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# Optimal Allocation of Energy Storage Allocation based on Sceneario Method

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**Abstract:**
The time characteristic of pv is one of the important factors that restrict the accommodation of pv. In this paper, the main purpose is to improve the utilization rate of pv. Battery energy storage system is used to absorb the pv curtailment, and many benefits of energy storage in the operation process are analyzed, such as pv connected benefits, environmental protection benefits and so on. According to the time series -sequence characteristics, a large number of scenarios are generated and the scenario reduction technology based on KD distance is used to synthetically consider the benefit items and energy storage costs, so as to obtain comprehensive benefits with universality. Based on this goal, a model is constructed to optimize the capacity allocation of energy storage. In this paper, a mutually exclusive technology is proposed to optimize the operation strategy of energy storage. By introducing 0-1 auxiliary variables, considering the interrelated characteristics of charging and discharging power and over-limit power of energy storage during operation, the piecewise function representing the operation strategy of energy storage is linearized, thus significantly reducing the calculation time of the system. The effectiveness of the proposed method is verified by an example.

**Keywords:** PV accommodation, scenario generation and reduction, mutually exclusive technology, energy storage service life, optimal allocation of energy storage

## INTRODUCTION

The rapid development of clean energy such as photovoltaics is conducive to achieving sustainable energy development and reducing environmental pollution caused by fossil fuels. However, due to the fact that the low load period coincides with the high photovoltaic power generation period, if the system does not have the corresponding load to meet the dynamic balance of power generation and consumption, it may cause a large amount of abandoned light [1-2]. Large scale energy storage, due to its high energy density and flexible charging and discharging characteristics, can not only time shift electrical energy and change the photovoltaic power supply period, but also assist the grid in peak shaving and frequency regulation, improving the stability and safety of the entire power system after photovoltaic grid connection, thus becoming one of the effective ways to promote photovoltaic consumption. References [3-4] introduce the charging and discharging characteristics of various energy storage systems and their corresponding roles in various aspects of the power system. They provide a comprehensive analysis of the technical characteristics and economic evaluation methods of large-scale battery energy storage at present. However, due to the current high cost of configuring energy storage, it is of great significance for the long-term planning of energy storage to balance the cost of configuring energy storage with the benefits obtained.

At present, research on energy storage configuration mainly focuses on using energy storage to improve the grid connection capacity of photovoltaics and the stability and reliability of system operation after grid connection [5-7]. There are also studies that utilize the time shift ability of energy storage to improve the system's acceptance of electricity during low load periods through large-scale configuration of energy storage. Reference [8] points out that the decrease in downward peak shaving ability of thermal power units in winter is an important reason for the difficulty in photovoltaic consumption. On this basis, reference [9] proposes a method to relax the bottleneck of peak shaving by configuring energy storage, starting from the provincial power grid, in order to improve the photovoltaic acceptance capacity of the system, and analyzes the impact of the investment cost and operating period of energy storage on the configuration of energy storage. The above configuration of energy storage is from the perspective of absorbing discarded light, but the impact of energy storage lifespan on the configuration of energy storage is not considered. Reference [10] provides a review of the factors that affect the energy storage life of lead-acid batteries. On this basis, references [11-12] propose a variable life model for energy storage from the perspective of the impact of charging and discharging depth on energy storage life, and include it as an equiannual coefficient for energy storage configuration cost. Reference [13] constructs an energy storage configuration model that considers both the economic efficiency of wind energy consumption and the lifespan loss, with the goal of maximizing the net benefit of energy storage configuration. It takes into account the relevant constraints of energy storage exceeding the power limit to configure energy storage capacity, which has certain engineering significance. However, it still has the following shortcomings: (1) The efficiency of the model solving is low, and the constraints of power exceeding limits and energy storage charging and discharging strategies in the model are segmented functions, which takes too long to solve using optimization software; (2) The capacity and power configuration of energy storage devices are obtained under a single scenario, and the randomness of the scenario is not sufficiently considered, which raises doubts about its rationality.

Therefore, based on the existing work, typical scenarios are obtained using the scenario method, considering the economic benefits of energy storage configuration in different scenarios, and accurately measuring the impact of energy storage configuration in different scenarios on the final configuration. In addition, when solving the model, the use of mutual exclusion technology for linear optimization of the segmented energy storage operation strategy significantly improves the calculation speed of the system.

