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Economic Boundary Analysis of Echelon Utilization of Retired Power Battery Considering Replacement Cost

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As a large number of new energy electric vehicles are retired, the sequential utilization of retired power batteries has become one of the important means to improve the economic benefits of batteries, but there is a problem of disunity between available capacity and cycle life. Therefore, a peak-load power distribution method based on the principle of equal life of retired power batteries was proposed, which could effectively avoid the life difference caused by the battery difference and reduce the replacement cost. At the same time, in order to give reasonable investment suggestions for the stepwise utilization of retired power batteries, three economic boundary value models, including the payback period, peak–valley price difference, and investment cost, were constructed based on the leveling cost. Through the simulation of a 60 MW/160 MWh lithium iron phosphate decommissioned battery storage power station with 50% available capacity, it can be seen that when the cycle number is 2000 and the peak–valley price difference is above 0.8 yuan/kWh, it has investment value.

Keywords: decommissioning power battery, echelon utilization, peak cutting and valley filling, power distribution, economic boundary

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INTRODUCTION

The state attaches great importance to the development of the new energy electric vehicle industry and actively arranges it as a national strategic emerging industry. During the 14th Five-Year Plan period, the total scale of new energy electric vehicle production and sales will reach tens of millions of vehicles. However, when the EV battery's available capacity falls below 70–80%, it must be decommissioned (Zhao et al., 2021a; Li Y Q et al., 2021; Xie et al., 2020). At that time, the capacity of the decommissioned battery in China will be as high as 25 GWh (Zhang et al., 2021). Direct scrapping will not only increase the processing cost but also cause a waste of resources (Tian et al., 2020; Yan et al., 2019). To explicitly encourage the cascade utilization of power batteries, the five departments issued management measures for the cascade utilization of power batteries of new energy vehicles in September 2021 (Li J L et al., 2022). At the same time, the majority of academics turned their attention to retired power battery echelon utilization (Lai et al., 2021; Xu et al., 2019; Zhang H et al., 2020).

When the power battery is decommissioned, the available capacity is about 70%. If it is selected and reorganized to participate in power grid service, it can not only reduce the battery recovery pressure but also provide greater economic benefits (Jiang et al., 2021; Yu and Zhou, 2020; Gao et al., 2022; Sathrea et al., 2015; Sedighizadeh et al., 2019). According to Dipti et al. (2020), cascade lithium-ion batteries exhibit better environmental benefits than new batteries in some application scenarios, demonstrating the social value of cascade utilization of retired power batteries. Ma et al. (2021) applied decommissioned power batteries to wind power smoothing scenarios and then reduced the amount of abandoned air and improved the economic benefits of decommissioned power batteries by constructing the objective function of maximum daily returns. By establishing the cascade utilization model, Fan et al. (2021) improved the prediction accuracy of new energy and the revenue of retired batteries. The moving average method was used by Cui et al. (2020) to separate the predicted power fluctuation components of wind power, and then, retired power batteries were used to reduce wind power fluctuation and improve wind power consumption. From a demand-side management perspective, Fazelpour et al. (2014) and Finn et al. (2012) proposed that charging step utilization battery devices during off-peak load periods can reduce charging costs and studied the charging and discharging strategies of step utilization battery according to peak and valley pricing. Sun et al. (2021) proposed that the project exhibits investment value when the recovery price of step utilization battery is lower than 0.4 yuan/Wh. The normalization method is used to construct the economic boundary analysis model, according to Li and Li (2021). When the number of cycles is more than 2000 and the peak–valley price difference is 0.8 yuan/kWh, profits can be achieved.

From the above research, it is not difficult to find that it is feasible to use retired power batteries to participate in the peak load adjustment and fluctuation suppression of power grid from the perspective of economy and technology, but the available capacity and cycle life of retired batteries are not uniform (Zhang J et al., 2020), and how to construct the “peak–valley price difference” boundary value model in electricity market transactions has become a research focus (Cai and Li, 2021; Cao et al., 2021). Therefore, this paper proposes a retired power battery cascade utilization economic model and investment economic boundary model taking into account replacement cost. Compared with existing studies, this paper has the following contributions:

1) This paper proposes a peak-load power distribution method based on the principle of equal life of retired batteries to reduce the replacement cost increased by the difference in cycle life, thus improving the economy of the system.

