

# Selection Method for New Energy Output Guaranteed Rates Considering Optimal Energy Storage Configuration

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**Abstract**—The output of new energy represented by wind power and photovoltaic power features volatility and randomness. It is a practical approach to use the guaranteed rate with statistical characteristics to analyze the output coefficient of new energy. However, there is a lack of analysis and demonstration on the value of the new energy output guaranteed rate. To solve this problem, a selection method for the new energy output guaranteed rate considering optimal energy storage configuration is proposed. First, the influence of the new energy output guaranteed rate on the new energy output coefficient is analyzed. Secondly, with the goal of minimizing the comprehensive costs, an optimal configuration model of energy storage based on the output guaranteed rate of new energy is constructed, and particle swarm optimization is used for the optimization solution. Then, according to the optimal energy storage configuration results under different guaranteed rates, a reasonable new energy output guaranteed rate is determined by maximizing the comprehensive benefits obtained from energy storage. Finally, an example applied to the power grid in an area of Guangdong in Southern China is provided to illustrate the effectiveness of the proposed method.

**Index Terms**—Energy storage optimization, guaranteed output, guaranteed rate, new energy consumption.

## I. INTRODUCTION

THE energy consumption pattern dominated by traditional fossil energy leads to the continuous deterioration of energy resources and the ecological environment. A major issue facing the entire world is how to deal with the challenges of resources and the environment. In view of this problem, China proposed the goal of increasing the proportion of the renewable energy supply to over 60%. Developing new energy is the main solution to achieve this goal [1]–[3]. However, the output of new energy represented by wind power and photovoltaic

features volatility and randomness. This brings uncertainty to the planning and operation of the power system [4]–[8].

At present, a lot of research studies have been done on the analysis of new energy output characteristics at home and abroad. In general, the simulation of new energy output is an important basis for studying the influence of new energy on the power system. The core content of the simulation is to form a new energy output characteristic sequence consistent with statistical characteristics [9]. In references [10] and [11] the research progress of wind power's capacity reliability is introduced in detail, and the definitions and calculation methods of equivalent reliable capacity, equivalent conventional unit capacity, load-meeting capacity and guaranteed output under certain confidence are summarized. Reference [12] studies the wind power characteristics of Jiuquan, Gansu Province, and proposed the concept of guaranteed capacity and effective output, and made statistical analysis of guaranteed capacity and effective output using the guaranteed rate as a parameter. In the enterprise standard "Wind Power Grid Connection Technical Standard," China Southern Power Grid explicitly includes the guaranteed rate into the wind power characteristic index analysis, which provides a basis for wind power to be included in the calculation of electrical energy balance, and for the verification of the influence of wind power output on the power grid. Reference [13] studies the calculation method of new energy guaranteed output based on the guaranteed rate, and proposed a scheme to integrate the new energy guaranteed output into the grid reserve, which improved the absorption capacity of new energy.

The above research studies provide a good reference for the study of new energy output characteristics with strong practicability. But the value of the guaranteed rate has not been analyzed or demonstrated. In recent years, the development of energy storage technology has continued to mature and the cost has steadily decreased. Because of its ability to transfer electricity in time and space, it has become more and more widely used in new energy applications [14]–[16]. The idea of the optimal configuration of energy storage can be divided into two categories [17], [18]. One is to configure energy storage to meet the operational needs of the power system, in which the minimum system operating cost and energy storage investment cost are generally taken as the objective functions. In the other category, the energy storage is configured to increase economic value, and the maximum benefit is generally used as the objective function. In reference to the system operation

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problems caused by distributed power access, reference [19] puts forward an energy storage economic dispatch strategy with the goal of maximizing the comprehensive income of system loss and arbitrage from energy storage operations, which can effectively slow down the expansion of traditional substations, but simplifies distributed power output characteristics. In reference [20], the output guaranteed rate of new energy is taken as a variable, the trajectory sensitivity analysis model of probability power flow is established, the energy storage configuration strategy for the trajectory sensitivity is proposed, and the influence of the guaranteed rate on the energy storage configuration is qualitatively discussed. But it lacks a quantitative analysis method.

In light of this, this paper proposes a new energy output guaranteed rate selection method considering the optimal energy storage configuration.

1) The influence of the new energy output guaranteed rate on the new energy output coefficient is studied.

2) The optimal configuration model of energy storage based on the output guaranteed rate of new energy is constructed with the aim of minimizing the investment and maintenance cost of energy storage, power fluctuation cost and off-limit cost of the power flow. The particle swarm optimization algorithm is adopted for the optimization solution.

3) Based on the optimal configuration results of energy storage, the reasonable guaranteed rate of new energy output is determined by maximizing the comprehensive benefits of wind curtailment and light discarding, emission reduction and power supply reliability improvement obtained from energy storage.

Effectiveness of the proposed method is verified with a practical example, which provides a theoretical basis for the existing technical principles and serves as the boundary condition for the research of power grid planning and operations.

## II. GUARANTEED RATE OF NEW ENERGY OUTPUT

Reference [12] presents the definition of guaranteed capacity of wind power which is calculated as follows. Sort the wind power output from the largest to the smallest during the peak load period, and the guaranteed capacity of wind power is taken as the minimum output of wind power under a certain guaranteed rate. It is primarily used to measure the capacity of wind power participating in the power balance. While the effective wind power output refers to the maximum wind power output under a certain guaranteed rate, when the wind power is sorted from the smallest to the largest during the valley load period. It is primarily used to measure the capacity of wind power participating in peak load regulation balance.

