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Optimal Configuration of Different Energy Storage Batteries for Providing Auxiliary Service and Economic Revenue

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Featured Application: Energy storage providing auxiliary service

Abstract: Energy storage providing auxiliary service at the user-side has broad prospects in support of national polices. Three auxiliary services are selected as the application scene for energy storage participating in demand management, peak shaving and demand response. Considering the time value of funds, the user-side energy storage economy model is built. The model comprehensively considers the delayed transformation income, the government subsidy income, the auxiliary service income and the whole-life-cycle cost factor. According to the cost and benefit analysis, an energy storage optimization configuration model is proposed. The model takes maximum revenue of industrial user in energy storage's whole-life-cycle as the objective function. Then, the Cplex solver is employed to solve the model. In addition, four indexes are utilized to evaluate the financial effect brought by the user-side energy storage. Finally, the revenue and configuration results of the four types of battery energy storage are calculated to verify the validity of the proposed model. In comparison to the value of evaluation index, planning suggestions are provided for the user-side energy storage providing different auxiliary services. Moreover, the conditions of profit and worthwhile investment are obtained through sensitivity analysis of energy storage providing peak shaving service.

Keywords: user-side energy storage; auxiliary service; optimal configuration; economic evaluation

1. Introduction

With fast development of the social economy and improvement of living standards of the residents, the national demand for electricity is growing increasingly. Meanwhile, the characteristics of the user's peak-to-valley difference are more obvious, which causes a large peak shaving pressure on the power system [1,2]. Although numbers of new energy sources connected to the grid have alleviated power shortage, the uncertainty and intermittentness have serious impact on the power quality of the grid [3–5]. Under this background, the issue of grid auxiliary services has been given widespread attention.

Energy storage, as an important approach to enhance the flexibility, economy and safety of traditional power systems [6–8], has gradually entered the auxiliary service market. So far, the United States, Japan, Germany and other countries have formulated a series of relevant industrial development plans and policies [9]. With rapid development of energy storage, China has also introduced a series of policies in recent years to encourage install user-side energy storage [10] and to support the user-side energy storage providing the auxiliary services [11]. Consequently, driven by these policies, China has currently focused on the development of the user-side energy storage.

Nowadays, the high investment cost of energy storage has become a key factor limiting its large-scale application [12]. The optimal capacity allocation and economic researches of the energy storage is crucial to the development of the energy storage industry. Hence, many scholars have carried out researches on this issue [13–16]. The investment optimization model is established in [13] to evaluate the value of large-scale storage energy in multiple links of generation, transmission and distribution. Nevertheless, the energy storage cost in the model does not consider the operation and maintenance cost. A comprehensive evaluation method is proposed for energy storage investment in distribution networks with high penetration of photovoltaic (PV) [14]. Aimed at peaking shaving and valley filling applications, the author of [15] carries out the economic evaluation in the wind-storage combined power generation system with a composite filter structure. However, these articles ignore the time value of funds by setting the fixed annual income, which causes the imperfections in the assessment of the overall value of energy storage. Meanwhile, the economic differences of different type of energy storage batteries are not considered.

User-side applications focus on the user's own revenue, while grid side applications pay more attention to reduce load fluctuation in order to lighten the burden of load supply pressure. The difference in the research perspective determines that the above studies cannot be directly applied to the user side. In the user-side energy storage research, the optimal design model is proposed to obtain energy storage configuration for industrial small-scale photovoltaic systems (SS-PV) [17]. Based on energy costs, emission reduction benefit and investment payback period, the three indicators comprehensively assess their economic performance and investment risks. In [18], the full life cycle cost model of the battery is established. Through analysis and calculation, the iron-lithium battery can only reduce the cost to 50%, and the energy storage on the user side can be economically feasible. It is unrealistic to limit the cost of technology and reduce costs in a short period of time, so it is necessary to find new ways of profit. With the openness of auxiliary services market in China, the participation of energy storage in auxiliary services will bring new revenue points to users, but there is still no specific commercial operation mechanism.

Based on the development trend of energy storage participating in the auxiliary service market in China, this paper proposes an energy storage allocation model and economic evaluation method for the user-side energy storage providing different auxiliary services. To meet the technical requirements of these three auxiliary services, valve regulated lead acid (VRLA), NAS, LiFePO4 (LFP) and Vanadium Redox (V-redox) are utilized as user-side energy storage battery selection. Considering the difficulty of recovering the cost and obtaining considerable profits in the short term, it is of practical significance to consider the income and cost over the full life cycle period. This paper thoroughly analyzes the situation that different types of energy storage battery provides auxiliary services to obtain revenue during full life cycle. According to the revenue, users can make investment decisions for different types of the energy storage. Through the sensitivity analysis, the economic conditions and investment conditions of the user-side energy storage providing peak shaving service are proposed.

The remainder of this paper is organized as follows. The economic model of user-side energy storage is analyzed in Section 2. Section 3 establishes the energy storage configuration model. Simulations and discussions are illustrated in Section 4. Finally, conclusions are given in Section 5.

2. User-Side Energy Storage Economy Analysis

2.1. Cost Model

Investment cost. Considering the actual application, the initial investment cost of energy storage is composed of power cost and capacity cost [19]. The specific mathematical model is described as follows:

$$C_{sys} = c_e S_N + c_p P_N \tag{1}$$

where C_{sys} is investment cost of energy storage (¥). c_e is unit capacity cost of energy storage (¥/kW). S_N is energy storage capacity (kWh). c_p is unit power cost of energy storage (¥/kW), and P_N is energy storage rated power (kW).

Operation and maintenance cost. The operation and maintenance cost of energy storage includes the energy storage system operating cost and the maintenance cost to ensure a good storage state, which is shown as follows:

$$C_{om} = c_{om} P_N \tag{2}$$

where C_{om} is annual operation and maintenance cost of energy storage (¥), and c_{om} is annual operation and maintenance cost coefficient of unit power of energy storage (¥/kW).

Total cost. According to the determined social discount rate and inflation rate, operation and maintenance cost over life cycle can be converted to present value at the initial stage of equipment purchase. Adding the investment cost of energy storage, the total cost of energy storage in the full life cycle period is described as follows:

$$C_{all} = C_{sys} + \sum_{t_s=1}^{N_s} C_{om} \left(\frac{1+ir}{1+id}\right)^{t_s} \tag{3}$$

where C_{all} is total cost of energy storage in full life cycle period (¥), N_s is lifespan of energy storage (year), t_s is used time of energy storage (year), ir and id are inflation rate and discount rate (%), respectively.

