Economic Study of Wind and Solar Power Generation with Energy Storage Configuration

Zhengyang Su [*,†], Jiangtao Huang [†], Limengdan Wu [†]

Xingzhi College, Zhejiang Normal University, Jinhua, China, 321100

* Corresponding Author Email: zhengyangsu003@163.com

† These authors contributed equally.

Abstract. With the growth of new energy demand, energy storage technology has a broad application prospect in solving the intermittency problem of wind power generation, improving the stability of the grid, and reducing the operating cost. This research first established and solved an efficient wind-solar economic allocation model for wind and solar energy storage configuration and economic cost. It obtained a total power supply cost of 6466.35 yuan for wind and solar power generation without energy storage configuration. Then, by establishing a collaborative optimization model for wind, solar, and energy storage, the target cost optimization for the economical operation of quantitative energy storage configuration was carried out. Finally, a collaborative cost minimization model for wind, solar, and energy storage was established to obtain the optimal operation strategy for energy storage with minimized costs. The collaborative cost minimization model for wind, solar, and energy storage can effectively optimize the energy storage power of 377kW and capacity allocation of 1130kWh, which is of great significance in ensuring the coordinated allocation of power operation and economic benefits for wind, solar, and energy storage in the country.

Keywords: Energy Storage Technology, Power Operation, Optimization Model, Electric Power Operation.

1. Introduction

With the continuous growth of global energy demand and the increasingly serious environmental issues, the development and utilization of new energy have become the focus of attention for governments and academic circles around the world. Wind energy and solar energy, as two important renewable energy sources, occupy an important position in the optimization of energy structure due to their clean and renewable characteristics. Some studies have indicated that microgrid energy storage is a new type of renewable energy supply and management technology [1-3]. However, the intermittent and unstable nature of wind and solar power generation poses many challenges for their large-scale application in the power grid.

To address the intermittency issue of wind and solar power generation, the application of energy storage technology has received widespread attention. The linear programming and particle swarm optimization algorithms used in this article have been extensively studied and applied in areas such as collaborative economic research on wind-solar energy storage [4, 5]. Currently, there are also many algorithms available to solve similar problems. Some studies have implemented artificial intelligence-enabled microgrid optimization operations for low-carbon economies by adopting heuristic algorithms, genetic algorithms, their improved algorithms, and particle swarm optimization algorithms [6]. A hybrid particle swarm optimization algorithm has been proposed in a study, which combines a stochastic weight-balanced particle swarm optimization algorithm and an immune mechanism to ensure that the initial particles are evenly distributed within the coordinate plane [7]. Through nonlinear weights and a subgradient optimization strategy, the algorithm improves its optimization ability and convergence speed. Another study established an economic operation cost minimization objective function for the microgrid system and utilized an improved particle swarm optimization algorithm to solve the model [8]. Another research adopted multiple normal random number perturbations to the evolution direction of particle swarm optimization algorithm speed and position, improving the accuracy of the MNPSO algorithm in optimizing the economic operation of microgrids [9]. In some studies, a chaotic fireworks algorithm was used to optimize the usage time of demand loads and the active power output of power sources in microgrids, demonstrating that the microgrid optimization operation model significantly improves the economic performance of microgrid system operation [10].

In this paper, our objective is to analyze the economic performance of wind-solar energy storage operation, both with and without the configuration of quantitative energy storage, based on typical daily wind and solar power generation. To achieve this goal, planning functions are used to determine the purchase amount of wind-solar energy storage, wind and solar curtailment amount, total power supply cost, and average power supply cost per unit. Then, by establishing linear programming equation functions combined with the particle swarm optimization algorithm, we seek to identify the optimal operation strategy for energy storage. Finally, we derive the optimal power supply cost for wind-solar energy storage and analyze whether the quantitative energy storage scheme is the optimal choice. This analysis will help us understand the role of energy storage in enhancing economic performance and delve deeper into the key factors influencing the economic viability of wind-solar energy storage operation.

2. Economic Analysis of Wind and Solar Power with Energy Storage

The data for this research was sourced from http://shumo.neepu.edu.cn/#/. The data underwent normalization processing. Based on the normalized data, the formula for coordinated wind and solar power generation is $F_F=r\cdot p$, where F represents the coordinated wind and solar power generation, r represents the unit value, and p represents the installed capacity of the wind and solar power configuration.