The above definition primarily depicts the application of wind power guaranteed rate in power system planning from the perspective of power balance. Its core is to adopt relatively harsh scenarios to meet the adequacy of power balance and peak load regulation balance. Subject to geographical conditions, development costs and other factors, new energy tends to be concentrated in areas with a relatively weak power grid structure. Large-scale access of new energy brings great pressure to local power grid operations, resulting in

an overload of transmission lines or main transformers in extreme conditions. Therefore, it is of practical significance to introduce the concept of guaranteed rate to analyze the probabilistic power flow in measuring the influence of new energy on local power grid outward power flow capacity [21].

The historical output sequence of new energy at the moment of  $t$  during the day is  $\mathbf{p}_t = \{p_{t,1}, p_{t,2}, \dots, p_{t,n}\}$ , then the new energy output under guaranteed rate  $\alpha$  is:

$$p_{t,\alpha} = \mathbf{p}_t(N_\alpha) \quad (1)$$

$$N_\alpha = \max(\text{floor}(n \times \alpha), 1) \quad (2)$$

where  $p_{t,1} \leq p_{t,2} \leq \dots \leq p_{t,n}$  ( $n$  is the number of the statistical historical output sample at time  $t$ ),  $N_\alpha$  is the index value of the new energy historical output sequence  $\mathbf{p}_t$  under guaranteed rate  $\alpha$  ( $0 \leq \alpha \leq 100\%$ ), whose minimum value is 1, and the floor means rounding down.

In actual analysis, in order to calculate the output of new energy units under construction and planning in adjacent areas, (1) can be expressed by the output coefficient. Then the new energy installations under construction and planning can be used for approximate conversion. The new energy output coefficient at time  $t$  under guaranteed rate  $\alpha$  can be expressed as:

$$k_{t,\alpha} = \frac{p_{t,\alpha}}{G} \quad (3)$$

where  $G$  is the installed capacity of new energy. Fig. 1 shows how the output coefficient changes with the guaranteed rate of a wind farm at 12:00. The output coefficient corresponding to 50% of the guaranteed rate is only 0.14. The output coefficient corresponding to 80% of the guaranteed rate is less than 0.50. The corresponding output coefficient reaches around 0.85 only when the guaranteed rate is as high as 95%. Fig. 2 shows the guaranteed rate output curve of the wind farm at different times. The curve can be used to calculate the active power flow of transmission lines or transformers under different guaranteed rates of the local power grid in a typical day:

$$P_{t,\alpha} = \sum k_{t,\alpha}^w G^w + \sum k_{t,\alpha}^s G^s + \sum P_t^g - P_t^{\text{load}} - P_{t,\alpha}^{\text{loss}} \quad (4)$$

where  $P_{t,\alpha}$  denotes the active power flow of transmission lines or transformers at time  $t$  under the guaranteed rate  $\alpha$ ,  $k_{t,\alpha}^w$  and  $k_{t,\alpha}^s$  denote the wind power and photovoltaic output

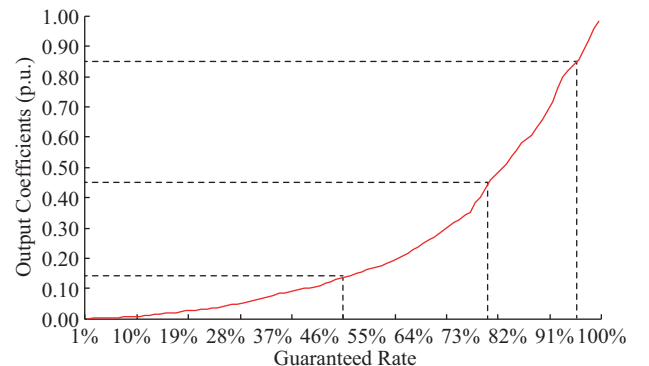


Fig. 1. Relationship between wind farm output coefficient and guaranteed rate.

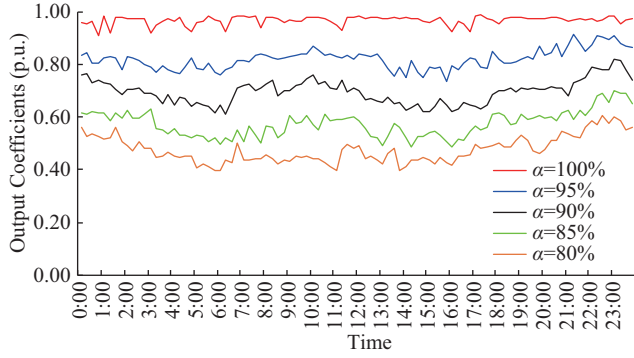


Fig. 2. Wind farm guaranteed rate output curves at different moments.

coefficients at time  $t$  under guaranteed rate  $\alpha$ , respectively.  $G^w$  and  $G^s$  represent the installed capacity of different wind farms and photovoltaic power stations in the local grid, respectively.  $P_t^e$  denotes the active power output of all conventional power sources in the local grid at time  $t$ .  $P_t^{\text{load}}$  and  $P_{t,\alpha}^{\text{loss}}$  represent the electrical load of the local power grid and system network loss at time  $t$ , respectively.

It can be seen that the value of the guaranteed rates has a huge impact on new energy output. It will have a further impact on the local power grid outward power flow. In literature currently available, the guaranteed rate is generally considered as 95% [12], [13], without detailed analysis or demonstration. This paper analyzes the influence of the energy storage optimization configuration results on power grid planning and operations under different guaranteed rates, considering the application of energy storage technology in new energy consumption. This paper also studies the selection method of the new energy output guaranteed rate.

