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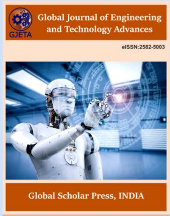

(Review Article)

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Capacity allocation method for PV-storage-charging stations considering energy storage lifespan and operational benefits

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Abstract

Integrated photovoltaic storage and charging power stations use photovoltaic power generation and energy storage systems to achieve energy self-sufficiency, reducing the impact on the grid during peak charging hours. In response to the current problem of insufficient facility scale or redundancy in the configuration of photovoltaic storage charging stations, this paper proposes a method for configuring the photovoltaic storage capacity of integrated charging stations considering the lifespan of energy storage and operational efficiency. First, the cost of charging stations is systematically analyzed, and an energy storage life assessment model based on battery characteristics is constructed; Secondly, with maximizing the annual comprehensive revenue of the charging station as the upper-level optimization objective and reducing the load fluctuation of the charging station and increasing the operating revenue of the charging station as the lower-level optimization objective, a two-tier optimization model for the coordinated allocation of photovoltaic energy storage was constructed; Finally, the results of the case study show that the proposed photovoltaic storage capacity allocation method for charging stations can reduce the load peak-valley difference and increase the profit of photovoltaic storage charging stations.

Keywords: PV-storage-charging station; Capacity allocation optimization; Two-layer optimization model; Energy storage lifespan assessment

1. Introduction

In recent years, with the continuous innovation of photovoltaic energy storage technology, its performance indicators have improved significantly, the cost structure has been optimized, and the contradiction between supply and demand in the power system has become increasingly prominent, photovoltaic energy storage integration technology is gradually completing the transition from demonstration pilot to large-scale commercial application. In the operation of the power system, the synergy between photovoltaic power generation and energy storage devices plays an irreplaceable role in enhancing the capacity to accommodate new energy, stabilizing peak and off-peak loads in the power grid, stabilizing power fluctuations, and improving the reliability of power supply.

As a fundamental part of system design, the scientific rationality of photovoltaic capacity allocation directly affects the power generation efficiency of the entire system. Research shows that an optimized photovoltaic configuration can increase system efficiency by 15% to 20%[1]. However, due to the intermittent nature of photovoltaic power generation and the initial investment cost and full life cycle operating expenses of energy storage equipment, the economic benefits of current photovoltaic energy storage projects still face significant challenges. Especially in scenarios where a high proportion of renewable energy is connected to the grid, simply increasing photovoltaic capacity may lead to serious curtailment of light, while over-provisioning of energy storage will significantly increase system costs. Therefore, how to improve the overall economic efficiency of the system through the coordinated and optimized allocation of

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photovoltaic and energy storage has become a key issue for integrated photovoltaic and energy storage power stations[2].

In terms of photovoltaic configuration research, reference [3] proposed an optimal configuration method based on net present value, which established a full life cycle cost model of photovoltaic systems, taking into account factors such as initial investment, operation and maintenance costs, and power generation revenue. This method has become a classic framework for photovoltaic capacity allocation. Reference [4] further considers the attenuation characteristics of photovoltaic modules and establishes a dynamic optimization model that takes efficiency attenuation into account, making the configuration results more in line with actual operating conditions. In recent years, machine learning methods have been widely applied in photovoltaic capacity configuration. Reference [5] uses long short-term memory networks to predict photovoltaic output and combines genetic algorithms to optimize capacity allocation, achieving good results in terms of prediction accuracy and economic benefits. Reference [6] presents a photovoltaic capacity allocation method based on multi-objective optimization, taking into account economic, environmental and reliability indicators, providing a new idea for photovoltaic power station planning.

In terms of energy storage configuration research, reference [7] points out that electric vehicle charging load may cause instability in the power grid. For this reason, the new configuration model of "charging station + energy storage + renewable energy" proposed in reference [8] shows good application prospects. Current research on the energy storage configuration of charging stations mainly focuses on optimizing the charging load of electric vehicles and reducing operating costs. Reference [9] conducted a simulation analysis by establishing an energy storage investment and operating cost model, and the results showed that the rational configuration of energy storage equipment in bus fast charging stations could effectively reduce the total cost. Reference [10] established a charging strategy optimization model to systematically explore the impact mechanism of energy storage configuration on the economy of bus fast charging stations, confirming that the energy storage system can significantly improve the economic benefits of the stations. In the study of energy storage capacity configuration, reference [11] precisely calculated the depth of battery charge and discharge based on the rain-flow counting method, comprehensively considered the life loss of the energy storage battery, and used the particle swarm optimization algorithm to solve the optimal energy storage capacity.

In terms of combined photovoltaic-storage configuration, reference [12] presents a model of combined photovoltaic-story-hydrogen configuration, which converts excess photovoltaic power into hydrogen energy for storage through electrolysis of water hydrogen technology. This not only solves the intermittent problem of photovoltaic power generation but also provides a new idea for the large-scale utilization of renewable energy. In terms of configuration methodology, reference [13] presents a game theory-based photovoltaic storage configuration method, which innovatively constructs a game of interests model involving multiple parties such as investors, grid companies and users, and obtains an acceptable optimal configuration scheme for all parties through Nash equilibrium solution, making the configuration scheme more feasible.