2) This paper constructs three economic boundary models based on leveling cost, including the payback period, peak–valley price difference, and investment cost, which can provide reasonable suggestions for the investment of retired power battery’s echelon utilization.

ECONOMIC OPTIMIZATION MODEL OF RETIRED POWER BATTERY CASCADE UTILIZATION

Step Utilization Cost Model of Retired Power Battery

The step utilization cost of power battery mainly includes battery recovery cost, equipment cost (power converter and management system cost), integration cost, replacement cost, operation and maintenance cost, and scrap cost.

Cost Recovery (C_1)

$$C_1 = C_B \cdot E_N, \tag{1}$$

where C_B is the unit price of the recovered battery, yuan/Wh, and E_N is the recovery rated capacity, Wh.

Equipment Cost (C_2)

$$C_2 = C_P \cdot P_N + C_M \cdot E_N, \tag{2}$$

where C_p is the unit price of the power converter, yuan/W; C_M is the unit price of the management system, yuan/Wh; and P_N is the recovery rated power, W.

Integration Cost (C_3)

Due to individual differences, charging and discharging efficiency, available capacity, rated power, etc., decommissioned power batteries need to be screened, classified, and assembled, thus increasing the cost:

$$C_3 = C_S \cdot E_N, \tag{3}$$

where C_S is the unit battery integration cost, yuan/Wh.

Replacement Cost (C_4)

Based on the individual differences of retired batteries, the service life termination time is not uniform during operation, and the battery body needs to be replaced constantly (Li et al., 2022; Lu et al., 2021). In the meantime, the battery access port management system cannot be reused and must be replaced at the same time. As a result, the cost of replacement includes both the battery body and the management system:

$$C_4 = n \cdot (C_B + C_M) \cdot E, \tag{4}$$

where n is the number of replacement times expressed as

$$n = \frac{N \cdot (T \cdot m)}{k}, \tag{5}$$

where N is the project cycle, k is the number of remaining cycles of the power battery, T is the number of operating days per year, and m is the number of cycles per day.

Operation and Maintenance Cost (C_5)

$$C_5 = C_W \bullet E_N, \tag{6}$$

where C_W is the annual operation and maintenance unit price, yuan/Wh/year.

Scrap Cost (C_6)

After the service life of power battery, the cost of residual body treatment is generally calculated by the residual value rate:

$$C_6 = -(C_1 + C_2 + C_3 + C_4 + C_5) \bullet \beta, \tag{7}$$

where β is the salvage rate.

Therefore, the power battery cost (C) can be expressed as follows:

$$C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6. \tag{8}$$

Retired Power Battery Step Utilization Income Model

At present, the power market is not perfect, and the incomes of energy storage mainly include the following: first, direct incomes of low storage and high generation to earn power price difference and peak adjustment compensation (Chen et al., 2022; Wang et al., 2020) and, second, indirect incomes of reducing thermal power generation through energy storage to save environmental costs (Li et al., 2020).

Peak Cutting and Valley Filling

$$B_1 = (\eta P_D - P_C)\Delta t P_{price,} \tag{9}$$

where B_1 is the income from peak cutting and valley filling, η is the charge–discharge efficiency, P_{price} is the real-time peak–valley price difference of power grid, $\triangle$t is each charge and discharge time, P_C is the charging power, and P_D is the discharge quantity.

Peak Adjustment Compensation

$$B_2 = e\sum_{t=1}^{T} \eta P_D, \tag{10}$$

where B_2 is the annual peak regulation compensation income and e is the contract price.

Environmental Income

$$B_3 = \sum_{h=1}^{H} \eta P_D \theta_h \Delta t P_{price,h,} \tag{11}$$

where B_3 is the environmental benefit, H is the total number of pollutants, θ_h is the emission density of the hth pollutant, and $P_{price,h}$ is the unit emission cost of the hth pollutant.

Therefore, the power battery income (B) can be expressed as follows:

$$B = B_1 + B_2 + B_3. \tag{12}$$

In summary, the net present value of successive utilization of retired power batteries can be expressed as follows:

$$NPV = \sum_{i=1}^{N} (B - C), \tag{13}$$

where N is the project cycle.

