Design of Compensation Mechanism for Energy Storage Participating in Auxiliary Services and Analysis of Its Investment Economics

Dong Dou[1a*], Yanyu Wang[1b], Yibo Su[2c], Wensheng Yang[1d], Hongbo Li[3e], Yunyi Wu[2f], Yan Li[1g]

[*]Corresponding author: [a]1105965831@qq.com, [b]516052727@qq.com, [c]su_yibo@ctg.com.cn, [d]582400460@qq.com, [e]hbli_tju@126.com, [f]wu_yunyi@ctg.com.cn, [g]liyan16@impc.com.cn

[1]Inner Mongolia Electric Power Economics and Technology Research Institute, Hohhot, China

[2]Research Center for Comprehensive Energy Technology, Science and Technology Research Institute, China Three Gorges Corporation, Beijing, China

[3]Power Dispatching Control Branch, Inner Mongolia Power (Group) Co., Ltd., Hohhot, China

Abstract—Energy storage can effectively solve the problems of insufficient power grid regulation capacity and increasing difficulty in frequency stabilization caused by a high proportion of renewable energy. However, China's current market mechanism for energy storage to participate in auxiliary services is not perfect, resulting in the lack of reasonable cost returns for energy storage that creates numerous external value, which seriously affects the commercial development of energy storage. To this end, this paper proposes a compensation mechanism for energy storage to participate in peak regulation and frequency regulation services on the premise of China's electricity market environment. Firstly, the compensation mechanism before and after energy storage participating in auxiliary services is analyzed, and the additional value created by energy storage participating in auxiliary services and the compensation principle are clarified. Secondly, a stepped peak shaving compensation mechanism considering cycle depth and a two-part frequency modulation compensation mechanism considering frequency modulation opportunity cost are proposed. Based on this, according to the different operation modes of energy storage, the revenue and cost models in the operation stage are constructed. Finally, the investment economics of energy storage participating in different auxiliary service scenarios are compared and analyzed through simulation experiments. The experimental results show that the investment economy of energy storage can be effectively improved by comprehensively using the peak regulation, frequency regulation compensation mechanism and electricity price arbitrage model proposed in this paper.

Keywords-Energy storage; Auxiliary services; Peak regulation; Frequency regulation; Compensation mechanism; Analysis of investment economy

1. Introduction

In order to cope with climate change, many countries in the world have proposed carbon neutral solutions. At the same time, China has also announced the goal of "carbon peaking in 2030 and carbon neutrality in 2060". As a major carbon emitter, China needs to build a new

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power system with new energy as the main body, and vigorously develop renewable energy such as wind power and photovoltaic to accelerate the process of decarbonization. However, it should be noted that large-scale and high-proportion new energy access will cause problems such as insufficient power grid regulation capacity and increased frequency stability. Energy storage has the advantages of large capacity, fast response and high efficiency, which can well solve the problems caused by the grid connection of new energy, and its auxiliary services such as peak shaving, frequency modulation and voltage regulation are an effective way to maintain the stability of grid voltage and frequency and reduce the distortion rate of power quality waveform. However, there are still some deficiencies in the compensation mechanism and management scheme of energy storage participating in the power market and auxiliary service market. It is still necessary to further clarify the market positioning and external value of energy storage, and improve the corresponding cost recovery mechanism and compensation mechanism, so as to stimulate the enthusiasm of energy storage investment and promote the construction and development of new power systems.

At present, the research on energy storage participating in the market mainly includes two aspects: the value analysis of energy storage and the design of energy storage oriented market system. The value analysis of energy storage is mainly based on the response speed, energy density, efficiency and other physical characteristics to calculate its comprehensive value in different application scenarios. In view of the storage function of energy storage, the reduction effect of energy storage on peak load and price, the saving of thermal power start-up and shutdown cost and the contribution of energy storage to the consumption of renewable energy are discussed [1-3]. For the discharge effect of energy storage, Mallapragada et al. [4] consider the influence of energy storage and renewable energy permeability, and analyze the substitution effect of energy storage on power generation capacity. In terms of the fast response characteristics of energy storage, Hu et al. [5] studied the potential of different types of energy storage to provide frequency regulation auxiliary services, Akhavan-Hejazi and Mohsenian-Rad [6] calculated the backup value of energy storage under various response speeds, Gupta et al. [7] analyzed the role of energy storage optimization to maintain grid voltage stability. The research on market system design for energy storage mainly focuses on energy market mechanism, capacity market mechanism, auxiliary service market mechanism and price mechanism. In terms of energy market, Silva-Monroy [8] proposed a method for ISO to determine the opportunity cost based on the predicted energy price to reflect the opportunity cost of energy storage, Chen and Jing [9] allowed energy storage to submit a quotation curve according to the state of charge at the end of the period so as to reflect the value of its stored energy. Relevant literature studies the capacity value of energy storage based on the PJM power market, and points out that the actual capacity value of energy storage is not only related to its own maximum discharge power and maximum capacity, but also closely related to the net load curve and energy storage penetration. Opathella et al. [10] proposed a method to determine the capacity value according to the capacity support performance of energy storage during the peak load period of the historical system. In terms of ancillary services market, Liu et al. [11] proposed a joint clearing model of energy and ancillary services for energy storage considering the opportunity cost of energy storage. Lv et al. [12] designed an auxiliary service mechanism adapted to the operation of energy storage according to the characteristics of the fast charge-discharge switching capability of energy storage. In the research on the price mechanism, Yan et al. [13] designed a new electricity price mechanism for energy storage, so as to give energy storage a more reasonable cost report. The above research has important reference value for energy storage to participate in market-oriented transactions. However, most of the literature is based on the US electricity market, and there are few studies on China's ancillary service market. Since there is no peak shaving service in the ancillary service market in the United States, the application of energy storage has certain limitations. At present, China's ancillary service market is in its infancy, and most of the regulations are aimed at conventional units. The ancillary service market suitable for energy storage still needs to be studied and improved.