2.2. Revenue Model

Delayed transformation income. With the rapid charge and discharge characteristic, energy storage can cut down peak load of the users to delay the cost of transformer upgrade. The delayed transformation benefit is shown as follows:

$$S_1 = C_{inv}\left[1 - \left(\frac{1+ir}{1+id}\right)^{n}\right] P_N \tag{4}$$

$$n = \frac{\log_{10}(1+\lambda)}{\log_{10}(1+\tau)} \tag{5}$$

where S_1 is delayed transformation income (¥), C_{inv} is one-time investment cost coefficient required for electricity transformer upgrade (¥/kW), n is delay time of transformer upgrade after adding energy storage (year), λ is annual growth rate of load (%), τ is peak clipping rate (%), respectively.

Direct income. Driven by the time-of-use price, energy storage charges when the electricity price is low and discharges when the electricity price is high. In this way, the revenue is seen as direct income. One day's direct income and the total direct income over life cycle are described in Equations (6) and (7), respectively.

$$B_2 = \sum_{t=1}^{T} m_t(t)[P_{dis}(t)U_{dis}(t) - P_{ch}(t)U_{ch}(t)]\Delta t \tag{6}$$

$$S_2 = \sum_{t_s=1}^{N_s} B_2 D \left(\frac{1+ir}{1+id}\right)^{t_s} \tag{7}$$

where B_2 is direct income of energy storage on a day, $m_t(t)$ is time-of-use electricity price (¥/kWh). $P_{dis}(t)$ and $P_{\mathrm{ch}}(t)$ are the charging power and discharging power at tth period (kW), respectively. $U_{dis}(t)$ and $U_{ch}(t)$ are the charging and discharging state of energy storage at tth period, respectively. T is total number of intervals in a day and its value is 96. Δt is the time interval and its value is 15 (min). S_2 is total direct income in the full life cycle of energy storage (¥). D is annual running days of energy storage (day).

Government subsidies To promote the development of energy storage, the government will subsidize the energy storage. The government subsidies in a day is described in Equation (8). Considering the discount rate and inflation rate, the total income of government subsidies over life cycle of energy storage is shown in Equation (9).

$$B_3 = \sum_{\mathrm{t}=1}^{T} m_e P_{ch}(t) U_{ch}(t) \Delta t \tag{8}$$

$$S_3 = \sum_{t_s=1}^{N_s} B_3 D (\frac{1+ir}{1+id})^{t_s} \tag{9}$$

where B_3 is government subsidies of energy storage on a day (¥), m_e is government subsidized electricity price (¥/kWh), and S_3 is total income of government subsidies in full life cycle of energy storage (¥).

Auxiliary service income. Currently, the user-side energy storage providing auxiliary services can be mainly divided into three categories: peak shaving, demand response, and demand management. In the actual situation, users may select one or more services to participate in. As shown in Equation (10), peak shaving revenue is the income for the peak power reduction. The demand response revenue is the subsidy for users to reduce the peak power consumption in response to the grid command, which is shown in Equation (11). Demand management revenue is the monthly electrical capacity charge saved from replacing transformer capacity charge with demand charge after the installation of energy storage, which is shown in Equation (12). Demand charge is calculated based on the monthly maximum power, while the specific charging method is outlined in [20]. Total income of auxiliary service in the full life cycle of energy storage, which is shown in Equation (13):

$$B_{ls} = \sum_{t=1}^{T} m_{ls} P_{dis}(t) U_{dis}(t) \Delta t \tag{10}$$

$$B_x = \frac{1}{30}(S_T c_{dj} - \begin{cases} 40a & b \leq 1.05a \\ 40a + 80(b - 1.05a) & b > 1.05a \end{cases}) \tag{11}$$

$$B_p = \sum_{t=1}^{T} m_{dr} P_{dr}(t) \Delta t \tag{12}$$

$$S_4 = \sum_{t_s=1}^{N_s} B_{ls} D (\frac{1+ir}{1+id})^{t_s} \delta + \sum_{t_s=1}^{N_s} B_x D (\frac{1+ir}{1+id})^{t_s} \mu + \sum_{t_s=1}^{N_s} B_p D (\frac{1+ir}{1+id})^{t_s} \varphi \tag{13}$$

where S_4 is the total income of auxiliary service over full life cycle of energy storage (¥), B_{ls} is peak shaving income after the installation of energy storage on a day (¥), B_p is demand response income after the installation of energy storage on a day (¥), B_x is saved electrical capacity charge after adding energy storage on a month (¥). δ, μ and φ are binary variable associated to the user's energy storage participation in the peak shaving service, demand management service and demand response service, respectively. m_{ls} is unit peak shaving income coefficient (¥/kWh). a is expected monthly maximum demand power that user reports to the state grid company (kW). b is user's actual measured monthly maximum power (kW). According to the charging standard of state grid company, demand charge equals to the reported monthly maximum power (a) multiplying by the unit power price, when the user's actual measured monthly maximum power (b) does not exceed 105% of the reported monthly maximum power (a). Taking a certain area of China, for example, the value of unit power price is 40. In addition, when b exceeds 1.05a, the excess will be penalized in a doubled manner. S_T is transformer capacity and its value is 7050 (kVA), c_{dj} is price coefficient charged by unit transformer capacity and its value is 30 (¥/kVA). m_{dr} is unit demand response compensation coefficient (¥/kWh). $P_{\mathrm{dr}}(t)$ is responsive power at tth period (kW).

3. Energy Storage Configuration Model

3.1. Objective

Due to the fact that economics is the premise for users to install energy storage, economical optimality is adopted as the capacity allocation criterion. According to the above economic analysis of the user-side energy storage, the whole revenue contains delayed transformation income, direct income, government subsidies and auxiliary service income. Combining cost analysis of energy storage systems, this paper takes the maximum net income in the full life cycle of energy storage as the objective function, which is described as follows:

$$\max F = S_1 + S_2 + S_3 + S_4 - C_{all} \tag{14}$$

where F is net income in the full life cycle of energy storage (¥).

3.2. Constraints

Power balance constraint.

$$P_{grid}(\mathrm{t}) = P_{load}(t) + P_{ch}(t)U_{ch}(t) - P_{dis}(t)U_{dis}(t) \tag{15}$$

where $P_{grid}(t)$ is power purchase from the grid at tth period (kW), $P_{load}(t)$ is load power at tth period (kW).