## PHOTOVOLTAIC POWER SIMULATION

Scene simulation

The output power of photovoltaic panels $P_{\mathrm{PV}}$ is directly proportional to the intensity of light, which can be expressed by equation (1):

$$P_{\mathrm{PV}} = \begin{cases} P_{\mathrm{PV},N} \dfrac{\eta}{\eta_N}, & \eta \le \eta_N \\ P_{\mathrm{PV},N}, & \eta \ge \eta_N \end{cases} \tag{1}$$

The formula $P_{\mathrm{PV},N}$ and $\eta$ are respectively the rated power and rated light intensity of the photovoltaic cell pack. Its power factor can be adjusted between 0.98 lagging and 0.98 leading.

Generation of photovoltaic output scenarios

As a typical power generation equipment that utilizes natural resources, the output of photovoltaic cells is influenced by various factors and has strong uncertainty. Fully considering the uncertainty of photovoltaics during the planning phase can improve the economic and environmental friendliness of the configuration scheme during operation. The DG dual layer optimization model in this article aims to minimize the annual total cost as the planning objective, and needs to calculate the distribution network operation cost based on the photovoltaic output sequences of different typical days. Therefore, this article proposes a method for generating typical solar photovoltaic power scenes based on historical data.

Firstly, based on historical data, the kernel density estimation method [9] is used to generate the probability density function of photovoltaic output for each hourly period of 24 hours a day, as shown in equation (2):

$$\hat{f}_h^t(x^t) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x^t - X_i^t}{h}\right) \tag{2}$$

In the formula, $n$ is the number of days of historical data; $t$ indicates the time period; $h$ ,the bandwidth estimated for kernel density; $X_i^t$ , fill in the photovoltaic output for the i-th time period in the historical data.

Then, the probability distribution functions of 24 time periods were sampled to generate 5000 sets of photovoltaic output daily sequences, and K-means clustering was used to finally generate typical solar photovoltaic output scenarios, which were used for subsequent model calculations.

## A MATHEMATICAL MODEL FOR ENERGY STORAGE CONFIGURATION

Energy storage operation strategy

In traditional power grids, when the load curve remains unchanged, reducing the output of thermal power units is usually used to provide grid space for photovoltaics, and the current photovoltaic output is used as much as possible to achieve the goal of reducing solar power waste. Therefore, the difference between the existing conventional unit output and load demand in the current system is the absorbable photovoltaic power PW, a(t):

$$P_{W,a}(t) = P_L(t) - P_{G,\min}(t) \quad (3)$$

In the formula, PL (t) is the system load power at time t; PG, min(t) is the minimum power generation of the unit at time t.

When the photovoltaic output exceeds the difference between the power required by the load and the power at the minimum output of the existing unit, the excess power is called the out of limit power generation. The amount of discarded light in the system is the accumulation of discarded light power over time. Therefore, the out of limit power PY (t) and out of limit electricity EY (t) at photovoltaic time t are:

$$P_Y(t)=\begin{cases} P_W(t) - P_{W,a}(t) \text{ ,} P_W(t) \geq P_{W,a}(t) \\ 0 \text{ ,} P_W(t) < P_{W,a}(t) \end{cases} \quad (4)$$

$$P_W(t) = \sum P_w(t) \quad (5)$$

$$E_Y(t) = \sum_{\Delta t=1}^{24} P_Y(t) * \Delta t \quad (6)$$

In the formula, PW(t) is the total output of the photovoltaic installation; Pw(t) is the output of a single photovoltaic point at time t. EY(t)is the total electricity consumption during a single time limit exceeding period.

Due to the fact that the charging and discharging of energy storage is a continuous process, the magnitude of the power exceeding the limit varies over time. If the photovoltaic power of the energy storage and absorption electric field needs to be exceeded through configuration, the determination of the operating power of the energy storage is related to the exceeded power, in order to ensure that the energy storage device can absorb the photovoltaic as much as possible. Energy storage should be charged at the point where the light power is discarded. The energy storage charging power Pess (t) is:

$$P_{ess}(t) = \begin{cases} 0, \quad P_Y \leq 0 \\ P_Y(t), \quad 0 < P_Y(t) < P_{essN} \\ P_{essN}, \quad P_Y(t) \geq P_{essN} \end{cases} \quad (7)$$

In the formula, PessN is the rated power of energy storage.

During a charging and discharging cycle, if the amount of energy continuously discarded exceeds the amount of stored energy, charging will not be carried out until the next discharge. That is, the charging power of the stored energy will not change with the change of the power exceeding the limit and will remain zero until the next discharge before charging begins. Its constraint expression is:

$$P_{ess}(t) = 0, E_Y(t) > E_{ess} \quad (8)$$

In the formula, Eess is the maximum capacity for configuring energy storage.