Based on the analysis of the above problems, this paper proposes a compensation mechanism for energy storage to participate in paid peak shaving and frequency regulation auxiliary services that adapt to the development of China's current electricity market, and calculates and analyzes its investment economy under different operating modes. The rest of the paper is organized as follows: Section 2 analyzes the compensation mechanism of energy storage participating in ancillary services market. Section 3 proposes a compensation mechanism for energy storage to participate in peak and frequency regulation services. Section 4 establishes a cost model and a benefit model for energy storage to participate in ancillary services market. Section 5 presents the computational results and comparisons. Finally, Section 6 gives the conclusion.

2. Principles of compensation mechanism for ancillary services

2.1 Compensation Principle without Energy Storage

In the absence of energy storage to participate in auxiliary services, the power system uses thermal power to participate in deep peak regulation to reduce the curtailment of wind power companies. In this mode, the changes of on-grid electricity and income of wind power companies and thermal power companies are shown in Figure 1.

In Figure 1, Q_w' and Q_w represent the on-grid electricity of wind power before and after the peak shaving auxiliary service, Q_g' and Q_g represent the on-grid electricity of thermal power before and after the peak shaving auxiliary service, p_w represents the on-grid electricity price of wind power, and p_g represents the on-grid electricity price of thermal power. After thermal power participates in peak shaving auxiliary services, its on-grid power decreases by Q_g'-Q_g, and wind power companies increase on-grid power by Q_w-Q_w'. In this case, the revenue of thermal power enterprises due to the reduction of on-grid electricity is the area $efQ_w'Q_w$, that is, s_3. The increased revenue of wind power enterprises due to the increase in on-grid electricity is the area $abQ_w'Q_w$. Since the on-grid price of wind power is higher than the on-grid price of thermal power, the total system revenue will increase by the area $abef$ after the peak-shaving auxiliary service is adopted. In order to stimulate the enthusiasm of thermal power enterprises to participate in peak shaving auxiliary services, and to make up for the cost of increasing coal consumption due to the reduction of load rate, wind power enterprises need to extract a part of the income ($s_2 + s_3$) from the increased power generation they obtain to compensate thermal power enterprises to achieve mutual benefit and win-win for both parties.

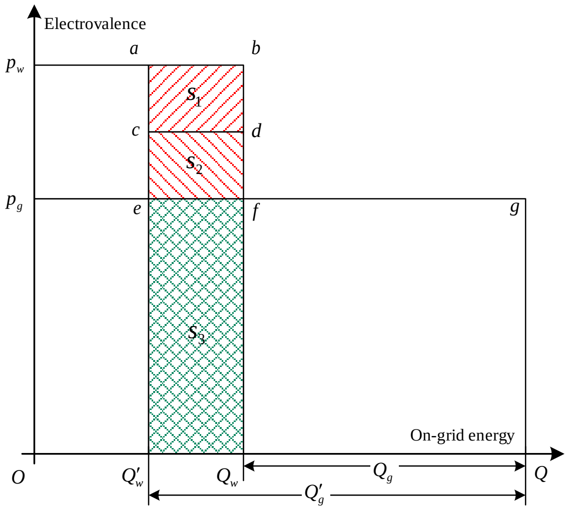

Figure 1 System Revenue Change and Compensation Principle of Thermal Power Participating in Peak Shaving Auxiliary Service

2.2 Compensation Principle with Energy Storage

After the energy storage participates in the auxiliary service of peak regulation, the energy storage can act as a load to replace the deep peak regulation of thermal power to absorb the abandoned power of wind power. In this mode, the changes of on-grid electricity and income of wind power companies and thermal power companies, as well as the compensation of energy storage, are shown in Figure 2.