Energy storage constraint. The operational constraints of the battery energy storage mainly include the upper and lower bounds of SOC, charge and discharge power limit constraints, charge and discharge state constraints and energy storage SOC coupling constraints, as well as SOC state regression constraint [21].

$$\begin{cases} SOC_{\min} \le SOC(t) \le SOC_{\max} \\ U_{dis}(t) + U_{ch}(t) \le 1 \\ 0 \le P_{dis}(t) \le U_{dis}(t)P_{dis\max} \\ 0 \le P_{ch}(t) \le U_{ch}(t)P_{ch\max} \\ SOC(t+1) = SOC(t) + \frac{P_{ch}(t)\eta_{ch}}{S_N}\Delta t - \frac{P_{dis}(t)}{\eta_{dis}S_N}\Delta t \\ SOC(96) = SOC(1) \end{cases} \tag{16}$$

where $SOC(t)$ is state of charge of energy storage in tth period, SOC_{min} is lower limit of SOC and SOC_{max} is Upper limit of SOC. $P_{dis\max}$ is maximum discharge power of energy storage and $P_{ch\max}$ is maximum discharge power of energy storage. η_{ch} is charging efficiency of energy storage and η_{dis} is discharging efficiency of energy storage. SOC (96) is SOC at 96th period and SOC (1) is SOC at 1st period.

It can be seen that the proposed metathetic model form a linear optimization problem with constrains. To solve this kind of problem, there are various effective algorithm, such as the branch and bound algorithm, or the cut plane method. At the same time, there are some ready-made software or code packages, such as Cplex, Lpsolve, Yalmip and so on. Cplex possesses the advantages of high efficiency and stability in solving mathematical programming problems, but its modeling statements are complex. On the contrary, Yalmip's modeling statements are simple and can support multiple solvers. Consequently, Yalmip (R20160923, Yale University, New Haven, CT, USA and 2016) is utilized to build the mathematical model shown in equation, then the Cplex solver (Cplex12.5, IBM, Armonk, NY, USA and 2015) is applied to obtain the optimization in the MATLAB (MATLABR2014b, The MathWorks company, Natick, MA, USA and 2014) environment [22,23].

3.3. Evaluation Index

Since the user's decision of energy storage construction actually belongs to an investment problem, evaluation indicators in financial management are employed in this paper. Four indexes are utilized to evaluate the economics of the user-side energy, including net present value (NPV), energy storage recovery period, internal return rate (IRR) and profit index.

Net present value (NPV). NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project [24], which is shown as follows.

$$NPV = B_{allt} - C_{allt} \tag{17}$$

where B_{allt} is present value of the total revenue of energy storage in the whole life-cycle period (¥). C_{allt} is present value of the total cost of energy storage in the whole life-cycle period (¥).

Energy storage recovery period. The period of energy storage recovery is the time when the total revenue of the user is equal to the cost of energy storage investment, which is described as follows:

$$N_T = C_{all} / A_{ben\_all} \tag{18}$$

where N_T is recovery period for the investment in energy storage(year). A_{ben_all} is annual revenue brought by energy storage (¥).

Internal return rate (IRR). IRR refers to the discount rate when the current value of the net cash flow of the investment project is equal to zero for each year. In a word, the IRR is equal to the discount rate when the net present value is zero. It reflects the affordability of the currency depreciation that the project investment income can withstand, and also means the ability to resist risks during the operation of the project. It is the main dynamic indicator for examining the profitability of the project, which is expressed as follows:

$$\sum_{t_s=0}^{N} (B_{t_s} - C_{t_s})(1 + IRR)^{-t_s} = 0 \tag{19}$$

where B_{t_s} is the present value of the total revenue of the project at year t_s(¥), C_t is Present value of the total cost of the project at year t_s(¥).

Profitability Index (PI). The profit index means the ratio of the present value of the future cash flow after the user invests in energy storage to the present value of the original investment amount. This indicator is used to evaluate the profitability of users' investment and energy storage participation in different auxiliary service projects.

$$PI = \frac{\sum\limits_{t_s=0}^{N} \frac{A_{ben\_all}}{(1+id)^{t_s}} - \sum\limits_{t_s=0}^{N} \frac{C_{om}}{(1+id)^{t_s}}}{C_{sys}} - 1 \tag{20}$$

4. Simulation and Discussion

This section presents the economic evaluation of energy storage batteries providing auxiliary service and compares the results with the optimal configuration obtained by the proposed method. Additionally, the profit condition and investment condition are proposed through sensitivity analysis.

The 15-min load data in a typical day used here are from an industrial large user in a certain area of Jiangsu Province. At present, typical battery types on the user side include VRLA, NAS battery, LFP and V-redox. The specific parameters of these batteries are from [18], which are shown in Table 1. The initial value of each energy storage battery's SOC state is 0.5 at the beginning of optimization, and the range of SOC of energy storage is between 0.2 and 1. The battery discharging and charging rate is 0.5C. In addition, the time of use electricity price policy is applied as shown in Table 2. Referring to [25,26], the related economic parameters are shown in Table 3.

Table 1. Parameter of batter energy storage. VRLA: Valve regulated lead acid, LFP: LiFePO4, V-redox: Vanadium Redox.

Type of Battery	c_e (¥/kWh)	c_p (¥/kW)	Efficiency	Lifespan (Year)
VRLA	1240	31	0.75	5
NAS	2790	124	0.7	15
LFP	3224	155	0.85	10
V-redox	3720	124	0.7	10

Table 2. Time of use electricity prices.

Load Period	Hour (h)	Electricity Price (¥/kWh)
Peak period	8:00–12:00, 17:00–21:00	1.0902
Valley period	0:00–8:00	0.318
Flat period	12:00–17:00, 21:00–24:00	0.6451

Table 3. Economic rated parameters.

Parameters	Values
ir (%)	1.5
id (%)	9
C_{inv} (¥/kW)	100,000
m_e (¥/kWh)	0.03
m_{ls} (¥/kWh)	0.05
m_{dr} (¥/kWh)	5

Three auxiliary service scenarios are considered in the simulation including demand management, peak shaving and demand response. The results of optimal configuration and economic evaluation for three scenarios are discussed as follows.

4.1. Simulation Results of Energy Storage Participating in Demand Management

Optimization results. The results of energy storage batteries' configuration and economic evaluation indexes are shown in Table 4. Figure 1 illustrates each cost and income term for demand management with four different energy storage batteries. According to the results, user can make a fortune with four energy storage batteries for providing demand management service. By analyzing the income items from Figure 1 it can be seen that more than 80% of the revenue comes from the auxiliary service revenue. Comparing the values of NPV, PI and IRR, VRLA is recommended to user for the highest return.