The amount of power purchased can be obtained from normalized data, and the formula for coordinated wind-solar power purchases is:

$$E_P=\sum_{i=1}^{3}\sum_{j=1}^{24}N_{WT}+N_{PV} \tag{1}$$

In the formula, E_P represents the typical daily load data of wind-solar energy storage, while N_{WT} and N_{PV} represent the daily load data of wind power and photovoltaic at the j-th moment of wind-solar energy storage, respectively. The amount of power curtailed at the i-th moment, due to the lack of an energy storage battery, is:

$$Q_L=\sum_{i=1}^{3}\sum_{j=1}^{24}\max\left\{f_j+k_j-F_j\right\} \tag{2}$$

In the formula, Q_L represents the amount of power curtailed from wind-solar energy storage, f_j represents the wind power generation in the j-th period of wind-solar energy storage, and k_j represents the photovoltaic power generation in the j-th period of wind-solar energy storage. F_j represents the purchased electricity quantity of wind-photovoltaic energy storage in the jth time period.

Based on the data, the operation rule of wind-solar energy storage is that renewable energy generated by wind and solar power is preferentially supplied to the local load. If there is insufficient power, it will be purchased from the main grid. However, excess power is not allowed to be sold to the main grid. The total power supply cost is:

$$D_{OM}=C_{WT}F_F+C_{PV}F_F+C_CE_P \tag{3}$$

The price of purchasing electricity from the main grid is C_C; the electricity purchase costs from wind power and photovoltaic for wind-solar energy storage are C_{WT} and C_{PV}, respectively. D_{OM} represents the total power supply cost.

The average unit power purchase cost is $L_{Avg}=D_{OM}/E_P$, where L represents the unit power purchase cost of wind-solar energy storage. System power balance:

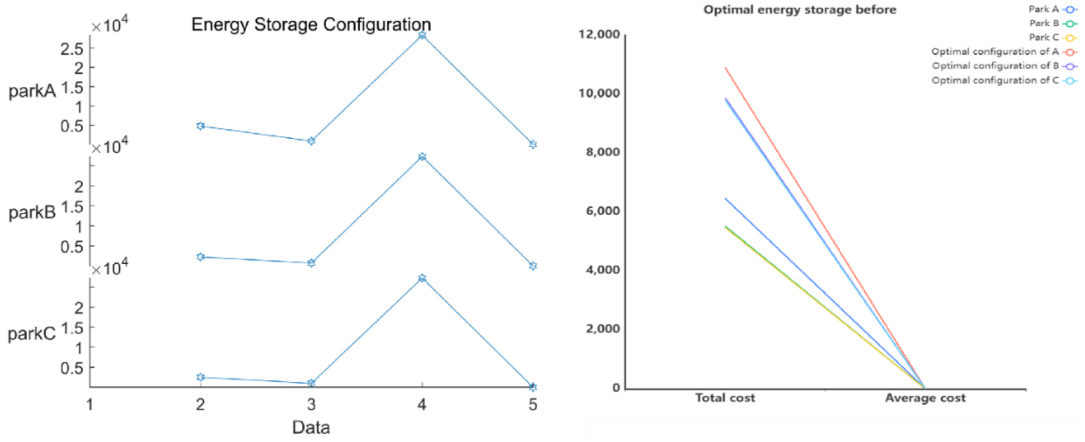
$$P_{L\max} = P_{PV} + P_{WT} + E_P \tag{4}$$

In the formula, P_{Lmax} represents the load power in the microgrid with wind-solar energy storage; P_W represents the wind power generation capacity in the wind-solar energy storage; P_{PV} represents the photovoltaic power generation capacity in the wind-solar energy storage.

Based on linear programming, an efficient wind-solar economic allocation model was established. Using MATLAB software for programming and solving, the power purchase, wind, and solar power curtailment, total power supply cost, and average unit power supply cost for each park without energy storage configuration are shown in Table 1.