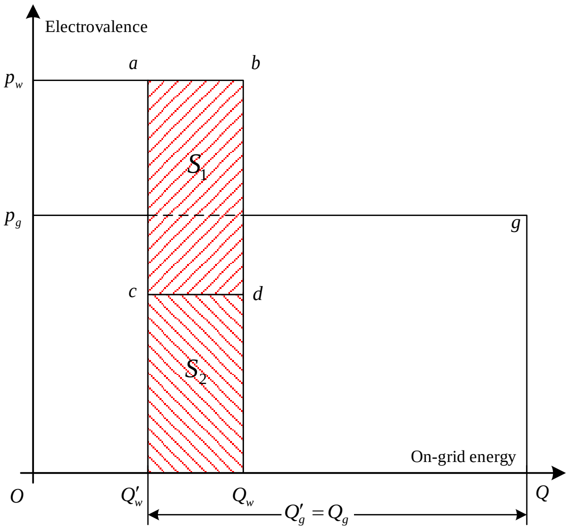

Figure 2 System Revenue Change and Compensation Principle of Energy Storage Participating in Peak Shaving Auxiliary Services

In this mode, the on-grid electricity of wind power increases from Q_w' to Q_w, while the on-grid electricity of thermal power remains unchanged, $Q_g' = Q_g$. Wind power thus increases revenue $abQ_w'Q_w$. The system as a whole increases the income $abQ_w'Q_w$. Compared to a model without energy storage participating in ancillary services, it increases revenue s_3. And thermal power companies do not need to bear the cost of increasing coal consumption due to reducing the load rate. In this model, thermal power companies do not need to passively undertake auxiliary services and affect their normal income. Wind power enterprises and energy storage share the increased revenue due to the increase of on-grid electricity from wind power through a reasonable distribution principle, which are S_1 and S_2, and $S_1 > s_1$ respectively.

Therefore, replacing thermal power with energy storage to participate in auxiliary services can effectively improve the overall revenue of the system. Using additional system benefits to provide reasonable compensation for energy storage can effectively improve the operational efficiency of energy storage and its investment enthusiasm.

3. Design of compensation mechanism for auxiliary services

Since the profitability of energy storage is greatly affected by policies, and the current market mechanism, compensation mechanism and cost recovery mechanism for energy storage to participate in auxiliary services are not clear, it is necessary to design a scientific and reasonable compensation mechanism to stimulate energy storage to participate in the auxiliary service market. At present, peak regulation and frequency regulation are the two main application scenarios for energy storage to participate in the auxiliary service market. These two parts of income are the main source of income for energy storage to participate in the ancillary services market. Therefore, this paper focuses on the design of compensation mechanism for the two auxiliary service functions of peak regulation and frequency regulation provided by energy storage.

3.1 Design of Compensation Mechanism for Peak Shaving

According to China's current ancillary service policy, conventional paid peak shaving units such as thermal power can obtain different peak shaving prices according to different output reduction intervals. Similarly, under different charging and discharging depths, the charging capacity of the energy storage is different, and the peak regulation effect is also different. Therefore, referring to the peak shaving rules of conventional units, a stepped-type paid peak shaving compensation mechanism for energy storage is formulated. The specific compensation mechanism for peak shaving is designed as follows:

(1) When the charging depth of the energy storage is different, its charging capacity, service life, and annual cost to be recovered are different. Therefore, a step-by-step compensation method similar to that of conventional units can be considered to compensate the energy storage for participating in the auxiliary service of peak regulation. When energy storage power stations with market access qualifications participate in paid peak shaving transactions, step-by-step compensation is adopted based on the cycle depth. Taking 25% as a compensation interval, the compensation increases in turn with the increase of the cycle depth.

(2) When the energy storage power station participates in peak regulation, the peak regulation effect under different cycle depths is different. When energy storage participates in peak shaving with a higher cycle depth, due to the long peak shaving time and the restricted operation mode, the peak shaving revenue accounts for a higher proportion of the total energy storage revenue. On the contrary, although the peak shaving time is short, energy storage has more opportunities to participate in other modes (such as reducing deviation assessment, etc.) to make profits, the profit path is more flexible, and the proportion of peak shaving revenue is relatively low. From the perspective of the power grid, when the energy storage participates in paid peak regulation at a low cycle depth, the peak regulation effect is less effective than that of the deep charging energy storage due to the small amount of energy charged by the energy storage. Therefore, the peak shaving contribution of each interval is converted by multiplying the peak shaving effect of the energy storage at the maximum cycle depth by the proportional coefficient k_i. Under the condition of one charging and one discharging of the energy storage every day, the paid peak regulation compensation is:

$$\lambda_{peak,i} = k_i \frac{(c_{bat}E + c_p P)\dfrac{i(1+i)^n}{(1+i)^n - 1}}{\dfrac{L(D_m)D_m E}{n}} \tag{1}$$

where $\lambda_{peak,i}$ is the paid peak regulation price of energy storage, k_i is the peak regulation contribution coefficient, c_{bat} is the unit energy cost of energy storage, E is the rated capacity of energy storage, c_p is the unit cost of energy storage power conversion, P is the rated power of the energy storage, i is the benchmark investment rate of return, n is the service life of the energy storage, and $L(D_m)$ is the number of cycles at the maximum charge-discharge depth D_m.