Objective Function and Constraints

By configuring energy storage to absorb the discarded solar energy when the photovoltaic limit is exceeded, and obtaining relevant benefits. And configuring energy storage not only incurs investment and maintenance costs, but also the cost of energy storage losses caused by its own losses during the charging and discharging process. Therefore, considering different photovoltaic output scenarios, while considering the benefits and costs of configuring energy storage, a model is established with the goal of maximizing the economic benefits of configuring energy storage within the planning period.

$$\max C(P_{ess}, E_{ess}) = 365\sum_{i=1}^{I} p_i(C_{sale,i} + C_{env,i} - C_{ess,loss,i}) - C_{ess,inv} - C_{ess,op} \quad (9)$$

In the formula, $P_{ess}$ represents the power configuration of energy storage in the system; $C_{sale,i}$, $C_{env,i}$ in scenario i, the photovoltaic power station obtains benefits from disposing of solar energy and reducing environmental pollution by configuring energy storage; $C_{ess,loss,i}$ the loss cost of energy storage during operation in scenario i. $C_{ess,inv}$, $C_{ess,op}$ are the investment cost, operation and maintenance cost, and life loss cost of energy storage throughout the entire planning period; $p_i$ the probability of occurrence for each scenario, where d is the d-th day and I is the number of scenarios; The simulation time is measured in years, with a unit time scale of hours.

The corresponding constraint conditions are:

$$\begin{cases} 0 \le P_{ess}(t) \le P_Y^{\max} \\ 0 \le E_{ess}(t) \le E_Y^{\max} \\ P_{ess}(t) \ge 0, E_{ess}(t) \ge 0 \end{cases} \quad (10)$$

In the formula, $P_Y^{\max}$, $E_Y^{\max}$ are the maximum value of the system's photovoltaic power exceeding the limit and the maximum value of the daily photovoltaic total power exceeding the limit.

Energy Storage Benefit Analysis

(1) Energy storage promotes photovoltaic grid connection benefits

The amount of discarded light in the system before and after energy storage configuration is different, and the difference in the amount of discarded light before and after configuration is the amount of electricity that can generate additional benefits from energy storage. The expression is as follows:

$$C_{sale,i} = \alpha E_{ess,w,i} \quad (11)$$

$$E_{ess,w,i} = \sum_{m=1}^{M_d} \int_{t_{m_1}}^{t_{m_k}} P_{ess,i}(t)dt \quad (12)$$

In the formula, $\alpha$ is the unit price of photovoltaic grid connection; m is the number of photovoltaic periods that require energy storage and consumption for the mth time; Md is the total number of times energy storage charging and discharging is required on day d; tm1,tmk are the start and end times of the day when energy storage needs to be charged; Eess, w, i are the amount of discarded solar energy consumed in the i-th scenario after configuring energy storage compared to when energy storage is not configured.

(2) Environmental benefits

By configuring energy storage to reduce wasted light and improve the system's ability to absorb photovoltaics, the environmental pollution caused by burning fossil fuels is reduced, and the environmental benefits of the system are increased. The current proportion of fossil fuels is still relatively high, and reducing the pollutants generated by power generation mainly focuses on calculating the amount of SO2 emissions.

$$C_{env} = \beta m_{so_2} E_{ess,w,i} \quad (13)$$

In the formula, $\beta$ is the unit price for treating SO2 emissions; mSO2 is the amount of SO2 released per unit of electricity generated by the thermal power unit.

Energy storage cost analysis

(1) Investment and operation costs

During the planning year, the configuration and operation costs of energy storage are only related to the capacity and power of the energy storage. The calculation formula is as follows:

$$C_{inv}+C_{op}=c_{ess,P}P_{ess}+c_{ess,E}E_{ess}+c_{ess,E}P_{ess} \tag{14}$$

In the formula, cess,P, cess,E, cess,op represent the power, capacity, and operation and maintenance unit price of the configured energy storage.

(2) Energy storage loss cost

At a conventional temperature of 25 ℃ and a single discharge rate, the lifespan of energy storage is mainly related to its discharge depth and number of cycles. Taking lithium batteries as the research object of the system, the rated cycle times corresponding to different discharge depths were fitted, and the fitted curve is shown in Figure 2. The expression is as follows:

$$B_{Dod}=35321e^{(-3.77D_{od})}+3818e^{(-0.7865D_{od})} \tag{15}$$

In the formula, BDod, Dod respectively represent the number of charge and discharge times and depth of charge and discharge for energy storage.

