Optimal Configuration and Economic Analysis of Wind-Solar-Storage Resources in Multi-Park Hybrid Microgrids Based on Hybrid Intelligent Algorithms

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Abstract. To solve the problems of low renewable energy utilization and high grid dependence in multi-park hybrid microgrids (MPHMs), this paper aims to develop a centralized optimization framework for the wind-solar-storage resource configuration to realize the coordinated operation of new energy suppliers, integrated energy service providers and end-users. An multi-objective economic dispatch model considering source-storage-load-grid coordination, time-of-use pricing and demand response incentive, as well as technical constraints of energy storage is established. An improved hybrid intelligent algorithm combining NSGA-III with enhanced solution selection based on clustering is designed to efficiently solve the optimization problem and obtain practical configurations. The proposed method is applied to a system including industrial, commercial and residential parks with different loads and renewable generation capacity. Simulation results indicate that the optimal energy storage configuration can eliminate the renewable curtailment in all parks and reduce both daily electricity purchasing cost from main grid and total daily power supply cost. These results demonstrate that coordinated planning can improve both sustainability and economy of MPHMs. Sensitivity analyses validate that the solution is robust to the variations of storage cost, incentive policy and renewable generation capacity. The proposed method performs better than non-storage scenario even in unfavorable cost conditions. The proposed scalable and practical method provides a valuable reference for optimizing multi-area microgrids and integrated energy systems.

Keywords: Multi-party interest game; Wind-solar-storage optimization; Source-storage-load -grid coordination; Multi-objective optimization; Economic demand response.

1. Introduction

Multi-park hybrid microgrids (MPHMs) is an integrated and intelligent energy supply mode, which takes multiple adjacent industrial parks, commercial areas and residential areas as the basic units. It integrates wind, photovoltaic and energy storage resources distributed in different parks to form a localized energy supply system to improve energy efficiency and reduce carbon emissions [1].

On the one hand, wind and solar power are intermittent and fluctuating with a great influence of weather, season and time. Although the geographical dispersion in multi-park cases can smooth the time variation to some extent, there is still a large time difference between the renewable generation and local load [2]. For example, the PV power generation reaches the peak in the noon, but some industrial load may appear in the morning or evening; the wind power reaches the maximum in the midnight or off-peak load area [3]. A large amount of renewable energy is wasted, and the wind and photovoltaic power are curtailed, which seriously affect the integration of renewable energy. On the other hand, more renewable energy is absorbed through coordinated planning to improve local renewable energy absorption by reasonable allocation and optimal scheduling.

On the contrary, because of the uncertainly of renewable generation, most existing microgrid systems still largely rely on the main grid as backup power source and balancing source. When output of renewable is insufficient or load demand increases, microgrids can only purchase power from the main grid to ensure reliability; while on the contrary, the energy will be fed back to the main grid when surplus energy is generated by the microgrids [4]. Such power purchase and power feedback will bring extra burden and security risk to the main grid, especially when the renewable penetration is high, it may even cause voltage fluctuation and frequency instability [5]. Meanwhile, the volatility of main grid electricity price may bring extra security risk and high cost to the microgrid economics through frequent power trading in the main grid. Therefore, decreasing reliance on the main grid and enhancing the self-sufficiency and autonomous operation ability of microgrids have become key to ensure the energy security and sustainable economic development.

Based on the collaborative optimization model of multi-park hybrid microgrids with wind, solar and storage resources, considering the influence of various factors such as the characteristic of renewable generation, characteristic of load demand, energy storage performance and economic cost, this paper uses hybrid intelligent algorithms to solve the optimal configuration and operation plan [6]. Significantly reduce the power exchange with the main grid and improve the system resilience and economic performance. In order to achieve the low-carbon, intelligent and sustainable development of regional energy system, the research results will provide scientific decision support for the planning, construction and operation of multi-park hybrid microgrids.

2. Model Formulation and Scenario Setup

2.1 Centralized Optimization and Solution Considering Multi-Party Interests

The objective for new energy suppliers is to maximize revenue, which comes from market revenue of wind and solar generation minus operation and maintenance costs:

$$max f_1 = \sum_{t=1}^{24} \left(p_{WT,t}E_{WT,t} + p_{PV,t}E_{PV,t}\right) - C_{RE} \tag{1}$$

$$min f_2 = C_{ESS} + \sum_{t=1}^{24} \left(p_{\text{grid},t}E_{\text{grid},t} + p_{\text{curt}}E_{\text{curt},t}\right) \tag{2}$$

Here, C_{ESS} is the daily amortized investment cost of the energy storage system, calculated using the straightline depreciation method based on energy storage power cost (750 yuan/kW), capacity cost (1600 yuan/kWh), a 10-year design life, and a 5% residual value. The curtailment penalty is introduced to incentivize higher renewable energy utilization and reduce energy waste.

The user's objective is to minimize electricity costs while obtaining subsidies through participation in demand response:

$$min f_3 = \sum_{t=1}^{24} p_{\text{user},t}E_{\text{user},t} - \sum_{t=1}^{24} p_{IDR}\Delta E_{\text{shift},t} \tag{3}$$

In this expression, $p_{\text{user},t}$ is the user's electricity price at time t (consistent with the main grid's time-of-use pricing, with no difference among industrial, commercial, and residential users), $\Delta E_{\text{shift},t}$ is the amount of load reduced or shifted by the user through demand response at time t. To avoid excessive disruption to normal user operations, the maximum load reduction is capped at 12%.