(3) When the energy storage only participates in paid peak regulation, it can be compensated in steps according to the charging depth. In this case, its charge fee is waived, and it will not be compensated for discharge. If the energy storage wants to participate in the energy market at the same time for arbitrage, the charging fee of the energy storage is settled according to the electricity price of the current period. The charged electricity is regarded as its own electricity and can be directly integrated into the power grid.

3.2 Design of Compensation Mechanism for Frequency Regulation

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Adopting an auxiliary service mechanism based on frequency regulation effect will help to reflect the superiority of energy storage frequency regulation performance and increase its income. Therefore, we adopt a two-part compensation system to compensate energy storage power stations for participating in frequency regulation services in the form of "capacity compensation + mileage compensation". The calculation methods of the two compensation methods are as follows:

(1) The energy storage AGC capacity is calculated according to the difference between the upper and lower limits of the adjustment capacity put into AGC operation. The capacity compensation in each dispatch period is converted according to the opportunity cost caused by the energy storage's inability to participate in energy market arbitrage due to the provision of frequency regulation services. The conversion method is as follows:

$$\lambda_{cap} = C_{op} = \frac{S_{profit}}{2PN} \tag{2}$$

where λ_{cap} is the capacity compensation price of energy storage participating in frequency regulation in each trading cycle, C_{op} is the opportunity cost of energy storage that cannot arbitrage due to providing frequency regulation services, S_{profit} is the maximum daily profit of energy storage of the same specification in the arbitrage mode, $2P$ is the capacity of frequency regulation. Since the charging of the energy storage can be regarded as a down ward frequency regulation, and the discharge can be regarded as an upward frequency regulation, it can obtain a capacity twice the declared power. N is the number of daily trading cycles. The formula for calculating S_{profit} is as follows:

$$S_{profit} = \max \sum_{t=1}^{N} \lambda_e(t)[P_{e\_dis}(t) - P_{e\_cha}(t)]\Delta T \tag{3}$$

where $\lambda_e(t)$ is the electricity price at time *t*, $P_{e\_dis}(t)$ and $P_{e\_cha}(t)$ are the discharge power and charging power of the energy storage at time *t* in the arbitrage mode, and ΔT is the time interval in a unit period.

(2) The mileage compensation for energy storage mainly compensates for its life loss cost caused by frequent charging and discharging, and is converted according to the one-time investment cost minus the income of frequency regulation capacity during the operation cycle. In the process of frequency regulation, the energy storage is not always charged and discharged at the maximum power. Assume that the amount of electricity called for charging or discharging within 1h is βP. The frequent actions of frequency modulation in this time period are equivalent to one full cycle of βP in the calculation. Calculate the number of cycles and the service life according to the cycle depth $\beta P / E$ per hour. Assuming that under a full cycle with an hourly cycle depth of $\beta P / E$, the average mileage of energy storage per hour is $m_\beta P$, and the average mileage converted into the transaction cycle is mP. In this case, the mileage compensation for frequency reduction is:

$$\lambda_{mil} = \frac{(c_{bat}E + c_p P)\dfrac{i(1+i)^n}{(1+i)^n - 1} - 2PT\lambda_{cap}}{\dfrac{L(D_\beta)m_\beta P}{n}} \tag{4}$$

where λ_{mil} is the mileage price of frequency regulation, T is the total number of dispatching cycles per year, n is the service life of the energy storage in the frequency regulation mode, $L(D_\beta)$ is the number of cycles calculated according to the cycle depth, β is the ratio of the actual call power to the reported power per hour, m_β is the average hourly mileage factor.

4. Benefit and cost model of energy storage in the operation phase

According to the above analysis, the benefits of energy storage come from three business models: peak regulation, frequency regulation and energy market. Energy storage users can formulate reasonable charging and discharging plans to participate in single or hybrid business models. Energy storage users aim to maximize profits and formulate reasonable operation strategies. This process mainly involves financial indicators such as the benefits of peak regulation, the benefits of frequency regulation, the arbitrage benefits of electricity prices, operation and maintenance costs. These financial metrics are calculated as follows.

4.1 The Benefits of Peak Shaving

The benefits of peak shaving mainly come from the step-by-step compensation for energy storage. The benefits are calculated as follows:

$$W_s = \sum_{t \in T_1} \lambda_{peak,i} \cdot P_{s\_cha}(t) \cdot \Delta T \tag{5}$$

where T_1 is the trading time period of paid peak shaving, $\lambda_{peak,i}$ is the price of paid peak shaving, $P_{s\_cha}(t)$ is the charging power of the energy storage at time *t* in the peak shaving mode, and ΔT is the time interval of the transaction cycle.

4.2 The Benefits of Frequency Regulation

In the frequency modulation mode, the benefits of energy storage include capacity compensation and mileage compensation, which are calculated as follows:

$$W_{fr} = \sum_{t \in T_2} (2\lambda_{cap} + m\lambda_{mil}) \cdot P_{fr}(t) \tag{6}$$

where T_2 is the trading period of energy storage participating in frequency regulation, *m* is the average frequency regulation mileage coefficient converted to each dispatch cycle, and $P_{fr}(t)$ is the bidding power of energy storage participating in frequency regulation at time *t*.