Table 4. Energy storage configuration and economic evaluation results of demand management. NPV: net present value; IRR: internal return rate; PI: profit index

Battery	Energy Storage Rated Power (kW)	Energy Storage Capacity (kWh)	Energy Storage Cost in Full Life Cycle (¥)	Estimated Income in Full Life Cycle (¥)	Recovery Period (Year)	NPV (¥)	IRR (%)	PI (%)
VRLA	672.29	1344.58	1,758,100	7,704,400	1.14	5,946,300	42.82	338.16
NAS	304.9	609.82	2,062,300	14,034,000	2.2	11,971,700	39.18	320.18
LFP	279	588	2,119,400	11,514,000	1.84	9,394,600	39.15	313.26
V-redox	304.9	609.82	2,548,700	10,978,000	2.32	8,429,300	14	230.72

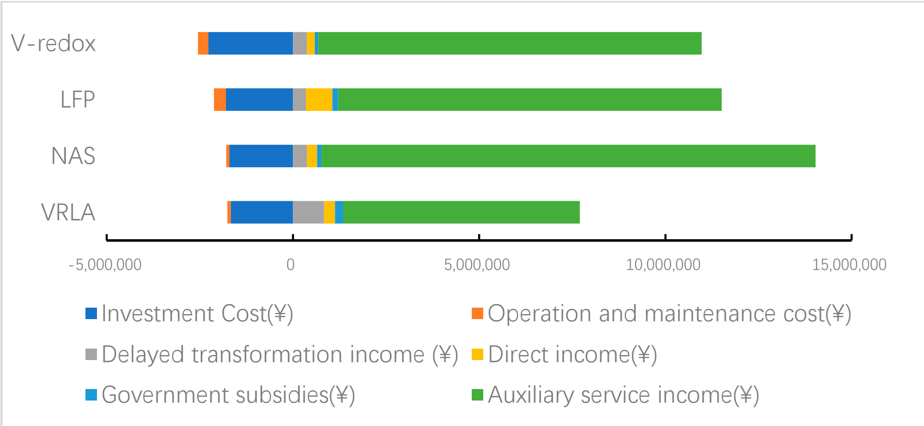

Figure 1. Each cost and income term of demand management with four different energy storage batteries. VRLA: valve regulated lead acid, NAS, LFP: LiFePO4, V-redox: Vanadium Redox.

Energy Storage Charging and Discharging Results. Under the best battery selection, the user load power is shown in Figure 2. The charge and discharge power of VRLA is shown in Figure 3. The battery discharges in the peak period to cut down the maximum demand power for more revenue. Meanwhile, attracted by the electricity price difference, the battery charges in the valley period and flat period.

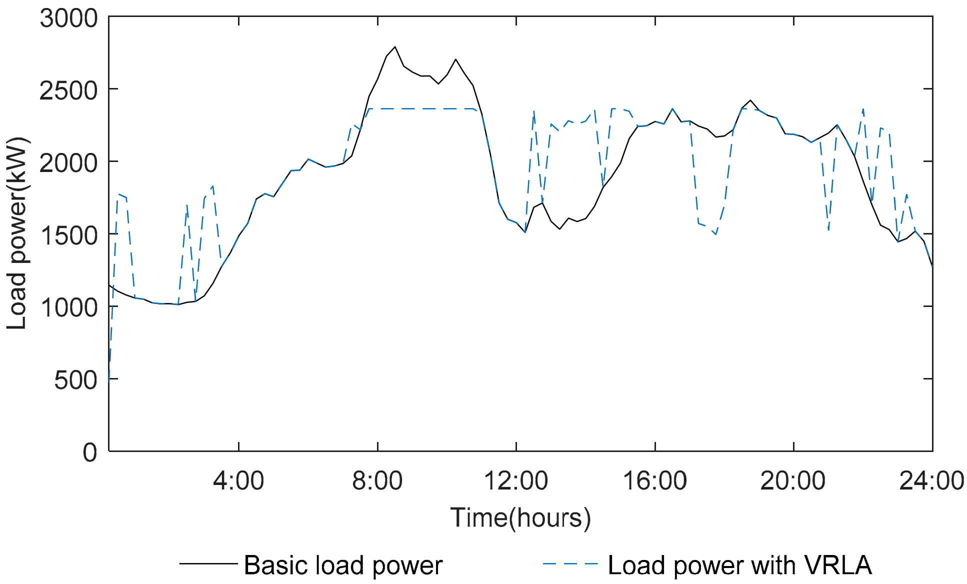

Figure 2. User load power with VRLA (Demand management).

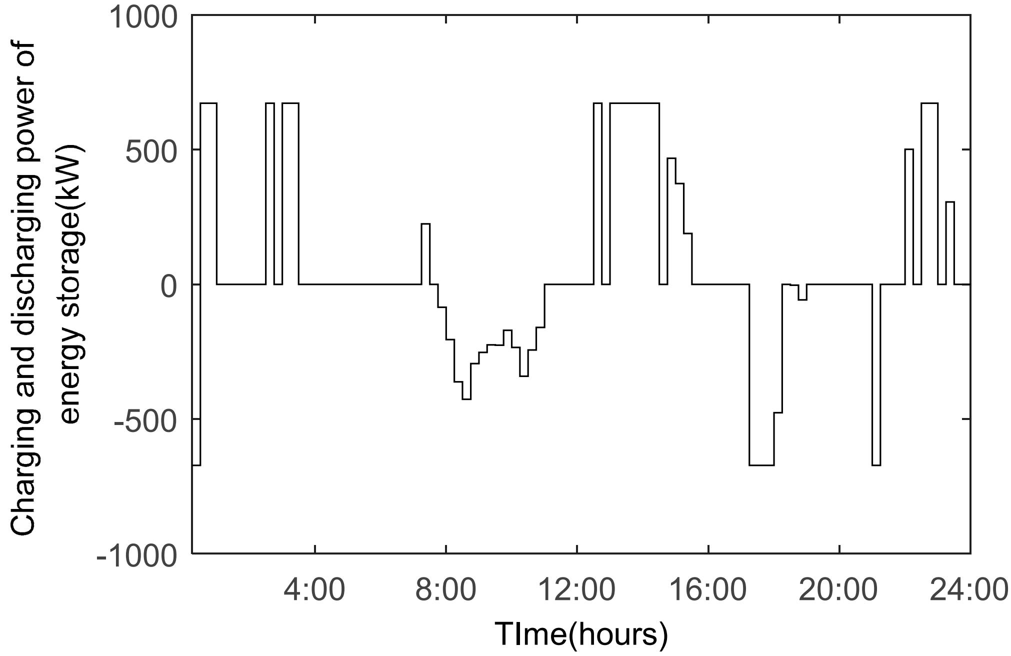

Figure 3. Charging and discharging power of VRLA.

Simulation result verification. To verify the optimization configuration results of VRLA, the NPV of this service in whole-life-cycle period with the change of energy storage power is illustrated in Figure 4. Net income of users increases in the beginning and then decreases with the increase of energy storage. This trend results from the fact that the growth rate of revenue is not enough to offset the growth rate of energy storage cost after the energy storage increases to a certain capacity. Under this trend, optimal capacity is exited. From Figure 4, it is seen that the user's revenue reaches the highest when the energy storage power is 672.29 kW, which also verifies the simulation result.

