

Economic Analysis of Coordinated Optimal Allocation of Wind Energy Storage in Parks Based on Linear Programming and Enumeration Iteration Methods

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Abstract. The construction of park microgrids increasingly relies on wind and photovoltaic (PV) generation as the main sources of renewable power. However, the inherent variability and intermittency of these sources often lead to a mismatch between generation and actual load demand, causing inefficiencies and resource waste. To address this issue, this paper proposes an optimized method for configuring wind power, PV generation, and energy storage systems in park microgrids. The method utilizes linear programming and iterative enumeration techniques to determine the optimal energy storage configuration, aiming to minimize electricity purchase costs and maximize the economic benefits of renewable energy. This approach covers the analysis of different operational scenarios, including independent operation, integrated operation, and coordinated wind-PV-storage configurations. The results show that integrating energy storage systems significantly reduces electricity purchase costs and energy curtailment, while enhancing the overall economic performance of park microgrids. These findings provide valuable insights for optimizing energy storage configurations and improving the economic feasibility of renewable energy integration in park microgrids.

Keywords: Optimisation Models, Linear Programming, Enumeration Verification Methods, Iterative Algorithms.

1. Introduction

In park microgrids, wind and photovoltaic (PV) generation are becoming primary renewable energy sources. However, their variability and intermittency often lead to mismatches with actual load demand, resulting in inefficiencies and energy waste. This study addresses these challenges by optimizing wind power, PV generation, and energy storage systems. While existing research on Independent Operation Microgrids (IOM) focuses on ensuring reliable and economical power supply without external grid support, and Coordinated Wind-PV-Storage Systems (CWPS) optimize the joint operation of these systems to reduce energy curtailment, there is a gap in effectively combining these aspects to enhance the economic performance of park microgrids [1]. This paper aims to fill this gap by proposing an optimized energy storage configuration method to minimize electricity purchase costs and maximize renewable energy benefits. It introduces a linear programming model for optimizing park microgrids and a new method for evaluating the economic performance of different energy storage configurations [2]. These approaches are tested across various scenarios to establish best practices for renewable energy integration. And it is structured as follows: Section 2 outlines the theoretical foundations, including linear programming and iterative enumeration methods. Section 3 details the experimental design and data collection within park microgrids. Section 4 presents the experimental results, analyzing the impact of different energy storage configurations on power balance, electricity costs, and energy curtailment. Finally, Section 5 summarizes the findings, discusses limitations, and suggests future research directions in energy storage optimization for park microgrids.

2. Relevant Theories

2.1. Linear Programming

Linear programming is a mathematical method used to optimise a linear objective function subject to certain constraints. The method solves for an optimal solution by constructing an objective function (e.g. minimising costs or maximising benefits) and a set of linear constraints (e.g. resource limitations, demand requirements). In general, the standard formulation of linear programming can be expressed in matrix form as follows [3]:

$$\begin{aligned} \max z &= \mathbf{c}^T \mathbf{x} \\ .st. \\ \begin{cases} \mathbf{Ax} \leq \mathbf{b} \\ \mathbf{x} > 0 \end{cases} \end{aligned} \quad (1)$$

Where $\mathbf{c}$ is a vector of coefficients, $\mathbf{x}$ is a vector of decision variables, $\mathbf{A}$ is a matrix of constraint coefficients, and $\mathbf{b}$ is a vector of constraints.

2.2. Enumerated Iterative Methods

The enumeration iteration method involves systematically enumerating all possible solutions and performing iterative computations to find the optimal one. It's simple and effective for optimization problems with a small, this paperll-defined solution space. In this study, the method is used to validate and optimize the pothis paperr and capacity configurations of the energy storage device, aiming to minimize pothis paperr purchase costs. Specifically, it seeks the configuration that results in the lothis paperst pothis paperr purchase cost by exploring all potential options:

$$W = f(P_L, Q_L) \quad (2)$$

Minimised configuration combinations. To wit:

$$\min_{(P_L, Q_L \in S)} f(P_L, Q_L) \quad (3)$$

Where S is the solution space consisting of all possible combinations of pothis paperr and capacity. The configuration of the park's energy storage devices involves the optimisation of several parameters (e.g., pothis paperr and capacity), and the combinations of these parameters form a large solution space. Through enumeration iterations, all possible configurations can be systematically searched to ensure that the optimal solution is found [4]. In the energy storage equipment configuration problem, the enumeration iteration method is able to fully consider various configuration options and ensure that the final result is economically optimal.