4.3 Profits from Electricity Price Arbitrage

The benefit of energy storage using electricity price for arbitrage is:

$$W_e = \sum_{t \in T3} \lambda_e(t)[P_{e\_dis}(t) - P_{e\_cha}(t)]\Delta T \tag{7}$$

where T_3 is the electricity price trading period of energy storage, and other parameters are consistent with formula (3).

4.4 Operation and Maintenance Costs

The cost of energy storage operation and maintenance is mainly the funds invested to ensure the normal operation of the energy storage system during its life cycle, including the test, installation and maintenance costs of the energy storage system. The operation and maintenance cost is generally estimated approximately according to a certain proportion of the initial investment:

$$C_{opr} = \mu(c_{bat}E + c_p P) \tag{8}$$

where μ is the annual operation and maintenance cost coefficient of energy storage.

The energy storage operator aims at maximizing the total revenue, considering the power and energy constraints of the energy storage, and determines the charging and discharging strategy of the energy storage through optimization calculations.

5. Simulation study

5.1 Simulation Setup

Based on the operation data of the power grid in *area A* of China, electrochemical energy storage is selected for simulation analysis. The energy storage specification is 10MW/5MWh, the design life is 10 years, the recovery residual value rate is 10%, the operation and maintenance cost rate is 1%, and the benchmark investment rate of return *i* is 5%. It is assumed that the electricity can be restored to the initial level of the day after the daily operation of the energy storage. Taking the peak-valley electricity price in *area A* as the electricity price parameter, the electricity price data are shown in Table 1.

Table 1 Peak-valley time-of-use electricity price information

Period name	**Period**	**Price ($/kWh)**
Trough hours	0:00-7:00	0.045212
	23:00-0:00	
Normal hours	7:00-8:30	0.086375
	11:30-14:30	
	17:30-19:00	
	21:00-23:00	

Peak hours	8:30-11:30 14:30-17:30 19:00-21:00	0.127539

Other parameter settings related to energy storage are shown in Table 2.

Table 2 Parameters related to energy storage

Symbol	**Value**	**Unit**	**Symbol**	**Value**	**Unit**
c_{bat}	372.5	\$/kWh	m_{β}	3.5	-
c_p	89.4	\$/kW	k	0.01	-
N	96	-	$SOC_{\max}$	0.9	-
β	0.13	MWh/MW	$SOC_{\min}$	0.2	-

5.2 Compensation Mechanism

5.2.1 Compensation mechanism for peak shaving

According to formula (1), the ladder price of energy storage participating in peak shaving services can be calculated, as shown in Table 3.

Table 3 Tiered compensation prices for energy storage

Depth of discharge (%)	**Peak shaving factor**	**declared price/ (\$/kWh)**
0-25	0.25	31.29
25-50	0.5	62.58
50-75	0.75	93.87
75-100	1	125.16

5.2.2 Compensation mechanism of frequency modulation

According to formula (2)-formula (4), the capacity price and mileage price of energy storage participating in the frequency regulation service can be calculated, which are $\lambda_{cap} = \$0.213 / MW$ and $\lambda_{mil} = \$2.248 / MW$ respectively.

5.3 Multi-scenario Analysis

Energy storage can generate revenue through one or more business models. We use the scenario analysis method to calculate and analyze the benefits and investment economics of energy storage participating in different business models. Four scenarios are set. Scenario 1 represents that the energy storage only participates in the frequency regulation service. Scenario 2 represents that energy storage only participates in peak shaving services. Scenario 3 represents that energy storage participates in a hybrid business model of peak shaving and price arbitrage. Scenario 4 represents a hybrid business model in which energy storage participates in peak regulation, frequency regulation and electricity price arbitrage. The operation and economic benefits of energy storage in each scenario are analyzed as follows.

(1) Scenario 1: Only participate in the frequency adjustment service

The typical daily operation strategy of energy storage in this scenario is shown in Figure 3.

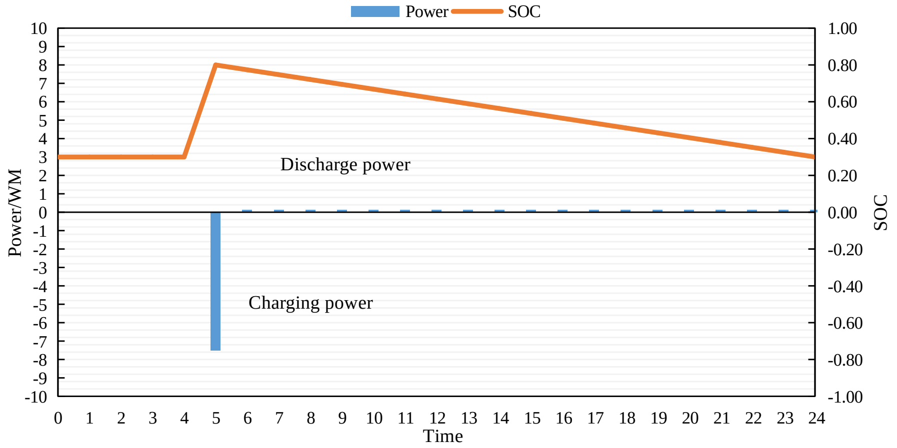

Figure 3 Operation strategy of energy storage in Scenario 1.