POWER DISTRIBUTION METHOD OF RETIRED POWER BATTERY STEP UTILIZATION

Due to the difference in rated capacity loss and available power consumption (as shown in **Figure 1**) (Fan et al., 2021), the charging and discharging efficiency and depth of decommissioned power batteries are different. As a result, the available capacities of retired power batteries vary (Klein et al., 2016; Zhao et al., 2021b). If the even distribution principle is followed when participating in peak-load cutting and valley filling, it may result in insufficient energy supply for some batteries and redundancy for some batteries. At the same time, if the battery is charged and discharged sequentially according to the size of available capacity, it may increase the battery imbalance damage (that is, the battery charge and discharge frequency is not uniform) and then increase the replacement cost. As a result, based on the principle of decommissioned power battery life span, this paper proposes a method to allocate charging and discharging power based on battery capacity, thereby avoiding the problem of increasing replacement cost caused by inconsistent charging and discharging. The specific implementation process is as follows:

Step 1: Determine the required charge–discharge efficiency of the system ($\triangle P$).

Step 2: Initialize the total available capacity of the current retired power battery ($\triangle P_D$):

$$\Delta P_D = \sum_{k=1}^{K} \Delta P_k, \tag{14}$$

where $\triangle P_k$ is the available capacities of retired power batteries in group K and K is the total number of groups.

Step 3: Determine the ratio coefficient of charge and discharge by the processing method of normalization (g):

$$g = \begin{cases} \dfrac{\Delta P}{\Delta P_D}, \Delta P \le \Delta P_D \\ 1, \quad \Delta P \ge \Delta P_D. \end{cases} \tag{15}$$

Step 4: Determine the charge and discharge amount of each group:

$$\Delta P_{k\_1} = \Delta P_k \bullet g. \tag{16}$$

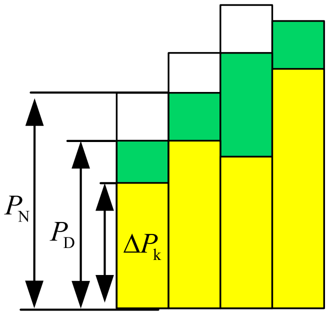

FIGURE 1 | Schematic diagram of available capacity of different retired power batteries.

ECONOMIC BOUNDARY MODEL BASED ON LEVELING COST

Payback Period Boundary Model

The levelized cost of energy (LCOE) is widely used at home and abroad to evaluate the economy of power generation projects (Li and Li, 2021). The boundary of the investment payback period refers to the time required for power generation projects from investment to full investment recovery. The longer the project investment payback period, the higher the investment risk:

$$\begin{cases} \sum_{i=0}^{n} NPV = 0, \\ \sum_{i=1}^{n} \frac{R_i}{(1+r)^i} = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i}, \end{cases} \tag{17}$$

where R_i is the income in the ith year, C_i is the input cost in the ith year, n is the boundary life of the payback period, and r is the discount rate.

The power battery ladder utilization gains can be expressed by the sum of discounted values multiplied by the LCOE and the current year's power production E_n, and then, **Eq. 14** can be further expressed as follows:

$$\sum_{i=1}^{n} \frac{LCOE \times E_n}{(1+r)^i} = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i}, \tag{18}$$

$$E_n = \eta \times DOD \times E_N, \tag{19}$$

where η is the charge–discharge efficiency and the depth of discharge (DOD) is the charge–discharge depth.

Investing in the LCOE Boundary Model

The investment LCOE boundary value refers to the LCOE required to recover the investment in the whole life cycle, according to **formula (15)**:

$$LCOE = \frac{\sum_{i=1}^{N} \frac{C_i}{(1+r)^i}}{\sum_{i=1}^{N} \frac{E_n}{(1+r)^i}} \tag{20}$$

Investment Cost Boundary Model

The boundary value of investment cost refers to the maximum acceptable recovery cost value of investment recovery within the whole life cycle according to the current LCOE value (about 0.7 yuan/kWh) (Fan et al., 2021):

$$C_B = \left(LCOE \times \sum_{i=1}^{N} \frac{E_n}{(1+r)^i} - \sum_{i=1}^{N} \frac{(C_4 + C_5)}{(1+r)^i} - C_2 - C_3 - C_6 \right) \Big/ E_N \tag{21}$$

ANTI-TRUTH ANALYSIS

Simulation Parameters

Taking 60 MW/160 MWh as an example, the usable capacity of the energy storage system is 50%, the specific parameters are shown in **Table 1** (Li and Li, 2021), the peak-to-valley time-of-use electricity price of non-residential users is shown in **Table 2**, the capacity decay rate is calculated according to 5%/100 times (Sun et al., 2021), and the environmental cost parameters are shown in **Table 3**.