Considering the need to protect the lifespan of lithium iron phosphate batteries, the SOC operating range is limited to:

$$0.15 \leq SOC_t \leq 0.85 \tag{4}$$

Second is the charge/discharge power constraint.

$$E_{ESS,ch,t} \leq P_{ESS} \cdot \Delta t \cdot 0.92 \tag{5}$$

Here, Δt is the time resolution (1 hour), and 0.92 is the charge-discharge efficiency, ensuring the constraint matches the actual performance of the storage equipment.

$$E_{WT,t} + E_{PV,t} + E_{ESS,dis,t} + E_{\text{grid},t} = E_{\text{user},t} + E_{ESS,ch,t} + E_{\text{curt},t} \tag{6}$$

This constraint ensures real-time energy supply-demand matching in each time period, avoiding system fluctuations due to power shortages or surpluses.

2.2 Economic Impact Analysis of Unconfigured Energy Storage Scenarios

The objectives are to reduce the amount of electricity purchased from the external grid, lower the costs associated with purchasing electricity, improve the area's self-sufficiency in energy, and optimize generation and load management to minimize wasted wind and solar power due to overproduction.

Constraints considered in the model include:

$$P_{\text{Total}}(t) = P_{\text{Generation}}(t) + P_{\text{Purchased}}(t) + P_{\text{Stored}}(t) \tag{7}$$

In each time period, the total generation, purchased electricity, and charge/discharge amounts of the energy storage system must meet the load demand for that period.

$$SOC_{min} \le SOC \le SOC_{max} \tag{8}$$

$$P_{\text{storage}}^{max} \le P_{\text{storage}} \le P_{\text{storage}}^{max} \tag{9}$$

$$P_{pv} \le P_{pv}^{max} \tag{10}$$

2.2.1 Considering Curtailment Cost and Energy Storage System Cost

When configuring energy storage systems for each park, both the cost of curtailed energy and the cost of the storage system should be considered comprehensively. That is, if the cost of deploying an energy storage system is too high, it may be economically reasonable to allow some energy curtailment. With a power unit price of 800 RMB/kW and an energy unit price of 1800 RMB/kWh, and the state of charge (SOC) γ is allowed within the range of 10%–90%, with a charging/discharging efficiency of η = 95%.

Let the number of energy storage units be N. At this point, the curtailed energy is:

$$Q_{di} = (Q_{ii} - max\{Q_{Ei} + R_i, P_{Lmax}\})H(Q_{ij} - max\{Q_{Ei} + R_i, P_{L\,max}\}) \tag{11}$$

The total power supply cost then becomes:

$$C_s = \sum_{i=1}^{24} C_s = \sum_{i=1}^{24} Q_k P_k \tag{12}$$

Objective Function:

$$min\ C_s = \sum_{i=1}^{24} C_{si} + C_p + C_e = \sum_{i=1}^{24} Q_{bi} P_k + \sum_{i=1}^{24} 800\, Q'_{Ei} + \sum_{k=1}^{24} 1800\, Q_{Ei} \tag{13}$$

For Park A:

$$P_{pv,A} \ge Q_{bi} \ge R_i \tag{14}$$

For Park B:

$$P_{w,B} \ge Q_{bi} \ge R_i \tag{15}$$

For Park C:

$$P_{w,C} + P_{pv,C} \ge Q_{bi} \ge R_i \tag{16}$$

Therefore, the following constraint applies:

$$Q_{Ei} \le \gamma(100 - \eta Q'_{Ei}) \tag{17}$$

$$\eta Q'_{Ei} \ge (R_i - Q_{bi})H(R_i - Q_{bi}) \tag{18}$$

2.2.2 Park Power Supply Optimization via Energy Storage Introduction

By introducing energy storage systems, the goal is to optimize the park's power supply structure to minimize total electricity costs over a day. For this purpose, a joint objective programming model is established, considering the synergistic effects of wind, solar, and energy storage facilities. The constraints can be described as follows:

$$\begin{cases} 0.1 < soc < 0.9 \\ e_{soc} = 0.95 \end{cases} \tag{19}$$

At any given moment, if the generated power from wind/solar sources and the remaining capacity of PV (including storage) are insufficient to support the park's load.

$$s = L - m_k - q_s \tag{20}$$

After completing a day's tasks, the remaining electricity on PV units is considered as curtailed wind/solar power, represented as:

$$\mathrm{n} = q_s + s - L \tag{21}$$

where n denotes the amount of curtailed wind/solar power.

The total power supply cost includes the costs of wind and solar generation, energy storage configuration, and electricity purchased from the main grid, which can be expressed as:

$$\begin{gathered} \mathrm{k} = f_i Q_i + f_i \sum_{i,j}^{24} q_{ij} + s + w_i \\ f_i = \begin{cases} 0.5, \text{Wind Power Cost} \\ 0.4, \ \text{Solar Power Cost} \end{cases} \end{gathered} \tag{22}$$

where k represents the total power supply cost, $0.5f_iQ_i$ is the price of electricity from PV installations at the initial moment for different parks, and w_i represents the energy storage configuration for different parks.

$$\begin{gathered} w_i = 1800 + 800 q_i \\ q_i = (50,100) \end{gathered} \tag{23}$$

where q_i represents the energy storage for different parks. The average unit cost per kWh can be considered as the cost of electricity consumed per hour:

$$a = \frac{k}{24} \tag{24}$$

$$\begin{gathered} \min \mathrm{k} = f_i Q_i + f_i \sum_{i,j}^{24} q_{ij} + s + w_i \\ \begin{cases} 0.1 < soc < 0.9 \\ e_{soc} = 0.95 \\ s = L - m_k - q_i \\ n = q_i + s - L \\ f_i = 0.4, 0.5 \\ w_i = 1800 + 800 q_i \\ q_i = (50,100) \end{cases} \end{gathered} \tag{25}$$