Table 1. Operation Costs of Wind-Photovoltaic Energy Storage

Wind energy storage Park	Wind Energy Storage Park A	Wind Energy Storage Park B	Wind Energy Storage Park C
Electricity purchase	4911.13	2421.30	2713.39
Abandon wind and light power	948.20	901.50	1131.02
Total power supply cost	6466.35	5521.90	5481.08
Average power supply cost per unit of electricity	0.82	0.72	0.70



(A) (B)

Figure 1. (A) Energy Storage Configuration; (B) Optimal energy storage before

As can be seen from Figure 1, there are various key factors that affect its economic performance. For example, the amount of power purchased depends on the temporal matching degree between the wind-solar power generation capacity and the load power in the park. When the wind-solar power generation capacity cannot meet the load demand, the park needs to purchase power from the main grid. The amount of wind and solar power curtailment refers to the electricity generated by wind and solar power that exceeds the load demand but cannot be utilized. This portion of power will be wasted as it is not allowed to be sold to the main grid, along with the possibility of high operation and maintenance costs for energy storage equipment.

3. Economic Analysis of Microgrid with Energy Storage Configuration

According to the data, Energy Storage that lithium iron phosphate battery stores power, and the power of the battery is P, the energy is E. The unit price of power is P_p, the unit price of energy is e_p, the SOC (State of Charge) allowable range is 10%-90%, the charge/discharge efficiency is 95%, and the operational lifespan is calculated as 10 years. In the process of battery charging and discharging, the following constraints need to be considered:

According to the data, lithium iron phosphate batteries are used for energy storage. The unit price of power is Pp, the unit price of energy is ep, the SOC (State of Charge) allowable range is 10%-90%, the charge/discharge efficiency is 95%, and the operational lifespan is calculated as 10 years. In the process of battery charging and discharging, the following constraints need to be considered:

To ensure the battery's lifespan and operational safety, S_{SOC} (State of Charge) is an important decision variable for the energy storage controller to prevent overcharging and over-discharging of the battery. When S_{SOC} reaches the maximum capacity of the battery (i.e., S_{max}=90%), the energy storage controller will control the battery to stop charging. When S_{SOC} reaches the minimum charge state of the battery, the energy storage controller will control the battery to stop discharging. S_{min} is typically 10% of the battery's capacity [11]. Namely:

$$E_{SOC,t+1} = E_{SOC,t} - P_- + P_+ \tag{5}$$

$$S_{\min} \le S_{SOC} \le S_{\max} \tag{6}$$

The lifespan of a battery is also related to its charge and discharge rates, and excessively high charge and discharge rates can reduce the battery's lifespan. The charge and discharge capacity per hour cannot exceed 20% of its maximum capacity. Let Δt represent 1h, and P_+ and P_- represent the charge and discharge power per unit hour, respectively. That is:

$$\begin{cases} P_+ \le 0.2E_{bat} / \Delta t \\ P_- \le 0.2E_{bat} / \Delta t \end{cases} \tag{7}$$

The power balance of a system with wind-solar energy storage:

$$P_{L\max} = P_{PV} + P_{WT} + E_P + P_{SOC} \tag{8}$$

In the equation, P_{Lmax} represents the load power in the microgrid with wind-solar energy storage; PW represents the wind power generation power in the wind-solar energy storage; P_{PV} represents the photovoltaic power generation power in the wind-solar energy storage; and PSOC represents the output of the energy storage battery, and if its value is negative, it indicates a charging state [12].

The output power constraint of the energy storage device's battery is:

$$P_{SOC.\min} \le P_{SOC} \le P_{SOC.\max} \tag{9}$$

In the above equation, $P_{SOC.\min}$ and $P_{SOC.\max}$ represent the minimum and maximum output power of the battery in the energy storage device, respectively. If the value is negative, it represents the charging power.

The total cost of quantitative energy storage for lithium iron phosphate batteries is expressed as:

$$C_{bs} = P \times P_p + E \times e_p \tag{10}$$

To establish a target function for minimizing the cost of quantitative energy storage, this article combines the above formulas to create a composite microgrid power supply optimization configuration model that includes wind power, photovoltaic power, power purchased from the main grid, and battery supply. The main components of the target function include the total power supply cost of wind-solar energy storage, the amount of electricity curtailed, and the configuration of a quantitative energy storage battery. The goal is to minimize the daily investment cost while meeting the power supply reliability requirements of the park. The economic mathematical model is established as follows:

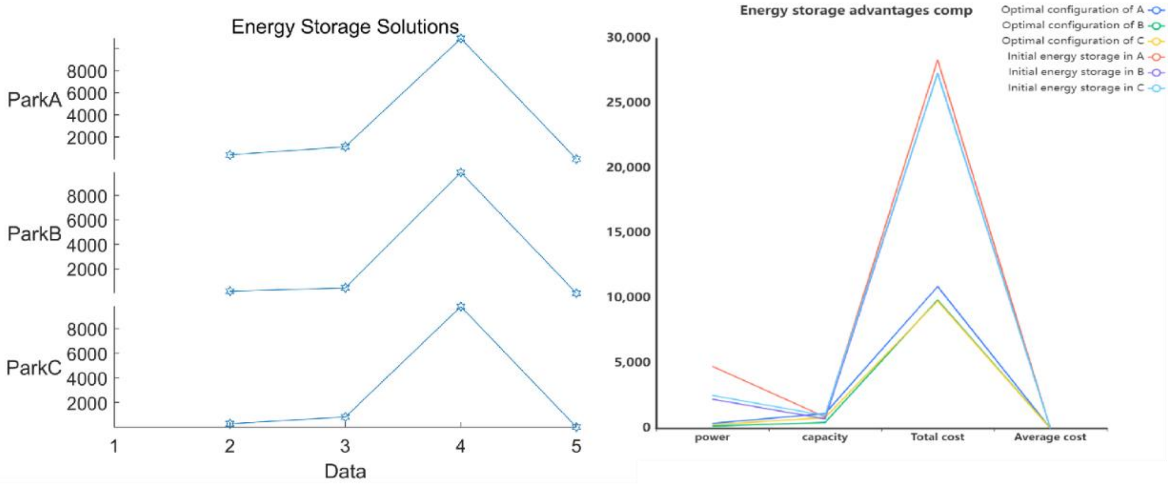
$$\min f_1 = D_{OM} + Q_L + C_{bs} \tag{11}$$

$$S.t.\begin{cases} E_{SOC,t+1} = E_{SOC,t} - P_- + P_+ \\ S_{\min} \le S_{SOC} \le S_{\max} \\ \begin{cases} P_+ \le 0.2E_{bat} / \Delta t \\ P_- \le 0.2E_{bat} / \Delta t \end{cases} \\ P_{SOC.\min} \le P_{SOC} \le P_{SOC.\max} \end{cases} \tag{12}$$

Based on linear programming, a collaborative optimization model for wind-solar energy storage was established. Using MATLAB software to program the Particle Swarm Optimization (PSO) algorithm, the optimal electricity purchased, amount of wind and solar energy curtailed, total power supply cost, and average power supply cost per unit of electricity for three parks with quantitative energy storage for wind-solar configuration were obtained, as shown in Table 2.

Table 2. Operating Costs of Wind-Photovoltaic Quantitative Energy Storage

Park area	Energy storage after park A	Energy storage after Park B	Energy storage after Park C
Electricity purchase	4771.11	2242.30	2529.30
Abandon wind and light power	869.99	722.41	990.10
Total power supply cost	28349.43	27331.90	27298.11
Average power supply cost per unit of electricity	3.61	3.54	3.52



(A) (B)

Figure 2. (A) Energy Storage Solution; (B) Energy storage advantages comp

This article compares the electricity purchased, amount of wind and solar energy curtailed, total power supply cost, and average power supply cost per unit of electricity for three parks with and without energy storage configurations, and develops optimal energy storage operation strategies and electricity purchase plans as shown in Table 2.

Based on Figure 2, the economic operation of each park has been improved in some small aspects. The main reason should be the decrease in power purchase. Compared with the quantitative configuration of batteries, the power purchase of the three parks has decreased, indicating that battery configuration helps reduce the demand for power purchase. As for the abandoned wind and solar power, after the optimal configuration of batteries, the abandoned wind and solar power of the three parks has been reduced, indicating that battery configuration helps improve the utilization of wind and solar energy.