### III. RESEARCH ON OPTIMAL CONFIGURATION OF ENERGY STORAGE

#### A. Optimal Objective Function

From the perspective of promoting the consumption of new energy and meeting the need of power supply security, the optimal energy storage configuration should not only meet the thermal stability limit of the transmission lines or transformers at the guaranteed rate  $\alpha$ , but also have certain economic efficiency. Based on the above goals and the existing research ideas, the energy storage charge-discharge power is set as the decision variable  $\mathbf{X}_\alpha$ .

$$\mathbf{X}_\alpha = [p_{1,\alpha}^{\text{es}}, p_{2,\alpha}^{\text{es}}, \dots, p_{t,\alpha}^{\text{es}}, \dots, p_{T,\alpha}^{\text{es}}] \quad (5)$$

where  $p_{t,\alpha}^{\text{es}}$  denotes the energy storage charge-discharge power at time  $t$  under the guaranteed rate  $\alpha$ . The value of  $p_{t,\alpha}^{\text{es}}$  is positive when the energy storage is charging, and negative when discharging.  $T$  denotes the settlement window during working hours of energy storage in a typical day.

Then the objective function of energy storage optimization is:

$$\begin{cases} \min_{\mathbf{X}_\alpha} f = C_{\text{cost}}(\mathbf{X}_\alpha) + C_{\text{fluc}}(\mathbf{X}_\alpha) + C_{\text{over}}(\mathbf{X}_\alpha) \\ \text{s.t. } \mathbf{H}(\mathbf{X}_\alpha) \leq 0 \end{cases} \quad (6)$$

where  $C_{\text{cost}}(\mathbf{X}_\alpha)$  denotes the energy storage investment and maintenance cost.  $C_{\text{fluc}}(\mathbf{X}_\alpha)$  denotes the transmission lines or transformers power fluctuation cost.  $C_{\text{over}}(\mathbf{X}_\alpha)$  denotes the transmission lines or transformers off-limit power flow penalty.  $\mathbf{H}(\mathbf{X}_\alpha)$  denotes the set of constraints.

In the above objective function, the investment and maintenance costs of energy storage are primarily related to its scale, which is in the category of planning; while the power fluctuation cost and the off-limit power flow penalty are related to the charge-discharge strategy, which is in the category of operation. Studies have shown that planning and operations have mutual influence during the process of optimal energy storage configuration [22], and the two are coupled through equality and inequality constraints.

a) The new energy guaranteed rate output curve mentioned above is primarily based on a typical intra-day analysis. In order to unify the time scale, the service life of energy storage is used to convert  $C_{\text{cost}}(\mathbf{X}_\alpha)$  into a daily average cost calculation, namely:

$$C_{\text{cost}}(\mathbf{X}_\alpha) = \frac{\beta}{(1 - (1 + \beta)^{-Y})D} \sum_{y=1}^Y \frac{C_y}{(1 + \beta)^y} \quad (7)$$

where  $\beta$  denotes the discount rate,  $Y$  denotes the energy storage service life (years),  $D$  denotes the annual energy storage operating days, and  $C_y$  denotes the energy storage fixed investment in year  $y$ .  $C_y$  is calculated as follows:

$$\begin{cases} C_1 = (c_1 + c_2) \times E^{\text{es}}(\mathbf{X}_\alpha) + c_3 \times P^{\text{es}}(\mathbf{X}_\alpha) \\ C_{2 \sim Y} = c_2 \times E^{\text{es}}(\mathbf{X}_\alpha) \end{cases} \quad (8)$$

where  $E^{\text{es}}(\mathbf{X}_\alpha)$  denotes the energy storage capacity under guaranteed rate  $\alpha$ ,  $P^{\text{es}}(\mathbf{X}_\alpha)$  denotes the energy storage power under guaranteed rate  $\alpha$ .  $c_1$  denotes the unit capacity cost of the energy storage system,  $c_2$  denotes the operation and maintenance cost of the energy storage system, and  $c_3$  denotes the unit power cost of the energy storage system.

b) The optimal configuration of energy storage should effectively improve the power flow characteristics of the power grid from which the new energy is sent out, and also smooth the power fluctuations. Power fluctuation cost can be expressed as:

$$C_{\text{fluc}}(\mathbf{X}_\alpha) = \lambda \sqrt{\frac{1}{T} \sum_{t=1}^T (P_t(\mathbf{X}_\alpha) - P_{t,\text{avg}}(\mathbf{X}_\alpha))^2} \quad (9)$$

where  $\lambda$  denotes the unit power fluctuation penalty coefficient,  $P_t(\mathbf{X}_\alpha)$  is the active power flow of the transmission lines or transformers considering the energy storage charge-discharge power decision variable  $\mathbf{X}_\alpha$ , and  $P_{t,\text{avg}}(\mathbf{X}_\alpha)$  is the expectation of  $P_t(\mathbf{X}_\alpha)$ , which can be expressed as:

$$\begin{cases} P_t(\mathbf{X}_\alpha) = P_{t,\alpha} - p_{t,\alpha}^{\text{es}} - \Delta P_{t,\alpha}^{\text{loss}} \\ P_{t,\text{avg}}(\mathbf{X}_\alpha) = \frac{1}{T} \sum_{t=1}^T P_t(\mathbf{X}_\alpha) \end{cases} \quad (10)$$

where  $\Delta P_{t,\alpha}^{\text{loss}}$  denotes the amount of change in the system network loss considering the energy storage charge-discharge power  $p_{t,\alpha}^{\text{es}}$  at time  $t$ .