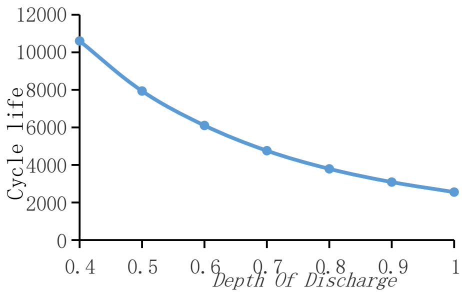


Fig.1 Relationship between cycle life of energy storage and depth of discharge

Due to the fixed total amount of energy exchange during a complete rated charging and discharging process of energy storage. It is believed that its lifespan is also determined in this situation, so when a certain depth of charging and discharging is carried out in a single operation, the charging and discharging capacity can be measured by the conversion coefficient corresponding to the effective capacity during the rated charging and discharging process. The total amount of electricity discharged under its rated state EN is:

$$E_N=B_{Dod,N}D_{odn}E_{ess} \tag{16}$$

In the formula, BDod,N are the number of cycles corresponding to the rated operating process; Dodn is the rated depth of charge and discharge.

The conversion factor defined in reference [12] in the article is the ratio of the cycle life corresponding to a single operation of energy storage to the cycle life corresponding to the rated discharge depth. The actual operating energy storage life can be described as the product of the total charge and discharge amount at rated state and the conversion factor during the energy storage life cycle. The expression for the conversion factor of discharge depth is:

$$\gamma_{Dod,a}=\frac{B_{Dod,N}}{B_{Dod,a}}=\frac{35321e^{(-3.77D_{od,N})}+3818e^{(-0.7865D_{od,N})}}{35321e^{(-3.77D_{od,a})}+3818e^{(-0.7865D_{od,a})}} \tag{17}$$

From this, it can be concluded that the equivalent discharge amount from the discharge process of energy storage from the rated capacity Emax to the discharge depth of Dod,a to the remaining capacity of(1-Dod,a)Eess at the rated discharge depth is:

$$E_a = \eta^{\mu_a} \gamma_{Dod,a} E_{an} \qquad (18)$$

Similarly, the expression that characterizes the transformation of energy storage from the rated state through the discharge process at a depth of Dod and b to the equivalent discharge amount at the rated discharge depth of (1-Dod, b) Eess equivalent to the discharge amount at the rated discharge depth is:

$$E_b = \eta^{\mu_b} \gamma_{Dod,b} E_{bn} \qquad (19)$$

In the formula, $\eta$ is the efficiency of charging; $\mu_a$ and $\mu_b$ discharging energy storage;All are two-dimensional variables that characterize the charging and discharging state of energy storage, with -1 being discharge and 1 being charging; Ean, Ebn respectively represent the total amount of charge and discharge of the battery during a single transition from full capacity to discharge 1-Dod,a,1-Dod,b; The difference between the two equations is the change in the charging and discharging capacity of the energy storage during the actual operation of a single charging and discharging state change.

Therefore, the expression for the cycle life loss of energy storage in the i-th scenario is:

$$E_{ess,loss,i} = \sum_{m=1}^{M_d} \mu_{m(ab)} (\eta^{\mu_{m(ab)}} \gamma_{Dod,a,i} E_{an} - \eta^{\mu_{m(ab)}} \gamma_{Dod,b,i} E_{bn}) \qquad (20)$$

In the formula, $\mu_{m(ab)}$ is a two-dimensional variable with values of 1 and -1, representing the process of changing from discharge depth Dod,a to discharge depth Dod,b during the m-th charge and discharge state of energy storage. The charging is 1 and the discharging is -1; $\gamma_{Dod,a,i}$ ,the conversion factor for the discharge depth of Dod,a in scenario i. $\gamma_{Dod,b,i}$ ,Ebn is similar to $\gamma_{Dod,a,i}$ ,Ean.

The daily loss cost of configuring energy storage is expressed as:

$$C_{ess,loss,i} = \frac{E_{ess,loss,i}}{E_N} (C_{inv} + C_{op}) \qquad (21)$$

Capacity configuration strategy for energy storage devices

The weight of each typical scenario obtained after scenario reduction can represent the weight of the energy storage capacity obtained under each typical scenario in the final energy storage configuration. Therefore, in the article, the final energy storage configuration of the system is determined by the product of the weight of each typical scenario after scene reduction and the energy storage configuration in the corresponding scenario.

$$E_{ess} = \sum_{i=1}^{I} \varepsilon_i E_{ess,i} \qquad (22)$$

In the formula, $\varepsilon_i$ represents the weight of each typical scenario; Eess,i is the energy storage capacity configuration obtained through equations (9) to (21) in the i-th scenario.

