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Dynamic economic evaluation of hundred megawatt-scale electrochemical energy storage for auxiliary peak shaving

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Abstract

With the rapid development of wind power, the pressure on peak regulation of the power grid is increased. Electrochemical energy storage is used on a large scale because of its high efficiency and good peak shaving and valley filling ability. The economic benefit evaluation of participating in power system auxiliary services has become the focus of attention since the development of grid-connected hundred megawatt-scale electrochemical energy storage systems (ESS). Based on the relationship between power and capacity in the process of peak shaving and valley filling, a dynamic economic benefit evaluation model of peak shaving assisted by hundred megawatt-scale electrochemical ESS considering the equivalent life of the battery is proposed. The model considers the investment cost of energy storage, power efficiency, and operation and maintenance costs, and analyzes the dynamic economic benefits of different energy storage technologies participating in the whole life cycle of the power grid. Then, according to the current ESS market environment, the auxiliary service compensation price, peak-valley price difference and energy storage cost unit price required to make the energy storage technology achieve the balance of payments are calculated, and the economic balance points of different energy storage types are clarified. Finally, based on the measured data of different provincial power grids, the economies of six energy storage types applied to three provincial power grids are compared and analyzed, and the rationality and effectiveness of the relevant models proposed are verified. The work has theoretical guiding significance for the economic benefit evaluation of hundred megawatt-scale electrochemical energy storage.

Highlights

1 A proportional relationship between grid filling power and capacity demand is proposed. It is used to determine the energy storage configuration for auxiliary peak shaving.
2 A dynamic economic evaluation model considering energy storage investment and maintenance costs, electricity profit, and auxiliary service compensation is proposed.
3 In the three provincial power grids, the economics of 6 hundred megawatt-scale electrochemical energy storages are compared and analyzed.
4 Auxiliary service compensation, time of day rate, and energy storage cost that enable energy storage to reach an economic equilibrium point are determined.

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Keywords Peak shaving, Energy storage system, Optimal configuration, Dynamic benefit, Economic balance point

1 Introduction

In recent years, global wind power has developed rapidly. Taking China as an example, by the end of October 2022, the installed capacity of wind power was about 350 GW, representing a year-on-year increase of 16.6% and accounting for 14.0% of the country's cumulative installed power generation capacity [1]. However, because of the anti-peaking characteristics of wind power, the peak-to-valley difference of the grid load is increased, and consequently the grid faces a large peaking pressure [2–4]. The uncertainty of renewable energy grid connection is deeply affected by weather, season, geographical location and other factors, so energy fluctuation and uncertainty are relatively large. This will also affect the storage and transportation of energy. Therefore, the development of renewable energy needs to consider its random factors. The establishment of an energy storage power station is to better absorb new energy and improve its utilization rate. The focus of this paper is to establish a dynamic economic benefit evaluation model through energy storage assisted peak regulation with the background of the relatively large cost of energy storage technology, so as to prevent the impact of power fluctuation on the power grid. Finally, the economic balance point required to achieve balance of payments when a variety of energy storage assisted power grid peak regulations are determined, and the energy storage configuration scheme with the best prospects is proposed.

Energy storage technology can realize the peak-shaving of the load Because of its high-quality two-way adjustment capability, which provides a new idea for the power grid to ease the peaking situation [5, 6]. Compared with other energy storage technologies, electrochemical energy storage requires fewer geographical conditions and has higher energy efficiency, and thus has the broadest application prospects [7–9]. At present, several domestic and foreign companies have begun to implement demonstration projects at 10–100 MW level electrochemical energy storage power stations participating in the peaking auxiliary service of the power grid. However, because of the high investment cost of electrochemical energy storage, how to improve its economics in the market has become a research hotspot in recent years [10–13].

In addition to the high cost of electrochemical energy storage, it also faces problems such as unclear application value and imperfect participation in market mechanisms. In response to this, relevant policy documents have been issued to encourage the establishment of relevant compensation mechanisms to promote the development of energy storage technology. We will use this as an entry point to study electrochemical energy storage technology in the current Chinese market environment.

Related research on energy storage assisted peak regulation is reviewed here. Reference [14] uses the fluctuating energy costs in competitive energy markets to realize the additional benefits of energy storage systems (ESS), and a gradient based heuristic optimization algorithm is used to calculate the optimal charge–discharge plan to improve the economic income of the ESS. In [15], a semi-determined planning method is used to realize the economic dispatch of a high-throughput DC microgrid for distributed generators and ESS, whereas [16] evaluates the feasibility of transferring power consumption from cold ESS to electrical ESS. Reference [17] proposes a strategy for determining the best implementation opportunities for new ESS: mining deployment, telecommunication towers, and remote islands. In [18], the technical implementation difficulty and economic cost of HES and CES are evaluated and compared to propose a mathematical modeling optimization method to minimize the cost of electricity received from the grid. From the perspective of improving energy storage operation income and reducing energy storage investment cost, reference [19] proposes an energy storage optimization strategy of postponing substation expansion and establishes an energy storage economic operation model that maximizes energy storage operation arbitrage income and energy storage network loss income. Reference [20] establishes a battery simulation model based on the working mechanism and external characteristics of VRB. The voltage and current loss characteristics of a vanadium REDOX battery are studied in the rated charging and discharging mode, and finally the optimized operation strategy of an energy storage module is proposed. In [21], an energy sharing platform is proposed to balance the fluctuations of renewable energy to improve the reliability of the system, and the capacity and energy sharing method of the hybrid BESS and TESS system are provided to realize the comprehensive use of heat, gas and electricity sharing. Reference [22] puts forward a new type of dual-port mixed diode topology and adaptive super capacitor energy buffer management strategy. Compared with the existing topology, the proposed topology not only reduces system cost, size, and control complexity, but also improves efficiency. An adaptive

supercapacitor buffer energy management strategy is also designed to decrease battery degradation. In [23], a road piezoelectric micro-energy acquisition and storage system is proposed. It systematically studies the influence and law of energy storage under different traffic conditions and on-site open traffic conditions, verifies the reliability of energy storage, and evaluates the on-site electrical conversion efficiency and energy storage efficiency in open traffic conditions. Reference [24] presents a tool for multi-service scheduling of ESS by integrating optimization models with distribution system simulators. This provides insight into the value that ESS can bring when used in a stacked manner with multiple services. Reference [25] proposes a new efficient and environmentally friendly hybrid energy production/storage system, which aims to minimize the pollutant emissions of compressed air energy storage technology, while fully solving the intermittency and power reduction problems of the grid with high renewable energy penetration rate. In [26], an integrated generation and customer station ESS expansion planning model is proposed with high temporal resolution, operational details of generation units and ESS, and load scheduling optimization, whereas [27] proposes an optimized charging scheme to minimize the impact of EV charging demand on distribution transformers. The proposed model is based on load and meteorological data in Texas, USA, to reduce energy consumption costs and avoid transformer overload and life loss.

However, the continuous development of energy storage technology has broadened its application field beyond microgrids, but there are limited studies on peaking as the application scenarios for ESS. In this paper, China's three provincial-level power grids will be used as application cases for electrochemical energy storage, and the economics of participating in grid-assisted peak-shaving will be analyzed.

In the process of analysis, the configuration of the ESS and the type of ESS are the key factors affecting its economy. Energy storage configuration can support the development of renewable energy, such as solar energy, wind energy, etc., and consequently unstable renewable energy can be converted into stable power output to promote energy transformation. In addition, energy storage configuration can reduce carbon emission and environmental pollution. By converting renewable energy into electricity output, energy storage configurations can reduce the use of fossil energy, thereby reducing carbon emissions. Reference [28] proposes a bi-level optimal configuration method of energy storage assisted grid peak regulation considering both economy and wind power consumption, while [29] proposes an economical optimal energy storage configuration method under flexibility constraints. It considers both economy and flexibility as a bi-level optimization model. Reference [30] uses ESS for peak shaving and valley filling, and establishes an energy storage configuration model with the goal of maximizing the multi-link benefits of energy storage. In [31], a parsimonious optimization model is developed to analyze whether electricity storage limits the transition to renewable energy, whereas [32] uses a random mixed-integer linear programming (MILP) optimization model to evaluate the economics of ESS. Reference [33] proposes a hybrid ESS (HESS) control strategy and uses the Lingo solution method to achieve the optimal configuration of HESS to achieve the best economic benefits. In [34], an analytic hierarchy process (AHP)-based framework is proposed for determining the economic combination of storage combinations in three cases. Reference [35] proposes a comprehensive planning scheme to determine the location and capacity of the interconnected Internet data center and battery ESS (BESS) in the smart grid, in which the computing performance index of the Internet data center and the operating standard of the grid are coordinately considered as three interrelated but conflicting objectives, and the coupling influence between the network and energy is modeled. Reference [36] proposes a unique energy storage method, which combines the three types of energy storage to establish the optimal energy storage capacity allocation model, optimizes the capacity of the grid-connected wind power photovoltaic storage hybrid power system, and analyzes the model with an optimization algorithm. In [37], a bipolar optimization model of grid-side BESS with coordinated planning and operation is proposed from the perspective of electricity marketization, and a multi-objective two-layer model is established for the optimal configuration of BESS for analysis. Reference [38] develops an evaluation algorithm coupled with a genetic evolutionary algorithm, and solves a vector optimization problem to find the optimal configuration of the size and number of CHP gas engines and the battery size, to maximize the energy saving and minimize the recovery cycle. Reference [39] presents a mathematical model for the configuration of a multi-type BESS, and studies the effects of battery type and capacity degradation characteristics on the optimal capacity configuration of BESS and the power scheduling scheme of HPS. In [40], the relationship between the power of charging and discharging systems and the storage time is identified to ensure profit, while [41] analyzes the optimal response algorithm of self-interested optimization using a multi-agent capacity optimization method based on game theory. Reference [42] proposes a hybrid integer nonlinear programming (MINLP) model to optimize BESS configurations with multiple types of batteries. [43] proposes a controller based on deep reinforcement learning (DRL)