c) The off-limit power flow penalty is expressed as:

$$C_{\text{over}}(\mathbf{X}_\alpha) = \gamma \int \Delta P_t(\mathbf{X}_\alpha) dt \quad (11)$$

where  $\gamma$  denotes the unit off-limit power penalty coefficient,  $\Delta P_t(\mathbf{X}_\alpha)$  is the amount of off-limit power, which can be expressed as:

$$\Delta P_t(\mathbf{X}_\alpha) = \begin{cases} P_t(\mathbf{X}_\alpha) - P_{\text{lim}}, & P_t(\mathbf{X}_\alpha) > P_{\text{lim}} \\ 0, & P_t(\mathbf{X}_\alpha) \leq P_{\text{lim}} \end{cases} \quad (12)$$

where  $P_{\text{lim}}$  denotes the thermal stability limit of the transmission line or transformer.

### B. Constraints

The constraint set  $\mathbf{H}(\mathbf{X}_\alpha)$  contains equality constraints and inequality constraints. Equality constraints primarily include system power balance constraints, storage power and capacity constraints, energy storage capacity state recursion constraints, etc. Inequality constraints primarily include node voltage constraints, power supply output constraints, energy storage output power constraints, state of charge constraints, etc. System power balance constraints, node voltage constraints, and power supply output constraints belong to the normal constraints of the power flow calculation. There has been a lot of discussion about these constraints in related papers. Therefore, no further discussion will be included here.

a) Energy storage power and capacity constraints are:

$$\begin{cases} P^{\text{es}}(\mathbf{X}_\alpha) = \max(|p_{t,\alpha}^{\text{es}}|), \forall t \in T \\ E^{\text{es}}(\mathbf{X}_\alpha) = \frac{1}{S_M - S_m} \sum_{t=1}^{\Delta T} \left( u_t^c \eta_c p_{t,\alpha}^{\text{es}} + \frac{u_t^d}{\eta_d} p_{t,\alpha}^{\text{es}} \right) \end{cases} \quad (13)$$

where  $S_M$  and  $S_m$  denote the maximum allowable state of charge and the minimum allowable state of charge of energy storage, respectively.  $\Delta T$  is the calculation period of a charge (discharge) cycle.  $\eta_c$  and  $\eta_d$  denote the efficiency of the energy storage under the state of charge and discharge, respectively.  $u_t^c$  is the energy storage charging code at time  $t$ , which is 1 when charging, and 0 in other time periods.  $u_t^d$  is the energy storage discharging code at time  $t$ , which is 1 when discharging, and 0 in other time periods.

$$u_t^c = \begin{cases} 1, & p_{t,\alpha}^{\text{es}} > 0 \\ 0, & p_{t,\alpha}^{\text{es}} \leq 0 \end{cases} \quad u_t^d = \begin{cases} 1, & p_{t,\alpha}^{\text{es}} < 0 \\ 0, & p_{t,\alpha}^{\text{es}} \geq 0 \end{cases} \quad (14)$$

b) The energy storage capacity state recursive constraint is [23]:

$$e_{t+1,\alpha}^{\text{es}} = e_{t,\alpha}^{\text{es}} + \left( u_t^c \eta_c p_{t,\alpha}^{\text{es}} + \frac{u_t^d}{\eta_d} p_{t,\alpha}^{\text{es}} \right) \Delta t \quad (15)$$

where  $e_{t,\alpha}^{\text{es}}$  denotes the remaining capacity of energy storage at time  $t$ , and  $\Delta t$  denotes the time interval of the calculation period.

c) The energy storage output power constraint should meet the requirement that the charge-discharge power does not exceed the upper and lower power limits at any time, namely:

$$-P^{\text{es}}(\mathbf{X}_\alpha) \leq p_{t,\alpha}^{\text{es}} \leq P^{\text{es}}(\mathbf{X}_\alpha) \quad (16)$$

d) The energy storage state-of-charge constraint requires that the energy storage capacity must be within the specified state-of-charge range at any time, ie.

$$S_m E^{\text{es}}(\mathbf{X}_\alpha) \leq e_{t,\alpha}^{\text{es}} \leq S_M E^{\text{es}}(\mathbf{X}_\alpha) \quad (17)$$

### C. Solution Method

As mentioned above, based on the new energy output guaranteed rate, formula (6) is the optimization goal together with all the relevant constraints, and represents the optimal energy storage configuration model constructed in this paper. This model belongs to the classical multi-decision variable optimization problem. In this paper, the particle swarm optimization (PSO) algorithm, which is widely used in power system planning and operations, is adopted for the solution [24], [25].

The optimal energy storage charge-discharge strategy is denoted as  $\mathbf{X}_{\alpha,\text{best}}$ . Then the energy storage rated power and rated capacity can be calculated according to (13), denoted as  $P_{\alpha,\text{best}}^{\text{es}}$  and  $E_{\alpha,\text{best}}^{\text{es}}$ , respectively.