2. Optimization framework and cost analysis for capacity allocation of photovoltaic storage charging stations

2.1. Capacity configuration framework for photovoltaic storage charging stations

In the photovoltaic energy storage charging system constructed in this study, the photovoltaic power generation section operates independently, and the electricity it generates is only used to meet the charging demand or stored in the energy storage device, without energy exchange with the external grid. The configuration framework of the photovoltaic storage capacity is shown in Figure 1, where X^{ESS} and X^{PV} are the capacities of the storage system and the photovoltaic system, respectively. In the photovoltaic storage charging station system, the electric vehicle charging station operator meets the charging needs of electric vehicles and earns revenue by coordinating grid power purchase, photovoltaic power generation, and the charging and discharging of the energy storage system. The electricity generated by the photovoltaic system can be prioritized to charge the energy storage battery or directly supplied to the EV for charging, but the surplus electricity does not reverse into the grid. At the same time, the electricity purchased from the grid can be used either to charge the energy storage system or directly to charge the EV.

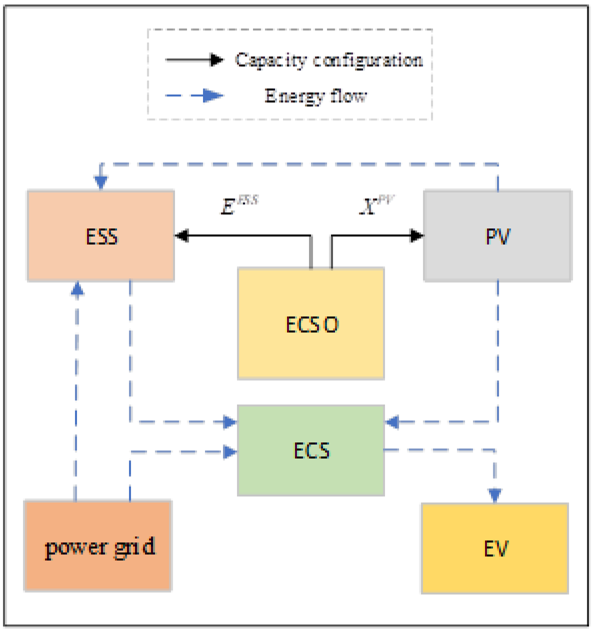


Figure 1 Capacity configuration framework for photovoltaic storage charging stations

2.2. Cost analysis of photovoltaic storage charging stations

2.2.1. Construction cost of the photovoltaic storage system

The initial investment in a photovoltaic energy storage system mainly includes hardware costs such as photovoltaic modules, inverter equipment, energy storage batteries, and bidirectional converters. Considering the time value of funds, the total investment cost is converted into an annual equivalent cost. The annualized construction costs of photovoltaic and energy storage systems are represented by formulas (1) and (2), respectively.

$$F_{PV} = C^{PV} X^{PV} \times \frac{r(1+r)^{m_P}}{(1+r)^{m_P} - 1} \quad (1)1$$

$$F_{ESS} = (C^{ESS} X^{ESS} + C^{PCS} P_{\max}^{ESS}) \times \frac{r(1+r)^{m_B}}{(1+r)^{m_B} - 1} \quad (2)2$$

Where: C^{PV} is the unit cost of the photovoltaic system; X^{PV} is the configured capacity of the photovoltaic system; C^{ESS} and C^{PCS} respectively is the cost per unit of energy storage capacity and the unit price of the bidirectional converter; X^{ESS} and $P_{\max}^{ESS}$ respectively is the capacity of the energy storage system and the maximum output power; r is the discount rate; m_p and m_B respectively is the life cycles of the photovoltaic module and the energy storage battery.

2.2.2. Operating and maintenance costs of the photovoltaic storage system

The photovoltaic storage system needs to be inspected and maintained regularly to ensure its safe and efficient operation. These maintenance costs are part of the necessary daily operating costs and will generally increase as the installed capacity of the system increases. The annual equivalent cost of operation and maintenance is calculated by formula (3).

$$F_O = (C^{ESS} X^{ESS} + C^{PCS} P_{\max}^{ESS}) y^{es} + C^{PV} X^{PV} y^{pv} \quad (3)3$$

In the formula: y^{es} represents the annual maintenance cost coefficient of the energy storage system; y^{pv} represents the annual operating number of the photovoltaic component.

2.2.3. Operating income

Charging stations usually adopt the peak-valley electricity price mechanism when purchasing electricity from the grid, but charge users uniformly, so their main profit model is the electricity price difference arbitrage. The annual operating income can be estimated by formula (4).

$$F_A = 365 \times \sum_{t=1}^{T} \left[P_t^{EV} \cdot C_t^{EV} - P_t^{grid} \cdot C_t^{grid} \right] \tag{4}$$

In the formula: P_t^{EV} represents the electric vehicle charging load at time t; C_t^{EV} is the electricity price charged to the user at that time; P_t^{grid} is the power purchased from the grid at time t; C_t^{grid} is the unit price of electricity purchased at that time; T is the number of periods of the optimization cycle (in this study, T is set to 24).