Economic Benefit Analysis

The decommissioned power battery model is solved by a genetic algorithm (Chen, 2016; Hlal et al., 2019; Saini and Gidwani, 2022; Jiang et al., 2019), in which the original load (Wei et al., 2021) and peak adjusted curve are shown in **Figure 2**, and the output curve after peak shaving of the decommissioned power battery is shown in **Figure 3**. Assuming that the decommissioned power battery's service life and project life are both 5 years, no need exists for replacement costs at this time, and the annual investment cost and income of the decommissioned power battery are shown in **Table 4**.

According to **Figure 2**, finding that energy storage demonstrates a good effect of "peak shaving and valley filling" is not difficult, effectively assisting the power grid to participate in peak regulation. Simultaneously, according to **Table 4**, it can be seen that the decommissioned power battery demonstrates certain economic benefits in participating in peak shaving, and the investment payback period is 4.2 years, which can recover the cost during the life cycle and exhibits investable value.

Profit Margin Analysis

Analysis of Economically Sensitive Parameters

According to **formula (17)**, the current LCOE = 0.86 (yuan/kWh); however, the current peak-to-valley electricity price difference is 0.6 yuan/kWh, indicating that the decommissioned power battery ladder uses only the peak–valley electricity price difference income that relies on peak-to-valley filling, and it does not exhibit profitability. When combined with the cost of the decommissioned power battery in **Table 4** and the parameters in **Table 1**, it is clear that the price of the recovery price, the number of cycles, and the technical cost (including equipment cost and integration cost) of the single battery result in a significant impact on the economic

TABLE 1 | Parameters of echelon energy storage.

Parameter	Numerical value	Parameter	Numerical value
C_B (yuan/Wh)	0.5	T (days)	330
C_P (yuan/W)	0.5	N (years)	10
C_M (yuan/Wh)	0.15	η	0.85
C_S (yuan/Wh)	0.3	r	5%
C_W (yuan/kWh/year)	0.05	k (number of cycles)	2,500
e (yuan/kWh)	0.5	m	2
β	5%		

TABLE 2 | Time-of-use (TOU) power price.

Species	Peak		Flat section		Trough		Peak–valley price difference
	Period	Price	Period	Price	Period	Price	
Residents	8:00–12:00 17:00–21:00	1.0	12:00–17:00 21:00–4:00	0.6	04:00–8:00	0.3	0.7
Industrial	8:00–12:00 17:00–21:00	1.3	12:00–17:00 21:00–4:00	0.8	04:00–8:00	0.4	0.9

TABLE 3 | Type and cost of emissions.

Gas species	Displacement (kg/MWh)	Cost (yuan/kg)
Dust	0.5	2.92
SO_2	0.5	6.24
NO_x	0.75	8.03
CO_2	0.3	0.03
CO	0.05	1.01

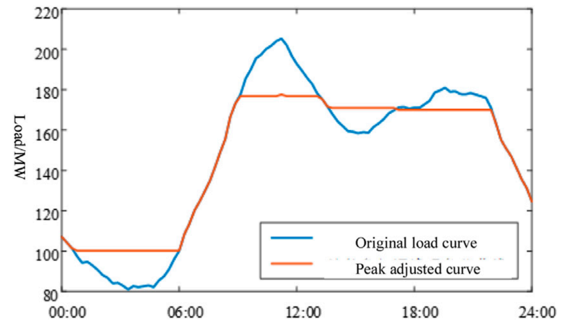

FIGURE 2 | Comparison diagram of post-peak load involving original load and energy storage.