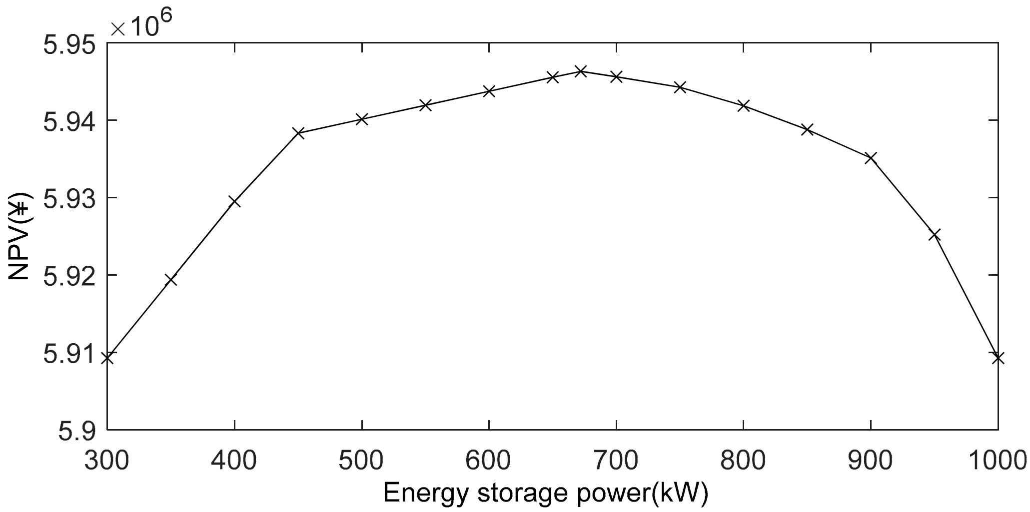

Figure 4. VRLA energy storage power economic evaluation results.

Actual energy storage configuration. In actual energy storage construction, the optimization results should be approximated calculated based on the actual battery capacity. According to the simulation results, the optimal capacity of VRLA battery is 1344.58 (kWh). The basic cell parameters are 2 V/1000 Ah, so the single battery capacity is 2 (kWh). Then, the number of cells required for the battery is 672.29 (1344.58 kWh/2 kWh). To meet the range of the inverter port voltage in the energy storage device (planning with 400 V as an example), 200 single cells need to be connected in series.

Then, it is necessary to connect 3.36(672.29/200) groups. Therefore, in practical applications, there are 4 battery groups and each of the 200 cells is connected in series to form one battery group. The total number of cells required for the battery is 800.

4.2. Simulation Results of Energy Storage Participating in Peak Shaving

Peak shaving. Table 5 shows the results of energy storage configuration and economic evaluation under participation in the load peak shaving. In addition, each cost and income term for the service with four different energy storage batteries is illustrated in Figure 5. Energy storage participation in the load peak shaving is a loss. Through the analysis of the income items, the auxiliary service revenue accounts for a large proportion, while the subsidy price of the current peak-filling valley is low, resulting in a loss of energy storage investment. As a result, it is not recommended that the user only select the load peak shaving service as the energy storage income item.

Table 5. Energy storage configuration and economic evaluation results of load peak shaving.

Battery	Energy Storage Rated Power (kW)	Energy Storage Capacity (kWh)	Energy Storage Cost in Full Life Cycle (¥)	Estimated Income in Full Life Cycle (¥)	Recovery Period (Year)	NPV (¥)	IRR (%)	PI (%)
VRLA	284.58	569.17	744,200	593,000	−0.97	−151,200	−8	−21.47
NAS	304.9	609.82	2,062,300	765,000	−19.54	−1,297,300	−14	−76.25
LFP	279	206.23	2,119,400	1,215,100	−4.69	−904,300	−12	−50.26
V-redox	304.9	609.82	2,548,700	678,800	−23.78	−1,869,900	−23	−82.42

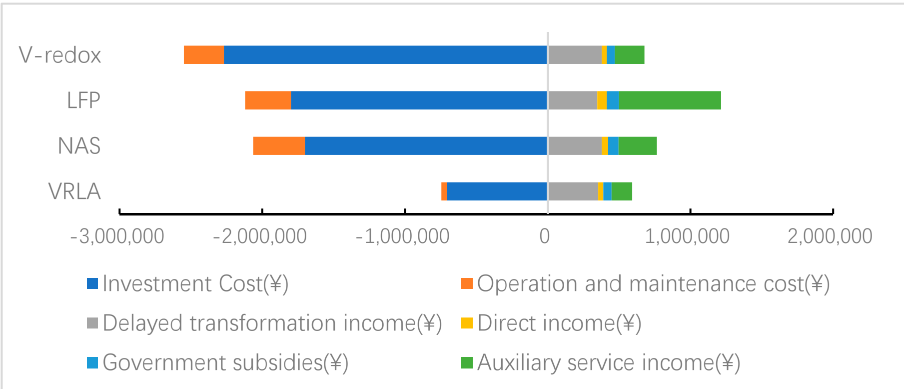

Figure 5. Each cost and income term of four different energy storage batteries for peak shaving.

Energy Storage Charging and Discharging Results. Under the best battery selection, the user load power is shown in Figure 6. The charge and discharge power of VRLA is shown in Figure 7. Energy storage can effectively cut down the peak power to obtain the peak shaving revenue, however, the revenue cannot cover the whole investment.

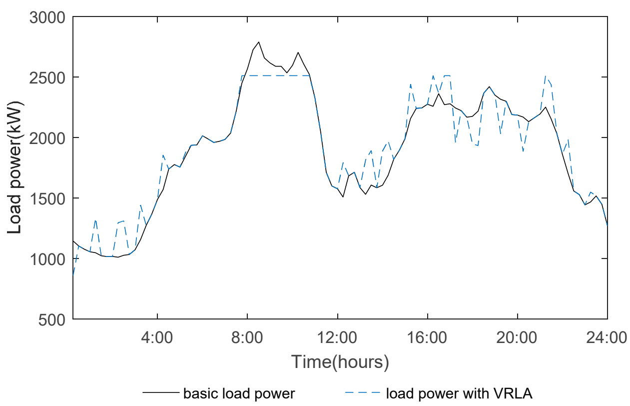

Figure 6. User load power with VRLA (Peak shaving).

