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# Coordinated Optimization Configuration of Wind-PV-Storage in Park Microgrids

**Yawen She[1,a,*], Yi Lu[2,b], Jiaxun Chen[3,c], Yue Yu[3,d], Xinchuan Qiu[4,e]**

*[1]Shenyang University of Chemical Technology, Shenyang, Liaoning Province, China*
*[2]Nanjing Normal University, Nanjing, Jiangsu Province, China*
*[3]Xiamen University, Xiamen, Fujian Province, China*
*[4]Jimei University, Xiamen, Fujian Province,China*
*a. 2543339578@qq.com, b. 1530139660@qq.com, c. 35820222202112@stu.xmu.edu.cn,*
*d. 2497289114@qq.com, e. xinchuanqiu@jmu.edu.cn*
**corresponding author*
*[†]These authors contributed equally and are designated as co-first authors.*

***Abstract:*** Park microgrids integrate wind power, photovoltaic (PV) power, and the main power grid to meet load demands. To improve the utilization of wind and solar power, energy storage systems are configured to address the mismatch between load demand and generation schedules, thereby reducing energy curtailment. Based on actual generation and consumption data from different parks, this study establishes a mathematical model to optimize energy storage configuration and power purchasing strategies and analyzes their impact on economic performance. By conducting comparative analyses of independent and collaborative park operation models, this study investigates the economic benefits of coordinated optimization of wind, solar, and storage systems and proposes the optimal energy storage configuration strategy, offering significant reference value for park microgrid planning and operation. Initially, the data from Appendix 2 were processed to derive the actual wind and PV power generation of individual parks and the collaborative park at each time period. These figures were compared against the corresponding load demand to calculate the power purchase volume for each time period. Without considering energy storage configurations, a mathematical model and associated formulas were developed to define boundary power regulation and calculate the power purchase volume, total purchase volume, total power supply cost, and energy curtailment for each park at different times. Using traditional optimization methods, the economic performance was evaluated by maximizing the utilization rate of wind and solar power and solving for the unit power supply cost and energy curtailment. Finally, the models and data established in this study were analyzed and summarized to determine the optimal configuration scheme for wind-PV-storage systems.

***Keywords:*** Park microgrid, wind power, photovoltaic power, energy storage system, optimization configuration, economic analysis, genetic algorithm

## 1. Introduction

With the rapid development of renewable energy, microgrid systems have become an important solution for addressing the integration of distributed energy sources and meeting power load demands.

Among these, wind and photovoltaic (PV) power generation, as clean energy sources, play a crucial role in microgrids. However, due to the uncertainty and intermittency of wind and PV power, a temporal mismatch often exists between their generation and the power load demand [1].

In park microgrids, to enhance the utilization rate of wind and PV power, a high proportion of installed capacity is typically allocated to meet the park's load demands. However, the volatility of wind and PV power generation can lead to the inability to fully utilize part of the power, resulting in wind and solar curtailment. This phenomenon increases the overall power supply cost of the park. To address this issue, energy storage technology has emerged as a critical solution [2]. Energy storage devices can temporarily store wind and PV power generation and release it as needed.

Therefore, park microgrids need to consider coordinated configuration schemes for wind, PV, and storage systems to maximize the utilization of wind and solar power, minimize curtailment, and reduce overall power supply costs. Through economic analysis and optimization of independent operation, collaborative operation, and coordinated wind-PV-storage configuration schemes, this study provides essential reference data for the planning and operation of park microgrids.

## 2. Problem Analysis

### 2.1. Analysis of the Problem

#### 2.1.1. Subproblem 1.1

First, the data from Appendix I and Appendix II were processed through dimensional normalization to obtain the wind and PV power generation and load power of the three parks for each time period. A mathematical model was established, where the consumed power at each moment was set as the output, and the maximum power of the generation equipment was set as the constraint condition. Four key indicators—purchased electricity volume, curtailed wind and solar power volume, total power supply cost, and average unit power supply cost—were analyzed, and the corresponding results were calculated. Lastly, the key factors influencing economic performance were analyzed based on wind power prices, PV prices, and the daily park load.

#### 2.1.2. Subproblem 1.2

This subproblem analyzes the optimal operation strategy and power purchase plan for a 50kW/100kWh energy storage system. The total daily power supply cost was set as the objective function, with the energy storage strategy as the decision variable. The goal was to minimize the cost of configuring the energy storage equipment and purchasing power while ensuring that the state of charge (SOC) of the energy storage system and its charging and discharging efficiency remained within allowable limits. The final power supply cost was calculated and compared to the results of Subproblem 1.1 to determine whether the economic performance of the three parks improved.

#### 2.1.3. Subproblem 1.3

Finally, the study examines whether the 50kW/100kWh energy storage scheme is optimal. Under the same constraints, the optimal energy storage strategy and capacity configuration scheme were derived to further optimize the economic performance of the park microgrid.