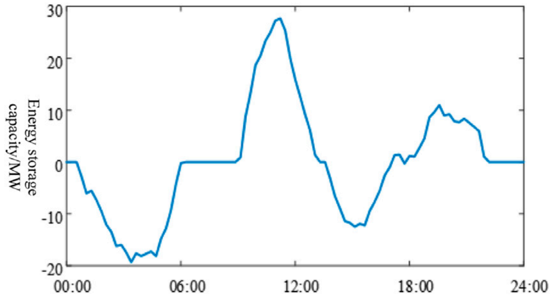

FIGURE 3 | Output curve of the decommissioned power battery.

utilization of the decommissioned power battery ladder. Therefore, this section analyzes the relationship between battery recovery unit price, technical cost, and LCOE sensitive parameters in the case of 1,500 cycles, 2,000 cycles, and 2,500 cycles, respectively, as shown in **Figures 4–6**, respectively.

In **Figure 4**, when the number of cycles k = 1,500 times, the battery cost boundary is about 0.4 yuan/kWh, and the technical cost boundary is 0.25 yuan/kWh, or the sum of the two is about 0.65 yuan/kWh. In **Figure 5**, when k = 2,000 times, the battery cost boundary is about 0.5 yuan/kWh, and the technical cost boundary is 0.35 yuan/kWh, or the sum of the two is about 0.85 yuan/kWh. In **Figure 6**, when k = 2,500 times, the battery cost boundary is about 0.52 yuan/kWh, and the technical cost boundary is 0.35 yuan/kWh, or the sum of the two is about 0.87 yuan/kWh. However, when the number of cycles exceeds 2,000, the boundary cost change is not obvious because the charging and discharging power, depth, and usable capacity of decommissioned batteries are essentially identical, with the only difference being the difference in life.

It is not hard to see from **Figures 4–6** that, under the same battery recycling unit price and technical cost, the LCOE continues to decline as the number of cycles increases. At present, the maximum peak-to-valley price difference of the electricity price of Jiangsu residents is 0.8154 yuan/kWh, while the peak-to-valley price difference of 35 kV industrial users can reach 0.89 yuan/kWh, and the peak-to-valley price difference of 1–10 kV industrial and commercial users in Beijing can reach 1.14 yuan/kWh. When the number of cycles exceeds 2,000 times, making a profit is a possibility. At the same time, the National Development and Reform Commission issued the “Notice on

TABLE 4 | Annual investment costs and benefits of decommissioning power batteries.

Cost and benefit items and composition		Amount of money
Fixed investment cost (ten thousand yuan)	Battery investment cost	8,000
	Equipment investment cost	3,900
	Integration cost	1800
Average annual investment cost (ten thousand yuan)	Operation and maintenance cost	80
	Scrap cost	-17.2
Average annual income (ten thousand yuan)	Direct income	3,293.3
	Environmental income	35.1
NPV (ten thousand yuan)		525.6

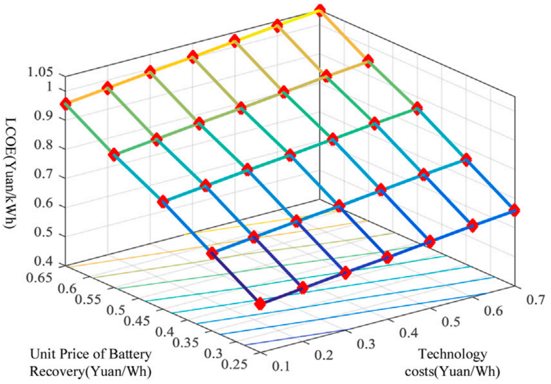

FIGURE 4 | K = 1,500 times sensitive cost parameter relationship.

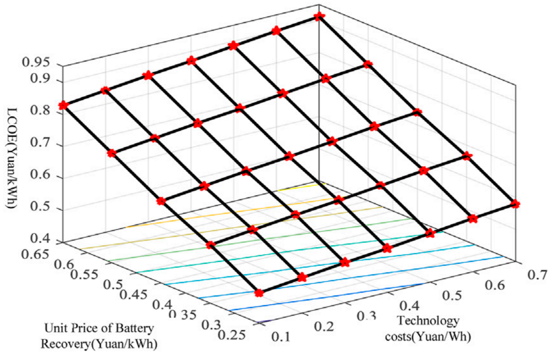

FIGURE 5 | K = 2,000 times sensitive cost parameter relationship.