to manage the state of charge (SOC) of multi-energy ESS (M-EESS). This can better serve the power grid to provide frequency response. Reference [44] proposes a layered programming model to obtain the optimal configuration (number, location, and size) of BESS for bus voltage regulation and energy cost reduction, while [45] shows that in order to adapt to the changes of CHP load and power generation, a simultaneous optimization scheme of LBSS storage capacity design and operation strategy formulation is adopted. The above studies used the corresponding mathematical model to optimize the ESS configuration, but in the optimization process, the power and capacity of the ESS have a clear constraint relationship. When the provincial power grid participates in a peak regulation auxiliary service, the configuration of the ESS should be selected according to the specific peak regulation requirements and load characteristics. Therefore, this paper proposes a matching relationship between power system capacity demand and valley filling power, and constrains the configuration of ESS and the load characteristics of provincial power grids under a given peak shaving demand.

In the economic analysis of different energy storage types, reference [46] analyzes the technical and economic efficiency of a highly efficient reversible solid oxide battery system for distributed ESS. In [47, 48], the key technologies of compressed air ESS and their economics are analyzed considering life cycle costs, direct income, and potential benefits, while in [49], the optimal economic and technical scale is analyzed when lithium-ion batteries are connected to wind farms, and the optimal battery cost is evaluated in the presence of battery aging. References [50–52] use electric vehicle batteries as the research object to analyze the economic impact of cost, capacity, life, depth of discharge, and battery health on the secondary use of electric vehicle batteries. A method is proposed to accelerate the measurement of energy capacity of lithium-ion batteries. This provides a method for future circular economy strategies for electric vehicles. Reference [53] studies the economics of cryogenic energy storage technology when using market arbitrage.

There are also economic analyses of other types of energy storage, but there is lack of comparative analysis of the economics of different energy storage technologies in the same application scenario. Reference [54] proposed an optimization model that includes a novel dispatch control strategy for an HESS and analyzed techno-economic performance. Reference [55] analyzes the economic performance of the development of distributed solar photovoltaic with reused batteries as ESS. In [56], the optimal life cycle costs (LCC) of photovoltaic-powered cooling systems for three off-grid applications are analyzed by comparing seven different system configurations with battery and thermal energy storage. In [57], to propose a method to determine the optimal capacity, an overall technical and economic model of a microgrid is established, and variables such as photovoltaic system power, azimuth, battery size, converter rating, capital investment and electricity price are analyzed. In this paper, three different provincial power grids in China will apply six types of electrochemical energy storage, including lithium iron phosphate, lithium titanate, lead–carbon, lead-acid, sodium-sulfur, and vanadium flow batteries. Peak auxiliary services, and comparative analysis of the economic benefits of each energy storage type in the life cycle will be carried out.

In addition, in the economic evaluation of ESS, energy storage economic dispatch plays an important role in improving energy efficiency, reducing energy costs, and ensuring the reliability of power supply. It is an important means to achieve sustainable energy supply and energy revolution. To provide a more general economic analysis method for grid-side energy storage, reference [58] mainly considers the auxiliary service income that can be clearly calculated under policy conditions when calculating the value income. Looking at a scenario of an electric vehicle charging station, reference [59] establishes an economic analysis model of optical storage and charging joint system from the perspective of low carbon. The model reasonably evaluates the investment cost and annual operation cost of photovoltaic power generation and battery energy storage, the benefits of delaying the upgrading of power grid, of energy saving and emission reduction, and of power generation. A method for calculating the annual total benefit of the combined system under the constraints of system power balance, photovoltaic and energy storage operation is also proposed. In [60], the energy efficiency technology cost, benefit, and economic recovery period of the ESS are evaluated, and the impact of the corresponding incentive measures on the investment recovery period is analyzed. In [61], a stochastic unit commitment model with energy storage capacity is proposed to analyze the short-term profitability and energy storage capacity of conventional generators at different regeneration penetration levels. Reference [62] provides economic compensation for energy storage investors from the aspects of unit reserve capacity and investment cost compensations to evaluate the economics of ESS. When analyzing hybrid energy storage, the combination of multiple energy storage technologies can optimize energy storage efficiency, avoid the limitations of a single energy storage technology, and improve the overall energy utilization efficiency of the system. Hybrid energy storage technology can promote the development and use of renewable energy, reduce

the dependence on traditional energy, and further promote sustainable development. Reference [53] analyzes the technical characteristics, market price fluctuations, and the impact of energy costs on the economics of ESS, while [63] proposes three systems, including a photovoltaic system, hydrogen power generation, consumption and storage system, and a thermal system, and carries out technical and economic evaluation of a hybrid combined power generation system. To maximize economic profits, an algorithm is proposed in [64] to determine the optimal ESS scale required by photovoltaic and wind turbine suppliers using their historical power generation curves and compensation prices. The optimal size of ESS is evaluated by net present value (NPV).

This paper will evaluate the dynamic economic benefits of each energy storage type in the life cycle from the perspective of energy storage investors, combined with the electricity revenue, investment cost, and operational and maintenance cost of the ESS [65]. By considering the two factors of the construction period of the energy storage power station and the capital loan in the dynamic benefit model, the results are more accurate. Finally, considering the current ESS market environment, the effects of auxiliary service compensation, peak-to-valley electricity price difference, and ESS cost on economic benefits of ESS are analyzed, and the economic equilibrium point of energy storage technology is clarified.

The rest of the paper is organized as follows: in Sect. 2, the ESS configuration model of the grid auxiliary peaking service is established. The model includes the power system capacity demand and the valley filling power ratio relationship, and the ESS capacity and power allocation model. Section 3 establishes the dynamic economic benefit evaluation model of ESS assisted peak shaving, including various ESS income and cost calculation models, ESS operational constraints, and battery equivalent life calculation method. Section 4 is a description of the case conditions, whereas Sect. 5 analyzes the economic comparison examples of six energy storage types applied to three provincial power grids. Finally, the main contents and results are summarized in Sect. 6.

2 ESS configuration model

When the ESS participates in the auxiliary service of grid peak shaving, the capacity and power configurations of the ESS must be determined. Each configuration should be selected according to the peaking demand and load characteristics of the power grid. The peaking demand of the power grid and the characteristics of the load valley period will affect the capacity configuration of the ESS, while the charging power of the ESS and the characteristics of the load peak period will affect the power configuration.

2.1 Relationship between capacity demand and valley filling power in the grid

The capacity demand of the energy storage can be calculated by the filling power and the characteristics of the valley load, as:

$$E=\int_{t_1}^{t_2}\eta_C\left(P_T+P_{load,\min}-P_{load,t}\right)dt \tag{1}$$

where P_T is the given filling power, E is the capacity demand of the energy storage, $P_{load,min}$ is the minimum value of load power, and $P_{load,t}$ is the load power at time t. η_C is the charging efficiency of the energy storage, t_1 is the starting time of the period of the valley filling, and t_2 is the ending time of the period of the valley filling. When $P_T+P_{load,min}-P_{load,t}>0$, the tth time is in the period of the valley filling.