2.2.4. Delay the indirect benefits of grid expansion

The application of photovoltaic storage systems can effectively delay the demand for expansion or upgrading of the distribution system. This part of the economic benefit can be regarded as an indirect benefit, and its calculation is based on formulas (5) to (7). It is assumed that the introduction of energy storage can delay the upgrade cycle of distribution facilities by charging stations.

$$F_s = \frac{sP_{\max}^{\text{load}}}{\sigma} \times \frac{r(1+r)^{m_y}}{(1+r)^{m_y} - 1} \tag{5}$$

$$m_y = \frac{\lg(1+\omega)}{\lg(1+\varepsilon)} \tag{6}$$

$$\omega = \frac{P_{\max}^{load} - P_{\max,i}^{load'}}{P_{\max}^{load}} \tag{7}$$

In the formula: s is the cost per unit capacity; σ is the capacity expansion ratio; ε is the annual growth rate of electric vehicle load; ω is the peak shaving rate; $P_{\max}^{load}$ and $P_{\max,i}^{load'}$ are respectively the maximum load before configuration and the maximum load in year i after configuration.

2.2.5. Reduce the cost of distribution capacity

According to the national power industry norms, when the rated capacity of the transformer of an electricity-consuming unit exceeds 315kVA, the electricity pricing method shall follow the large industrial electricity price system, and a fixed capacity electricity fee shall be paid based on the installed capacity of the transformer. In this case, the capacity charges that can be reduced by optimizing the configuration of the charging station can be determined by the following calculation model.

$$F_{RC} = \frac{12M(P_{\max}^{load} - P_{\max,i}^{load'})}{\mu} \tag{8}$$

In the formula: M is the monthly distribution capacity cost; μ is the capacity margin of the distribution system, usually 80%. Since the electricity load of electric vehicles and the capacity of the energy storage system may vary from year to year, the savings in distribution capacity cost should be calculated on an annual basis.

2.3. Energy storage life model

Building a battery life model for energy storage helps to accurately assess battery costs and replacement cycles. Battery life is highly dependent on how it operates. The higher the depth of discharge, the shorter the cycle life. First, analyze the changes in the depth of discharge of the battery through the rain-flow counting method to identify the complete chard-discharge cycle; Then, based on the correspondence between the depth of discharge and cycle life, assess the battery's health status to predict its remaining useful life.

2.3.1. (1) Energy storage battery health assessment model

The characteristic of gradually decaying capacity over the battery's service life is also a key concern. The State of Health (SOH) of a battery is defined as the ratio between the current available capacity and the initial capacity. Literature [13] derived the mathematical relationship between SOH and the number of cycles based on experimental analysis, and its mathematical expression is as follows:

$$SOH_{dod}(N_m) = 1 + a_{dod}N_m + b_{dod}N_m^2 + c_{dod}N_m^3 \qquad (9)9$$

In the formula: a_{dod} , b_{dod} , c_{dod} represent the coefficients of the first-order, second-order, and third-order terms respectively.

During the long-term operation of energy storage devices, repeated charge and discharge cycles can exacerbate their performance degradation, so it is necessary to evaluate SOH regularly. The operation steps are as follows:

- Use the rain flow counting method to extract the values of the depth of battery discharge for each cycle and sort them in ascending order;
- Divide the depth of discharge into four intervals: [0, 0.4], (0.4, 0.6], (0.6, 0.8], (0.8, 1], and count the number of cycles n_1 in each interval;
- Substitute n_1 into formula (9) to calculate the battery health under the interval [0, 0.4]. Then, convert it to the second interval n_2 and combine it with n_2 to calculate the battery health in the second interval.

$$SOH_{dod}^{i-1}(n_{i-1}) = f_{i-1}(n_{i-1}) \qquad (10)10$$

$$SOH_{dod}^{i}(n_i) = f_i(f_i^{-1}(SOH_{dod}^{i-1}(n_{i-1})) + n_i) \qquad (11)11$$

- Iterative calculations were conducted based on formulas (10) and (11) to evaluate the battery health status (SOH) in the 3rd and 4th time periods respectively. Ultimately, the remaining available battery capacity X_n^{ESS} of the energy storage system at the end of the operation cycle is determined by the cumulative algorithm.

$$X_n^{ESS} = X^{ESS} \cdot SOH_{dod}^4 \qquad (12)$$

3. Double-layer model for Capacity configuration optimization of photovoltaic storage charging stations

When configuring the capacity of photovoltaic storage, the larger the capacity configuration of photovoltaic storage, the more obvious the smoothing effect on the charging load of electric vehicles, but it also brings higher construction costs. Therefore, a balance should be struck between construction investment and load regulation capacity. In order to achieve the economic and efficient operation of the system, this paper conducts a comprehensive analysis from multiple perspectives such as cost input, expected returns, and load optimization effects, and uses the two-layer optimization theory to establish a photovoltaic storage capacity configuration model. Through the upper and lower layer game mechanism, the optimal capacity configuration scheme is obtained. This type of problem has a two-layer structure, with both the upper and lower layers containing independent optimization objectives and constraints, which influence each other and jointly determine the final solution. The model is as follows:

$$\begin{cases} \min\limits_{x} F_1(x,y) \;\; s.t. \;\; g(x,y) \le 0 \\ \min\limits_{y} F_2(x,y) \;\; s.t. \;\; h(x,y) \le 0 \end{cases} \quad (13)12$$

In the formula: x, g, and F_1 represent the decision variables, optimization objectives, and constraints in the upper model, respectively; F_2, h and y correspond to the decision variables, optimization objectives and constraints of the lower model, respectively.