2.3 Cost-Driven Energy Storage Configuration Optimization

In the case where energy storage is not required, the following equation holds:

$$\sum_{i,j}^{24} q_{ij} \le Q \tag{26}$$

When the electricity generated at any given time and the remaining photovoltaic capacity are insufficient to support the load of the integrated park system.

$$s = L - m_k - q_s \tag{27}$$

After completing a day's operation, the remaining electricity on the PV units is considered as curtailed wind/solar power, which can be expressed as:

$$\mathrm{n} = q_s + s - L \tag{28}$$

where n denotes the amount of curtailed energy.

The total power supply cost includes the costs of wind and solar power generation as well as electricity purchased from the main grid, which can be expressed as:

$$\begin{gathered} \mathrm{k} = f_i Q_i + f_i \sum_{i,j}^{24} q_{ij} + s \\ f_i = \begin{cases} 0.5, \text{Wind Power Cost} \\ 0.4, \text{ Solar Power Cost} \end{cases} \end{gathered} \tag{29}$$

$$a = \frac{k}{24} \tag{30}$$

2.4 Comparative Analysis of Wind-PV-Storage Coordination Strategies

The objective of this section is to optimize the configuration of energy storage systems in each park and develop optimal storage strategies based on load forecasting and power generation forecasting. First, coordinated wind-PV-storage configurations are developed under two scenarios: independent park operation and integrated park operation. The wind-PV-storage coordinated configuration planning model is formulated as follows:

Optimization Method: Mixed Integer Linear Programming (MILP)

(1) Optimization Variables: $P_{\text{buy}}, E_{ch}, E_{\text{dis}}, U_{ch,}^t, U_{dis}^t, P_{\text{waste}}, P_{\text{newWT}}, P_{\text{new}\,PV}$

(2) Objective Function:

$$\begin{gathered} F = 3000 P_{\text{new}\,WT} + 2500 P_{\text{new}\,PV} + \frac{C_{\text{battery cap}}\, SOC_{max} + C_{\text{battery power}}\, E_{max}}{3650} + \sum \Big(C_{\text{buy}} P_{\text{buy}} \\ + C_{PV}\left(1 + \frac{P_{\text{new}\,PV}}{P_{PVmax}}\right) * P_{PV} + C_{WT}\left(1 + \frac{P_{\text{newWT}}}{P_{WTmax}}\right) * P_{WT} \Big) \end{gathered} \tag{31}$$

(3) Constraints:

Power Balance: $\left(1 + \frac{P_{\text{newWT}}}{P_{WT\max}}\right) * P_{WT} + P_{\text{buy}} + \left(1 + \frac{P_{\text{new}\,PV}}{P_{PV\max}}\right) * P_{PV} + E_{\text{dis}} = P_{\text{load}} + E_{\text{ch}} + P_{\text{waste}}$

Battery State Constraints: $SOC_i^{t+1} = SOC_i^t + E_{ch}^t \eta_{ch} - E_{dis}^t / \eta_{ds}$

Battery Capacity Variation Limits: $SOC_{\max} * 0.1 \le SOC^t \le SOC_{\max} * 0.9$

Battery Charging/Discharging State Constraints: $0 \le [E_{ch}^t, E_{dis}^t] \le [U_{ch}^t E_{\max}, U_{dis}^t E_{\max}]$

No Simultaneous Charging and Discharging Allowed: $U_{ch} + U_{dis} <= 1$

Other Technical and Economic Constraints: $P_{\text{buy}} > 0 \& P_{\text{waste}} > 0 \quad SOC^0 = SOC^{23}$

The monthly electricity cost is calculated as:

$$C_{oxt,m} = C_s + C_{out} \tag{32}$$

where $m = 1,2,\ldots,12$ represents the 12 months. To specify independent operation wind-PV coordination configurations for each park, similar constraints apply.

Objective Function:

$$min \sum_{m=1}^{12} C_{ost,m} \tag{33}$$

Constraints:

$$\begin{cases} P\varphi \ge Q_{bi} \ge R_i \\ Q_{Ei} \le \gamma(\beta - \eta Q'_{Ei}) \\ \eta Q'_{Ei} \ge (R_i - Q_{bi}) H(R_i - Q_{bi}) \end{cases} \tag{34}$$

3. Case Study and Result Analysis

3.1 Case Design and Experimental Analysis

3.1.1 Dataset

Based on the established model, solving through MATLAB yields the electricity purchase volumes for different times as shown in Figure 1.