## 3. Model Assumptions

1. The energy loss during the transmission process is not considered.

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2. Since the generation and load data provided in the problem represent typical daily values, interpolation is not meaningful. Therefore, hourly data are used for analysis, disregarding intra-hour temporal mismatches between generation and load.

3. Given the specified state of charge (SOC) range of 10% to 90%, with a lifespan of 10 years, we assume that battery health is controlled by limiting the effective usable capacity to 80% of the total battery capacity. Under this premise, the losses associated with energy storage configuration, such as maintenance costs and long-term degradation of power and capacity, are not considered. The cost of energy storage equipment is averaged over each day to obtain the daily cost [3].

4. Similarly, losses or maintenance caused by aging of generation equipment are not considered in this study, and the rated power is assumed to remain constant over time.

The symbols used in this paper are explained in Table 1.

Table 1: Symbol Descriptions

| Symbol | Description | Unit |
|---|---|---|
| $\mathrm{E}_{\mathrm{purchase}}$ | Power purchased from the main grid | kWh |
| $E_{waste}$ | Curtailment of wind and solar power | kWh |
| $P_{load}$ | Power load required by the park | kW |
| $P_{pv}$ | PV power output | kW |
| $P_w$ | Wind power output | kW |
| $SOC$ | State of charge of the storage battery | % |
| $E_{now}$ | Current energy state of the storage battery | kWh |
| $E_{ch,max}$ | Maximum energy capacity of the storage battery | kWh |
| $P_{ch}(t)$ | Current chargeable power of the storage battery | kW |
| $\mathrm{P}_{ch,max}$ | Maximum charging power of the storage battery | kW |
| $\mathrm{P}_{ch,rel}(t)$ | Actual charging power of the storage battery | kW |
| $P_{dch}(t)$ | Current dischargeable power of the storage battery | kW |
| $P_{pv,new}$ | Newly added PV power output | kW |
| $P_{w,new}$ | Newly added wind power output | kW |

## 4. Model Development and Solution

### 4.1. Model Development and Solution

#### 4.1.1. Data Preprocessing

Before solving the problem, the data from Appendix 2 were normalized to a consistent unit of kW. The wind power and photovoltaic (PV) generation for different parks in each time period were obtained, and the relevant results were calculated by considering the maximum capacities of the PV and wind power installations. The normalized results are shown in Table 2:

Table 2: Normalized Values After Data Processing

| Time | A PV Generation | B Wind Power Generation | C PV Generation | C Wind Power Generation |
|---|---|---|---|---|
| 0:00 | 0.000 | 230.100 | 0 | 73.2 |
| 1:00 | 0.000 | 382.800 | 0 | 108.75 |
| 2:00 | 0.000 | 296.800 | 0 | 197.95 |

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Table 2: (continued).

| | | | | |
|---|---|---|---|---|
| 3:00 | 0.000 | 444.400 | 0 | 91.55 |
| 4:00 | 0.000 | 502.900 | 0 | 235.8 |
| 5:00 | 0.000 | 360.900 | 0 | 310.75 |
| 6:00 | 0.000 | 240.200 | 0 | 147.3 |
| 7:00 | 4.350 | 47.300 | 6.3 | 60.7 |
| 8:00 | 226.950 | 153.800 | 196.8 | 12.5 |
| 9:00 | 451.500 | 106.800 | 378.84 | 151.15 |
| 10:00 | 578.325 | 51.800 | 476.16 | 9.8 |
| 11:00 | 641.625 | 216.900 | 535.5 | 61.2 |
| 12:00 | 639.825 | 354.600 | 539.94 | 166.75 |
| 13:00 | 588.150 | 219.400 | 493.26 | 132.65 |
| 14:00 | 482.775 | 111.000 | 400.02 | 61 |
| 15:00 | 318.150 | 218.600 | 256.5 | 81.65 |
| 16:00 | 46.425 | 377.900 | 12.96 | 132.25 |
| 17:00 | 0.000 | 342.100 | 0 | 170.4 |
| 18:00 | 0.000 | 500.800 | 0 | 159.15 |
| 19;00 | 0.000 | 464.600 | 0 | 164.95 |
| 20:00 | 0.000 | 219.700 | 0 | 85.15 |
| 21:00 | 0.000 | 178.300 | 0 | 82.75 |
| 22:00 | 0.000 | 153.500 | 0 | 94.85 |
| 23:00 | 0.000 | 0.000 | 0 | 116.15 |

### 4.1.2. Model Development and Solution for Subproblem 1.1

#### 4.1.2.1. Model Development

Since Subproblem 1.1 does not require energy storage configuration, it is assumed that all PV and wind power devices operate under no-load conditions and that the generation devices do not have energy storage capabilities. Several key indicators are defined as follows:

The **Purchased Electricity Volume** refers to the amount of power procured from the main grid to meet the park's load demand **when** the load demand exceeds the total power generated by PV and wind. The formula is defined as:

$$E_{purchase} = \sum_{0}^{24}\left[\int_0^t \mathrm{P}_{load}\,\mathrm{dt} - \int_0^t (\mathrm{P_{pv}} + \mathrm{P_w})\mathrm{dt}\right] \tag{1}$$

$$\int_0^t \mathrm{P}_{load}\,\mathrm{dt} > \int_0^t (\mathrm{P_{pv}} + \mathrm{P_w})\mathrm{dt} \tag{2}$$

Where:

$E_{purchase}$ is the power purchased from the main grid.