4. Economic Study of Optimized Energy Storage Solutions

Based on the capacity optimization configuration problem in this article, assuming that the fluctuation characteristics of wind-solar-load power remain unchanged, let's explore whether the scheme of quantitatively configuring energy storage for wind and solar is optimal. According to the information we've gathered, most of the mainstream energy storage batteries on the market are 100kW/225kWh and 700kW/1400kWh. Therefore, the following constraints are established:

$$\begin{cases} 50kW/100kWh < a \le 100kW/225kWh \\ 100kW/225kWh < a \le 700kW/1400kWh \end{cases} \tag{13}$$

By incorporating these constraint conditions into the objective function have:

$$\min f_2 = D_{OM} + Q_L + C_{bs} \tag{14}$$

$$S.t.\begin{cases} E_{SOC,t+1} = E_{SOC,t} - P_- + P_+ \\ S_{\min} \le S_{SOC} \le S_{\max} \\ \begin{cases} P_+ \le 0.2E_{bat}/\Delta t \\ P_- \le 0.2E_{bat}/\Delta t \end{cases} \\ \begin{cases} 50kW/100kWh < a \le 100kW/225kWh \\ 100kW/225kWh < a \le 700kW/1400kWh \end{cases} \end{cases} \tag{15}$$

To formulate the optimal operation strategy for energy storage and power purchase plans, the Particle Swarm Optimization (PSO) algorithm is used in this paper. Due to its few parameters and ease of implementation, the PSO algorithm possesses strong global search capabilities for optimizing nonlinear and multimodal problems. Different improved methods will effectively enhance its convergence and optimization capabilities.

PSO initializes with a group of random particles (random solutions). Then it finds the optimal solution through iterations. In each iteration, particles update themselves by tracking two "extrema." After finding these two optimal values, particles update their velocities and positions according to the following equations [13].

$$v_i = v_i + c_1 \times rand() \times \left(pbest_i - x_i\right) + c_2 \times rand() \times \left(gbest_i - x_i\right) \tag{16}$$

$$x_i = x_i + v_i \tag{17}$$

In the above equations, i=1, 2, ..., N, where N is the total number of particles in the swarm. v_i represents the velocity of the particle; *rand( )* is a random number between (0, 1); x_i is the current position of the particle; c_1 and c_2 are learning factors, often set as c_1=c_2=2; the maximum value of v_i is Vmax (greater than 0), and if v_i exceeds Vmax, then v_i is set to Vmax.

Currently, the more commonly used strategy is the linearly decreasing weight strategy [14].

$$\omega^{(t)} = \left(\omega_{ini} - \omega_{end}\right)\left(G_k - g\right)/G_k + \omega_{end} \tag{18}$$

In the equations, G_k represents the maximum number of iterations; ω_{ini} represents the initial inertia weight; ω_{end} represents the inertia weight when iterating to the maximum evolution generation; typical weights are ω_{ini}=0.9, ω_{end}=0.4 [15].

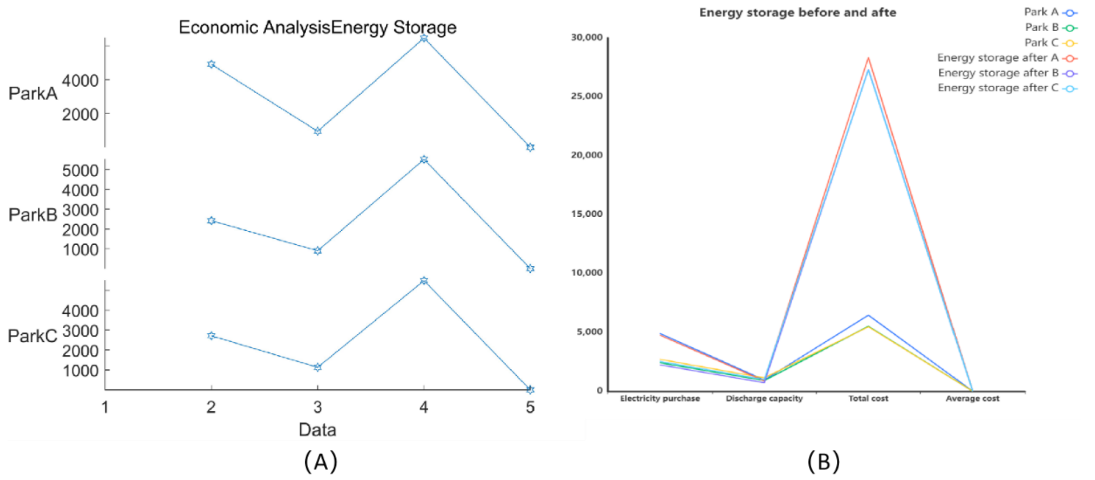
The introduction of ω has greatly improved the performance of the PSO algorithm. For different search problems, the global and local search capabilities can be adjusted, enabling the PSO algorithm to be successfully applied to many practical problems.