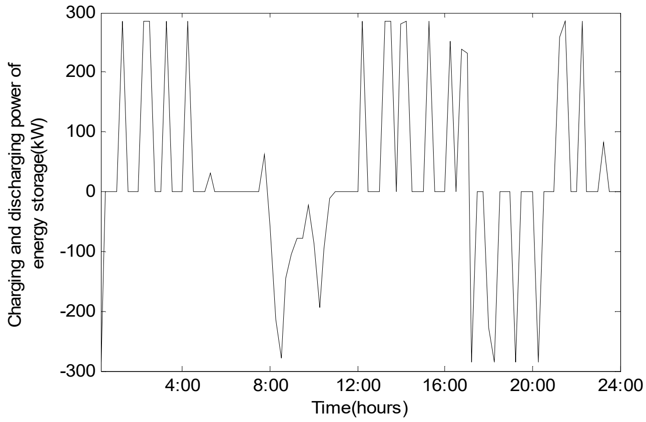

Figure 7. Charging and discharging power of VRLA.

4.3. Simulation Results of Energy Storage Participating in Demand Response

Demand response. The results of the energy storage configuration and economic indexes are shown in Table 6 with different types of batteries. In addition, each cost and income term for the service with four different energy storage batteries are illustrated in Figure 8. From the results of Table 6, it can be seen that the user-side energy storage providing the demand response auxiliary service is economically profitable. Comparing the index of NPV, IRR and PI, the user can make a fortune by choosing the VRLA battery at the current stage. In the case of a certain revenue, the lower is the energy storage cost, the higher the profit index will be. Meanwhile, VRLA batteries have the lowest energy storage costs.

Table 6. Energy storage configuration and economic evaluation results of demand response.

Battery	Energy Storage Rated Power (kW)	Energy Storage Capacity (kWh)	Energy Storage Cost in Full Life Cycle (¥)	Income in Full Life Cycle (¥)	Recovery Period (Year)	NPV (¥)	IRR (%)	PI (%)
VRLA	284.58	569.17	744,200	1,920,200	1.96	1,176,000	48	163.07
NAS	304.9	609.82	2,062,300	3,736,500	8.6	1,674,200	9	89.47
LFP	279	206.23	2,119,400	3,144,800	7	1,025,400	10	52.06
V-redox	304.9	609.82	2,548,700	2,999,300	8.7	450,600	4	15.88

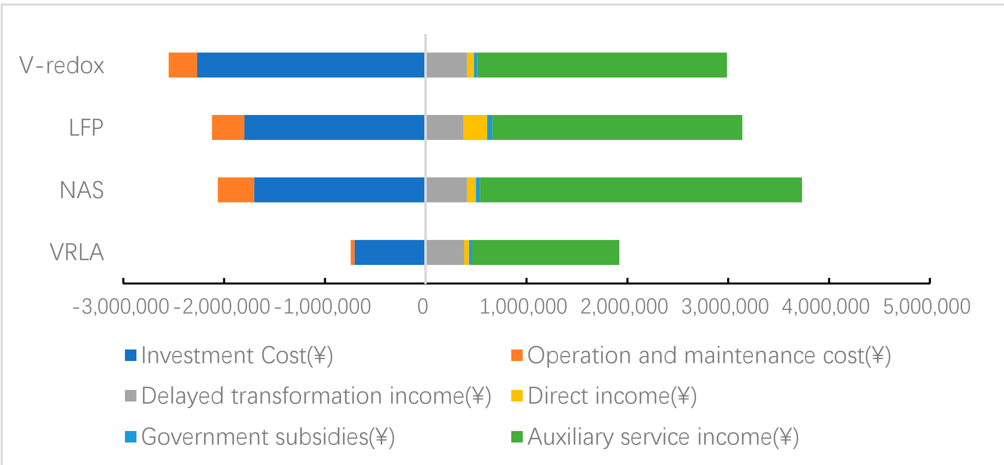

Figure 8. Each cost and income term of four different energy storage batteries for demand response.

Energy Storage Charging and Discharging Results. The load power with the best battery selection is shown in Figure 9. The charge and discharge power of VRLA is shown in Figure 10. The battery discharges in the peak period to response the grid command. Due to the low electricity price, the battery charges in the valley period and flat period.

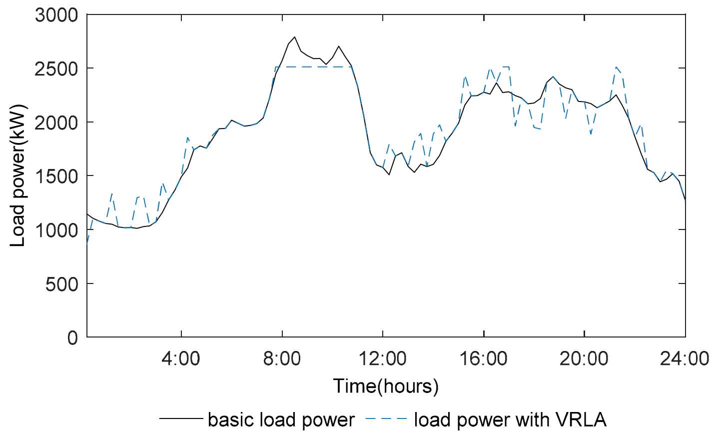

Figure 9. User load power with VRLA (Demand response).

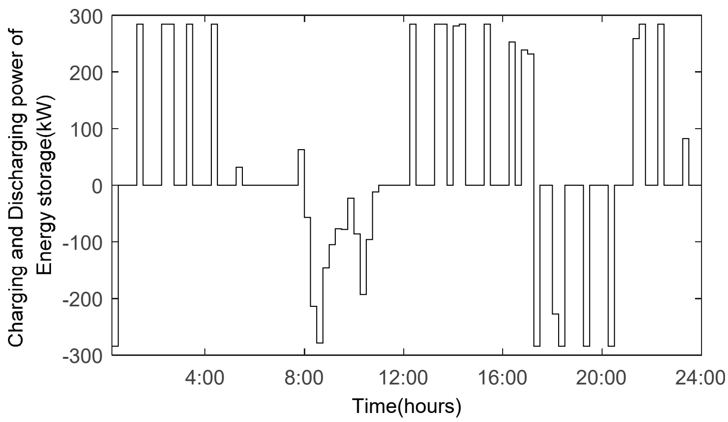

Figure 10. Charging and discharging power of VRLA.

4.4. The Impact of the Time Value of Funds on the Optimization Results

To research the impact of the time value of funds on the allocation of energy storage capacity, this paper takes the user-side energy storage participation in demand management services as an example with VRLA. Through the evaluation index of IRR and PI, the energy storage configuration results with taking the factor into account or not are compared, which is shown in Figure 11.

