limitations of the presented research can be seen in the fact that the results are based on the economic evaluation of three types of EES projects. In cases of other types of EES, the technical characteristics will be different, especially in different application scenarios. Further research will be more focused on the comprehensive value of multiple applications of energy storage in power systems, especially in the ancillary services market and other services.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

YX: conceptualization, methodology, and writing—original draft. JP and LC: data curation, visualization, and software. PL: investigation and validation. TM: resources and writing—reviewing and editing.

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## GLOSSARY

$\alpha$	Percentage of annual reduction in battery installation costs	$C_{rep}$	Discounted value of the replacement cost of batteries
$\beta$	The $\beta_{th}$ time to replace the battery	$C_{sys}$	Energy storage system cost
$\gamma$	Recycling coefficient	$D$	Annual operating days
$\lambda_{P/E}$	Ratio of the nominal power capacity of the energy storage system to the nominal energy capacity	$DoD$	Depth of discharge
$\eta_{bat}$	Conversion efficiency	$E_{Discharge}$	Discharge of the energy storage system
$\eta$	Round-trip efficiency	$E_{nom}$	Nominal energy capacity
<b>Capex</b>	Capital expenditure	<b>IRR</b>	Internal return rate
$C_{bat}$	Battery cells cost	$k$	Battery replacement times
$C_c$	Unit energy cost of civil construction	$l$	Battery lifetime
$C_{civ}$	Civil construction cost	<b>LCOS</b>	Levelized cost of storage
$C_E$	Unit energy cost of battery	$N$	Service lifetime of the plant
$C_e$	Charging electricity price	<b>Opex<sub>n</sub></b>	Operation and maintenance costs
<b>Charging<sub>n</sub></b>	Annual value of charging cost	$o_u$	Self-discharge rate
$C_i$	Insurance cost	<b>P</b>	Own capital ratio
$C_l$	Labor cost	$P_l$	Loan period
$C_m$	Maintenance cost	$P_{nom}$	Nominal power capacity
$C_{om}$	Unit energy cost of the <i>Opex</i>	$P_s$	Service lifetime
$C_{oth}$	Other fixed costs	$q$	Deprecation rate
$C_p$	Unit power cost of PCS	$R_l$	Loan interest rate
$C_{pcs}$	Power conversion cost	$t$	Nominal discharge time
$C_{pcs-e}$	Unit power conversion cost in the energy-usage scenario	<b>Tax<sub>n</sub></b>	Annual tax amount of a power plant
$C_{pcs-p}$	Unit power conversion cost in the power-usage scenario	$T_e$	Education surcharges
$C_{psm}$	Power station management cost	$T_i$	Income tax
$C_{rec}$	Discounted residual value of a power station	$T_l$	Land use tax
		$T_u$	Urban maintenance and construction tax
		<b>VAT</b>	Value-added tax