Conversion of operational strategies based on mutual exclusion technology

In order to shorten the computation time when solving the system model, the article proposes to use mutual exclusion technology to convert the operating strategy of energy storage. In probability theory, mutually exclusive events are defined as: the intersection of events A and B is an empty set, and in a single experiment, events A and B will not occur simultaneously [18]. If A and B are mutually exclusive, the relationship is as follows:

$$P(A+B) = P(A) + P(B) \text{ and } P(A) + P(B) \le 1 \qquad (23)$$

In the formula, $P(\cdot)$ is the probability of the event occurring.

Using the theory of mutual exclusion to linearize the segmented function of energy storage, the operating strategy of energy storage is expressed as an inequality. Since the operating strategy of the power exceeding limit PY(t) in equation (7) can only be in a single interval at each moment, the three inequalities in equation (7) are mutually exclusive. To make them hold simultaneously, it is necessary to introduce 0-1 auxiliary variables dY,t,r, and the maximum positive number D. When the charging power of the energy storage is in this range, its auxiliary variables dY,t,r=0 (at which point D is forced to be 0), and the corresponding inequality holds. If the remaining intervals dY,t,r=1, then the remaining two inequalities also hold. Specifically, as follows:

$$P_{Y,m-1} - d_{Y,t,r} D \le P_Y(t) \le P_{Y,m} + d_{Y,t,r} D \quad (24)$$

$$\sum_{r=1}^{3} d_{Y,t,r} = 2 \quad (25)$$

$$\begin{cases} P_{ess}(t) = \sum_{r=1}^{3} k_{ess,r} P'_{Y,r}(t) \\ P_{Y,r}(t) = P'_{Y,r}(t) + P''_{Y,r}(t) \\ P'_{Y,r}(t) = -(1-d_{Y,t,r}) d_{ess,r} / k_{ess,r} \\ P_Y(t) = \sum_{r=1}^{3} P_{Y,r}(t) \end{cases} \quad (26)$$

Equation (24) in the formula represents the constraint for judging the power limit interval; dY,t,r indicate that the power exceeding the limit at time t is in the r interval; Equation (25) represents the number of segmented intervals; Pess,r(t) andPY,r(t) are the values of Pess(t) and PY(t) in the r segment interval, respectively; PY,r(t) is divided into two parts:P′Y,r(t) and P″Y,r(t); PY,m is the value of PY at the segment point m; kess,r, and dess,r are the coefficients of the first-order and constant terms of the Pess(t) function in the r interval, respectively.

## ANALYSIS OF EXAMPLES

Example Background

Using data from literature for energy storage configuration in the county power grid, the installed capacity of the power supply in this area is 4.32 × 104 kW, maximum load 2.34 × 104 kW, the installed capacity of photovoltaic is 6119 kW, which is 0.08 $/kg. Taking 7 kg/(MWh), the capacity configuration cost of lithium batteries is 1.88 million/MWh, the power configuration cost is 1 million/MWh, and the operation and maintenance cost is 240000/MWh. The state of charge of energy storage can cycle from 0 to 1, with an initial state of charge set to 0.5 and a charging and discharging efficiency of 0.93. Use Cplex software for solving.

Using the scene generation method proposed in this article (where the commonly used Gaussian kernel function is selected as the kernel function), three typical scenario output curves are obtained, as shown in Figure 2; The probabilities of the three scenarios appearing are 0.34, 0.221 5, and 0.438 5, respectively.