In Figure 3, when the charging power of the energy storage is negative, it indicates the charging state, and when it is positive, it indicates the discharging state. The bidding capacity for energy storage to participate in the frequency regulation service is 10 MW downward and 10 MW upward (the shaded part in the Figure 3 represents the bidding capacity). The energy storage is down-converted by 7.5MW at t=5, and its SOC increases from 0.3 to 0.8. In order to ensure that the energy storage capacity returns to the initial state at the end of the daily operation, the energy storage is discharged, and the discharge power is 0.13MW.

In this scenario, the service life of the energy storage is 3.7 years, and its operation status and investment economic analysis are shown in Table 4.

Table 4 Investment economic analysis of energy storage in Scenario 1

Project name		**Value**
Cash outflow (M$)	Initial investment cost	2.76
	Operation and maintenance cost	0.03
	Annual value of expenses	0.85
	Cash flow present value	2.85
Cash inflow (M$)	Annual operating benefit	0.76
	Residual value	0.28
	Annual income	0.76
	Present value of cash inflows	2.76
Economic analysis indica-	NPV (M$)	-0.09

tors	Payback period (year)	3.73
	IRR	2.98%

In scenario 1, the annual cost of energy storage is 0.85 million dollars, the annual income is 0.76 million dollars, the NPV is -0.09 million dollars (negative number), the payback period is 3.73 years (3.7 years longer than the service life), the IRR is 2.98% (less than the benchmark yield of 5%). Therefore, in this scenario, the cost of energy storage cannot be recovered during its service life, and it is not economical to invest.

(2) Scenario 2: Only participate in peak shaving services

The typical daily operation strategy of energy storage in this scenario is shown in Figure 4.

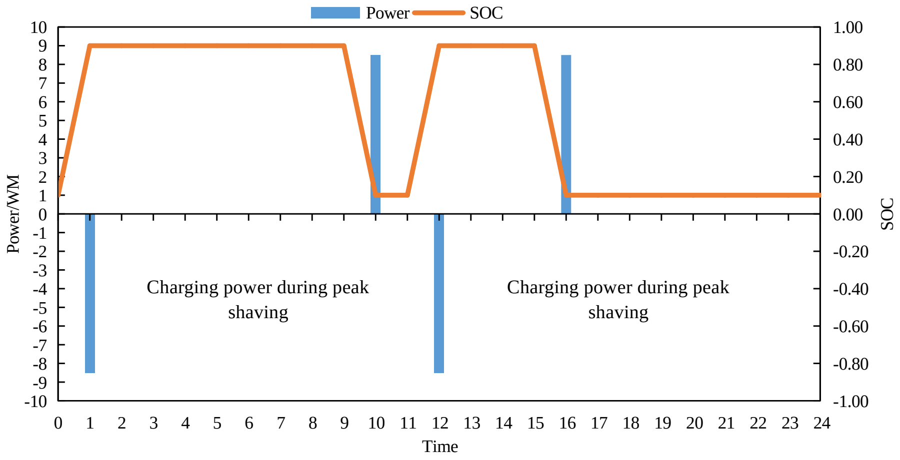

Figure 4 Operation strategy of energy storage in Scenario 2.

In this scenario, the charging compensation for energy storage is performed according to the step compensation price provided in Table 3. The charging electricity fee is exempted, but the energy storage needs to be discharged according to the needs of the dispatch center, and will not be compensated during discharge. In Figure 4, the energy storage has performed peak shaving operations with a charging power of 8MW at t=1 and t=12, respectively. And according to the dispatching needs, the peak shaving operation was carried out with the discharge power of 8MW at t=10 and t=16.

In this scenario, the service life of the energy storage is 9.6 years, and its operation status and investment economic analysis are shown in Table 5.

Table 5 Investment economic analysis of energy storage in Scenario 2

Project name		**Value**
Cash outflow (M$)	Initial investment cost	2.76
	Operation and maintenance cost	0.03
	Annual value of expenses	0.40

	Cash flow present value	2.96
Cash inflow (M$)	Annual operating benefit	0.38
	Residual value	0.28
	Annual income	0.38
	Present value of cash inflows	3.00
Economic analysis indicators	NPV (M$)	0.04
	Payback period (year)	7.85
	IRR	5.28%

In scenario 2, the annual cost of energy storage is 0.4 million dollars, the annual income is 0.38 million dollars, the NPV is 0.04 million dollars (positive number), the payback period is 7.85 years (less than the service life of 9.6 years), the internal rate of return is 5.28% (greater than the benchmark rate of return of 5%). Therefore, in this scenario, the cost of energy storage can be recovered within its service life, and it has certain investment economy.