## IV. SELECTION METHOD OF NEW ENERGY OUTPUT GUARANTEED RATE

In the previous paper, the optimal energy storage configuration method is studied based on the new energy output guaranteed rate. Results of the optimal energy storage configuration are different with different guaranteed rates. The corresponding new energy output guaranteed rate is determined by seeking to maximize the comprehensive benefits considering the system value of wind curtailment and light discarding benefits, emission reduction benefits, and power supply reliability improvement benefits brought about by different configuration results. This can be considered as the boundary conditions for power grid planning and operational research, which is:

$$\max F_\alpha = B_{\text{dis},\alpha} + B_{\text{em},\alpha} + B_{\text{re},\alpha} - C_{\text{cost},\alpha} \quad (18)$$

where  $F_\alpha$  denotes the comprehensive benefit of energy storage configuration under the guaranteed rate  $\alpha$ .  $B_{\text{dis},\alpha}$ ,  $B_{\text{em},\alpha}$ , and  $B_{\text{re},\alpha}$  denote the wind curtailment and light discarding benefit, emission reduction benefit, and power supply reliability improvement benefit, respectively.  $C_{\text{cost},\alpha}$  denotes the annual value of energy storage investment.

a) The benefit of wind curtailment and light discarding with energy storage under the guaranteed rate  $\alpha$  is:

$$B_{\text{dis},\alpha} = (E_{\text{dis},0} - E_{\text{dis},\alpha}) \sigma \quad (19)$$

where  $\sigma$  denotes the average on-grid electricity price of new energy.  $E_{\text{dis},0}$  is the annual amount of wind curtailment and light discarding without configuration of energy storage, and  $E_{\text{dis},\alpha}$  is the annual amount of wind curtailment and light discarding power with the energy storage configuration under the guaranteed rate  $\alpha$ , which are expressed as:

$$\begin{cases} E_{\text{dis},0} = \sum_{d=1}^D \left( \frac{1}{100} \sum_{\alpha=1\%}^{100\%} (\int \Delta P_{t,\alpha} dt) \right) \\ E_{\text{dis},\alpha} = \sum_{d=1}^D \left( \frac{1}{100} \sum_{\alpha=1\%}^{100\%} (\int \Delta P_t(\mathbf{X}_{\alpha,\text{best}}) dt) \right) \end{cases} \quad (20)$$

where  $\Delta P_{t,\alpha}$  and  $\Delta P_t(\mathbf{X}_{\alpha,\text{best}})$  can be calculated by referring to (12).

b) When the cost of carbon emission is considered, the emission reduction benefit of energy storage with a guaranteed rate of  $\alpha$  is as follows, benefiting from the benefits of wind curtailment and light discarding:

$$B_{em,\alpha} = (E_{dis,0} - E_{dis,\alpha})P_C\chi \quad (21)$$

where  $P_C$  denotes the approved carbon emission price,  $\chi$  denotes the carbon dioxide reduction factor per unit of electricity.

c) In a power failure incident, the energy stored in the energy storage is supplied to the users to maintain their uninterrupted power supply, thus improving the reliability of the power supply [26]. The benefit of power supply reliability improvement with the energy storage configuration under the guaranteed rate  $\alpha$  is:

$$B_{re,\alpha} = \min(P_{av}^{load}, P_{\alpha,best}^{es})T_{re}\delta \quad (22)$$

where  $T_{re}$  denotes the annual power outage time,  $P_{av}^{load}$  denotes the average power load during the power outage, and  $\delta$  denotes the cost of unit outage loss.

d) The annual value of energy storage investment  $C_{cost,\alpha}$

can be calculated with reference to (7). In order to be consistent with the time scale of comprehensive benefits, the impact of the annual operating days  $D$  is no longer considered, and  $P_{\alpha}^{es}$  and  $E_{\alpha}^{es}$  in (8) should be replaced by the rated power  $P_{\alpha,best}^{es}$ , best and the rated capacity  $E_{\alpha,best}^{es}$  of the energy storage.

According to the above research ideas, the calculation flow of the selection method of the new energy output guaranteed rate considering the optimal configuration of energy storage proposed in this paper is shown in Fig. 3.

## V. CASE ANALYSIS

An example of the power grid in a certain area of Guangdong Province is used for analysis. A simplified geographic connection of the power grid is shown in Fig. 4. There is one 500 kV substation (A1), two 220 kV substations (B1, B2), operating in a looped network with A1, and fifteen 110 kV substations (C1–C15) in the grid which are centered around B1 and B2, respectively. Due to the richness of wind and solar resources in the region, there are eleven wind farms