However, because of the different daily load characteristics, it is not sufficiently accurate to obtain the energy storage capacity configuration with typical day data. Figure 1 shows the schematic diagram of the power demand

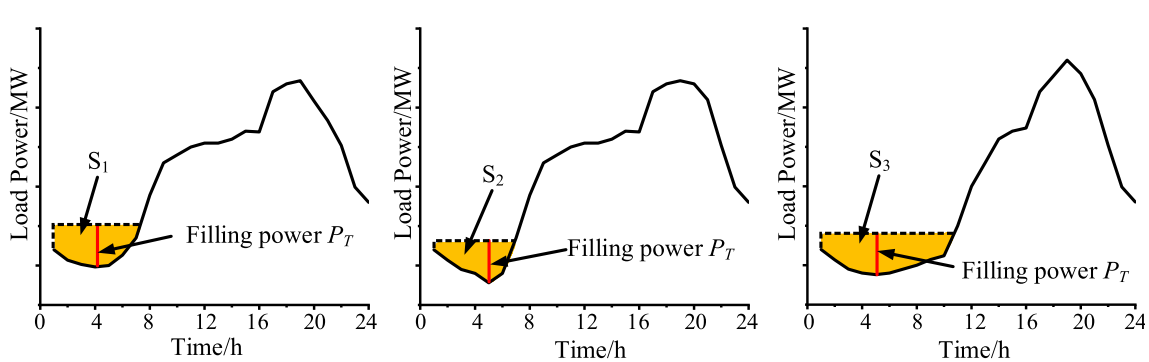

Fig. 1 Schematic diagram of the power demand of typical days with three different load characteristics

calculation based on the typical days of three different load characteristics.

It can be seen from Fig. 1 that under the same filling power P_T, the electricity demands of the three typical daily load are: $E_{B,1}=S_1$, $E_{B,2}=S_2$, $E_{B,3}=S_3$, and $E_{B,3}>E_{B,1}>E_{B,2}$. Because of the different load characteristics of each day, the amount of electricity required each day is different. Therefore, the daily demand for electricity in the filling power of PT will form the following matrix:

$$E_B = [E_{B,1}, E_{B,2}, \ldots, E_{B,d}] \tag{2}$$

where E_B is the capacity demand matrix of the power system per day, and d is the sample length.

In addition, to eliminate data acquisition bias in the sample, this section uses the confidence interval method to optimize the capacity demand matrix. The specific calculation process is described as follows:

- Convert the capacity demand matrix into a normal distribution function:

  $$E_B \sim N(\mu, \sigma^2)$$

  where $N(\mu, \sigma^2)$ is a normal distribution function expression, μ is the normal distribution function position parameter, i.e., the average value of E, and σ^2 is the variance of E.
- Select the confidence level as β to find the corresponding confidence interval, using:

  $$P\left(\overline{E_B} - z_{\alpha/2}\sqrt{\sigma^2} \le \mu \le \overline{E_B} + z_{\alpha/2}\sqrt{\sigma^2}\right) \approx \beta \tag{3}$$

  $$E'_B = \left[\overline{E_B} - z_{\alpha/2}\sqrt{\sigma^2}, \overline{E_B} - z_{\alpha/2}\sqrt{\sigma^2}\right] \tag{4}$$

  where $P(\cdot)$ is the probability expression, $\overline{PE}$ is the average value of the matrix PE, $\alpha=(1-\beta)$, $\beta\in[0,1]$, and $z_{\alpha/2}$ can be obtained by the norming instruction in MATLAB software.

The capacity configuration of the ESS can be selected from the above range of capacity requirements, and the longer the sampling length, the higher the accuracy of the range.

2.2 Matching relationship between power and capacity configuration of ESS

After determining the capacity of the ESS in the above range, the corresponding ESS power configuration model is given. The ESS should meet the maximum charging power during the load valley period (according to peaking demand, P_T is the maximum charging power during the load valley period) and the maximum discharge power during the load peak period.

The charging power of the ESS during the load period and the maximum discharge power during the peak load period are obtained by the control strategy shown in Fig. 2.

From the control strategy in Fig. 2, the actual stored power matrix and the maximum discharge power matrix in the sample are obtained as follows:

$$E_{B'} = \left[E_{B',1}, E_{B',2}, \ldots, E_{B',d}\right] \tag{5}$$

$$P_S = [P_{B,1}, P_{B,1}, \ldots, P_{B,d}]. \tag{6}$$

The power required by the ESS for a given capacity configuration is:

$$P_B = \max[P_T, P_S] \tag{7}$$

Similarly, the longer the sampled length, the higher the applicability of the ESS power P_B.

2.3 Energy storage operation constraint

The ESS is subject to a series of constraints during its operation, as described below.

(1) ESS power constraints

$$\begin{cases} 0 \le P^C_{B,d,t} \le P^C_B \\ 0 \le P^D_{B,d,t} \le P^D_B \end{cases} \tag{8}$$

where $P^C_{B,d,t}$ and $P^D_{B,d,t}$ are the charge and discharge power of the ESS on the dth day and the tth time. P^C_B and P^D_B are the maximum charge and discharge power of the ESS, respectively.

(2) ESS state of charge constraints

$$E_{SOC,d,t} = E_{SOC,d,t-1} + \frac{\eta_C}{E}(P^C_{B,d,t}\Delta t) - \frac{1}{\eta_D E}(P^D_{B,d,t}\Delta t) \tag{9}$$

$$E_{SOC,\min} \le E_{SOC,d,t} \le E_{SOC,\max} \tag{10}$$

$$E_{SOC,start} = E_{SOC,end} \tag{11}$$

where $E_{SOC,d,t}$ is the state of charge on the dth day and the tth time of the ESS, E is the rated capacity of the ESS, while η_C and η_D are the charge and discharge efficiencies of the ESS, respectively. E and $E_{SOC,max}$ are the upper and lower limits of the ESS, respectively, while $E_{SOC,start}$ and $E_{SOC,end}$ are the state of charge at the initial and end moments of the ESS, respectively.