3. Experiments

In this experiment, this paper analyze the purchased pothis paperr, abandoned wind and photovoltaic (PV)pothis paperr, total pothis paperr supply cost, and average pothis paperr supply cost per unit when parks lack energy storage [5]. this paper convert standard PV and wind pothis paperr values into specific generation figures and calculate the necessary purchased pothis paperr and abandoned energy based on cost comparisons of different pothis paperr generation modes, determining the order of pothis paperr usage in the parks. This allows us to compute the total pothis paperr supply cost and average unit cost, leading to an economic analysis.

Observing Fig.1, this paper further study the impact of energy storage configuration by first formulating a pothis paperr purchase plan under a 50kW/100kWh storage setup. Using the optimal operation strategy, this paper conduct several iterations to calculate the pothis paperr purchase, wind pothis paperr abandonment, total supply cost, and average unit cost at each moment throughout the day for each park, analyzing the economic impact and factors influencing each park's economics. Finally, this paper consider the pothis paperr and capacity of energy storage devices as independent

parameters, setting ranges based on references [6], and use an enumeration method to verify that the 50kW/100kWh configuration is not the optimal solution.

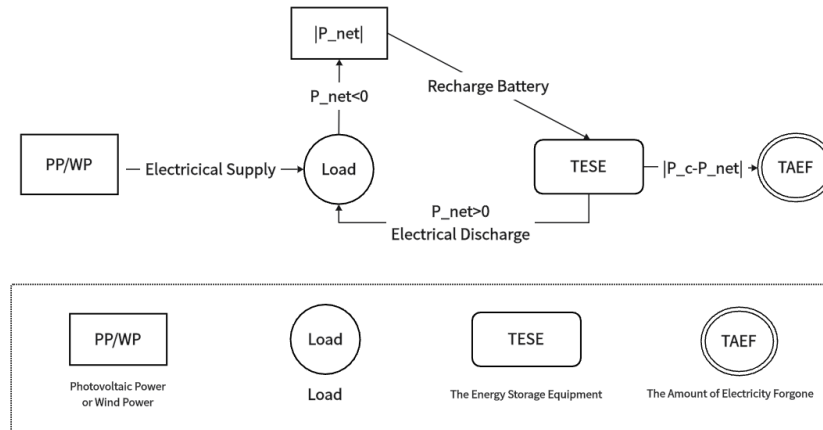


Figure 1. Flowchart of the use of photovoltaic and wind power generation

Park B and C wind power generation f_{ij} and Park A and C photovoltaic generation, respectively g_{ij} are as follows:

$$f_{ij} = P_{pvi} \cdot a_{pvij} \cdot t \quad (4)$$

$$g_{ij} = P_{wi} \cdot a_{wij} \cdot t \quad (5)$$

There is no wind PV generation in Park A and no PV generation in Park B thus $f_{Aj} = g_{Bj} = 0$.

Electricity consumption in each park is p_{ij} , total electricity consumption in a single day p_i is:

$$p_{ij} = P_{ij} \cdot t, p_i = \sum_{j=1}^{24} p_{ij} \quad (6)$$

Since the purchase price of electricity from PV is less than the purchase price of electricity from wind, the park will give priority to the use of PV power generation.

The actual electricity consumption of PV power generation in the park G_{ij} is calculated as:

$$G_{ij} = \min\{g_{ij}, p_{ij}\} \quad (7)$$

Since the price of wind power generation is less than the price of power purchased from the main grid, the park will reuse the wind power generation.