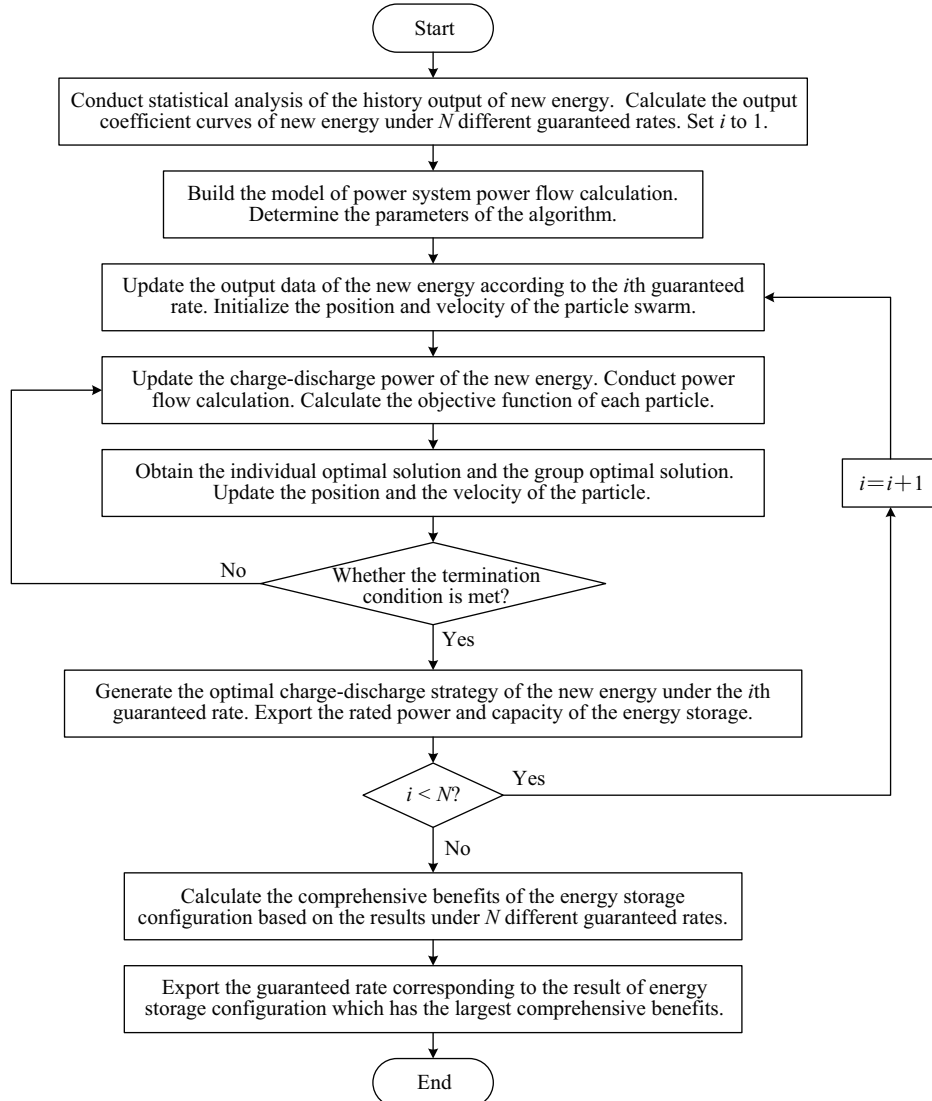


Fig. 3. Calculation process of selection of new energy output guaranteed rate.

(W1-W11, with a total installed capacity of 830 MW) and nine PV stations (S1-S9, with a total installed capacity of 460 MW) connected to it. This represents a typical regional grid for new energy outward transmission. A typical daily load characteristic curve of the region is shown in Fig. 5, the calculation method is as follows: perform curve fitting according to the average value of the load at each time on different dates, and select the date on which the load curve has the smallest deviation from the fitted curve as a typical day. The load curve is then standardized to form a typical daily load characteristic curve.

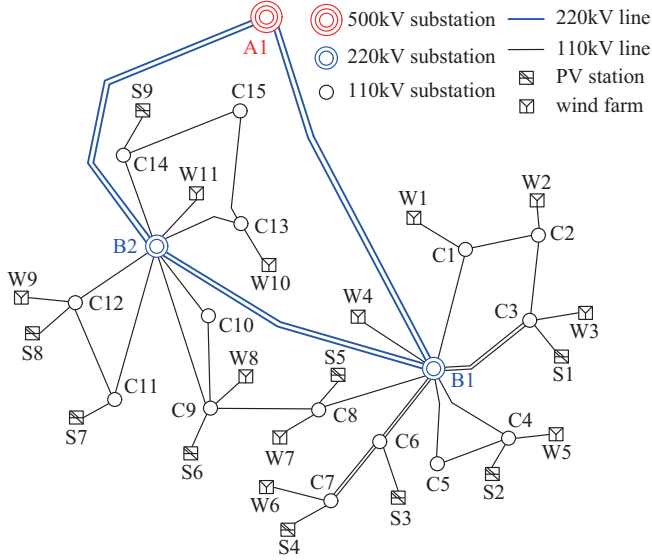


Fig. 4. Schematic diagram of geographic connection of power grid in a certain area of Guangdong Province.

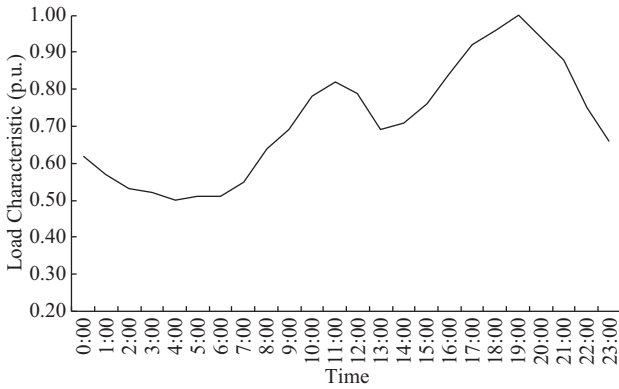


Fig. 5. A typical daily load characteristic curve.

#### A. Results of Optimal Energy Storage Configuration

The power flow of the transmission lines and transformers at any time can be calculated according to the power load demand, load characteristics and new energy output statistics under different guaranteed rates after constructing a power flow calculation model of the power system in the region. From the results of the power flow calculations, it can be seen that due to the small cross-section of the lines and the large installed capacity of new energy in the B2~C12~C11~B2

circle, the off-limits situation of the power flow is very serious in some periods.

The power flow curves of the B2~C12 line when the guaranteed rates are 90%, 95%, and 100%, respectively, are shown in Fig. 6. When the guaranteed rate is relatively small at 90%, the power flow of the B2~C12 line does not exceed the thermal stability limit at any time, which meets the requirements of new energy outward transmission. When the guaranteed rate is 100%, the power flow of the B2~C12 line exceeds the limit from 10:00 to 15:00, of which the maximum amount of off-limit power reaches 20.3 MW. Therefore, it doesn't meet the needs of new energy outward transmission. It can be seen that the greater the guaranteed rate, the higher the output coefficient of the new energy, the greater the off-limit power and electrical consumption.