3.1. Objective function

3.1.1. (1) Upper-level objective function

The upper-level optimization objective is to maximize the overall annual revenue of the charging station. This objective needs to take into account the investment and operation and maintenance expenses of the photovoltaic storage equipment, the economic benefits during operation, the reduction of capacity costs, and the economic benefits resulting from the delay in distribution network transformation. The objective function F_1 is as shown in formula (14).

$$\max F_1 = F_A + F_S + F_{RC} - F_{PV} - F_{ESS} - F_O \quad (14)13$$

3.1.2. (2) Lower-level objective functions

The core objective of the lower-level optimization is to improve the overall efficiency of the photovoltaic storage system by optimizing the distribution of charging load. Two alternative objective function schemes were designed. After simulation and comparison analysis, the scheme with better performance was finally selected as the optimization objective of the system configuration.

Objective function 1: To minimize the load peak-valley difference within the optimization cycle

$$f = \min(P_{\max}^{load} - P_{\min}^{load}) \quad (15)14$$

Objective function 2: To minimize the variance of the load and maximize the daily earnings of the charging station within the optimized time frame:

$$\begin{cases} f_1 = \min \dfrac{\sum\limits_{t=1}^{T}\left(P_t^{load} - P_{\text{avg}}\right)^2}{T} \\ f_2 = \max \sum\limits_{t=1}^{T}\left(P_t^{EV} C_t^{EV} - C_t^{grid} P_t^{grid}\right) \end{cases} \quad (16)15$$

In the formula: P_{avg} represents the average load level of the charging station within a day.

Objective function handling: Since Objective Function 2 is a dual-objective optimization problem, to simplify the solving process, functions f_1 and f_2 can first be standardized, thereby transforming it into a single-objective problem. The specific expression is as follows:

$$f_3 = \min\left(\delta_1 f_1 / f_{1\max} - \delta_2 f_2 / f_{2\max}\right) \quad (17)16$$

In the formula: $f_{1\max}$ represents the maximum variance of the charging station load within time T; $f_{2\max}$ is the maximum benefit without energy storage; δ_1 and δ_2 represents the weight coefficient, which is taken $\delta_1 = \delta_2 = 0.5$ in this paper.

3.2. Constraints

3.2.1. Power balance constraints

$$P_t^{Load} = P_t^{grid} + P_t^{PV} + P_t^{ESS} \quad (18)17$$

In the formula: P_t^{PV} represents the power generation of the photovoltaic system at time *t*; P_t^{ESS} is the amount of charge or discharge at time *t*.

3.2.2. Energy storage charge and discharge rate constraints

The charge and discharge rate of energy storage is the ratio of power to battery capacity. Excessively high charge and discharge rates may accelerate the degradation of battery performance. For the sake of battery protection, this study limits the maximum allowable charge and discharge rate to 0.4 X^{ESS} , and its mathematical constraints are expressed as:

$$0 \le \left| P_t^{ESS} \right| \le 0.4 X^{ESS} \quad (19)18$$

To ensure that the energy storage system does not perform charging and discharging simultaneously at the same time, this paper establishes the following charging and discharging constraints for the energy storage system:

$$\begin{cases} -X^{ESS} \cdot (1-u_t) \le P_t^{ESS} \le X^{ESS} \cdot u_t \\ 0 \le P_t^{ESS,ch} \le P_{\max}^{ESS} \cdot u_t \\ -X^{ESS} \cdot (1-u_t) \le P_t^{ESS,diss} \le 0 \\ P_t^{ESS} = P_t^{ESS,dis} + P_t^{ESS,ch} \end{cases} \quad (20)19$$

In the formula: u_t is a binary variable, $u_t = 1$ represents energy storage discharge, $u_t = 0$ represents energy storage charging; $P_t^{ESS,dis}$ and $P_t^{ESS,ch}$ are respectively the power components for discharge and charging; $P_{\max}^{ESS}$ is the maximum charge or discharge power for energy storage.

3.2.3. Charge and discharge depth constraints

To prevent the storage battery from aging faster due to overcharging or over discharging, it is necessary to ensure that it operates within a reasonable range of state of charge, and the range constraints are:

$$S^{\min} \le S_t \le S^{\max} \quad (21)20$$

In the formula: S_t represents the state of charge of the energy storage system at time *t*; $S^{\min}$ represents the minimum state of charge of the energy storage system; $S^{\max}$ is the maximum state of charge of the energy storage system.