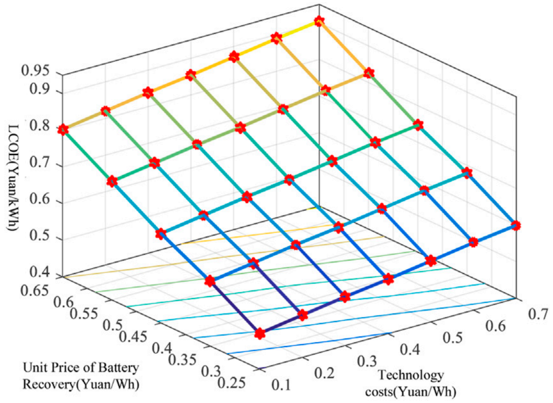

FIGURE 6 | K = 2,500 times sensitive cost parameter relationship.

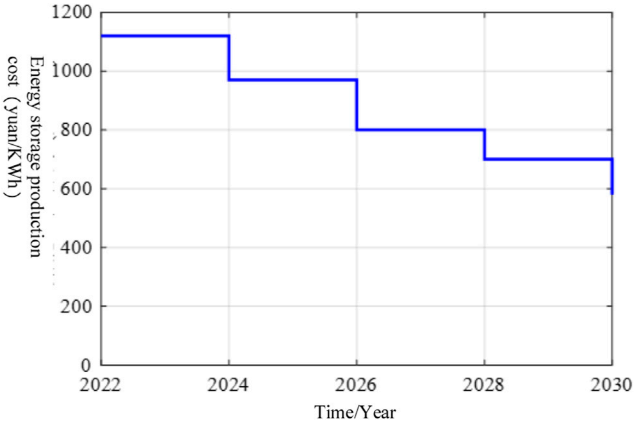

FIGURE 7 | Change trend of investment cost of the retired power battery.

Further Improving the Time-Sharing Electricity Price Mechanism" (National Development and Reform Commission, 2021), which stipulates that the peak-to-valley electricity price difference reaches 4:1, further providing usable space for energy storage investment.

Economic Boundary Value Analysis

In recent years, the price of lithium iron phosphate batteries and the cost of energy storage technology have both declined, further improving the profit margins of power battery cascade utilization. As a result, this section investigates the payback period boundary value, LCOE boundary value, and investment cost (battery recovery and technical cost) boundary value based on the aforementioned economic model of cascade utilization of power batteries. For the study of the payback period boundary value, assuming that the whole life cycle of the decommissioned power battery is 8 years, the number of cycles is 2,000 times, the current LCOE is 0.7 (yuan/kWh) (Li and Li, 2021), and the investment cost changes are shown in **Figure 7**. Then, the

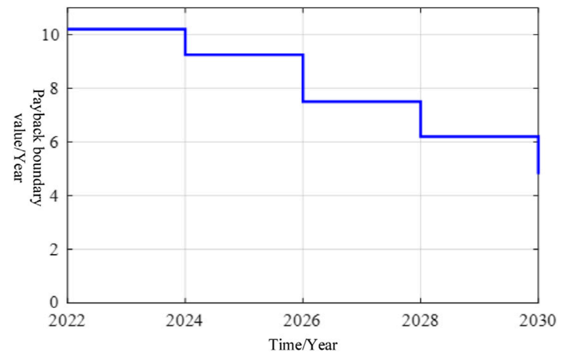

FIGURE 8 | Payback boundary value.

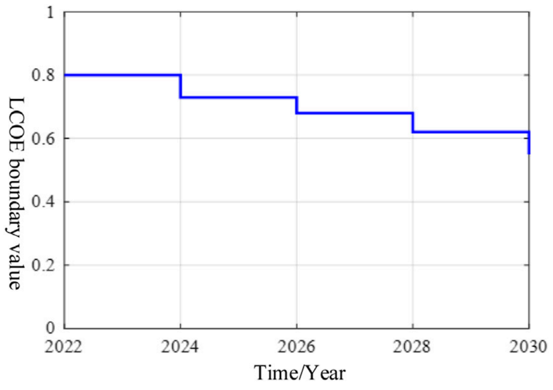

FIGURE 9 | LCOE boundary value.

relationship between the payback period boundary value and the evolution trend of energy storage cost is shown in **Figure 8**.