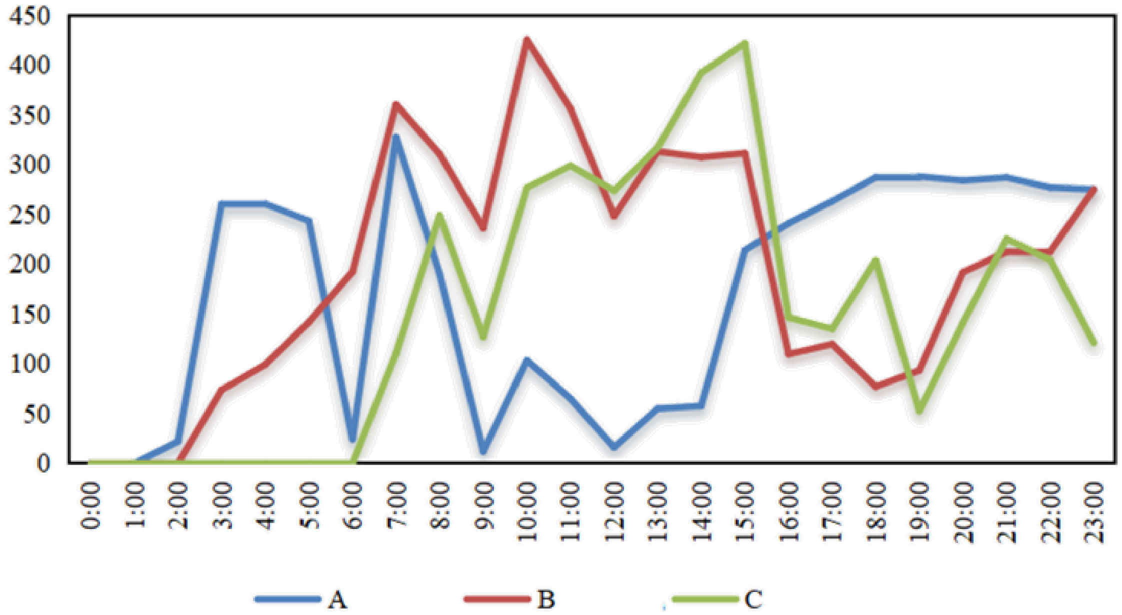

Figure 1. Changes in Electricity Purchase Volumes for Three Parks

According to the solution results, under the current energy storage configuration, the average minimum daily consumption is higher than without energy storage, indicating that the park's economy may not significantly improve at this power level. Clearly, the 50kW/100kWh energy storage solution might not be optimal, as there is still a considerable amount of curtailed energy.

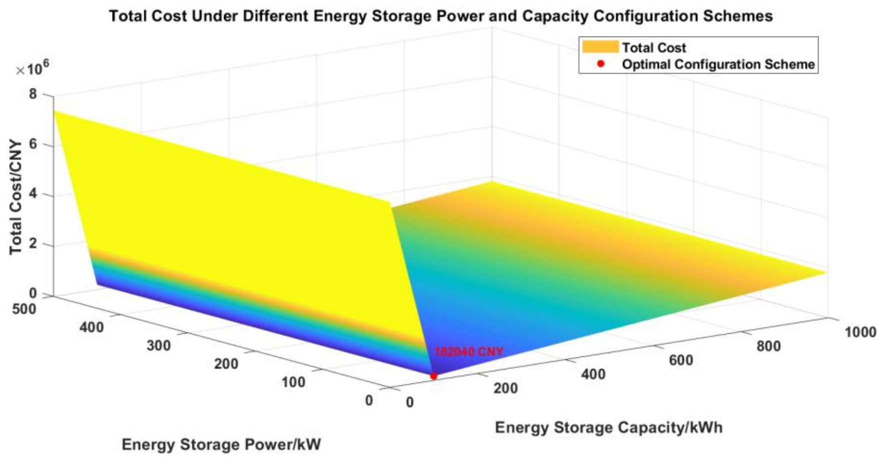

Figure 2. Total Costs Under Different Energy Storage Power and Capacity Configurations

By identifying the globally optimal battery transmission power/capacity, the optimal energy storage power and capacity configurations for each park are determined. The total cost results under different energy storage power and capacity configurations are shown in Figure 2.

Assuming that the fluctuation characteristics of wind power, photovoltaic power, and load remain unchanged, the optimal energy storage configuration, capacity, and total electricity purchase cost for each park were obtained based on the established model, as shown in Table 1.

Table 1. Optimal Energy Storage Configuration, Capacity, and Total Electricity Purchase Cost

Park	A	B	C
Total Purchased Electricity (kWh)	4015.66	1622.3062	1681.35195
Total Wasted Energy (kWh)	0	0	0
Total Power Supply Cost (RMB)	6604.4	4447.85	5176.15
Average Unit Cost (RMB/kWh)	0.83589	0.576894	0.6656573
Battery Power Limit (kW)	194.625	212.9	260.69
Battery Capacity (kWh)	1129.55	626.194	1269.75

3.1.2 Model Evaluation Indicators and Parameter Settings

To quantitatively evaluate the performance of the multi-park wind-solar-storage optimization model, an evaluation indicator system is constructed from both technical and economic dimensions. Based on system parameters and algorithm design, experimental parameter settings are determined to ensure the rationality of model solution and the comparability of results.

1). Model Evaluation Indicators

(1) Technical Performance Indicators

a. Renewable Energy Accommodation Rate

$$\eta_{RE} = \frac{E_{WT,act}+E_{PV,act}}{E_{WT,max}+E_{PV,\text{ max}}} \times 100\% \tag{35}$$

Which used to measure the utilization efficiency of renewable energy, with a target value of no less than 90%.

b. Curtailment Rate

$$\eta_{curt} = \frac{E_{curt,WS}}{E_{WT,max}+E_{PV,max}} \times 100\% \tag{36}$$

c. Energy Storage Utilization Rate

$$\eta_{ESS} = \frac{\sum_{t=1}^{24}\left(E_{ESS,ch,t}+E_{ESS,dis,t}\right)}{2\times E_{ESS,\text{ rated}}} \times 100\% \tag{37}$$

(2) Economic Performance Indicators

a. Total Power Supply Cost

$$C_{\text{total}} = C_{\text{grid}} + C_{ESS,\text{ ann}} + C_{\text{curt}}, \text{ in yuan/day} \tag{38}$$

b. Benefits/Costs of Each Stakeholder

Net income of new energy suppliers, total cost of integrated energy service providers, and electricity cost of users, corresponding to the objective functions respectively, used to evaluate the balance of multi-stakeholder interests.

c. Unit Power Supply Cost

$$c_{\text{unit}} = \frac{C_{\text{total}}}{E_{\text{total,user}}}, \text{ in yuan/kWh} \tag{39}$$

2). Experimental Parameter Settings

Three representative parks are considered: an industrial park (A), a commercial park (B), and a residential park (C), each with distinct load profiles and renewable installation capacities.