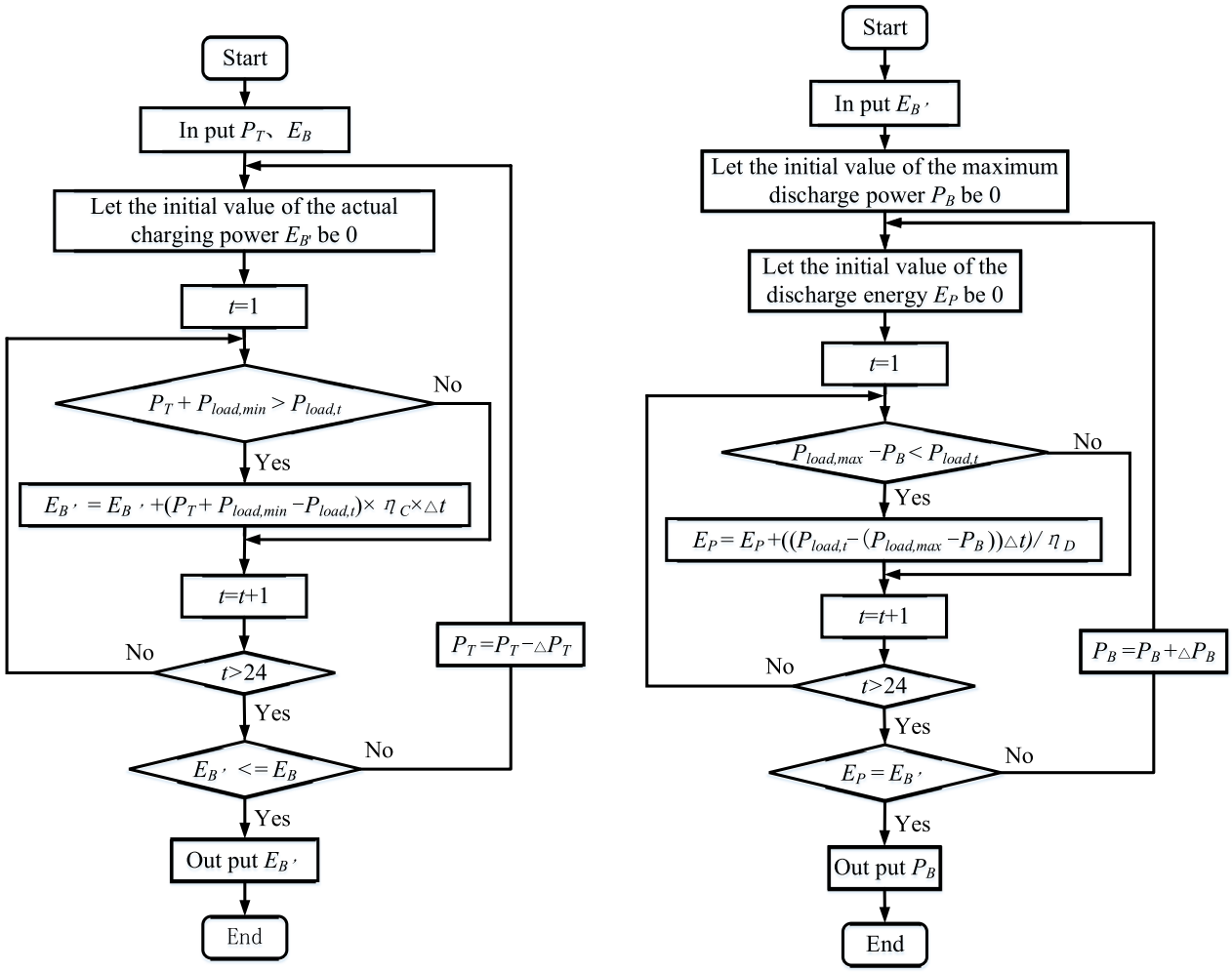

Fig. 2 Control strategy of ESS during low load period and peak load period

(3) ESS charge and discharge state constraints

$$B_{C,d,t} \times B_{D,d,t} = 0,\ (B_{C,d,t},\ B_{D,d,t}) \in [0,1] \tag{12}$$

where $B_{C,d,t}$ and $B_{D,d,t}$ are the charging and discharging operation states of the ESS on the dth day and the tth time, respectively, while 'in operation' is 1 and 'stop' is 0.

3 ESS dynamic economic assessment model

Based on the above energy storage configuration model, this paper proposes a dynamic economic evaluation model of hundred megawatt-scale ESS for auxiliary peak shaving. From the perspective of energy storage investors, the model considers the auxiliary service compensation profit, electricity profit, investment cost and maintenance cost of the energy storage to analyze the economic situation of the energy storage throughout its life cycle. Also, by analyzing the relationship between the charge and discharge depths of the ESS and the number of cycles, the equivalent life evaluation method of the ESS is added to predict the possible faults and their effects during use of the system. In addition, the model can also formulate corresponding parameter configuration schemes according to different types of research objects. Finally, by verifying and correcting the model results, it can conclude whether the ESS has the potential to achieve dynamic economic benefits and how to choose the optimal ESS configuration scheme.

This dynamic economic benefit evaluation model comprehensively considers various factors and is more comprehensive than the traditional static economic benefit evaluation method. It is suitable for the planning, design and optimization of BESS. By establishing a practical and operable dynamic economic benefit evaluation model, it

can not only promote the commercial application of ESS and the large-scale development and application of clean energy, but also provide technical support and decision-making reference for energy transformation and climate change protection.

The dynamic economic model of energy storage is as follows:

$$I_T = \left(\sum_{d=1}^{D} \sum_{t=1}^{T} \left(\left(I_{Z,d,t} + I_{P,d,t} - C_{Y,d,t} \right) \times \frac{1}{(1+r_s)^{(N+k)}} \right) \right) - C_I \tag{13}$$

where I_T is the net present value of the energy storage throughout its life cycle, D is the number of operating days of energy storage (energy storage life cycle), and T is the number of data sampling points per day. $I_{Z,d,t}$, $I_{P,d,t}$, $C_{Y,d,t}$ are the electricity profit, auxiliary service compensation profit, and maintenance cost of the ESS on the dth day and the tth time, respectively. C_I is the investment cost of energy storage, r_s is the discount rate, N is the number of years of energy storage operation on day d with $N=[d/365]$, and k is the construction period of the ESS.

The calculation of the profit and cost models, and the life assessment method are described in the following sub-sections.

3.1 Energy storage profit model

3.1.1 Electricity profit

In the process of peaking, the most direct benefit that energy storage investors can get is electricity profit. The income comes from using the time of day rate, storing electricity during the period of the valley's electricity price, and releasing electricity during the period of the peak's electricity price to obtain profit from the grid. The calculation is given as:

$$I_{Z,d,t} = \eta_D (P_{B,d,t}^{D} \Delta t) C_F - (P_{B,d,t}^{C} \Delta t) C_G \tag{14}$$

where C_F is the peak electricity price, and C_G is the valley electricity price.

3.1.2 Auxiliary service compensation profit

In addition to directly using the time-of-day rate to obtain electricity revenue, the process of using storage for auxiliary peak shaving offers some additonal potential profits. However, at present, these benefits do not have an authoritative policy to support them. Therefore, looking at the future development of energy storage, this paper sets an auxiliary service compensation profit when the energy storage supplies electricity to the grid, given as:

$$I_{P,d,t} = \eta_D (P_{B,d,t}^{D} \Delta t) C_f \tag{15}$$

where C_f is the price of the auxiliary.

3.2 Model of energy storage cost

3.2.1 Investment cost

The energy storage investment cost is mainly composed of capacity and power costs. The object of this paper is hundred megawatt-scale electrochemical energy storage, and its cost is a significant expense. For this cost, companies often cannot pay in one lump sum, and thus the impact of a capital loan factor is considered in the model, as:

$$C_I = \sum_{n=1}^{N_Z} \left(\left(\frac{C_E E_B}{N_Z} + \left(\frac{(C_E E_B \times (N_Z - n + 1))}{N_Z} \right) \times r_d \right) \times \frac{1}{(1+r_s)^n} \right) \tag{16}$$

where C_E is the capacity price, E_B is the capacity configuration, and C_P is the power price, all of the energy storage, E_P is its power, r_d is the annual interest rate, and N_Z is the loan life.

3.2.2 Maintenance cost

The energy storage maintenance cost is mainly related to the discharge capacity, given as:

$$C_{Y,d,t} = C_M P_{B,d,t}^{D} \Delta t \tag{17}$$

where C_M is the maintenance price.

3.3 Calculation method of energy storage equivalent life

The cycle life of energy storage is related to the depth of discharge. As this increases, it will cause a certain loss to the lifetime. In the actual calculation process, the daily discharge depth of the energy storage cannot reach 100%, so the actual cycle life will be higher than that at 100% discharge depth. In the control strategy adopted here, the energy storage is charged and discharged once a day, so its battery equivalent life can be expressed as:

$$C_{cycles} = \frac{N_U \times C_{tc}}{\sum_{d=1}^{N_U} \left(E_{BD,d} / E_B \right)} \tag{18}$$

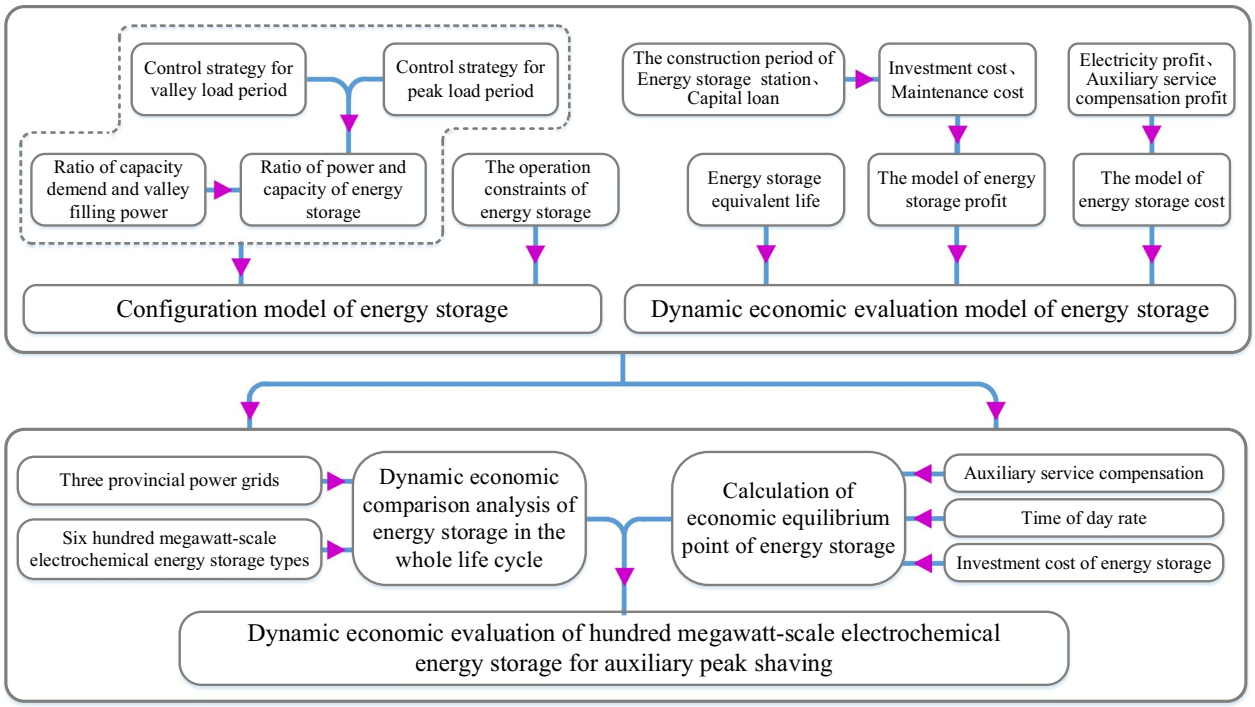

Fig. 3 Flow chart of energy storage dynamic economic analysis

where C_{cycles} is the equivalent life of energy storage. $E_{BD,\,d}$ is the daily discharge capacity, N_{LI} is the total number of days in the sampling data period, and C_{tc} is the number of energy storage cycles at 100% discharge depth.