(4) Continuity constraints of state of charge

$$S_t = S_{t-1} + P_t^{cha} \cdot \eta - P_t^{dis} / \eta \quad (22)21$$

In the formula: η is the energy conversion efficiency of the energy storage system during charging and discharging.

3.2.4. Installed capacity limit of photovoltaic storage

Considering the investor's financial situation and the space of the charging station, a reasonable capacity allocation plan for photovoltaic and energy storage should be formulated in combination with the actual situation of the charging station. The capacity constraints are as follows.

$$\begin{cases} X^{ESS} \le X_{\max}^{ESS} \\ X^{PV} \le X_{\max}^{PV} \end{cases} \quad (23)22$$

In the formula: $X_{\max}^{ESS}$ is the upper limit of energy storage capacity that the charging station can carry; $X_{\max}^{PV}$ is the maximum installed capacity of photovoltaic power that the charging station can allow.

4. Analysis of numerical examples

4.1. Parameter Settings

The typical electric vehicle load curve is shown in Figure 2, and the typical photovoltaic output situation is shown in Figure 3. Due to the constraints of the site space conditions, the installed capacity of photovoltaic power is relatively low, so the power supply is still mainly from the grid, and the photovoltaic system mainly serves as an auxiliary energy supply, without considering its power supply back to the grid. The operation strategy of photovoltaic storage charging stations is mainly to purchase electricity during off-peak hours based on the peak-valley electricity price and charge the owners according to the set rate, making profits from the electricity price difference. The detailed information of the time-of-use electricity price of the grid and the electricity price of the charging station is shown in Table 1, and the specific parameters of capacity configuration are shown in Table 2.

Table 1 Time periods and electricity price parameter Settings

Time periods	**Purchase electricity price/(yuan ·kWh^{-1}))**	**Charging electricity price/(yuan ·kWh^{-1})**
Peak hours (10:00-13:00, 17:00-22:00)	1	1.5
Off-peak hours (22:00-7:00)	0.3	1.5
Normal time (7:00-10:00,13:00-17:00)	0.6	1.5

Table 2 Related parameter Settings

Parameters	**Values**	**Parameters**	**Values**
C^{PV} /(yuan ·kW^{-1})	7000	y^{pv}	0.02
C^{ESS} /(yuan ·kWh^{-1})	2100	s/(yuan ·kW^{-1})	4100
C^{PCS} /(yuan ·kW^{-1})	1550	ε /(%)	2
r /(%)	8	S^{min}	0.2
m_p/(year)	20	S_{max}	0.9
M/(yuan ·kWA^{-1})	30	λ	0.9
y^{es}	0.01	σ	60

4.2. Load curve analysis of electric vehicle charging stations

It can be analyzed from Figure 2 that the peak load of electric vehicle charging stations mainly occurs from 9:00 to 17:00 and from 19:00 to 22:00. These two peak periods precisely overlap with the peak period of power grid electricity load. This situation not only increases the operational burden of the distribution network but also, due to the constant charging electricity price strategy adopted by the charging stations, This leads to a significant increase in the cost of purchasing electricity during peak hours, which directly affects the economic benefits of charging stations. As shown in

Figure 3, the photovoltaic output period coincides with a peak period of the charging station load. During this period, the photovoltaic output can be utilized to reduce the purchase of electricity from the grid, reduce the impact on the grid and increase the revenue of the charging station.