(3) Scenario 3: Mixed business model of peak regulation and electricity price arbitrage

The typical daily operation strategy of energy storage in this scenario is shown in Figure5.

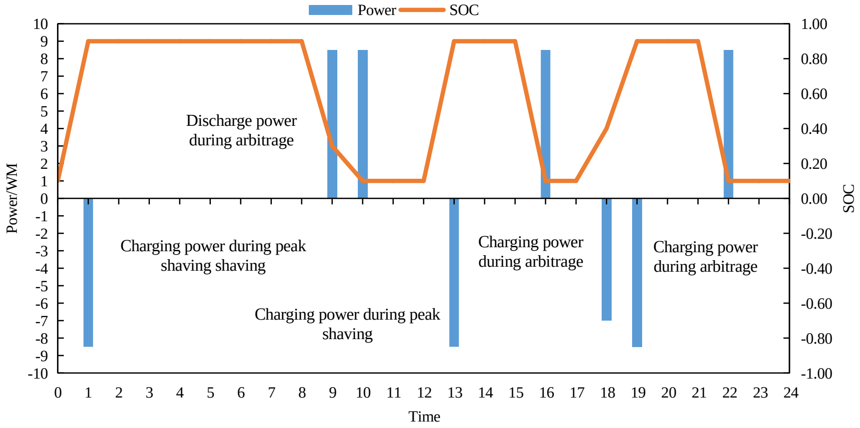

Figure 5 Operation strategy of energy storage in Scenario 3.

In this scenario, the charging and discharging electricity price of energy storage is settled according to the peak-valley electricity price. The energy storage participates in the paid peak shaving service through charging operations when the system load is low, and performs the step compensation provided in Table 3. During the peak period of system load, energy storage can conduct electricity price arbitrage through discharge operations. In Figure 5, energy storage participated in the paid peak shaving service with a charging power of 8.5MW at t=1 and t=13, and conducted electricity price arbitrage at t=9, 10, 16, 18, and 19.

In this scenario, the service life of the energy storage is 6.4 years, and its operation status and investment economic analysis are shown in Table 6.

Table 6 Investment economic analysis of energy storage in Scenario 3

Project name		**Value**
Cash outflow (M$)	Initial investment cost	2.76
	Operation and maintenance cost	0.03
	Annual value of expenses	0.54
	Cash flow present value	2.90
Cash inflow (M$)	Annual operating benefit	0.52
	Residual value	0.28
	Annual income	0.52
	Present value of cash inflows	3.00
Economic analysis indicators	NPV (M$)	0.10
	Payback period (year)	5.58
	IRR	5.90%

In scenario 3, the annual cost of energy storage is 0.54 million dollars, the annual income is 0.52 million dollars, the NPV is 0.1 million dollars (a positive number), and the payback period is 5.58 years (less than the service life of 6.4 years), the IRR of return is 5.90% (greater than the benchmark rate of return of 5%). Therefore, in this scenario, the cost of energy storage can be recovered within its service life, and it has certain investment economy.

(4) Scenario 4: Mixed business model of peak regulation, frequency regulation and electricity price arbitrage

The typical daily operation strategy of energy storage in this scenario is shown in Figure 6.

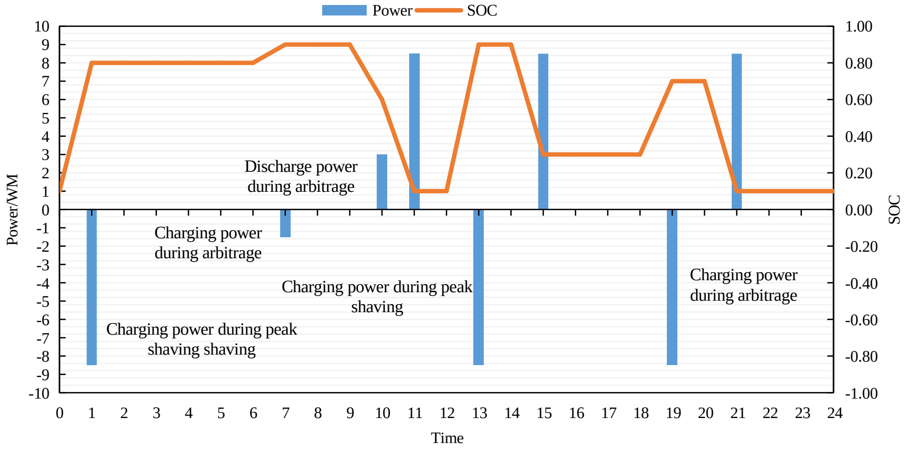

Figure 6 Operation strategy of energy storage in Scenario 4.