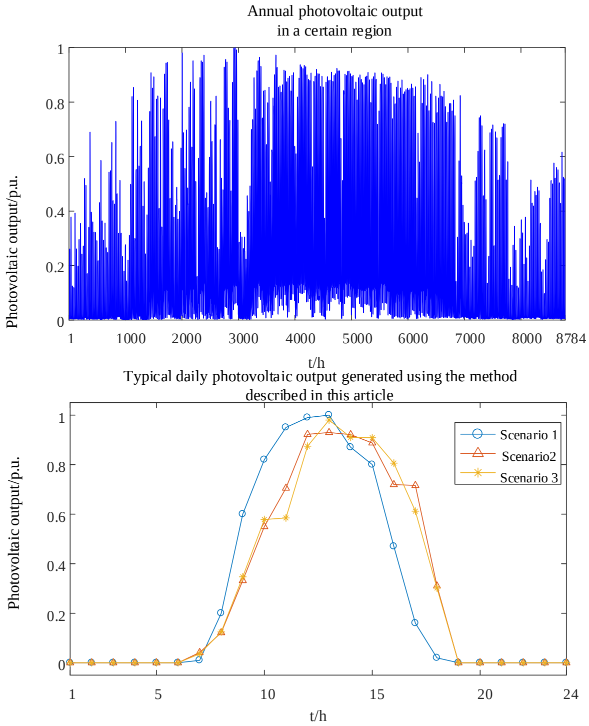


Fig.2 Historical outputs of photovoltaic and results of the scenario generation

Energy storage capacity configuration for typical scenarios

The amount of abandoned solar power in each typical output scenario is the product of the power exceeding the limit at different times and the corresponding time exceeding the limit.

Utilize the proposed model to optimize energy storage configuration in various typical scenarios, and compare the final configuration obtained through scenario method with the reference literature. The results are shown in Table 1.

Table 1. The result

| Scenario | Scenario1 | Scenario2 | Scenario3 | ref | Final configuration |
|---|---|---|---|---|---|
| Charging and discharging power/kW | 240 | 720 | 540 | 420 | 670 |
| Energy storage capacity/kWh | 960 | 290 | 810 | 1 010 | 630 |
| Solving time/s | 2.07 | 2.39 | 2.28 | 3.94 | / |
| Reduced rate of discarded light and electricity | 71.54 | 84.38 | 92.25 | 77.66 | 86.39 |
| Net benefit/102Y | 6.57 | 19.71 | 14.79 | 11.5 | 19.28 |
| Benefits of absorbing and discarding light/102Y | 38.75 | 116.26 | 87.2 | 67.82 | 113.68 |
| Environmental benefits/102Y | 0.22 | 0.65 | 0.49 | 0.38 | 0.64 |
| Configuration cost/102Y | 32.4 | 97.2 | 72.9 | 56.7 | 96.04 |

The capacity for configuring energy storage varies in different scenarios. This is because the power and duration of exceeding the limit vary in different scenarios. According to equations (6) and (7), they determine the power and capacity configuration of energy storage. The final energy storage configuration is obtained by multiplying the proportion of each scenario with the corresponding energy storage configuration in that scenario. From this, Table 2 shows that the final configuration of energy storage is 670 kW/630 kWh. Compared with the reference configuration of 420 kW/1 010 kWh, the following conclusions can be drawn through analysis:

(1) On the one hand, it is because the references directly configure a single scenario without considering the special scenario and its proportion, resulting in excessive allocation of energy storage capacity. The final configuration is to consider the weighted energy storage configuration for multiple photovoltaic output scenarios, which can simultaneously take into account the abandonment of light in most scenarios;

(2) From the perspective of computational time, the time taken to solve the energy storage configuration in each scenario using the proposed mutual exclusion technique is smaller than the time used in the reference literature. Even if multiple time periods are exceeded in Scenario 4, the computational time is also shorter than that in the reference literature. Therefore, the proposed method greatly reduces the calculation time.

## CONCLUSION

Starting from the perspective of configuring energy storage to absorb abandoned light in power systems, this article takes into account the operational loss characteristics of energy storage and constructs an energy storage optimization configuration model with the goal of maximizing the benefits obtained from consuming abandoned light. The conclusion is as follows:

To avoid the lack of representativeness in energy storage configuration for a single abandoned light scenario, the article proposes a scenario based method to obtain typical scenarios, and energy storage configuration is carried out based on each typical scenario. The final energy storage configuration is obtained by integrating the weight of each typical scenario with the sum of the power and capacity of the corresponding energy storage configuration in the scenario. And analyze the economic feasibility of the corresponding configuration. The calculation example shows that the final energy storage configuration can play a better coordination role between the cost of energy storage configuration and the benefits of grid connection from abandoned light.

The article adopts mutual exclusion technology to linearize the segmented operation strategy of energy storage. By simultaneously judging the operation interval and implementing corresponding charging and discharging strategies, it avoids the waste of computational space caused by comparing the energy storage charging and discharging power with the power exceeding the limit during each charging and discharging process, thereby improving the system's computational speed. The calculation results confirm this conclusion.

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