According to **Figure 8**, as energy storage costs are reduced, the payback period boundary value continues to shrink. For example, in 2026, when the energy storage cost is reduced to 0.8 yuan/kWh, the payback period boundary value is approximately 7.8 years, allowing the investment cost to be recovered over the life cycle. The payback period is reduced to 4.8 years when the cost of energy storage falls to 0.58 yuan/kWh in 2030.

In the study of LCOE boundary values, according to **Eq. 20**, it can be seen that the current LCOE = 0.86 (yuan/kWh), making the profit difficult. **Figure 9** depicts the relationship between the LCOE boundary value and the cost evolution trend of the decommissioned power battery when the total life cycle of the decommissioned power battery is 8 years and the number of cycles is 2,000.

From **Figure 9**, it is not difficult to find that, with the continuous reduction of costs, the LCOE boundary value continues to decrease, which indicates that the profit space is getting larger and larger, and when it is 2028, the LCOE is reduced to 0.6 yuan/kWh, meeting the current peak-to-valley price difference in most domestic provinces. A better chance of achieving profitability before 2028 occurs if the National Development and Reform Commission is constantly formulating and releasing the peak–valley electricity price spread policy.

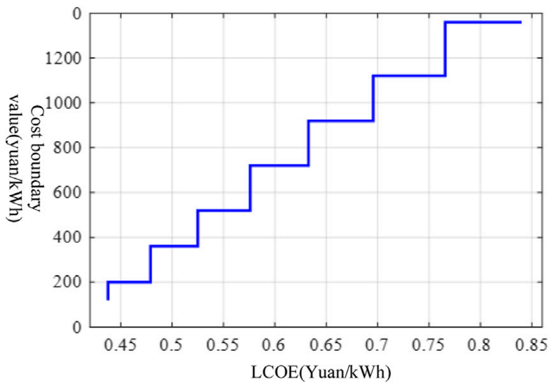

FIGURE 10 | Cost boundary value.

When the decommissioned power battery life cycle is 8 years and the number of cycles is 2000, the decommissioned power battery cost boundary study refers to the corresponding investment cost value when the LCOE boundary value changes. **Figure 10** depicts the relationship between the two.

From **Figure 10**, finding that the cost boundary value of decommissioned power batteries is directly proportional to LCOE is not difficult. Peak and trough electricity price spread in Jiangsu, Zhejiang, Hubei, and Shandong provinces will reach 0.7486 yuan/kWh, 0.503 yuan/kWh, 0.6116 yuan/kWh, and 0.568 yuan/kWh, respectively, under the new regulations. At this point, the national peak-to-valley electricity price difference is roughly 0.6 yuan/kWh, and if one only relies on “peak shaving and valley filling” to earn the peak-to-valley price difference income, the cost must be reduced to less than 0.8 yuan/kWh to achieve the decommissioning power battery cascade utilization profit. Combined with the cost change forecast of **Figure 7**, the investment recovery period needs to wait until 2026.

CONCLUSION

In this paper, an economic model of “peak-load cutting and valley filling” for retired batteries was established, as well as an economic boundary model based on leveling cost, to address the step utilization problem of a large number of retired power batteries. Through the simulation analysis of an actual decommissioned battery storage power station, the following can be concluded:

1) The decommissioned battery storage power station exhibits a good effect of “peak cutting and valley filling,” and it can effectively assist the power grid to participate in peak regulation. At the same time, it results in certain economic benefits, and the investment payback period is 4.2 years, which can recover the cost in the life cycle and exhibits investable value.

2) Battery recovery costs, technical costs, and cycle times all demonstrate an impact on the investment benefit and decision to decommission a battery storage power station. The retired battery

cascade utilization demonstrates an investment value when the cycle number is 2,000 and the peak–valley price difference is greater than 0.8 yuan/kWh.

3) With the continuous introduction of peak–valley price difference policy and the continuous development of energy storage technology, a large space of investment value exists for the cascade utilization of retired power batteries. This paper's analysis of an economic boundary model based on leveling costs provides a theoretical foundation for investors to make investment decisions.

In summary, the echelon utilization of decommissioned power batteries is affected by factors such as investment costs, peak-to-valley price differences, and cycle times. Therefore, when making investment decisions, investors need to make reasonable arrangements according to the actual working model.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

ZY proposed the research direction and guided the project. YW, WW and SD were the primary writers of the manuscript. YW and AL revised the article language. All authors discussed the results and provided feedback on the manuscript.

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