This study is based on a multi-park hybrid microgrid system integrating industrial, commercial, and residential parks, each with distinct load profiles and renewable energy configurations. The optimization model incorporates time-of-use electricity pricing, incentive-based demand response, renewable curtailment penalties, and lithium-ion energy storage as a flexible regulation resource. Load characteristics are defined as follows: Park A has a peak load of 8.5 MW, Park B 4.2 MW, and Park C 3.8 MW. Wind and solar generation profiles are derived from typical meteorological year data with an annual average wind speed of 5.2 m/s and daily average sunshine duration of 4.8 hours. The wind turbines have a rated power of 1.8 MW (cut-in speed: 3 m/s, rated speed: 12 m/s), while the PV modules have an efficiency of 19% and a unit capacity of 550 W. Installed capacities are 5 MW (A), 2 MW (B), and 3 MW (C) for photovoltaics.

System constraints include power balance at each time step, storage dynamics, and a maximum allowable load reduction of 12% under demand response programs. As a baseline, the system performance without energy storage is first evaluated. The results are shown in Table 2.

Table 2. Baseline Performance (No Storage Scenario)

Park	Grid Purchase (kWh)	Curtailment (kWh)	Total Cost (Yuan)	Unit Cost (Yuan/kWh)
A (Industrial)	4874.12	951.2	6863.16	0.869
B (Commercial)	951.2	897.5	4902.38	0.636
C (Residential)	1949.65	1128.02	5510.87	0.709

The SAA-based dispatch strategy further confirms that without storage, the system cannot effectively shift surplus renewable energy to peak periods.

3.1.3 Experimental Results

To validate the effectiveness of the optimized storage sizing, a comparison is made with a fixed initial configuration of 50 kW / 100 kWh per park. As shown in Table 3, the initial setup yields only marginal cost reductions and fails to eliminate curtailment.

Table 3. Performance Comparison: Initial vs. Optimal Storage Configuration

Park	Configuration	Total Cost (Yuan)	Curtailment Rate (%)	Cost Reduction vs. No Storage
A	50/100	6782.3	8.5	1.20%
A	Optimal	6604.4	0	3.80%
B	50/100	4815.6	9.2	1.80%
B	Optimal	4447.85	0	9.30%
C	50/100	5398.2	7.6	2.00%
C	Optimal	5176.15	0	6.10%

3.2 Calculation of Integrated Park Costs

This study aims to optimize the energy storage configurationfor each park in order to minimize electricity purchase costs and improve operational economics. First, we calculated the total power generation and total load for each park, and visualized the results as shown in Figure 3.

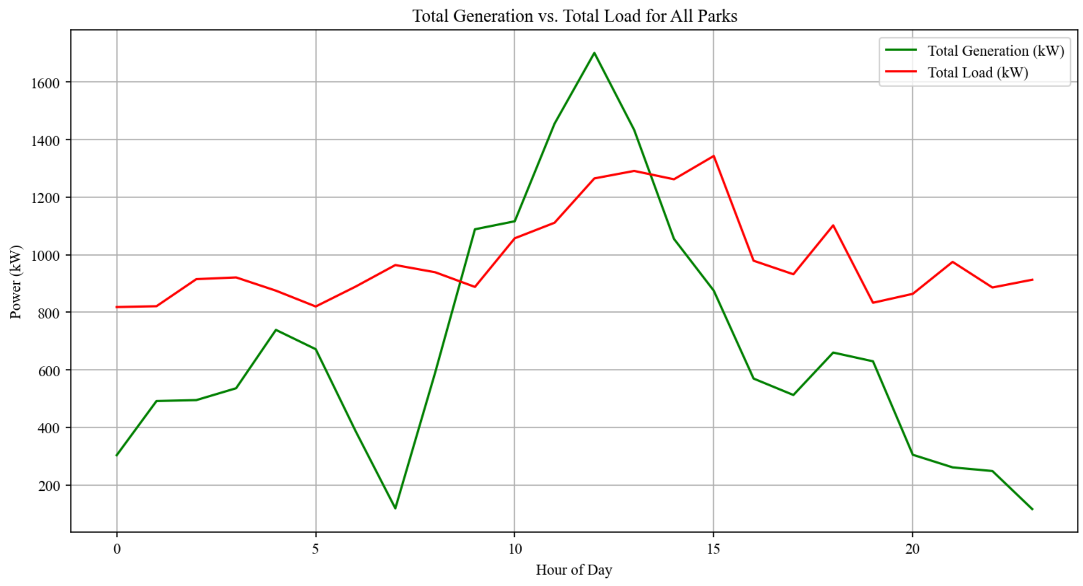

Figure 3. Total Power Generation and Total Load for Each Park

Based on the load demand at different times for the integrated park, the total electricity purchase volume, total power supply cost, unit power supply cost, and curtailment cost were calculated, as shown in Table 4.