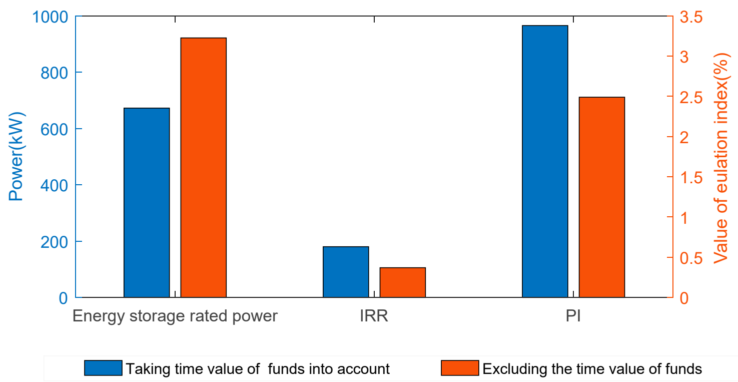

Figure 11. Comparison in configuration results and economic indexes. IRR: internal return rate; PI: profit index.

In the comparison between the two cases, the case that ignores the time value of the fund configurates bigger energy storage capacity but has lower value of IRR and PI. Specifically, the value of IRR falls by 26%, and the value of PI falls by 89%. Annual revenue is calculated invariant under the case excluding the time value of funds. In fact, the actual revenue is lower than expected values in the existence of depreciation of the currency. In this way, the storage configuration results will be too optimistic to achieve the initial estimation. It is, therefore, necessary to consider the time value of funds in the research of optimal energy storage configuration.

4.5. Sensitivity Analysis

Since the user-side energy storage providing load shaving service cannot reach revenue, it is critical to research its profit condition. Two influence factors, capacity cost of investment (c_e) and peak-valley electricity price difference (d), are sensitively analyzed using NPV index, respectively. What's more, only the NPV of the service can reach a certain, it is worthwhile for user to invest. Thus, the worthwhile investment condition is analyzed by the same factors using IRR for clearly comparison results. Since LFP is widely applied in user-side, LFP is taken as battery type. Two conditions are discussed as follows:

Profit condition. Under different energy storage investment costs and peak-valley electricity price, NPV of this project are displayed in Figures 12 and 13, respectively. As illustrated in Figure 12, the investment starts to make fortune when the unit capacity cost of the energy storage battery drops to 1500 (¥/kWh), which is 47% of the current cost. In addition, from Figure 13, it starts to make fortune when peak-to-valley electricity price difference is above 1.08 (¥). In other words, peak-to-valley electricity price difference should further extend to the 140% of the current price.

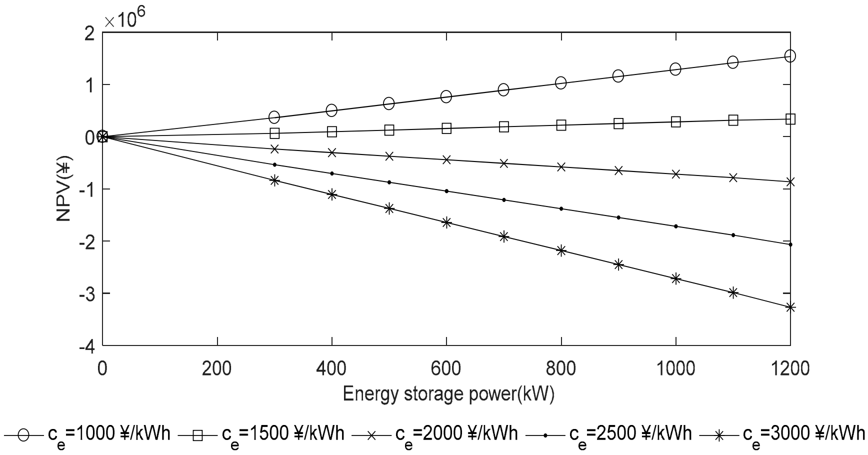

Figure 12. Economics of users participating in load peak shaving service under different energy storage costs.

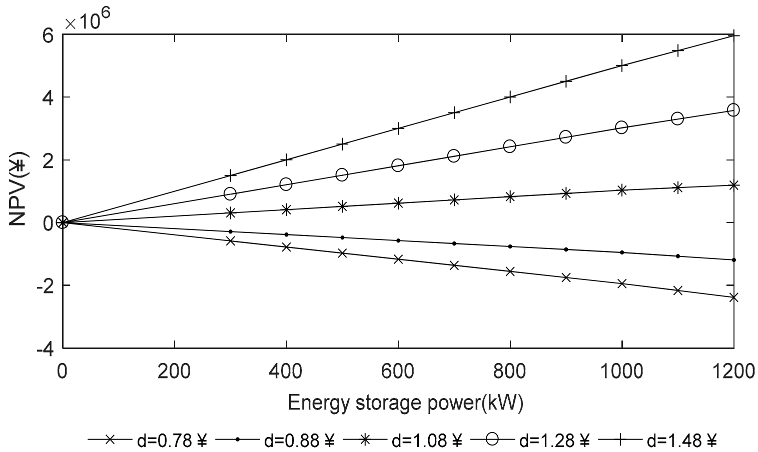

Figure 13. Economics of users participating in load peak shaving services under different peak-to-valley electricity price.

Investment condition. This paper refers to the project investment boundary standard widely recognized by the photovoltaic industry, that is, when the IRR of the full investment is greater than 9%, then the project is considered a worthwhile investment. Under different energy storage investment costs and peak-valley electricity prices, IRR of this project are displayed in Figures 14 and 15, respectively.

As shown in Figure 14, the LFP battery cost needs to be reduced to 1100 (¥/kWh) when the investment project reaches the boundary standard under the same conditions, which is 35% of the current cost. From the analysis of Figure 15, under the current energy storage cost, the yield of the investment project will reach 9%, and the peak- valley electricity price difference will reach 1.68 (¥). In other words, the peak-valley electricity price difference should further extend to the 140% of the current price difference.

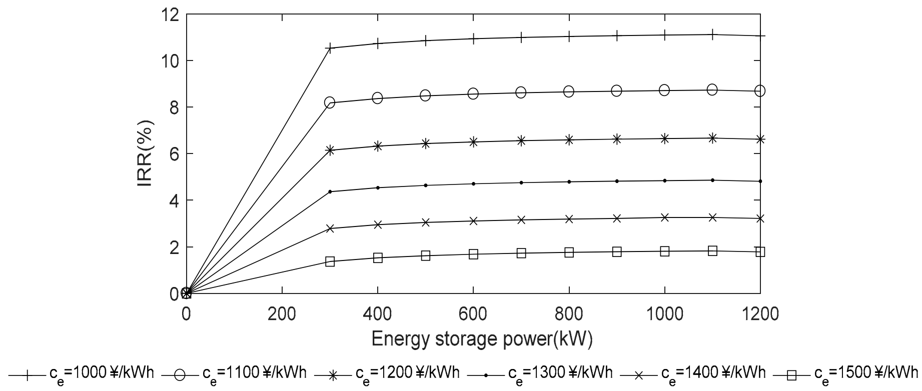

Figure 14. IRR index of users participating in load shaving service under different energy storage costs.