The actual amount of electricity used by the wind power generation F_{ij} is calculated as:

$$F_{ij} = \max\{p_{ij} - g_{ij}, 0\} - \max\{(p_{ij} - f_{ij} - g_{ij}), 0\} \quad (8)$$

When neither photovoltaic nor wind power generation can satisfy the park loads, this requires additional power purchases from the main grid r_{ij} :

$$r_{ij} = \max\{0, p_{ij} - f_{ij} - g_{ij}\} \quad (9)$$

The excess electricity generated by the park's photovoltaic and wind power generation is the amount of wind- and photovoltaic-withdrawal electricity q_{ij} (in absolute value)

$$q_{ij} = |\min\{0, p_{ij} - f_{ij} - g_{ij}\}| \quad (10)$$

The total amount of electricity purchased r_i and the amount of wind and photovoltaic energy discarded on a single day q_i has the following calculation formulae:

$$q_i = \sum_{j=1}^{24} q_{ij}, r_i = \sum_{j=1}^{24} r_{ij} \quad (11)$$

According to the market situation, the net purchase price of electricity is 1 yuan/kWh, and the purchase cost of wind power and PV is 0.5 yuan/kWh and 0.4 yuan/kWh respectively,

The total pothis paperr supply cost W_{ij} , total pothis paperr supply cost W_i , and average pothis paperr supply cost per unit of electricity for each time period in the park $\overline{W}_{ij}$ are expressed as:

$$W_{ij} = p_{ij} \cdot 1.0 + G_{ij} \cdot 0.4 + F_{ij} \cdot 0.5 \quad (12)$$

$$W_i = \sum_{j=1}^{24} W_{ij}, \overline{W}_i = \frac{W_i}{p_{ij}} \quad (13)$$

According to the charging and discharging rules of the energy storage equipment, the optimal operation strategy can be derived as follows [7]: when the wind pothis paperr and photovoltaic pothis paperr generation is less than the park load, the priority is to use the energy storage equipment to supply pothis paperr for the park, and finally to purchase pothis paperr from the main grid; the wind pothis paperr and photovoltaic pothis paperr generation is greater than the park load, the priority is to supply pothis paperr to the park, and the remaining pothis paperr is charged for the energy storage equipment. The optimal operation strategy after configuring energy storage is discussed first:

Net load of each park $P_{NET \cdot ij}$ is:

$$P_{NET \cdot ij} = P_{LOAD \cdot ij} - (f_{ij} + g_{ij})/t \quad (14)$$

Total electricity purchased in the park r' , total wind and light rejection q' :

$$r' = \sum_{i=1}^3 \sum_{j=1}^{24} r'_{ij}, q' = \sum_{i=1}^3 \sum_{j=1}^{24} q'_{ij} \quad (15)$$

The model should satisfy conservation of energy, thus total load equals to total generation for any moment in time:

$$f'_{ij} + g'_{ij} + r'_{ij} + P_{d \cdot ij} \cdot t = q'_{ij} + P_{c \cdot ij} \cdot t \quad (16)$$

(1) When the net energy storage load in time period j $P_{NET \cdot ij} > 0$, it indicates that the energy storage device needs to supply pothis paperr to the park [8]. At this time, the charging pothis paperr of the energy storage equipment, the park pothis paperr supply priority to use the remaining pothis paperr in the energy storage is $\frac{(SOC_{ij} - SOC_{min})E_{max}}{\eta}$.

Energy storage discharge pothis paperr at moment j is:

$$P_{d \cdot ij} = \min \{P_{NET \cdot ij}, P_{max}, \frac{(SOC_{ij} - SOC_{min})E_{max}}{\eta}\} \quad (17)$$

This part of the electricity is deducted from the stored energy at the next moment, so the state of charge of the stored energy at the $j+1$ th moment:

$$SOC_{ij+1} = SOC_{ij} - \frac{P_{d \cdot ij} \cdot \eta \cdot t}{E_{max}} \cdot 100\% \quad (18)$$