Combined with the models of the above-mentioned parts, we conduct an economic comparative analysis of six types of hundred megawatt-scale electrochemical energy storage in three provincial power grids. The specific analysis flow chart is shown in Fig. 3.

4 Description of the case conditions

This section describes the case conditions for the studies.

(1) The calculations are carried out using the 2016 annual load data of the Inner Mongolia Western Power Grid (the maximum load is 23,718 MW), the Liaoning Provincial Power Grid (the maximum load is 26,642 MW), and the Jilin Provincial Power Grid

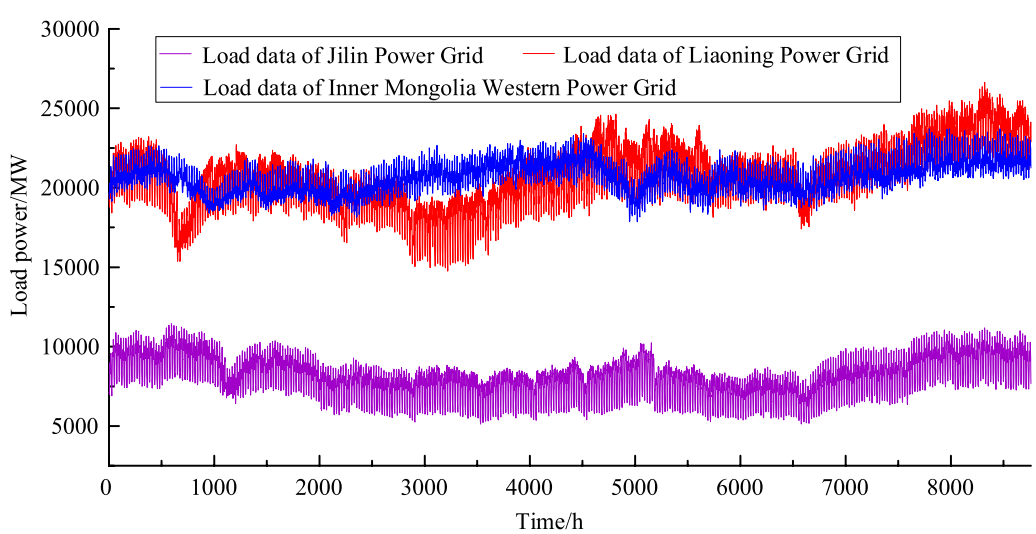

Fig. 4 Load data map of the three provinces

(the maximum load is 11,448 MW). These three provinces have large peak demands and are willing to carry out energy storage projects. The load data of the three provinces are shown in Fig. 4.

(2) The time-of-day rate of the Inner Mongolia Western, Liaoning, and Jilin Power Grids are shown in Table 1.

(3) The six energy storage types used in this paper are Lithium Iron Phosphate ($LiFePO_4$), Lithium Titanate (LiTi), Lead Carbon (Pb-C), Lead Acid Battery (LA), Sodium Sulfur (NaS), and Vanadium Redox Batteries (VR). The parameters of each energy storage type are listed in Table 2.

(4) To compare the economies of different energy storage types, the construction of all types is 1 year, the investment cost of the loan period is 10 years, and the discount rate is 2%.

(5) The matching relationship between the valley filling capacity and the power of the power system optimized by confidence interval method is studied. The dynamic economic evaluation model is used to analyze and compare the economies of the different battery types in different power grids. Through MATLAB simulation, the dynamic economic benefits of energy storage and the economic balance points of different batteries are calculated.

5 Description of the case result

5.1 Calculation method of energy storage equivalent life

Based on the annual measured data of Liaoning Provincial Power Grid, Jilin Provincial Power Grid, and Inner Mongolia Western Power Grids, we separately determine the capacity allocation ranges of the six ESS.

First, using the method in Sect. 2, the capacity allocation range of the corresponding ESS in different ESS

Table 1 Parameters for time of day rate of each province

Province	Peak price ($/MWh)	Flat price ($/MWh)	Valley price ($/MWh)
Inner Mongolia Western Power Grid (NMG-W)	126.01	84.01	42.02
Liaoning Provincial Power Grid (LN)	168.16	112.16	56.17
Jilin Provincial Power Grid (JL)	171.14	116.48	61.66

Table 2 Parameters of the 6 energy storage types

Energy storage types	Charging rate (%)	Discharge rate (%)	Capacity price ($/kWh)	Maintenance cost ($/MWh)	Cycle life/times (100% DOD)
$LiFePO_4$	0.97	0.97	520	7.45	3000
LiTi	0.97	0.97	1190	7.45	10,000
Pb-C	0.95	0.95	300	7.45	3000
LA	0.85	0.85	120	7.45	600
NaS	0.9	0.9	740	15	3000
VR	0.8	0.8	595	15	13,000

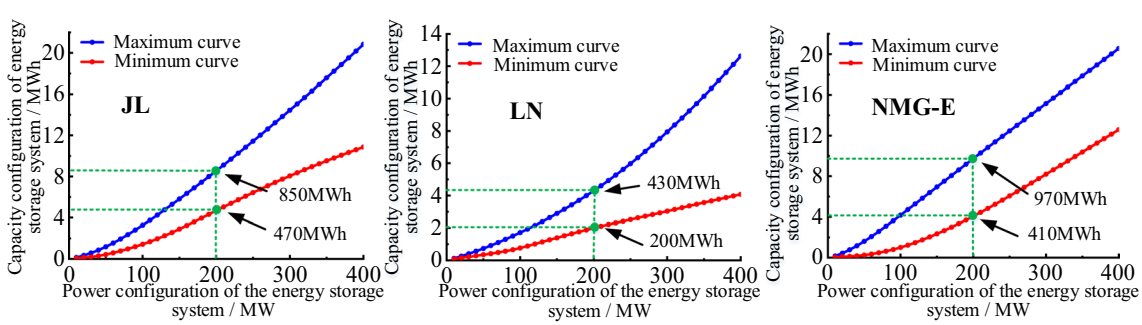

Fig. 5 Power and capacity relationship diagram of lithium iron phosphate BESS in different provincial power grids

power configurations is obtained. We select a confidence level $\beta = 90\%$, to process the capacity requirements of the energy storage system. Figure 5 shows the matching relationship between energy storage capacity and capacity of the lithium iron phosphate battery based on the annual measured data of different power grids.

According to the matching relationship in Fig. 5, with the gradual increase of the power configuration of lithium iron phosphate BEES, the capacity configuration range of the required ESS also gradually increases. Here 200 MW ESS is used for specific analysis, as can be seen in Fig. 5. The corresponding optimal energy storage configuration ranges are Jilin Power Grid: 470–850 MWh, Liaoning Power Grid: 200–430 MWh, and Western Inner Mongolia Power grid: 410–970 MWh. For different power grids, in the condition of the same energy storage power configuration, the corresponding optimal energy storage configuration capacity range is only related to the area's load peak/valley and the configured power amount. As can be seen from Fig. 4, in terms of load fluctuation, the Liaoning power grid has the greatest volatility, so the configuration capacity is the smallest; in the Jilin area and Mengxi area, although the load power is smaller, the fluctuation is relatively stable, so the two grids have larger configuration capacity. It can be seen that from the perspective of different power grids, because of the differences in different power grid loads, the capacity configuration ranges of the ESS will be significantly different. When the 200 MW ESS is also configured, the load capacity configuration of the different energy grids will have a large difference due to the different load characteristics.

Similarly, with the ESS power configured at 200 MW, the optimal capacity distribution ranges of the other five energy storage types are calculated, and shown in Fig. 6.