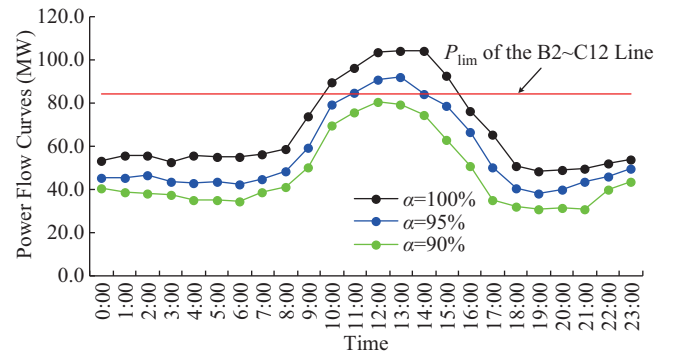


Fig. 6. Power flow curves of the B2~C12 Line under different guaranteed rates.

The research method in Section III is adopted to promote the consumption of new energy with energy storage configuration, while meeting the secure supply of electricity. The lithium battery system parameters used in the calculation example are shown in Table I. The unit power fluctuation penalty coefficient  $\lambda$  is 2,000 ¥/kW, and the unit off-limit power penalty coefficient  $\gamma$  is 10,000 ¥/kWh. During the optimization process, the number of particle swarms is set to 30, and the maximum number of iterations is 200. Taking  $\alpha = 100\%$  as an example, the optimized power flow curve and energy storage charge-discharge strategy are shown in Fig. 7.

TABLE I  
LITHIUM BATTERY PARAMETERS USED IN THE CASE

| Parameter              | Symbol   | Value                                      |
|------------------------|----------|--------------------------------------------|
| Charging efficiency    | $\eta_c$ | 0.85                                       |
| Discharging efficiency | $\eta_d$ | 0.9                                        |
| Max state of charge    | $S_M$    | 0.9                                        |
| Min state of charge    | $S_m$    | 0.1                                        |
| Unit capacity cost     | $c_1$    | 1200 ¥·kWh <sup>-1</sup>                   |
| Maintenance cost       | $c_2$    | 20 ¥·kWh <sup>-1</sup> ·year <sup>-1</sup> |
| Unit power cost        | $c_3$    | 300 ¥·kW <sup>-1</sup>                     |
| Discount rate          | $\beta$  | 7%                                         |
| Service life           | $Y$      | 10 year                                    |
| Annual operating days  | $D$      | 365 day                                    |

According to the optimal energy storage charge-discharge strategy in Fig. 7, it is concluded with (13) that when  $\alpha = 100\%$ , the energy storage rated power is  $P_{100\%,best}^{es} = 30.58$  MW, and the rated capacity is  $E_{100\%,best}^{es} =$

137.47 MWh. Furthermore, after performing the above operations for each guaranteed rate that causes power overrun of the B2~C12 line, the energy storage charge-discharge strategies under different guaranteed rates are obtained. The optimal configuration results are shown in Table II. When the guaranteed rate increases, the level of the new energy outward transmission curve rises rapidly, and the rated power and rated capacity of the energy storage that needs to be configured increases rapidly.

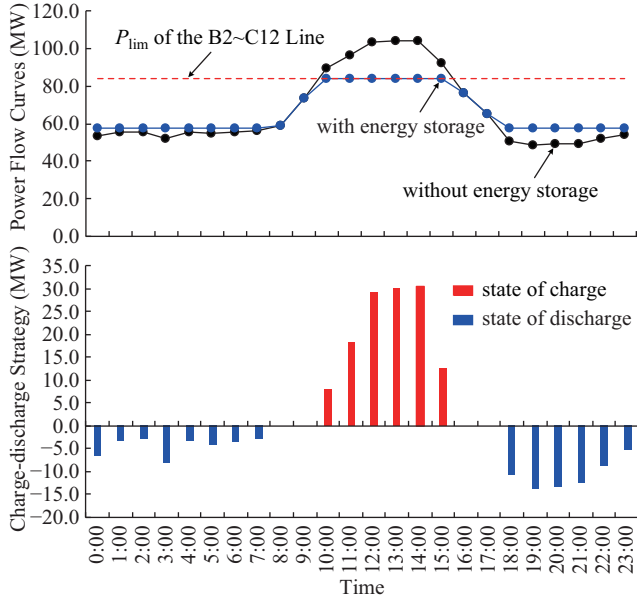


Fig. 7. Optimized power flow and energy storage charge-discharge curve when the guaranteed rate  $\alpha = 100\%$ .

TABLE II  
OPTIMAL ENERGY STORAGE CONFIGURATION RESULTS UNDER  
DIFFERENT GUARANTEED RATES

| Guaranteed rate $\alpha$ | Rated power /MW | Rated capacity /MWh | Guaranteed rate $\alpha$ | Rated power /MW | Rated capacity /MWh |
|--------------------------|-----------------|---------------------|--------------------------|-----------------|---------------------|
| 91%                      | 0               | 0                   | 92%                      | 0.28            | 0.3                 |
| 93%                      | 4.3             | 8.45                | 94%                      | 7.6             | 14.9                |
| 95%                      | 11.72           | 25.4                | 96%                      | 15.24           | 35.32               |
| 97%                      | 20.68           | 40.01               | 98%                      | 22.85           | 76                  |
| 99%                      | 28.56           | 103.83              | 100%                     | 30.58           | 137.47              |

### B. Determination of the Guaranteed Rate of New Energy Output

In part A, the optimal energy storage configuration that meets the outward transmission of new energy through the B2~C12 line under different guaranteed rates is calculated. Based on the result, this section further determines under which guaranteed rate the comprehensive benefits will be maximized.