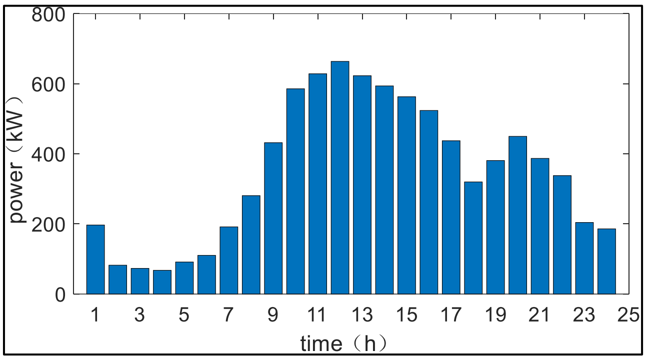


Figure 2 Electric vehicle load

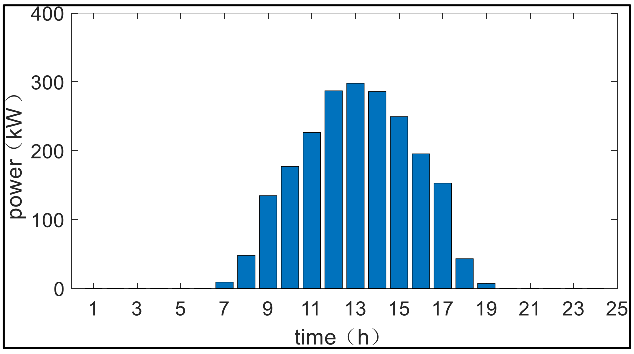


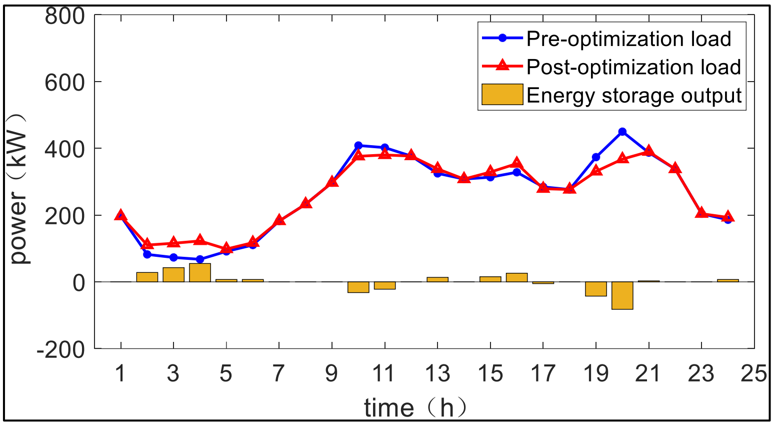
Figure 3 Photovoltaic output

Therefore, this paper upgrades the traditional charging station to a photovoltaic storage charging station, providing load support for the charging station through the collaborative work of photovoltaic power generation and energy storage equipment, thereby effectively easing the pressure on the regional distribution network and reducing the power purchase cost of the charging station.

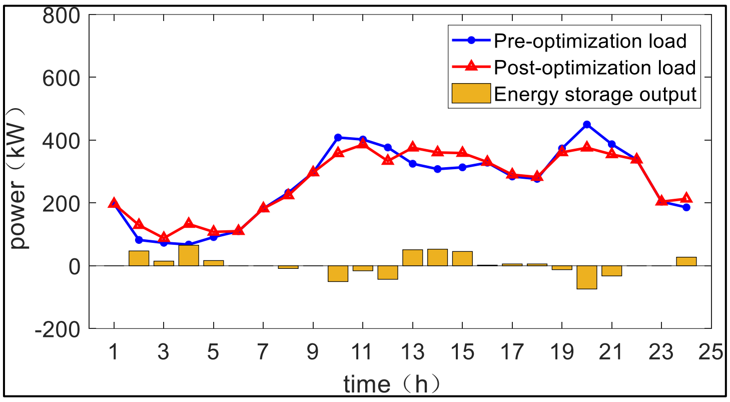
4.3. Analysis of the impact of optimization objectives on the results

In the case of uncertain photovoltaic storage capacity, this study employed a phased optimization approach to solve the problem. First, assume the capacity of energy storage and photovoltaic to be 210kWh and 300kW respectively. By comparing the optimization effect of the lower objective function, select the objective function with better performance for subsequent capacity configuration. The optimization results under different schemes are shown in Figure 4 and Table 3. Among them, optimization objective 1 is to minimize the peak-valley difference of load after the charging station is configured with photovoltaic storage, and optimization objective 2 is to minimize the variance of the load curve and maximize the daily profit after the charging station is configured with photovoltaic storage.

As shown in Figure 4, by comparing and analyzing the load curves under the two optimization strategies, it can be found that in the low electricity price range of 1:00-7:00, the energy storage devices in both schemes are selected for power storage, resulting in a significant increase in the power consumption within the station. During the high electricity price period from 10:00 to 13:00, the energy storage equipment of the second optimization strategy was in the energy release state, while the output power of the energy storage system of the first strategy was relatively limited as it did not reach the daily maximum load threshold. When entering the regular electricity price period from 13:00 to 19:00, with sufficient light resources, the energy storage capacity of the first scheme is relatively low, resulting in a large depression in the load curve; In contrast, the second scheme can effectively integrate photovoltaic power generation resources, give full play to the regulation function of the energy storage system, and significantly improve the overall energy efficiency of the charging facilities.



(a) Optimization objective 1



(b) Optimize objective 2

Figure 4 Results under different optimization objectives

A comprehensive analysis of the data in Table 3 shows that the photovoltaic and energy storage co-optimization scheme has significant advantages over the schemes without photovoltaic and energy storage and with only photovoltaic. Objective 1 and Objective 2 respectively reduced the peak-valley difference to 291.55kW and 298.04kW, a decrease of 49.1%-51.1% compared to the basic scenario. Among them, Objective 2 achieved the optimal load smoothing effect through the multi-period adjustment strategy, with a daily load variance of only 7,559 kw ^{2}, a decrease of 22.7% compared to objective 1.

Table 3 Optimization metrics

Schemes	**Peak-valley difference /kW**	**Daily load variance /kW**	**Daily earnings gain/yuan**
Photovoltaic storage is not included	596.25	38748	/
Only photovoltaics	382.28	13205	490.72
Optimization Objective 1	291.55	9776	578.43
Optimization Objective 2	298.04	7559	619.06

In terms of economy, the photovoltaic energy storage allocation optimization scheme has brought significant gains compared to the photovoltaic allocation alone. Optimization objective 2 has achieved a maximum daily profit increase of 619.06 yuan, an increase of 6.6% compared to Objective 1. The overall comparison shows that Objective 2 maintains a good peak-valley difference optimization effect while minimizing load variance to enhance grid stability and achieve optimal economic benefits, demonstrating the best overall performance. Based on the above analysis results, the optimization objective 2 with optimal load balancing and economic performance was determined as the lower-level optimization model for the subsequent photovoltaic storage system.