Based on linear programming, a collaborative cost minimization model for wind, solar, and energy storage was established. This model was then implemented in the Particle Swarm Optimization

(PSO) algorithm to find the best configuration of energy storage batteries. The results of the PSO algorithm were solved using MATLAB and are presented in Table 3.

Table 3. Optimized Wind-Photovoltaic Energy Storage Battery Solution

Park area	Optimal configuration of Park A	Optimal configuration of Park B	Optimal configuration of Park C
Energy storage power	377	163	274
Energy storage capacity	1130	444	821
Total power supply cost	10904.56	9881.70	9798.08
Average power supply cost per unit of electricity	1.37	1.28	1.26



(A)

(B)

Figure 3. (A) Economic Analysis Energy Storage; (B) Energy storage before and afte

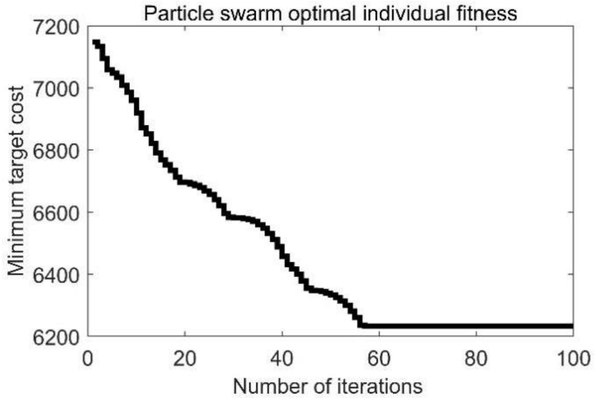


Figure 4. Particle swarm optimal individual fitness

Based on the analysis presented in Table 3, Figure 3 and Figure 4, the Particle Swarm Optimization (PSO) algorithm has successfully identified the optimal energy configuration, indicating that quantitative energy storage configuration is not the ideal solution. The results demonstrate that the optimized energy storage power capacity configuration for each park significantly outperforms the quantitative approach, primarily in terms of reducing wind and solar power curtailment. By fine-tuning the energy storage configuration, the predicted battery capacity is tailored to the specific conditions and requirements of each park, thereby making it more suited to energy demands and renewable resource availability. This approach helps enhance energy utilization efficiency, minimize wind and solar power curtailment, and effectively manage the total power supply cost and average cost per unit of electricity.

5. Conclusion

This paper studies the economics of wind-solar generation with energy storage configuration. The mismatch of wind and solar generation with load timing tends to cause power curtailment. Energy storage configuration can alleviate this problem but with high costs. Therefore, a model is established to consider investment and revenue comprehensively. Based on data and actual conditions, a mathematical model is built for analysis in this study. An efficient wind-solar economic configuration model is established based on constraint conditions, which plans the power purchase, wind and solar curtailment, total power supply cost, and average power supply cost per unit. For example, the power purchase, wind and solar curtailment, total power supply cost, and average power supply cost per unit for Park C are 2713.39, 1131.02, 5481.08, and 0.70 respectively. Details of other wind-solar energy storage parks are shown in Table 1. Subsequently, through the established wind-solar-storage collaborative optimization model, the optimal operation strategy and power purchase plan of energy storage are determined. For example, after energy storage, the power purchase, wind and solar curtailment, total power supply cost, and average power supply cost per unit for Park C are 2529.30, 990.10, 27298.11, and 3.52 respectively. Details of other wind-solar energy storage parks are shown in Table 2. According to the above analysis, a quantitative energy storage solution is not the optimal choice. Based on the wind-solar-storage collaborative cost minimization model, the optimal energy storage power and capacity configuration plan for each park are obtained. For example, the optimal energy storage power and capacity configuration for Park C are 274 and 821 respectively. Details of other wind-solar energy storage parks are shown in Table 3. It can be concluded that the wind-solar-storage coordinated configuration scheme established by the optimization model requires the least total cost and has high operational economics.

This article provides a research approach utilizing linear programming models in renewable energy-related fields. It leverages the powerful data optimization capabilities of particle algorithms to establish a wind-solar-storage collaborative cost minimization model. Experimental results show that the wind-solar-storage collaborative cost minimization model established in this article has the characteristics of fast optimization speed and ease of escaping from local optimal solutions, demonstrating its practical application value.

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