For the same power grid and configuration power the optimal configuration capacity is analyzed. It can be seen from Fig. 6 that the optimal capacity configuration ranges of the six energy storage types are not much different. Taking Jilin power grid as an example, at a configuration power of 200 MW, the maximum capacity configuration range of the six energy storage types is 400 MWh and the minimum is 200 MWh, with the fluctuation being within 50 MWh. This is because the capacity required for each energy storage type is only related to its charging and discharging efficiency. As these efficiencies of the six energy

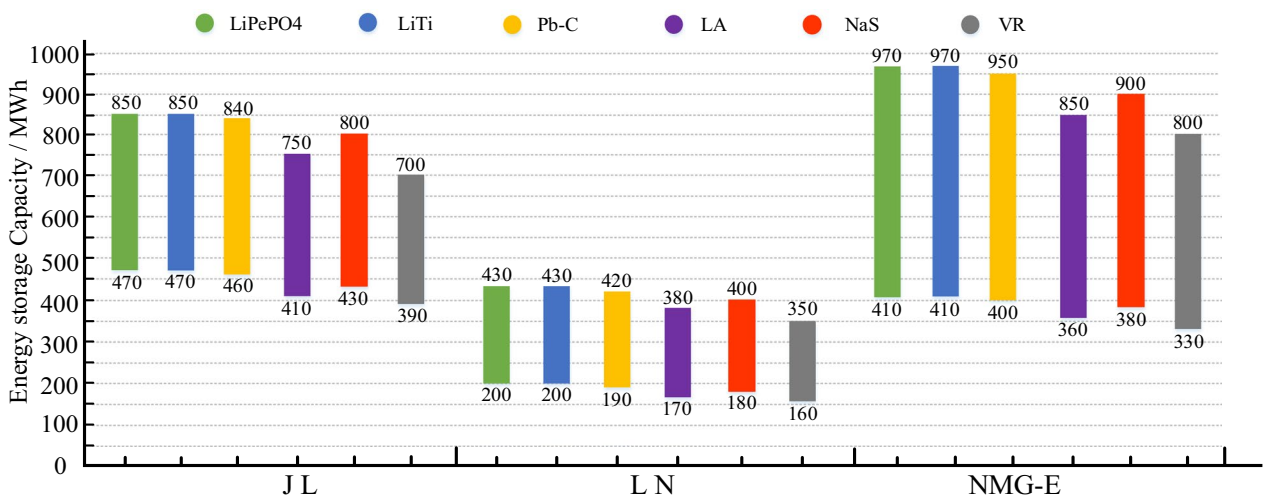

Fig. 6 Diagram of the capacity allocations of ESS for different provincial power grids ($P_B = 200$ MW)

Table 3 Parameter list for the configuration and cycles of ESS for different provincial power grids (the configured unit is MW/MWh)

	$LiFePO_4$	LiTi	Pb-C	LA	NaS	VR
Configuration (JL)	200/700	200/700	200/700	200/700	200/700	200/700
Cycles (JL)	3321	11,070	3362	731	3489	16,742
Configuration (LN)	200/350	200/350	200/350	200/350	200/350	200/350
Cycles (LN)	3502	11,675	3556	776	3707	17,710
Configuration (NMG-E)	200/800	200/800	200/800	200/800	200/800	200/800
Cycles (NMG-E)	3589	11,964	3639	796	3789	18,293

storage types are all around 90%, the differences in capacity configurations are not significant.

To compare the economies of different energy storage types more objectively in the selection process, the same ESS configuration should be used to analyze the six energy storage types of the same power grid. The energy stored by the ESS during low load is provided by wind energy. In order to reduce the abandoned wind power, the capacity configuration of the ESS should be selected to meet the wind power as much as possible. The larger the capacity of ESS is, the more wind it can receive. Therefore, according to the calculation results of the capacity allocation range in Fig. 6, combined with the calculation method of the equivalent life of battery in Sect. 3.3, the parameters of the ESS configuration and the number of cycles of each provincial power grid are shown in Table 3.

5.2 Analysis of dynamic economic benefits of energy storage assisted peak shaving

(1) Economic analysis during the whole life cycle

Without considering the compensation for energy storage auxiliary services, the 2016 full-year grid survey data of Inner Mongolia Western Power Grid, Liaoning Province Power Grid, and Jilin Power Grid are used, and the six types of energy storage technologies are involved in grid-assisted peak shaving services. For comparative analysis of economics, the total cost and total revenue scatter plots for each energy storage technology over the life cycle are shown in Fig. 7.

From the perspective of economic aggregates, in all ESS applications, the total cost of the ESS is higher than the total revenue. In the context of the lack of compensation policies for energy storage auxiliary services, it is difficult for ESS to earn profits solely from electricity income.

First, the economics of the six ESS under the same grid load are analyzed. Taking Jilin Province as an example, the lead-acid battery is the most economical when the ESS participates in the peak-shaving application of the power grid, and its NPV value is − 67.98 million dollars. This is followed by the lead–carbon, lithium iron phosphate, vanadium flow, and sodium-sulfur batteries. The lithium titanate battery is the least economical, with an NPV value of − 460.99 million dollars, and its total loss during the life cycle reaches 678.2% of the lead-acid battery. After analyzing the other two provinces, although the configurations of the six energy storage types are different from that of Jilin Province, the economics of the lead-acid battery are still optimal, and their NPV values are − 32.20 million dollars (LN) and − 84.55 million dollars (NMG-E), respectively. The NPV values of the lithium titanate battery are − 226.78 million dollars (LN) and − 670.01 million dollars (NMG-E), respectively, far higher than the other types of energy storage. From the above analysis, it is concluded that in different power grids, when the energy storage configuration power is the same and the energy storage capacity is similar, the lead-acid battery has the best NPV value and the best economy in the whole life cycle because of its lowest unit price. This is because the unit capacity cost of lead-acid battery is the cheapest, at only 120 $/kWh, while the unit capacity cost of the titanate battery is as high as 1190 $/

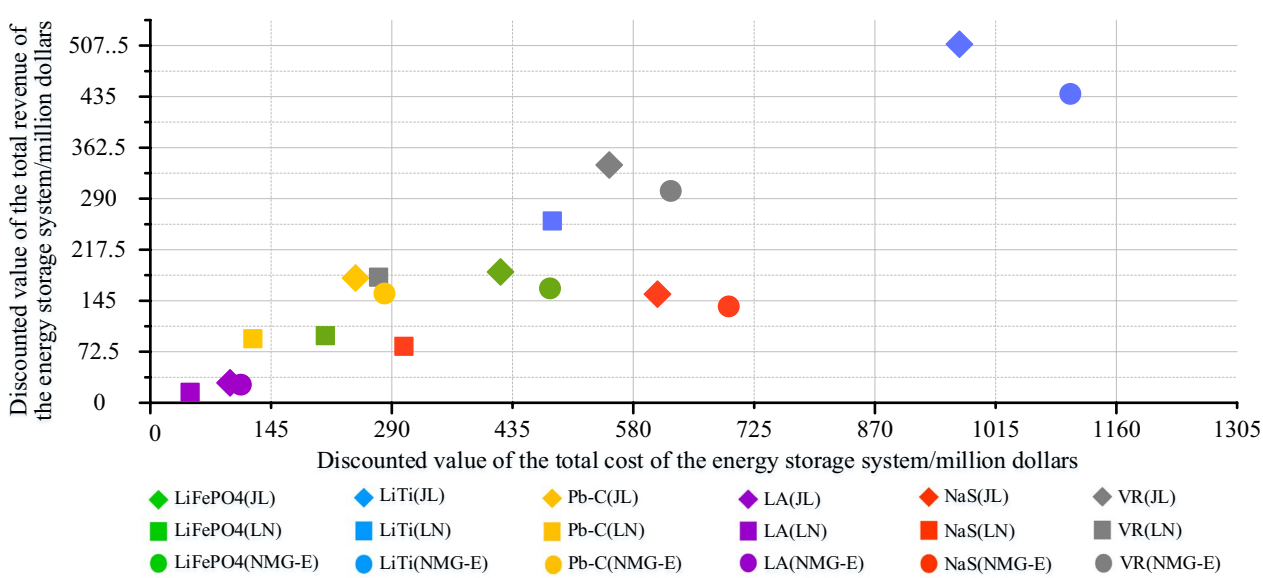

Fig. 7 Scatter plots of total cost and total revenue for each energy storage technology over its life cycle

kWh, 10 times the cost. In summary, when analyzing the economy from the perspective of life cycle, the unit cost of the ESS is the key factor affecting its economy.