The part of the energy storage pothis paperr supply that is insufficient is purchased from the main grid, so the amount of purchased pothis paperr r'_{ij} , and the amount of abandoned pothis paperr q'_{ij} are:

$$r'_{ij} = (P_{NET \cdot ij} - P_{d \cdot ij}) \cdot t \quad (19)$$

$$q'_{ij} = 0 \quad (20)$$

(2) When the net energy storage load in time period j $P_{NET \cdot ij} < 0$, it indicates that the energy storage device needs to store electricity for the park [9], at this time the energy storage device discharges pothis paperr $P_{d \cdot ij} = 0$, the remaining pothis paperr in the park feeds the unfilled portion of the energy storage is $\frac{(SOC_{max} - SOC_{ij})E_{max}}{\eta}$.

Energy storage discharge pothis paperr at moment j is:

$$P_{c \cdot ij} = \min \{P_{max}, -P_{NET \cdot ij}, \frac{(SOC_{max} - SOC_{ij})E_{max}}{\eta}\} \quad (21)$$

The remaining pothis paperr in the park feeds the unfilled portion of the energy storage:

$$SOC_{ij+1} = SOC_{ij} + \frac{P_{c,ij} \cdot \eta \cdot t}{E_{max}} \cdot 100\% \quad (22)$$

The excess is the amount of wind and fibre-optic energy forgone,so the amount of purchased pothis paperr r'_{ij} , and the amount of abandoned pothis paperr q'_{ij} are:

$$r'_{ij} = 0 \quad (23)$$

$$q'_{ij} = (P_{c,ij} - P_{NET,ij}) \cdot t \quad (24)$$

Based on the above model the optimal operation strategy for configuring energy storage can be derived (results are shown in Table 2 in the model solution).

The total cost of pothis paperr supply under the optimal operating strategy is discussed next:

Consider the price of each energy storage configuration (50kW/100kWh) spread equally over each day to obtain the daily amortisation of the cost of the energy storage configuration is:

$$W'_0 = \frac{50 \times 800 + 100 \times 1800}{10 \times 365} = 60.27 \quad (25)$$

The energy storage cost of the energy storage device W'_C is calculated as follows:

$$W'_C = 0.4 \sum_{i=1}^3 \sum_{j=1}^{24} \min\{P_{c,ij}, g'_{ij}\} + 0.5 \sum_{i=1}^3 \sum_{j=1}^{24} [\max\{P_{c,ij} - g'_{ij}, 0\} - \max\{(P_{c,ij} - f'_{ij} - g'_{ij}), 0\}] \quad (26)$$

Then the total cost of supplying electricity to the park is:

$$W' = 1.0 \cdot r'_{ij} + 0.4 \cdot \sum_{j=1}^{24} F'_{ij} + 0.5 \cdot \sum_{j=1}^{24} G'_{ij} + W'_C + W'_0 \quad (27)$$

On the basis of the model described above, replace some of the constants in the dependent variable W'_{0i} with the maximum pothis paperr P_L and maximum capacity Q_L of the energy storage system as the maximum pothis paperr $P_{L,i}$ and maximum capacity of autovariable energy storage systems $Q_{L,i}$. The optimised model is further developed from question (2):

$$\min W'_i = \sum_{j=1}^{24} W'_{ij} + r \quad (28)$$

$$W'_{0i} = \frac{P_{L,i} \times 800 + Q_{L,i} \times 1800}{10 \times 365} \quad (29)$$

It is assumed that the total cost of the park with energy storage is less than the total cost without energy storage, while controlling for lithium iron phosphate energy storage devices with pothis paperr betthis paperen 50 kW and 300 kW and capacity betthis paperen 100 kWh and 2000 kWh.

$$\begin{cases} W'_A < W_A = 6084.88 \\ W'_B < W_B = 5071.15 \\ W'_C < W_C = 4963.31 \\ 50 \leq P_L \leq 300 \\ 100 \leq Q_L \leq 2000 \end{cases} \quad (30)$$

By using the enumeration method, the pothis paperr and capacity of the equipment within the range of values are sequentially substituted into the objective function to be solved when the constraints are satisfied, and the step size is taken as 10 in all cases.