$\int_0^{24} P_{load}\,dt$ is the total daily load demand.

$\int_0^{24} (P_{pv} + P_w)dt$ is the total daily power generated by PV and wind.

The **Curtailment of Wind and Solar Power** refers to the surplus energy generated when the load demand is less than the total power produced by PV and wind. It is calculated as:

$$E_{waste} = \sum_{0}^{24}[\int_{0}^{t}(P_{pv} + P_{w})dt - \int_{0}^{t}P_{load}\,dt] \quad (3)$$

$$\int_{0}^{t}P_{load}\,dt > \int_{0}^{t}(P_{pv} + P_{w})dt \quad (4)$$

Where:
$E_{waste}$ represents the curtailment of wind and solar power.
The other terms are consistent with those defined above.

The **Total Power Supply Cost** is defined as the sum of the cost of power generated by wind and PV and the cost of electricity purchased from the grid. It can be expressed as:

$$B = E_{purchase} * 1 + (E_{i} - E_{waste}) * f_{i} \quad (5)$$

$$f_{i} = \begin{cases} 0.4\ PV\ Power\ Price\ \ i = 1 \\ 0.5\ Wind\ Power\ Price\ \ i = 2 \end{cases} \quad (6)$$

The **Average Unit Power Supply Cost** is the total power supply cost divided by the total daily load demand. It is given as:

$$a = \frac{B}{\sum_{0}^{24}\int_{0}^{t}P_{load}\,dt} \quad (7)$$

#### 4.1.2.2. Solution and Economic Analysis of the Model

Using the developed model and its corresponding metrics, Python was employed to solve the problem, yielding the relationships among load demand, purchased electricity, curtailed electricity, and renewable energy generation for each time period. The results are shown in Table 3:

Table 3: Results for Subproblem 1.1

| Park | Generation Volume (kWh) | Purchased Electricity (kWh) | Curtailed Electricity (kWh) | Total Power Supply Cost (¥) | Average Unit Cost (¥/kWh) |
|---|---|---|---|---|---|
| A PV | 3978.075 | 4874.125 | 951.200 | 6084.875 | 0.7701 |
| B Wind | 6175.200 | 2432.300 | 897.500 | 5071.150 | 0.6577 |
| C PV | 3296.28 | 2699.39 | 552.44 | 4963.311 | 0.6382 |
| C Wind | 2908.35 | | 575.58 | | |

To more intuitively observe the relationships among generation volume, purchased electricity, load demand, and PV and wind power generation, we created line charts and bar graphs, as shown in **Figures 1-3**.

For key factor analysis, sensitivity analyses were conducted focusing on generation prices, PV generation prices, and grid electricity prices. By varying one parameter while keeping the others constant, and using the percentage fluctuation of the parameter on the x-axis and the relative total cost percentage compared to the original total cost on the y-axis, visualizations were generated to analyze the decisive factors affecting economic performance. These results are shown in **Figures 4-6**.

The analysis revealed that **Park A** and **Park C** are more sensitive to grid electricity prices, whereas **Park B** is more sensitive to wind power prices. The higher the sensitivity, the greater the impact on economic performance.

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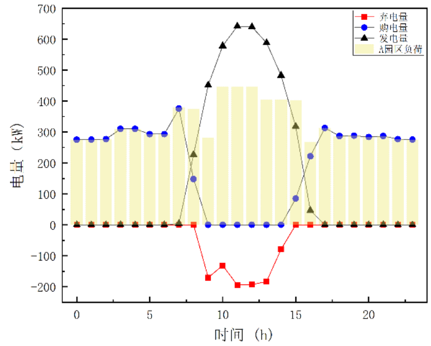