Secondly, for the same type of energy storage, the economics involved in peak shaving of different power grids are analyzed. When peaking services are performed for different power grids, the required ESS capacity configurations are different because of different load characteristics. As can be seen from Fig. 5, the ESS capacity demand in Liaoning Province is the smallest, while the Western Inner Mongolia power grid has the largest. The capacity cost of the ESS affects the key factors of its economy. The smaller the capacity configuration, the smaller the cost of input. Through calculation, the losses of the six energy storage types in the application of Liaoning Power Grid only account for about 49% of that of the Jilin Province power grid, and 36% of that of the Mengxi Power Grid.

(2) Analysis of daily average economic performance and peak shaving performance

However, it is quite one-sided to analyze the applicability of different types of energy storage technologies from the perspective of economic aggregates. The ESS involves a series of indicators such as cost, benefit, peak-to-valley difference improvement, and wind power acceptance when participating in the power grid peaking auxiliary service, and the number of cycles of different ESS are

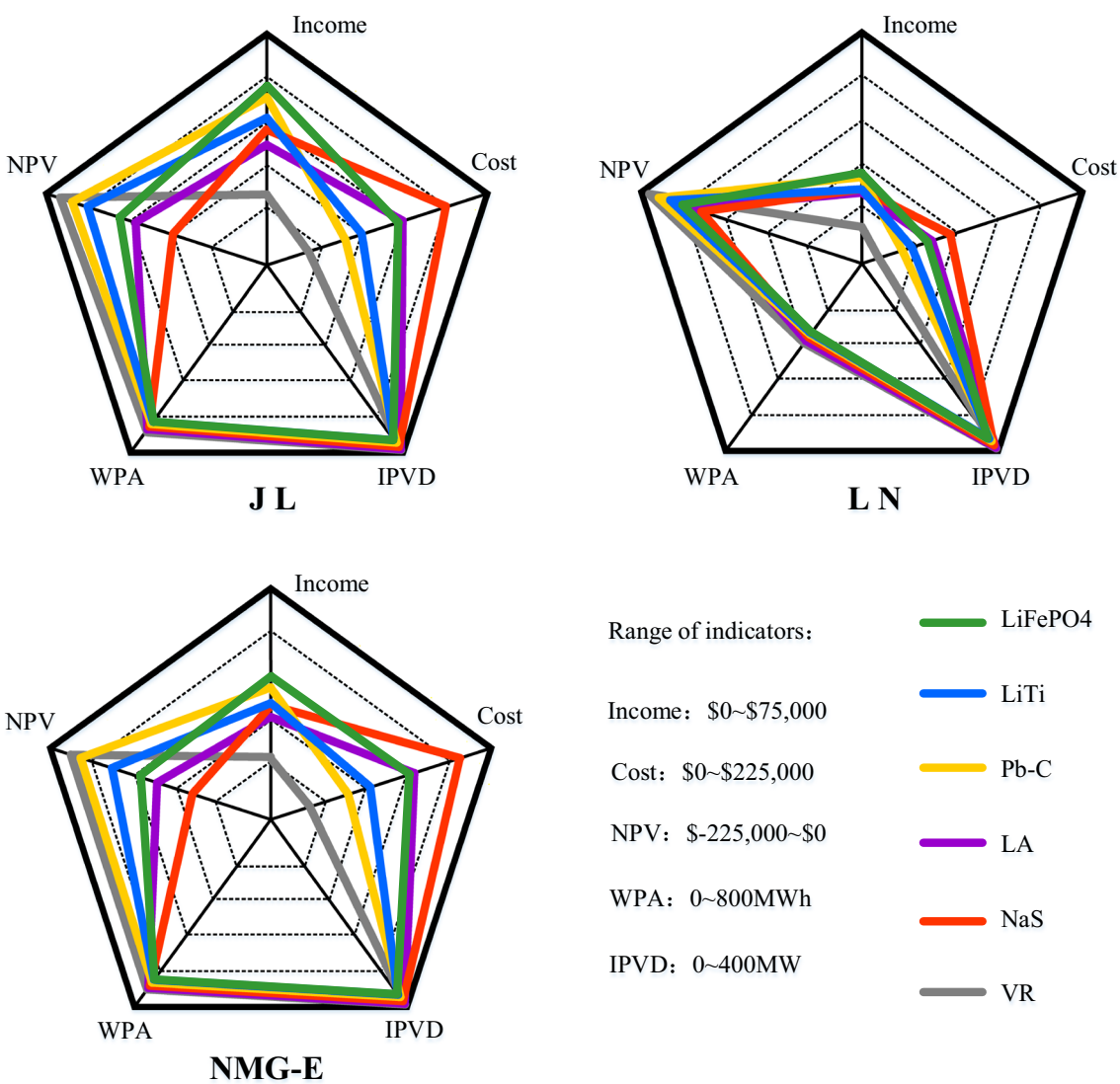

Fig. 8 Comparison chart of peaking indicators for each energy storage type (WPA is the wind power acceptance, IPVD is the peak-to-valley difference improvement, and each indicator in the figure is the daily average)

very different. Thus, in the following, the daily average of the factors are analyzed, and Fig. 8 compares the peaking indicators for each energy storage system.

First, the peak regulating effect of ESS is analyzed. As can be seen from Fig. 8, the power and capacity configurations of the six ESS are the same for the same region. Therefore, the average daily value of wind power acceptance and the average improvement of peak-valley difference of the six ESSs are very close, while the differences are only related to the charging and discharging efficiencies of the ESS.

For different regions, because of the different load characteristics of the power grids, the capacity configurations of the selected ESS are different, resulting in different energy storage capacities of the ESS when applying different power grids. As can be seen from Fig. 8, wind power acceptance in Liaoning is the lowest, at only about half of the 650 MWh in Mengxi and Jilin. This is because of the small configuration capacity in the Liaoning region, resulting in insufficient capacity of wind power consumption. However, because the power configuration of each ESS is 200 MW, the daily average improvement of the peak and valley difference of the ESS (which is related to the power of the ESS configuration) is not much different. From the above analysis, it can be concluded that the power configuration of the ESS will be directly related to the improvement effect of the ESS on the peak-valley difference of the power grid. The capacity configuration of the ESS based on the power of the ESS will directly affect wind power acceptance.

The economic aspects of ESS participation in power grid peak shaving is then analyzed. As can be seen from Fig. 8, when the energy storage type is applied in the Liaoning power grid, its daily average income has decreased, but its daily average cost has also decreased significantly. The average NPV for that provincial grid is slightly higher than for the other two grids, and the economics of each ESS applied to the Liaoning power grid is still optimal.

For the six energy storage technologies applied to the same grid, the economic priority of each type of energy storage is the same. The most economical one is the vanadium flow battery, followed by lead–carbon, lithium titanate, lithium iron phosphate, lead-acid, and sodium-sulfur batteries. Compared with the total economy of the energy storage system, it can be found that the total loss of the lead-acid battery is the lowest, but the number of cycles is also lower, resulting in the daily average NPV of the lead-acid battery being relatively low in the six types of energy storage. This is because the number of cycles is only about 750, i.e., the life is short, which results in a lower average daily return. The vanadium flow battery has the highest number of cycles, up to about 17,000, which is 23 times that of lead-acid batteries. As the NPV value is strongly correlated with the number of cycles of the battery type, the vanadium flow battery is the most economical energy storage type. Through the above analysis, it can be seen that in the same power grid, the economic analysis of the six energy storages should not only consider the unit price cost of capacity, but also consider the number of cycles of energy storage in the whole life cycle. The higher the number of cycles, the higher the daily average value of NPV, and the longer the service life.

5.3 Analysis of economic balance point of the energy storage system

According to the above analysis, in the current environment, ESS still cannot make profits when it participates in the peak regulating service of the power grid. Therefore, clear compensation measures are needed for large-scale application of ESS. At present, three main factors are affecting the economics of ESS:

(1) The corresponding energy storage auxiliary service compensation price.
(2) The electric energy efficiency of the ESS when participating in the peak regulation of the power grid is mainly determined by the peak-valley difference of the power grid.
(3) ESS capacity cost.

Therefore, this section considers these three factors separately and calculates the expected value of the auxiliary service compensation price, the peak-valley difference and capacity cost of ESS when reaching economic equilibrium. The calculation results are shown in Table 4.