4.4. Analysis of photovoltaic capacity configuration results considering the cost of the photovoltaic system

Constrained by site conditions and the cost of investing in energy storage, the upper limit of the installed capacity of the photovoltaic system for this charging facility was set at 350kW, and the total capacity of the energy storage device was limited to 500kWh. The optimized configuration results are shown in Table 4. As shown in Table 4, when the actual installed power of the photovoltaic array reaches 256kW, combined with a 402kWh energy storage system, an average annual comprehensive economic benefit of 4.563 million yuan can be achieved. According to this configuration plan, the transformation of the distribution network can be postponed by 10 years.

Table 4 Optimal configuration results of photovoltaic storage capacity

Optimization Objectives	**Photovoltaic (kW)**	**Energy Storage (kWh)**	**Comprehensive income (in ten thousand yuan)**
Optimization results	256	402	456.3

The optimized results of the photovoltaic energy storage system after commissioning are shown in Figure 5, and the corresponding SOC of the energy storage device is shown in Figure 6. The overall performance of the system has significantly improved, as can be seen from the optimization results after the operation of the photovoltaic storage system. From the perspective of load regulation effect, the energy storage system fluctuates its SOC within the range of 0.2 to 0.9 through the "two charges and two discharges" operation strategy. Charging is carried out during the peak photovoltaic output period to smooth out the fluctuations, and discharging is carried out during the peak load period in the evening to reduce the peak load and improve the peak-valley difference. This indicates that a reasonable energy storage operation strategy can achieve efficient and economic operation of charging stations through the allocation of electrical energy, and improve the utilization efficiency of energy storage resources.

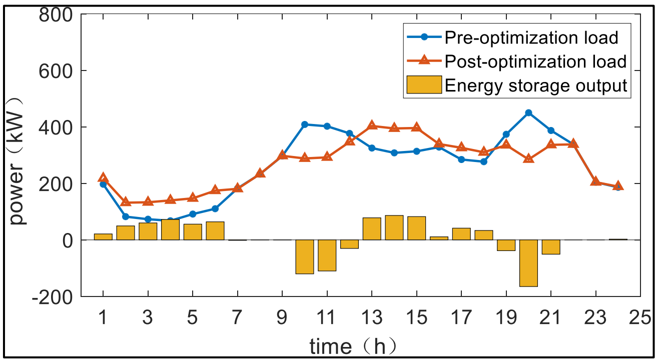


Figure 5 The optimization curve of the photovoltaic storage system in the first year of operation

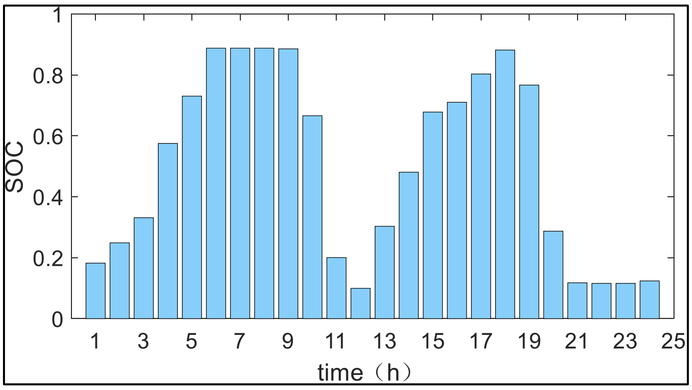


Figure 6 Energy storage system SOC

4.5. The Impact of energy storage lifespan on the Benefits of Photovoltaic energy storage Charging Stations

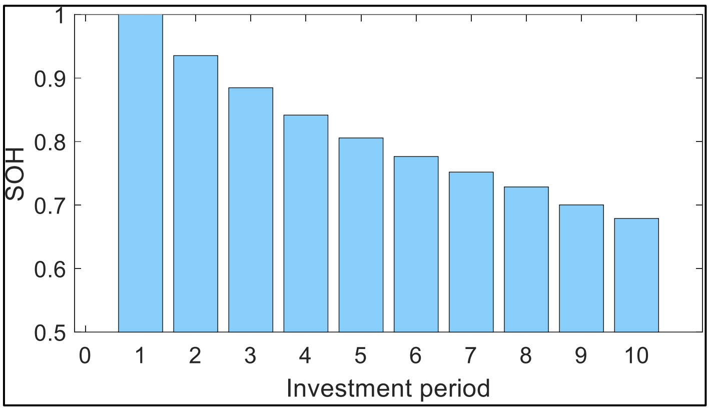
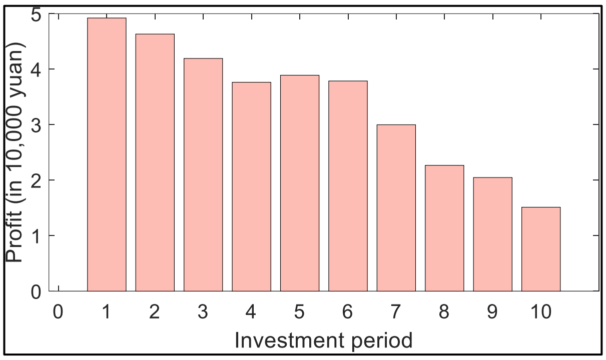
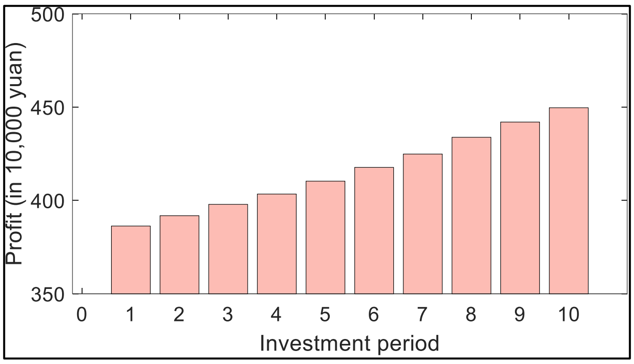