Figure 1: Results for Park A in Subproblem 1.1

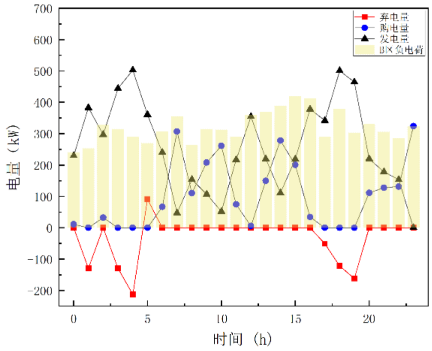


Figure 2: Results for Park B in Subproblem 1.1

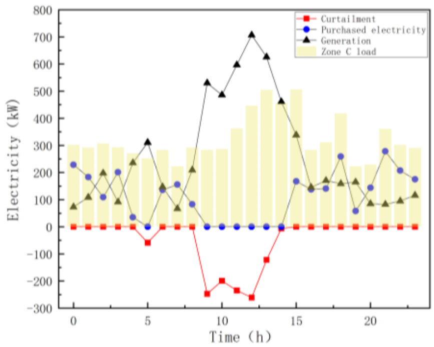


Figure 3: Results for Park C in Subproblem 1.1

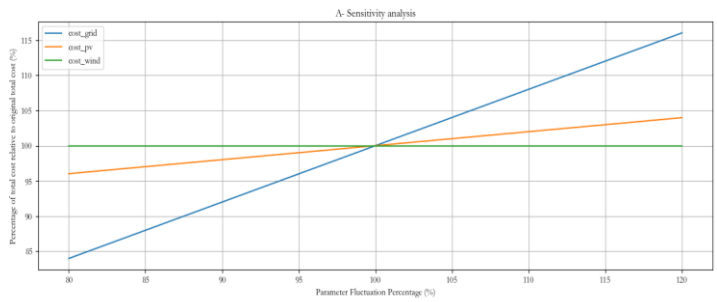


Figure 4: Sensitivity analysis of parameters for Park A in Subproblem 1.1

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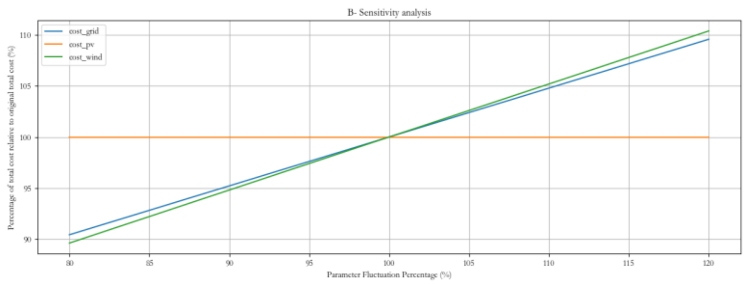


Figure 5: Sensitivity analysis of parameters for Park B in Subproblem 1.1

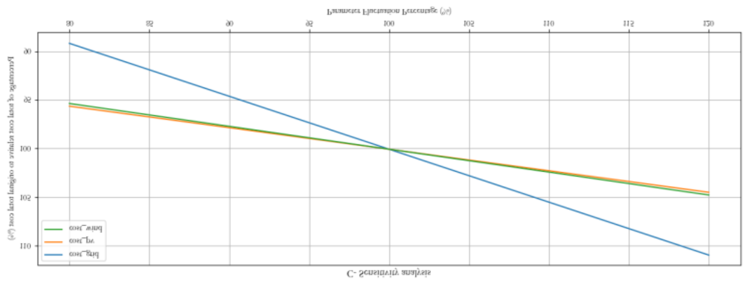

Figure 6: Sensitivity analysis of parameters for Park C in Subproblem 1.1

### 4.1.3. Model Development and Solution for Subproblem 1.2

#### 4.1.3.1. Independent Energy Storage Autonomous Operation Strategy

In this subproblem, a 50 kW/100 kWh energy storage system is introduced, adding new constraints to the problem. Similar to Subproblem 1.1, the goal is to minimize the total daily electricity cost, with the required cost of configuring the facility and minimizing power purchase costs in three aspects as constraints. A joint optimization model for wind power, PV power, and energy storage is developed to analyze and compare whether it improves the economic performance and operating costs of the three parks.

The energy storage constraints include the charging and discharging efficiency of lithium iron phosphate batteries, SOC (state of charge) range, and lifespan. A charging and discharging strategy is formulated to maximize the use of wind and solar power and reduce electricity purchases. The operating range is as follows:

$$\begin{cases} 10\% < SOC < 90\% \\ e_{soc} = 0.95 \end{cases} \tag{8}$$

Where:

SOC is the percentage range of battery charge, and $e_{soc}$ is the efficiency of the storage battery.

$$B_{daily\_cost} = (P_{power} * 800 + E_{capacity} * 1800)/t \tag{9}$$

An economic analysis model is introduced, consisting of power purchase cost and economic cost calculations. The total cost includes operational costs and energy storage system capital costs. The following energy storage strategies are applied [4]:

When there is excess power, store as much as possible in the energy storage system. Any remaining surplus is treated as curtailed power.

When power is insufficient, discharge from the energy storage system to meet load demand. Any shortfall is supplemented by power purchases from the grid.

An independent energy storage autonomous operation strategy is developed based on the wind-PV-storage microgrid conditions of each park. The energy storage system balances power fluctuations and ensures supply stability. Excess PV and wind power is stored to reduce curtailment, while stored power is discharged to address temporary grid power shortages.