The price from the auxiliary service compensation is analyzed first. It can be seen Table 4 that the compensation prices for lead–carbon batteries are 5.82 $/MWh, 3.35 $/MWh, and 29.69 $/MWh when applied in the three power grids in Jilin, Liaoning, and Western Inner Mongolia, respectively. The corresponding compensation prices required for vanadium flow batteries are 12.51 $/MWh, 8.88 $/MWh, and 30.13 $/MWh, respectively. The compensation price required by these two energy storage technologies to achieve economic equilibrium is the minimum. The lead-acid and sodium-sulfur batteries require the highest compensation price, at 20 times that of the above two batteries, and thus they are not suitable for large-scale access in terms of compensation price. In the application of power grids in Jilin Province and Liaoning Province, the compensation price required for lead–carbon and vanadium flow batteries is only about 2.91 $/MWh, which meets the economic conditions for large-scale application.

Table 4 Statistical table of auxiliary service compensation unit price, peak, and valley electricity price difference, and energy storage capacity unit price required for each energy storage type to achieve economic balance point

Energy storage type	Required price					
	The unit price for auxiliary service compensation ($/MWh)		Peak and valley electricity price difference ($/MWh)		The unit price of energy storage capacity ($/MWh)	
	Current price	Required price	Current price	Required price	Current price	Required price
LiFePO (JL)	0.0	97.1	107.0	204.1	509,461.4	289,665.2
LiTi (JL)	0.0	59.7	107.0	166.7	1,164,483.3	796,215.4
Pb-C (JL)	0.0	5.8	107.0	112.8	291,120.8	278,020.4
LA (JL)	0.0	167.0	107.0	273.9	116,448.3	45,123.7
NaS (JL)	0.0	239.9	107.0	346.9	727,802.0	228,529.8
VR (JL)	0.0	12.5	107.0	119.5	582,241.6	509,461.4
LiFePO (LN)	0.0	94.9	109.6	204.5	509,461.4	295,487.6
LiTi (LN)	0.0	59.5	109.6	169.1	1,164,483.3	802,037.8
Pb-C (LN)	0.0	3.3	109.6	113.0	291,120.8	283,842.8
LA (LN)	0.0	162.6	109.6	272.2	116,448.3	46,579.3
NaS (LN)	0.0	237.8	109.6	347.5	727,802.0	235,807.9
VR (LN)	0.0	8.9	109.6	118.5	582,241.6	531,295.5
LiFePO (NMG-E)	0.0	122.7	82.1	204.8	509,461.4	234,352.3
LiTi (NMG-E)	0.0	87.6	82.1	169.7	1,164,483.3	636,099.0
Pb-C (NMG-E)	0.0	29.7	82.1	111.8	291,120.8	225,618.6
LA (NMG-E)	0.0	185.2	82.1	267.2	116,448.3	37,845.7
NaS (NMG-E)	0.0	262.7	82.1	344.8	727,802.0	184,861.7
VR (NMG-E)	0.0	30.1	82.1	112.2	582,241.6	413,391.6

Secondly, the peak-valley price difference is analyzed. When lead–carbon and vanadium flow batteries are used in the three power grids, the peak-valley electricity price difference required to reach the economic equilibrium point is the least, at around 116.44 $/MWh. In the Jilin Province and Liaoning Province power grids, the peak-valley difference of 116.44 $/MWh is only slightly higher than the original peak-valley difference. However, because of the small difference between the original peak and valley of the Inner Mongolia Western Power Grid, for these two batteries to reach the economic balance point, the respective peak-to-valley spreads required are 36.17% and 36.70%, which are significantly higher than the increases in the peak-to-valley electricity spreads in the other two grids. For the other four types of storage, the offset prices and peak-valley spreads required to reach the economic equilibrium point are higher than for lead–carbon and vanadium flow batteries. In addition, the compensation price and peak-valley electricity price differences required for lead-acid and sodium sulfur batteries to reach the economic balance point are far higher than other types of energy storage. In the current domestic situation, these two types of energy storage are completed in a short time, but there are still great difficulties in gaining profits.

The capacity price of the energy storage system is now analyzed. Because the unit prices of different energy storage technologies vary greatly, the analysis is conducted through the decline of unit price of each energy storage type. Taking the Jilin power grid as an example, the unit price reduction required for six energy storage technologies to reach the economic balance point are lithium iron phosphate battery: 43.14%, lithium titanite battery: 31.63%, lead–carbon battery: 4.5%. Lead-acid battery: 61.25%, sodium-sulfur battery: 68.60%, and vanadium flow battery: 12.5%. It can be seen that the unit price reductions of lead–carbon and vanadium flow batteries to reach the economic balance point are the smallest, while those of the lead-acid and sodium-sulfur batteries are the largest. It can be seen that from the perspective of reducing the unit price of energy storage capacity, when realizing NPV = 0, lead–carbon and vanadium flow batteries are the easiest.

In addition, when the ESS of Jilin and Liaoning power grids participate in peak shaving, the compensation price, peak-valley electricity price difference and cost reduction required to reach the economic balance points are smaller than those of the Western Inner Mongolia power grid, so Jilin and Liaoning power grids are more conducive to the ESS participating in auxiliary peak shaving.

6 Conclusion

This paper has studied the dynamic economics of the auxiliary peak shaving in the electrochemical energy storage system, and the main conclusions are as follows:

(1) Through the ESS power-capacity and peak-to-valley power-capacity matching relationship proposed, six ESS are used for the ESS configurations for Jilin, Liaoning, and Inner Mongolia Western Power Grids. Because of the differences in the load characteristics of the three provinces, the capacity configurations of the ESS vary greatly under the same 200 MW ESS power configuration. Under the same peak shaving effect, the capacity of ESS in the Liaoning power grid is the smallest at 350 MWh, while the capacity of ESS required by the Western Inner Mongolia Power Grid is the largest at 800 MWh. For different energy storage technologies, the difference in capacity configuration is related to the charging efficiency. Therefore, the storage capacity configurations of the six ESS in the same grid are not much different.

(2) In terms of economic aggregates, for the same grid, lead-acid battery are much more economical than the other five types of BESS because of its smaller unit cost. From different grids, Liaoning Province has the least energy storage capacity demand at the same peak-shaving capacity, so the province has most to benefit from the application of ESS, followed by the Jilin and Inner Mongolia Western Power Grids.

(3) For daily average economics, although the economics of the vanadium flow battery are not the best in the whole life cycle, it has long cycle and long service life. Thus, according to the daily average economic point of view, the vanadium flow battery is the most economical.

(4) The auxiliary service compensation price, peak-to-valley electricity price difference, and ESS capacity unit price required for NPV = 0 are calculated for the six ESS in the three power grids. The results can provide a reference for relevant government departments, power grid companies, and ESS manufacturers to promote the large-scale application of high-quality energy storage resources in the power grid, and to solve the current problems of the gradual increase in the proportion of wind power and the lack of regulation capacity in the power grid.

In the analysis of the economic equilibrium point of energy storage, only the influence of the auxiliary service compensation price, the peak-valley price difference, and the unit price of ESS capacity on the economic equilibrium point of ESS is considered, while their effects on the NPV value are not comprehensively studied and analyzed. In the future, with in-depth research and analysis, the analysis of their combined effects on NPV will make the ESS more conducive to the application of the power grid and achieve better economic benefits.

List of symbols

$P_{B,d,t}^{C}$	Charging power of the energy storage system at day *d* and time *t*
$P_{B,d,t}^{D}$	Discharging power of the energy storage system at day *d* and time *t*
P_{B}^{C}	Maximum charging power of the energy storage system
P_{B}^{D}	Maximum discharging power of the energy storage system
$E_{SOC,d,t}$	State of charge of the energy storage system at day *d* and moment *t*
$E_{SOC,min}$	Lower limit of charge of the energy storage system
$E_{SOC,max}$	Upper limit of charge of the energy storage system
$E_{SOC,start}$	Initial state of charge of the energy storage system
$E_{SOC,end}$	State of charge at the end of the energy storage system
E_{B}	Capacity configuration of the energy storage system
$B_{C,t}$	Charging operation state of the energy storage system at time *t* on day *d*
$B_{D,t}$	Discharging operation state of the energy storage system at time *t* on day *d*
$I_{Z,d,t}$	Electricity revenue generated by the energy storage system at time *t* on day *d*
$I_{P,d,t}$	Auxiliary service compensation income generated by the energy storage system at time *t* on day *d*
$C_{Y,d,t}$	Operation and maintenance cost of the energy storage system at time *t* on day *d*
C_{I}	Investment cost of the energy storage system
r_{s}	Discount rate
C_{M}	Operation and maintenance unit price of the energy storage system
C_{f}	Subsidy in work points
N_{U}	Total charge and discharge cycles

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Author contributions
JL: Conceptualization, software, investigation, writing—original draft. GM: Conceptualization, methodology, writing—review and editing. JZ: Writing—review and editing, validation. CL: Investigation, writing—original draft. GY: Data curation. HZ: Data curation. GC: Data curation.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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