In this scenario, energy storage participates in paid peak shaving during the paid peak shaving period, conducts electricity price arbitrage operations during periods of high electricity prices, and participates in frequency regulation services during other periods to further increase revenue levels. In Figure 6, the bidding capacity for energy storage to participate in the frequency regulation service is 10 MW downward and 10 MW upward (the shaded part in Figure 6 represents the bidding capacity). Energy storage participated in the paid peak shaving service with a charging power of 8.5MW at t=1 and t=13, and participated in the electricity price arbitrage business model at t=7, 10, 11, 13, 15, 19, and 21.

In this scenario, the service life of the energy storage is 2.7 years, and its operation status and investment economic analysis are shown in Table 7.

Table 7 Investment economic analysis of energy storage in Scenario 4

Project name		**Value**
Cash outflow (M$)	Initial investment cost	2.76
	Operation and maintenance cost	0.03
	Annual value of expenses	1.14
	Cash flow present value	2.82
Cash inflow (M$)	Annual operating benefit	1.15
	Residual value	0.28
	Annual income	1.15
	Present value of cash inflows	3.09
Economic analysis indicators	NPV (M$)	0.26
	Payback period (year)	2.48
	IRR	9.90%

In scenario 4, the annual cost of energy storage is 1.14 million dollars, the annual income is 1.15 million dollars, the NPV is 0.26 million dollars (positive number), and the payback period is 2.48 years (less than the service life of 2.7 years), the IRR is 9.90% (greater than the benchmark rate of return of 5%). Therefore, in this scenario, the cost of energy storage can be recovered within its service life, and it has good investment economy.

(5) Comprehensive comparative analysis

We select NPV and IRR investment evaluation indicators with fixed evaluation standards to compare and analyze the investment economics in each scenario. The comparison of NPV and IRR under the four scenarios is shown in Figure 7.

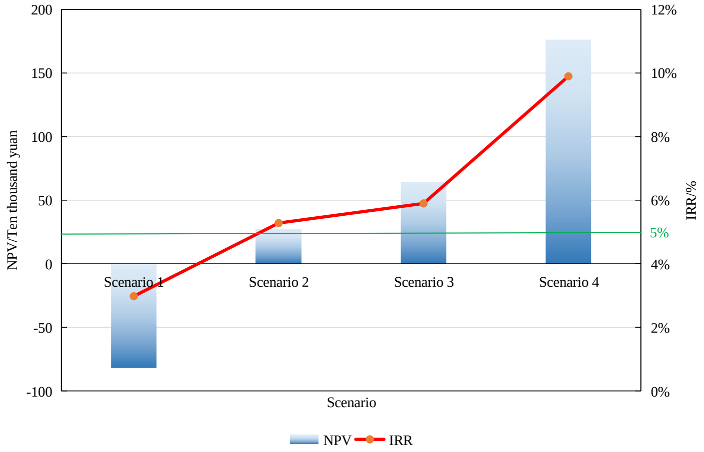

Figure 7 Comparative analysis of investment economics of energy storage in different scenarios.

It can be seen from Figure 7 that the NPV of scenario 1 is negative and the internal rate of return is lower than the benchmark rate of return of 5%, which is not economical. Therefore, even if there is compensation for frequency regulation auxiliary services, energy storage alone cannot recover costs in the life cycle by relying on frequency regulation auxiliary services. The NPV of Scenario 2, Scenario 3 and Scenario 4 are all positive, and the IRR is higher than the benchmark rate of return 5%. These three scenarios are all economical. The NPV and IRR of Scenario 2 are slightly higher than the break-even criteria, Scenario 3 is slightly better than Scenario 2, and the NPV and IRR of Scenario 4 are much higher than Scenario 2 and Scenario 3, with good investment economy. Therefore, stimulated by the compensation mechanism of peak shaving auxiliary services and frequency regulation auxiliary services, energy storage can achieve good operating benefits by optimizing operation strategies and participating in the hybrid business model of peak shaving, frequency regulation and electricity price arbitrage.

6. Conclusions

In order to solve the problem of incomplete compensation mechanism for energy storage participation in auxiliary service market in China, this paper proposes a stepped peak modulation compensation mechanism considering cycle depth and a two-part frequency modulation compensation mechanism considering frequency modulation opportunity cost, and verifies the effectiveness of the proposed method through a simulation example. The main conclusions are as follows:

(1) Energy storage can replace thermal power to participate in auxiliary services, which is conducive to improving the income of the whole system and promoting the consumption of new energy.

(2) In the process of energy storage participating in auxiliary service market, it is beneficial for energy storage to recover costs in auxiliary service market by including the levelized cost of energy storage into peak adjustment compensation price and the cost of capacity and mileage into compensation price.

(3) At present, the investment and construction cost of energy storage is still at a high level, and the compensation price of auxiliary services calculated according to the cost is higher than the current policy price.

(4) Energy storage participating in frequency modulation mode alone does not have investment economy, while the hybrid mode participating in peak modulation, frequency modulation and electricity price arbitrage through optimized operation has an internal rate of return of up to 9.9%, showing good economic performance of investment.

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