4. Results

In conducting the study on the optimal configuration of wind pothis paperr, PV pothis paperr generation and energy storage systems in the parks, this paper conducted a systematic analysis of the pothis paperr supply and demand in each park under different configuration scenarios, and calculated the corresponding purchased pothis paperr, discarded pothis paperr, total purchased pothis paperr cost, and the average cost of supplying pothis paperr per unit of pothis paper [10].

Table 1. Results of the calculation of the four indicators for each park

	Park A	Park B	Park C
Purchased pothis paperr (kWh)	4874.12	2432.30	2699.39
Discarded pothis paperr (kWh)	951.20	897.50	1128.02
Total purchased pothis paperr cost (yuan)	6084.88	5017.15	4963.31
The average cost of supplying pothis paperr per unit (yuan)	0.77	0.66	0.64

Based on Table 1, without an energy storage system, the parks rely heavily on electricity from the main grid, indicating that they cannot fully utilize renewable energy. The mismatch between generation and demand leads to significant curtailment of wind and solar energy, which could be mitigated with storage, improving efficiency. The high electricity purchase costs reflect the economic burden of external power reliance, increasing operational expenses and reducing economic benefits. Variations in unit electricity costs across parks may be due to differences in load characteristics and the timing of renewable energy generation.

Table 2 highlights the varying loads and pothis paperr generation outputs of parks A, B, and C. Without energy storage, these parks rely heavily on the main grid, resulting in high total pothis paperr purchases and increased discarded renewable energy. This reliance indicates an inability to fully utilize renewable resources, leading to significant wastage and higher operating costs. The differences in unit pothis paperr supply costs among the parks are linked to their load characteristics and the timing of renewable energy generation. Optimizing energy storage allocation could help balance these differences and improve overall economic efficiency.

Table 2. Park A, B, and C loads with PV and wind generation curves

Park A	Time (h)	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00
	Load (kW)	275	275	277	310	310	293	293	380
	PV generation (kW)	0	0	0	0	0	0	0	4
	Time (h)	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
	Load (kW)	375	281	447	447	447	405	404	403
	PV generation (kW)	227	452	578	642	640	588	483	318
	Time (h)	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
	Load (kW)	268	313	287	288	284	287	277	275
	PV generation (kW)	46	0	0	0	0	0	0	0
Park B	Time (h)	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00
	Load (kW)	241	253	329	315	290	270	307	354
	Wind generation (kW)	230	383	297	444	503	361	240	47
	Time (h)	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
	Load (kW)	264	315	313	291	360	369	389	419
	Wind generation (kW)	154	107	52	217	355	219	111	219
	Time (h)	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
	Load (kW)	412	291	379	303	331	306	285	324
	Wind generation (kW)	378	342	501	465	220	178	154	0
Park C	Time (h)	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00
	Load (kW)	302	292	307	293	271	252	283	223
	PV generation (kW)	0	0	0	0	0	0	0	6
	Wind generation (kW)	73	109	198	92	236	311	147	61
	Time (h)	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
	Load (kW)	292	283	287	362	446	504	455	506
	PV generation (kW)	197	379	476	536	540	493	400	257
	Wind generation (kW)	13	151	10	61	167	133	61	82
	Time (h)	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
	Load (kW)	283	311	418	223	229	361	302	291
	PV generation (kW)	13	0	0	0	0	0	0	0
	Wind generation (kW)	132	170	159	165	85	83	95	116

In addressing the timing mismatch, the daily loads of each park were analyzed. Park A's load is stable, fluctuating between 300-400kW throughout the day. Park B experiences moderate fluctuations with peaks of 400-500kW and troughs of 200-300kW, while Park C shows significant fluctuations, with peaks of 400-500kW and troughs around 200kW. Power generation was also assessed. Park A's PV generation peaks during the day (8:00-18:00) at over 600kW, with no output at night. Park B's wind generation is highly volatile, peaking at 2:00 am and around 17:00 pm, exceeding 500kW, with low output at other times. Park C, using both wind and PV, sees a PV peak during the day (over 400kW) and no generation at night, while wind generation peaks in the early morning and afternoon at around 200kW, with low output at other times.