(1) First, the PV power $P_{pv}$, wind power $P_{wt}$, and load demand $P_{load}$ are obtained. The power difference $\Delta P(t)$ is calculated as:

$$\Delta P(t) = P_{pv} + P_{wt} - P_{load} \tag{10}$$

**(2) When ΔP(t)>0:**

The PV and wind power generation meet load demand, with surplus power available. In this case, the SOC of the energy storage battery is checked. If the battery is not fully charged, calculate $P_{ch}(t)$、$P_{ch,rel}(t)$:

$$E_{now} = SOC * E_{ch,max} \tag{11}$$

$$P_{ch}(t) = \mathrm{MIN}\{\mathrm{P}_{ch,max}, (E_{ch,max} - E_{now})/0.95\} \tag{12}$$

$$\mathrm{P}_{ch,rel}(t) = \mathrm{MIN}\{\Delta \mathrm{P}(t), \mathrm{P}_{ch}(t)\} \tag{13}$$

If $\Delta P(t)$ is less than the current chargeable capacity $P_{ch}(t)$ , the load is supplied by PV and wind power, with the surplus charging the battery. Otherwise, surplus power is wasted. If the battery is fully charged, PV and wind power supply the load, and surplus power is curtailed. The SOC must not exceed 90%, and $P_{ch,max}$ is set to 50 kW.

(3) When $\Delta P(t) < 0$:

The PV and wind power generation cannot meet load demand. In this case, the SOC is checked. If the battery has stored energy, calculate $P_{dch}(t)$、$P_{dch,rel}(t)$

$$P_{dch}(t) = \mathrm{MIN}(E_{now}, \mathrm{P}_{dch,max}) \tag{14}$$

$$\mathrm{P}_{dch,rel}(t) == \mathrm{MIN}\{|\Delta \mathrm{P}(t)|, \mathrm{P}_{dch}(t)*0.95\} \tag{15}$$

If $|\Delta P(t)|$ exceeds the maximum discharging capacity $P_{dch}(t)$, additional electricity is purchased from the grid. Together with PV, wind, and storage, this satisfies the load demand. Otherwise, no grid power purchase is needed, and PV, wind, and storage alone supply the load. The SOC must not fall below 10%, and $P_{dch,max}$ is set to 50 kW.

#### 4.1.3.2. Model Solution and Economic Analysis

Using Python and optimization decision algorithms, the optimization decision process was illustrated in Figure 7. The states of energy storage devices, charging and discharging status, and grid electricity purchases for the three parks with the 50kW/100kWh energy storage configuration were analyzed over time, as shown in Figures 8-10. The relationships between electricity purchases, curtailed electricity, and supply costs under this configuration are summarized in Table 4.

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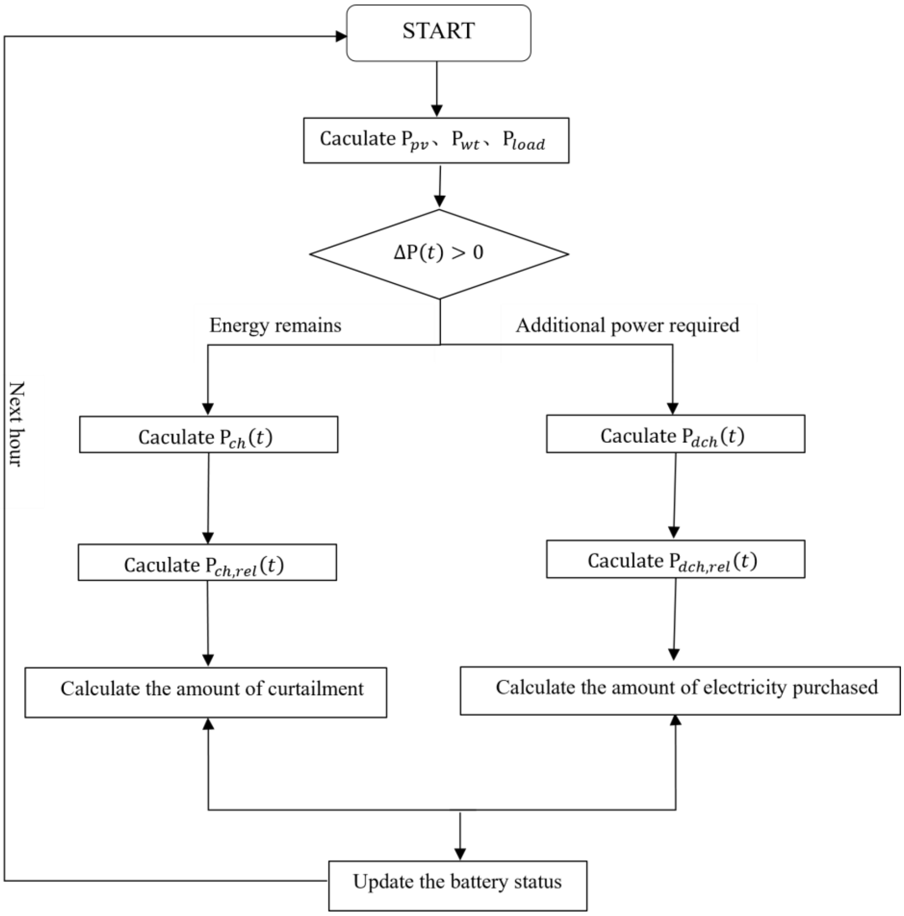