The calculation method of comprehensive benefits proposed in Section IV is adopted. The average on-grid price of new energy  $\sigma$  is set as 0.61 ¥/kWh, the carbon dioxide reduction factor per unit of electricity  $\chi$  is set as 0.98, and the carbon emission price  $P_C$  is set as 400 ¥/t. The annual power outage time  $T_{re}$  in this area is 11.29 hours.

According to (20),  $E_{dis,0}$  is 454.05 MWh. When  $\alpha = 100\%$ ,

it can be guaranteed that the regional power grid does not have wind curtailment and light discarding, namely,  $E_{dis,100\%}$  is 0. At this time, the benefit of wind curtailment, light discarding, and emission reduction are the largest, reaching 1.66 million yuan. Meanwhile, since the energy storage has a relatively large rated power, it can maintain the uninterrupted power supply to all users in the event of a power failure. The benefit of power supply reliability has reached 10.67 million yuan. However, due to the large scale of energy storage configuration, and because the annual value of investment is as high as 25.92 million yuan, the comprehensive benefit is negative. That is, the actual effect of energy storage planning at a guaranteed rate of 100% is not good.

According to the optimal energy storage configuration results in Table II, the comprehensive benefits under different guaranteed rates are calculated based on (13), as shown in Fig. 8. It can be seen from the figure that when the guaranteed rate  $\alpha$  is 97%, the maximum benefit  $F_{97\%}$  can be obtained which is 1.97 million yuan. When  $\alpha$  exceeds this value, due to the overall increase in the level of the output curve of the new energy, although the rated power of the energy storage is not greatly increased, the rated capacity of the energy storage is greatly increased, resulting in an increase in investment costs much greater than the increase in benefits. Based on the above analysis, a new energy output guaranteed rate of 97% can be selected in this case to analyze the impact of new energy on local power grid planning and implementation.

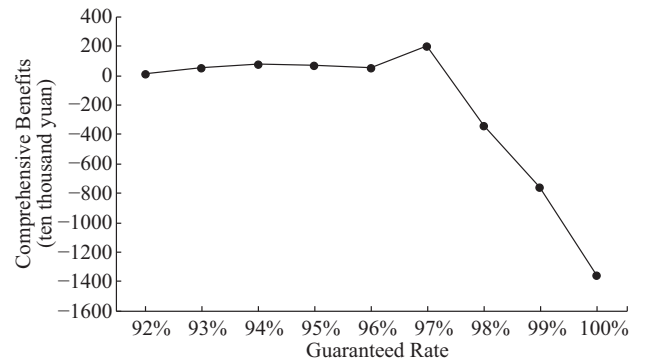


Fig. 8. Comprehensive benefits under different guaranteed rates.

Considering the influence of investment cost on the optimal configuration model and the comprehensive benefit of energy storage, a further analysis is conducted on the sensitivity of unit capacity cost of energy storage for the selection of the guaranteed rate. Fig. 9 shows the curves of comprehensive benefit with the guaranteed rate when  $c_1$  ranges from 300 ¥/kWh to 1500 ¥/kWh. When  $c_1 = 1500$  ¥/kWh, due to the high investment cost of the energy storage system and the low overall benefit, the guaranteed rate is set to a low value of 94% to improve the reliability of the power supply of important loads. When  $c_1 = 300$  ¥/kWh, due to the low investment cost of the energy storage system and high overall benefits, the guaranteed rate can be as high as 98% to meet the reliability of the power supply while promoting the consumption of new energy. When  $c_1$  is between 600 ¥/kWh and 1200 ¥/kWh, the guaranteed rate can be set to 97% as in this paper.

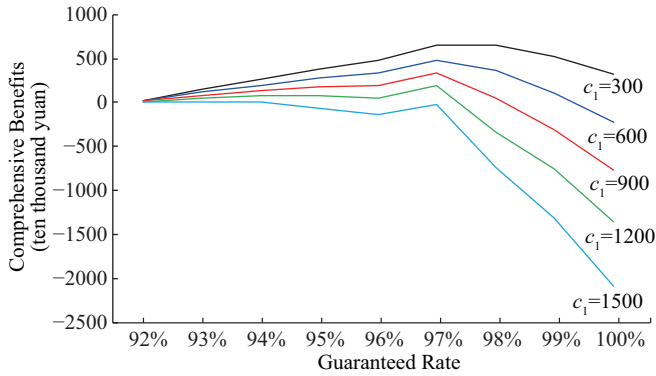


Fig. 9. A sensitivity analysis of  $c_1$  (unit capacity cost of energy storage) for the selection of the guaranteed rate.

## VI. CONCLUSION

In this paper, a new energy output guaranteed rate selection method considering the optimal energy storage configuration is proposed. The concept of guaranteed rate is introduced to analyze the output coefficient of the new energy with the statistics of its historical output. An optimal energy storage configuration model based on the new energy output guaranteed rate is constructed. According to the optimal configuration results under different guaranteed rates, a reasonable new energy output guaranteed rate is selected by maximizing the comprehensive benefits, such as wind curtailment and light discarding benefits, emission reduction benefits, and power supply reliability improvement benefits obtained with energy storage. On the one hand, it can provide analysis and an argumentation basis for the existing technical principles, on the other hand, it can be used as the boundary conditions to carry out grid planning and operational research.

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