Figure 7 Trends in the health status of energy storage batteries

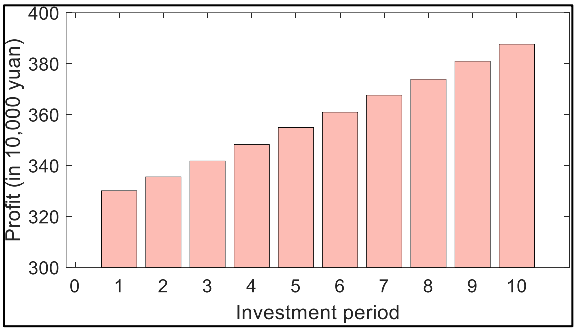
Based on the SOH assessment model for energy storage batteries presented in Section 2.3, the health level of the battery is evaluated by analyzing the SOC change curve of the energy storage battery in the first year of operation, and its remaining effective capacity is updated at the end of each year to optimize the operation strategy for the next year. This process continues until the battery's SOH drops below 0.3 and its use is terminated. In this photovoltaic storage configuration scenario, the upgrade and transformation of the charging station distribution network is delayed for 10 years. At the end of the 10th year, the SOH of the storage battery is 0.68, which is still suitable for continued use. Figure 7 shows the changes in the state of the energy storage battery.



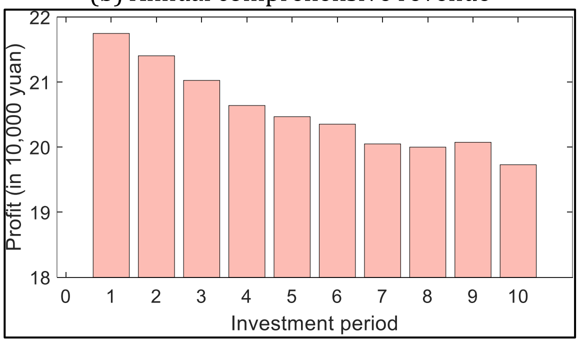
(a) Reduce the annual value of distribution capacity fees



(b) Annual comprehensive revenue



(c) Annual operating income



(d) Increase in annual operating income

Figure 8 Investment income chart

According to the analysis in Figure 8, the annual comprehensive revenue of charging stations shows a significant upward trend, mainly due to the continuous growth of annual operating revenue resulting from the expansion of charging load scale; However, the increase in annual operating revenue and the savings in distribution capacity fees have declined. The fundamental reason for this is that as the years of operation increase, on the one hand, the continuous increase in charging load leads to a decrease in the system regulation margin, and on the other hand, the decline in the health status of energy storage batteries weakens the load optimization ability. The combined effect of these two factors leads to a gradual increase in the load peak-valley difference rate. Ultimately, the overall benefits of these two types of derivative gains are weakened. The dynamic evolution of this revenue structure provides an important basis for optimizing the long-term operational strategy of photovoltaic storage charging stations.

5. Conclusion

This chapter focuses on the method of capacity allocation for photovoltaic storage charging stations. First, compare and analyze the results of different lower-level optimization objective functions by assuming the capacity value of photovoltaic storage, and select the better objective function as the lower-level optimization objective; Secondly, considering the investment cost and operational efficiency of the photovoltaic storage charging station, configure the photovoltaic storage capacity of the charging station; Finally, the future energy storage life of photovoltaic storage charging stations is evaluated, and the changes in energy storage life and their impact on the operation of photovoltaic storage charging stations are analyzed. The following conclusions were drawn through case studies:

- Taking the multi-objective function that takes into account both load fluctuation and operational efficiency as the objective of the lower-level optimization model can not only effectively reduce the load peak-valley difference and reduce load fluctuation, but also increase the operational income of the photovoltaic storage charging station, and its effect is better than that of the single-objective optimization function.
- The energy storage life of the photovoltaic storage charging station decreases year by year with the increase of operating years. Meanwhile, the decline of the health status of the energy storage battery weakens the load optimization ability, resulting in a decrease in the operational gain and distribution capacity cost of the photovoltaic storage charging station

Compliance with ethical standards

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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