Figure 7: Flowchart of the optimization decision algorithm

Table 4: Results for Subproblem 1.2

| | Grid Electricity Purchases (kWh) | Curtailment (kWh) | Total Cost (¥) | Average Unit Cost (¥/kWh) |
|---|---|---|---|---|
| A PV | 4798.125 | 866.9895 | 6102.833 | 0.7724 |
| B Wind | 2248.1 | 693.4003 | 5049.274 | 0.6549 |
| C PV | 2578.265 | 468.2295 | 4961.144 | 0.6380 |
| C Wind | | 525.5800 | | |

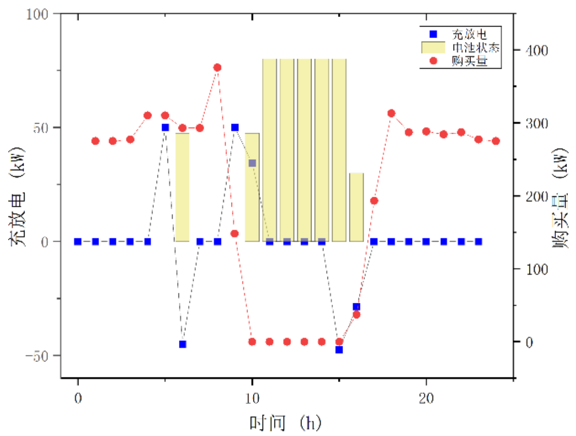


Figure 8: Battery status in Park A for Subproblem 1.2

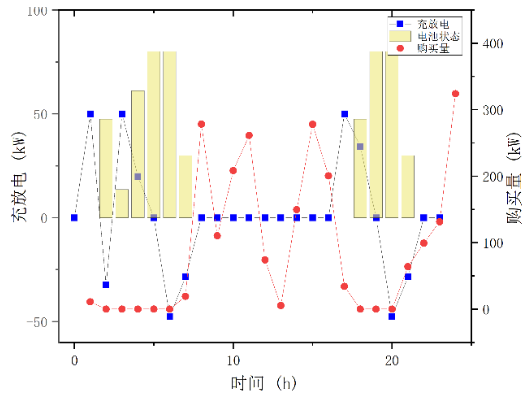


Figure 9: Battery status in Park B for Subproblem 1.2

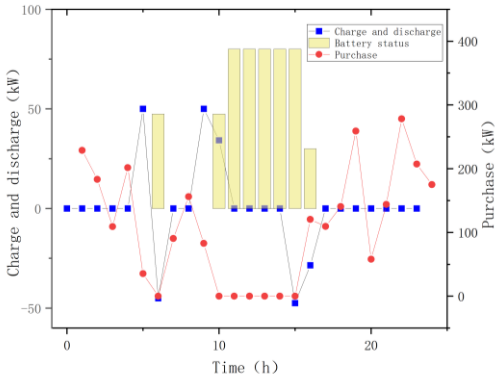


Figure 10: Battery status in Park C for Subproblem 1.2

### 4.1.4. Model Development and Solution for Subproblem 1.3

#### 4.1.4.1. Local Optimization Algorithm

Building on the mathematical model of Subproblem 1.2, modifications were made to the power and capacity parameters of the energy storage devices to derive the optimal energy storage configuration. In Subproblem 1.3, the wind and PV power fluctuation characteristics remain unchanged, and the optimal energy storage scheme for independent parks is introduced. The goal is to minimize the total daily electricity cost. The decision variables include 24-hour energy storage power, energy storage power, and capacity configurations for independent parks. Constraints include the battery SOC and charging/discharging efficiency. Exhaustive search and local optimization algorithms were applied to solve the problem.

#### 4.1.4.2. Model Solution and Economic Analysis

The exhaustive search method was employed to explore possible parameter combinations within a predefined range to find the optimal solution for the objective function [5].

Search Range Definition: The search ranges for storage power and capacity were set to 0–200 kW and 0–500 kWh, respectively.

Parameter Exploration: All potential combinations within the range were evaluated, and the economic analysis function was applied to calculate the total supply cost for each combination.

Optimal Combination Identification: The combination with the lowest cost was recorded [6].

The local optimization algorithm was then applied to refine the results from the exhaustive search by conducting a localized search around the initial estimate. This provided a more precise optimal

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solution with faster convergence. The combined use of exhaustive search for comprehensiveness and local optimization for efficiency yielded the optimal energy storage configurations. The process is shown in Figure 11, and the results are presented in Table 5.