Table 4. Integrated Park Costs

Economic Parameter	Value
Purchased Electricity (kWh)	8266.27
Curtailed Wind/Solar Energy (kWh)	1237.175
Total Power Supply Cost (RMB)	15536.8675
Average Unit Power Supply Cost (RMB/kWh)	0.66433777

3.3 Strategy of Integrated Park Operation

Firstly, preprocessing and visualization analysis were performed on the load data and wind/solar generation data of each park area. To visually demonstrate the load and generation conditions of each park area, typical daily load and generation power curves were plotted for each area. The results of load demand and wind/solar generation during a day for each park area are illustrated in Figures 4-6.

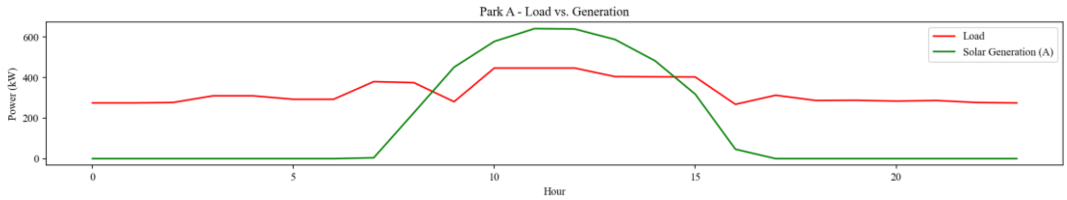

Figure 4. Load and Generation Conditions in Park Area A

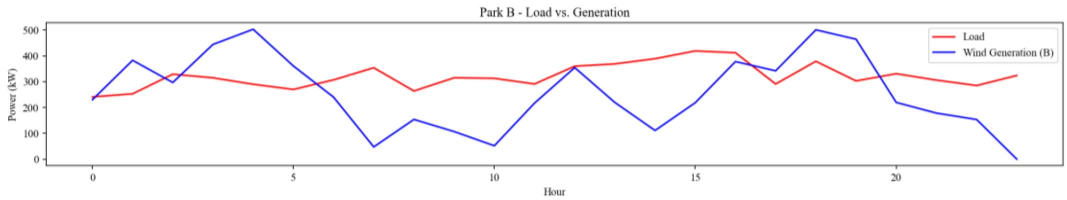

Figure 5. Load and Generation Conditions in Park Area B

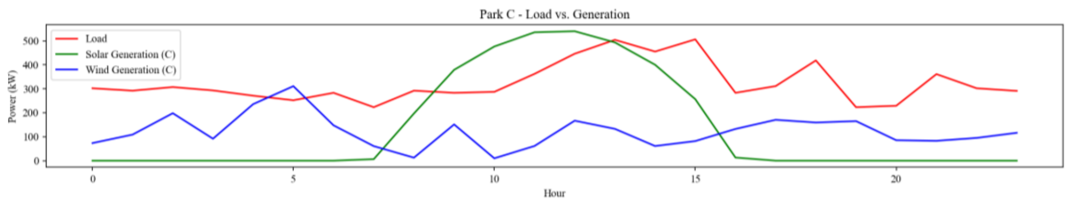

Figure 6. Load and Generation Conditions in Park Area C

Using the mathematical model mentioned above along with typical daily load data and daily wind/solar generation data from each park area, the electricity purchase volumes for each park area were solved using MATLAB, as shown in Figure 7.

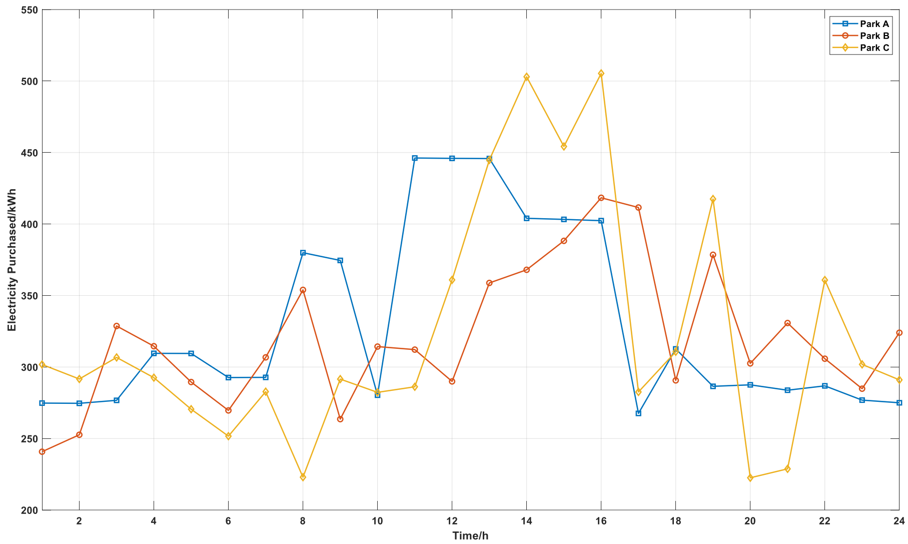

Figure 7. Electricity Purchase Volumes of Park Areas A, B, and C at Different Time Periods

The actual generation was calculated based on installed capacities, and electricity fees for wind and solar power were set. Economic indicators for each park area were then computed, resulting in the total electricity purchase volume, total wasted energy, total power supply cost, and average unit cost as follows:

Table 5. Economic Indicators for Each Park Area

Park Area	*A*	*B*	*C*
Total Purchased Electricity (kWh)	4874.12	951.20	1949.65
Total Wasted Energy (kWh)	951.2	897.5	1128.02
Total Power Supply Cost (RMB)	6863.1625	4902.38	5510.87
Average Unit Cost (RMB/kWh)	0.8686448	0.63585	0.7087

From Table 5, it can be observed that Park A has the highest total purchased electricity and total power supply cost. This indicates a strong dependence on the main grid and relatively weak self-generation capability. In contrast, Park B has the lowest total purchased electricity and total power supply cost, suggesting that it possesses a strong self-generation capacity and relies less on the main grid. Park C experiences the highest amount of wind and solar energy curtailment, reflecting its strong potential for renewable energy generation. However, due to the mismatch between load demand and generation timing, these resources are not fully utilized. Therefore, reducing wind and solar curtailment is key to improving renewable energy utilization and optimizing the energy structure. Park A can be attributed not only to its large electricity purchase volume but also to its low utilization rate of renewable energy, leading to higher overall power supply costs. In comparison, Park B has the lowest average unit cost, indicating more efficient utilization of renewable energy and better economic performance.

Based on the above mathematical model, using MATLAB simulations, optimal wind-PV-storage coordination configurations for each independently operating park were developed. Simulation results are shown in Figures 8-10.