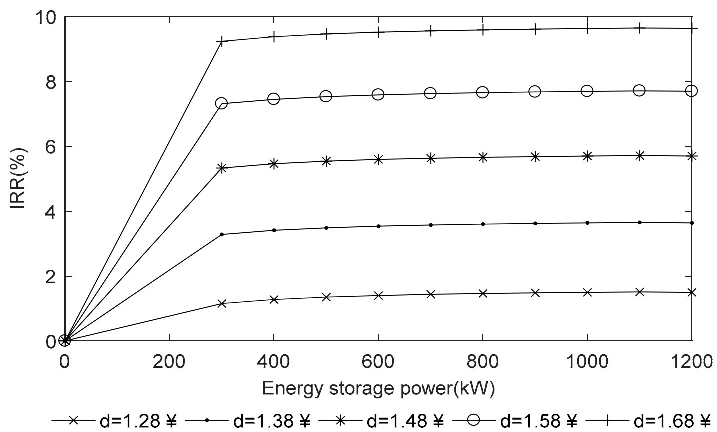

Figure 15. IRR of users participating in load peak shaving service under different peak-to-valley electricity price.

5. Conclusions

The user-side energy storage providing auxiliary services has drawn widely attention. On the basis of the full life cycle economic analysis, optimization configuration model for the energy storage providing different auxiliary services is proposed in this paper. Taking the maximum total net revenue over the full life cycle as the objective, the model comprehensively considers the delayed transformation income, the government subsidy income, the auxiliary service income and the life cycle cost factor. The established model is solved by the Cplex solver in this paper. To assess the profit of the configuration results and necessity of the energy storage installation, four indexes are adopted including NPV, energy storage recovery period, IRR and profit index. Finally, four kinds of batteries, VRLA, NAS, LFP and V-redox, are simulated to verify the effectiveness of the proposed model.

According to comparison of evaluation indexes of different types of battery, it is most economical for users to adopt VRLA battery storage to participate in demand management services. In addition, through sensitivity analysis, the economic conditions of the user-side energy storage to participate in the commercial applications of load peak shaving services are proposed. What is more, in the reference of PV industry investment boundary, the worthwhile investment situation of energy storage is discussed.

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Nomenclature

Variable Name	Nomenclature	Unit
C_{sys}	Investment cost of energy storage	¥
c_e	Unit capacity cost of energy storage	¥/kWh
S_N	Energy storage capacity	kWh
c_p	Unit power cost of energy storage	¥/kW
P_N	Energy storage rated power	kW
C_{om}	Annual operation and maintenance cost of energy storage	¥
c_{om}	Annual operation and maintenance cost coefficient of energy storage	¥/kW
C_{all}	Total life cycle cost of energy storage	¥
t_s	Used time of energy storage	year
N_s	Lifespan of energy storage	year
ir	Inflation rate	%
id	Discount rate	%
S_1	Delayed transformation income	¥
C_{inv}	One-time investment cost coefficient required for electricity transformer upgrade	¥/kW
n	Delay time of transformer upgrade after adding energy storage	year
λ	Annual growth rate of load	%
τ	Peak clipping rate	%
B_2	Direct income over life cycle of energy storage on a day	¥
S_2	Total Direct income over life cycle of energy storage	¥
$P_{ch}(t)$	Charging power of energy storage in the tth period	kW
$P_{dis}(t)$	Discharge power of energy storage in the tth period	kW
$U_{ch}(t)$	Binary variable associated to charging state of energy storage at tth period	/
$U_{dis}(t)$	Binary variable associated to discharging state of energy storage at tth period	/
$m_t(t)$	Time-of-use price	¥/kWh
T	Total number of interval in a day	/
Δt	Time interval, 15 min	min
D	Annual running time of energy storage	day
B_3	Government subsidies on a day (¥)	¥
S_3	Total income of government subsidies over life cycle of energy storage	¥
m_e	Government subsidized electricity price	¥/kWh
S_4	Total income of auxiliary service over life cycle of energy storage	¥
B_{ls}	Peak subsidy after the installation of energy storage on a day	¥
B_p	Demand response income after the installation of energy storage on a day	¥
B_x	Saved electrical capacity charged after adding energy storage on a month	¥
δ	Binary variable associated to the user's energy storage participation in the peak shaving service	/

Variable Name	Nomenclature	Unit
μ	Binary variable associated to the user's energy storage participation in the demand response service.	/
φ	Binary variable associated to the user's energy storage participation in the demand management service	/
m_{ls}	Unit peak shaving income coefficient	¥/kWh
P_{ls}(t)	Reduced load power at tth period	kW
a	Expected monthly maximum power that user reports to the state grid company	kW
b	User's actual measured monthly maximum power	kW
S_T	Transformer capacity	kVA
c_{dj}	Price coefficient charged by unit transformer capacity	¥/kVA
m_{ls}	Unit peak shaving income coefficient	¥/kWh
m_{dr}	Unit demand response compensation	¥/kWh
$P_{\mathrm{dr}}(t)$	Responsive power at tth period	kW
F	Net income of energy storage over the entire life cycle	¥
$P_{grid}(t)$	Power purchase from the grid at tth period	kW
$P_{load}(t)$	Load power at tth period	kW
$SOC(t)$	State of charge of energy storage at tth period	/
SOC_{min}	Lower limit of the state of charge storage	/
SOC_{max}	Upper limit of the state of charge storage	/
$P_{dis\mathrm{max}}$	Maximum discharge power of energy storage	kW
$P_{ch\mathrm{max}}$	Maximum charge power of energy storage	kW
η_{ch}	Charging efficiency of energy storage	/
η_{dis}	Discharge efficiency of energy storage	/
$SOC(96)$	SOC at 96th period	/
$SOC(1)$	SOC at 1st period	/
B_{allt}	Present value of the total revenue of the user's life cycle	¥
C_{allt}	Present value of the total cost of the user's life cycle	¥
N_T	Recycling period for the user to invest in energy storage	year
A_{ben_all}	Annual revenue of the user	¥
B_{t_s}	Present value of the total revenue of the project at year t_s	¥
C_{t_s}	Present value of the total cost of the project at year t_s	¥
PI	Profit index of investment energy storage projects	%

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