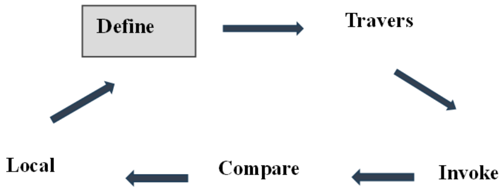


Figure 11: Flowchart of the local optimization algorithm

Finally, the corresponding results were obtained:

Table 5: Optimal Capacity Configuration Results

| | Park A | Park B | Park C |
|---|---|---|---|
| Optimal Power (kW) | 0kW | 130.151kW | 58.794kWh |
| Optimal Capacity (kWh) | 0kWh | 359.873kWh | 69.765kWh |

The exhaustive and local optimization methods yielded the following configurations for Parks A, B, and C, as shown in **Figures 12-14**:

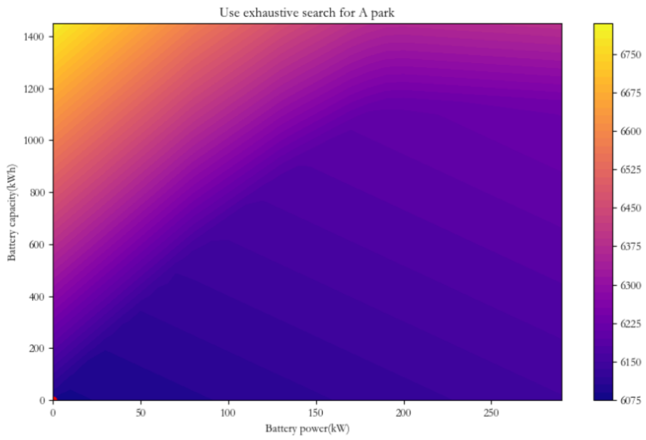


Figure 12: Exhaustive analysis for optimal energy storage configuration in Park A

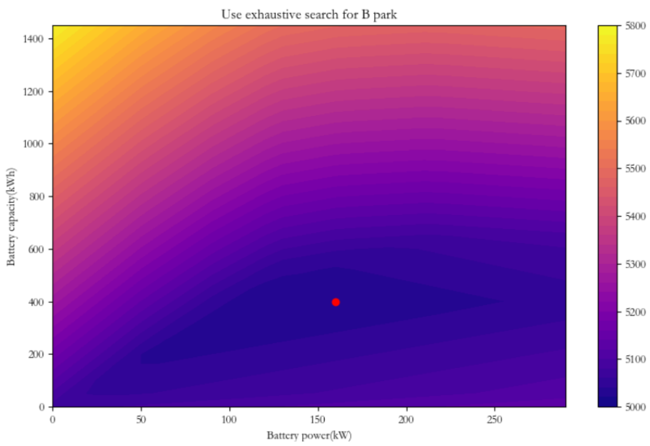


Figure 13: Exhaustive analysis for optimal energy storage configuration in Park B

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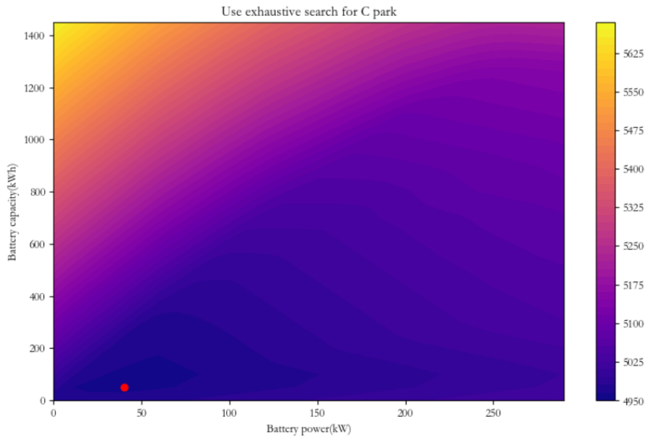


Figure 14: Exhaustive analysis for optimal energy storage configuration in Park C

Economic Analysis

For Park A, using the 0kW/0kWh configuration instead of the 50kW/100kWh configuration reduced total electricity costs and average unit costs, ensuring economic benefits. However, curtailment significantly increased, lowering resource utilization efficiency.

For Park B, the 130.151kW/359.873kWh configuration reduced total electricity costs, average unit costs, and curtailment compared to the 50kW/100kWh configuration, ensuring both economic and resource utilization benefits.

For Park C, the 58.794kW/69.765kWh configuration lowered total costs and average unit costs compared to the 50kW/100kWh configuration but resulted in slightly increased curtailment, reducing resource utilization efficiency.

The optimal energy storage configurations for Parks A, B, and C were compared with the 50kW/100kWh storage configuration, and the economic analysis is shown in Tables 6, 7, and 8.