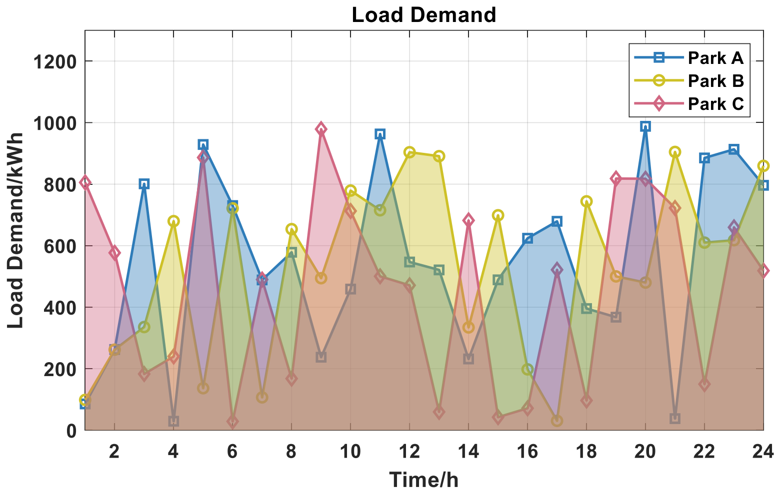

Figure 8. Load Demand of Each Park at Different Time Periods

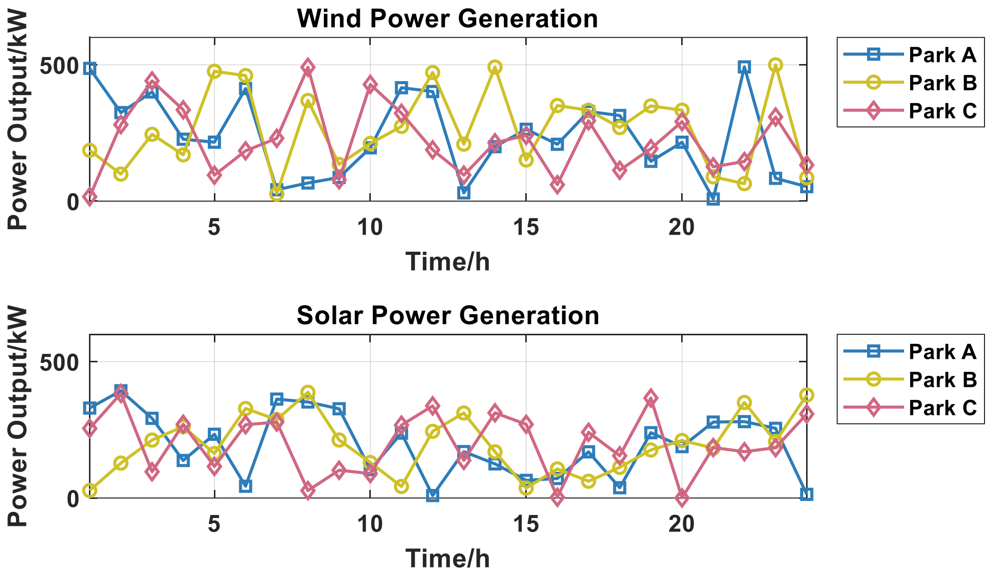

Figure 9. Wind and PV Simulation Results of Each Park at Different Time Periods

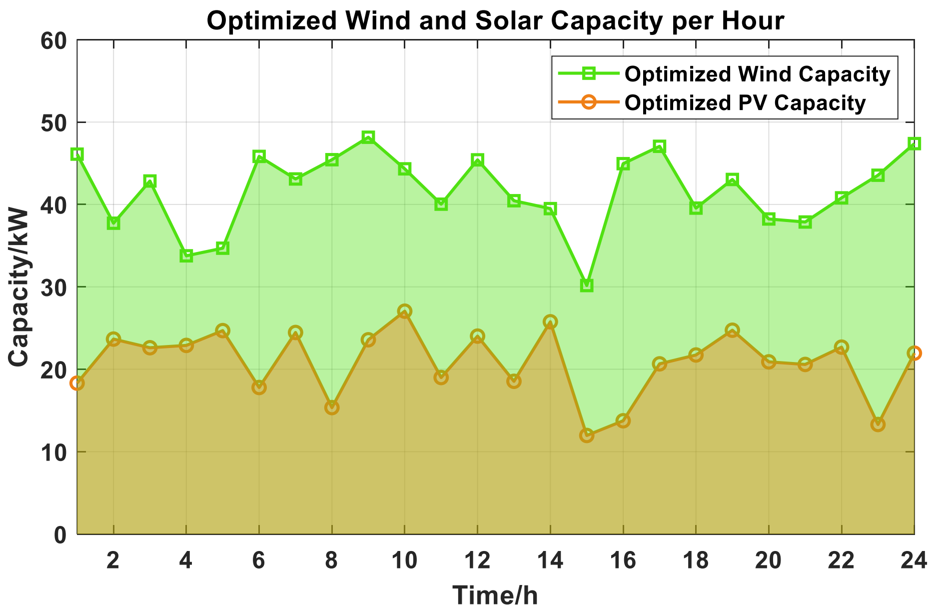

Figure 10. Wind and PV Simulation Results of Each Park

According to typical daily wind and PV power generation data for all 12 months of the year, and time-of-use electricity pricing, wind-PV-storage coordination configurations for independent park operations (using February as an example) were formulated. The results were obtained as shown in Table 6.

Table 6. Economic Analysis of Wind-PV-Storage Coordination Configurations After Increased Load Over a Full Year

Park	A	B	C
Purchased Electricity (kWh)	111123.097	78233.01641	49828.53565
Curtailed Energy (kWh)	415.4604055	3868.816727	6320.827746
Total Power Supply Cost (RMB)	3127746.05	2796621.52	2471922.169
Average Unit Cost (RMB/kWh)	0.722550056	0.662060738	0.580225828
Battery Power Limit (kW)	0.00002	174.7	363.3674375
Battery Capacity (kWh)	0	559.7875	1559.702558
Additional PV Capacity (kWh)	24.67482785	0	0
Additional Wind Capacity (kWh)	0	0	692.5738076

3.4 Parameter Sensitivity Analysis

Energy storage costs are critical to the economic feasibility of the microgrid, as they directly determine the investment scale and long-term amortization expenses of energy storage systems. This analysis focused on two core cost components: unit power cost and unit capacity cost, with perturbation ranges set to ±10% and ±20%. The impact on the integrated park's total power supply cost and energy storage configuration optimization results is shown in Table 7.

Table 7. Sensitivity Analysis of Energy Storage Costs

Parameter Perturbation	Total Power Supply Cost of Integrated Park (yuan/day)	Change Rate of Total Cost	Optimal Energy Storage Capacity (kWh)	Change Rate of Capacity
Baseline (750 yuan/kW; 1600 yuan/kWh)	14480.59	0%	1469.15	0%
Power cost +10% (825 yuan/kW)	14892.31	2.80%	1421.58	-3.20%
Power cost +20% (900 yuan/kW)	15304.03	5.70%	1374.01	-6.50%
Power cost -10% (675 yuan/kW)	14068.87	-2.80%	1516.72	3.20%
Power cost -20% (600 yuan/kW)	13657.15	-5.70%	1564.29	6.50%
Capacity cost +10% (1760 yuan/kWh)	14956.21	3.30%	1398.43	-4.80%
Capacity cost +20% (1920 yuan/kWh)	15431.83	6.50%	1327.71	-9.60%
Capacity cost -10% (1440 yuan/kWh)	14004.97	-3.30%	1539.87	4.80%
Capacity cost -20% (1280 yuan/kWh)	13529.35	-6.60%	1610.29	9.60%

4. Discussions

Optimization of wind, solar and storage resources in multi-area hybrid microgrids is a system-wide process that involves comprehensive consideration of technical performance, economic benefits and user interests. This paper shows that, by considering the typical load characteristics of industrial, commercial and residential areas and the temporal complementarity between wind and solar generation, a centralized coordination model can obtain a much better performance. Specifically, through appropriate storage operation strategies and demand response incentive mechanisms, the energy supply and load demand in each area present a certain degree of correlation. On the one hand, it can achieve load shifting, peak shaving and high self-consumption rate of renewable energy. On the other hand, incentive-based demand response can promote users to participate in system balancing and reduce costs through price and subsidy policies. The coordinated use of time-of-use pricing and subsidies can provide economic incentives for users to balance the system. The hybrid intelligent algorithm proposed in this paper improves the solution process of complex multi-objective problems by combining global search ability and decision-making support. It solves the practical problem of selecting the best solution from a large number of trade-off solutions and is applicable to real-world planning and operational decisions. The benefits of integrated resource planning will exist in different scenarios. Equipment cost, policy and load demand will change in different periods of time. The optimization model proposed in this paper can still play an effective role in this kind of dynamic and uncertain system environment.

5. Conclusion

This paper proposes an effective optimization framework to realize the coordinated operation of multi-area hybrid microgrids, integrating the interests of suppliers, service providers and users. The coordination model can achieve efficient energy management through the diversity of load and generation in different areas. The improved hybrid intelligent algorithm can ensure the high quality of the solution and provide practical decision-making support, making the method scalable and implementable. The multi-scenario example shows that the coordinated operation of multi-area hybrid microgrids has higher self-sufficiency, lower cost, and is less sensitive to uncertainties, compared with the isolated zone operation mode. From the engineering point of view, this paper provides practical engineering ideas for microgrid planning. The results of this paper provide a replicable experience for the extensive application of integrated source-grid-load-storage technology.

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