Table 6: Economic Analysis for Park A

| Configuration | Grid Electricity Purchases (kWh) | Curtailment (kWh) | Total Cost (¥) | Average Unit Cost (¥/kWh) |
|---|---|---|---|---|
| 50kW/100kWh | 4798.125 | 866.9895 | 6102.833 | 0.7724 |
| 0kW/0kWh | 4874.125 | 951.2 | 6084.875 | 0.7701 |

Table 7: Economic Analysis for Park B

| Configuration | Grid Electricity Purchases (kWh) | Curtailment (kWh) | Total Cost (¥) | Average Unit Cost (¥/kWh) |
|---|---|---|---|---|
| 50kW/100kWh | 2248.1 | 693.4003 | 5049.274 | 0.6549 |
| 130.15kW/359.87kWh | 1853.093 | 255.719 | 5018.831 | 0.6509 |

Table 8: Economic Analysis for Park C

| Configuration | Grid Electricity Purchases (kWh) | Curtailment (kWh) | Total Cost (¥) | Average Unit Cost (¥/kWh) |
|---|---|---|---|---|
| 50kW/100kWh | 2578.265 | 993.81 | 4961.144 | 0.6380 |
| 58.75kW/69.77kWh | 2593.346 | 1010.52 | 4957.424 | 0.6375 |

Observations

From the data, the following conclusions can be drawn:

For Park A: The optimized configuration of 0kW/0kWh reduces both the total electricity cost and the average unit electricity cost compared to the 50kW/100kWh configuration, achieving better economic performance. However, the curtailment of wind and solar power increases significantly, reducing resource utilization efficiency.

For Park B: The optimized configuration of 130.15kW/359.87kWh decreases both the total electricity cost and the average unit electricity cost compared to the 50kW/100kWh configuration. This reduces economic costs and enhances economic performance. Furthermore, the curtailment of wind and solar power also decreases, improving resource utilization.

For Park C: The optimized configuration of 58.749kW/69.765kWh reduces both the total electricity cost and the average unit electricity cost compared to the 50kW/100kWh configuration, achieving better economic performance. However, the curtailment of wind and solar power increases slightly, lowering resource utilization efficiency.

## 5. Conclusions

### 5.1. Summary of Findings

This study addresses the coordinated optimization of wind, PV, and storage systems in park microgrids. The data provided in the appendices were preprocessed, a foundational mathematical model was constructed, and key metrics were defined. The study calculated electricity purchases, curtailment, and power supply costs for each park without energy storage and analyzed the key factors influencing economic performance. It was found that the sensitivity to wind power prices, PV power prices, and grid electricity prices varied across parks.

After introducing energy storage systems, a joint wind-PV-storage optimization model was developed with the goal of minimizing total electricity costs while considering constraints such as storage costs, charging and discharging efficiency, and SOC. Optimization algorithms were used to solve the model, determining operational strategies and economic data for different storage configurations. Under storage configurations, the power supply costs of the parks varied compared to the non-storage scenario. Further optimization yielded the most cost-effective storage configurations for each park. The optimization effects varied: for some parks, no storage configuration minimized costs, while for others, specific storage configurations reduced costs, albeit with varying impacts on curtailment.

For park collaboration, economic indicators were calculated and compared with independent operations, showing that collaborative operations have advantages. The results indicated that the lowest supply cost occurred in collaborative operations without energy storage, as parks could share resources to enhance economic efficiency. However, adding energy storage increased supply costs but reduced curtailment. Considering factors such as the cost of wind and PV generation, investment payback periods, and load growth, genetic algorithms were used to optimize the wind-PV-storage configuration. The results highlighted varying additional generation configurations for different parks. Strategies were adjusted for peak-valley electricity prices and seasonal variations, and new configurations were recalculated, showing that park configurations are influenced by electricity prices and generation characteristics.

### 5.2. Model Evaluation

Advantages:

The model provides comprehensive economic analysis capabilities, covering multiple cost factors and the impact of curtailment.

It uses genetic algorithms for optimization, offering strong global search capabilities to solve complex nonlinear optimization problems effectively.

It fully considers the characteristics and economic factors of energy storage systems, making it highly relevant for real-world energy system design.

Detailed outputs, including new generation capacity, storage parameters, and power supply costs, enable decision-makers to make informed comparisons and choices.

The model is implemented in Python, making it easy to read, maintain, and integrate with other toolsets for further expansion.

Limitations:

Simplified assumptions, such as fixed electricity prices and basic load growth models, do not fully account for real-world complexities such as equipment aging and electricity price fluctuations.

Curtailment handling is limited to calculating curtailment volumes without exploring alternative uses.

Although optimization efficiency meets basic needs, there is room for further improvement.

## 5.3. Future Research Directions

Future studies could:

Improve curtailment handling mechanisms by exploring alternative uses or selling surplus power to other users, reducing economic losses.

Experiment with hybrid optimization algorithms or machine learning-based methods to enhance optimization efficiency and effectiveness.

Incorporate multi-objective optimization to minimize carbon emissions, maximize renewable energy utilization, and provide more comprehensive optimization schemes.

Include additional policy and environmental factors in economic analysis, such as renewable energy subsidies and carbon emission costs, for more comprehensive evaluations.

These enhancements aim to further refine the coordinated optimization of wind, PV, and storage in park microgrids, promoting more efficient and sustainable microgrid development.

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