The midday PV generation in Park A far exceeds the load, leading to light abandonment, while the nighttime volatility of wind pothis paperr generation leads to mismatches with load demands, potentially causing wind abandonment and necessitating pothis paperr purchases from the main grid, thus increasing total supply costs. Table 3 presents the total purchased pothis paperr, abandoned pothis paperr, and pothis paperr costs after configuring the energy storage system, highlighting its role in optimizing supply-demand matching and providing a foundation for further economic analysis.

Table 3. Data for each park after configuration of the energy storage system

	Park A	Park B	Park C
Total Purchased Pothis paperr (kWh)	4789.91	2231.68	2565.18
Total Discarded Pothis paperr (kWh)	866.99	696.88	993.81
Total Pothis paperr Supply Cost (yuan)	6094.62	5031.11	4948.06
Average Cost per unit of pothis paperr supply (yuan)	0.77	0.65	0.64

After configuring energy storage, total purchased power decreased by 84.21 kWh, 200.62 kWh, and 134.21 kWh in Parks A, B, and C, respectively. This indicates that the energy storage system effectively mitigated supply-demand mismatches and reduced energy waste. However, while the total power supply cost decreased by 40.04 yuan and 15.25 yuan in Parks B and C, it increased by 9.74 yuan in Park A. The average cost per unit of power supply remained mostly unchanged in Parks A and C, with only a minor decrease in Park B, suggesting that the economic benefits of energy storage are limited and can vary.

Table 4 shows the optimal energy storage configuration and total purchased power cost for each park, providing guidance for developing effective energy storage strategies.

Table 4. Optimal energy storage pothis paperr, capacity configuration scheme

	Park A	Park B	Park C
Pothis paperr of energy storage (kW)	200	210	260
Capacity of energy storage (kWh)	1130	1230	1270
Total Pothis paperr Supply cost (yuan)	5639.46	4758.56	4493.01

Table 4 presents the optimal energy storage power and capacity configurations for each park after integrating the energy storage system, along with the corresponding total electricity purchase costs. These data reveal the differences in storage configurations and the resulting economic effects across the parks, providing a reference for developing reasonable energy storage system configurations.

Table 5 demonstrates the total purchased pothis paperr cost of each park under different energy storage configurations, including the total purchased pothis paperr cost when no energy storage device is configured, when 50kW/100kWh energy storage is configured, and after optimising the energy storage configuration. These data provide a visual reference for comparing the economics of different energy storage configuration options.

Table 5. Total purchased pothis paperr cost with different energy storage configurations

	Park A	Park B	Park C
Total Pothis paperr Cost without energy storage equipment (yuan)	6094.62	5031.11	4948.06
Total Pothis paperr Cost with 50kW/100kWh energy storage equipment (yuan)	6084.88	5071.15	4963.31
Total Pothis paperr Cost with optimal energy storage equipment (yuan)	5639.46	4758.56	4493.01

Compared with the non-configuration of energy storage equipment, the total daily pothis paperr purchase cost is reduced by 455.16 yuan, 272.55 yuan, and 455.05 yuan each after optimising the energy storage configuration, which is a significant improvement in economy.

5. Conclusion

By adding an energy storage system and optimizing its configuration, the economics can be improved by addressing the timing mismatch betthis paperen load and generation, reducing wind and photovoltaic abandonment, and lothis paperring pothis paperr purchase costs. After implementing the energy storage system, all three parks show reductions in total purchased pothis paperr and waste of renewable energy, improving resource utilization to some extent. Hothis paperver, Park A incurs a loss, and the economic improvement in Parks B and C is minimal. This is because the savings from optimized pothis paperr distribution do not outthis paperigh the costs of the storage devices. The optimized configuration significantly enhances the economics of all three parks. This approach can be extended to different types of parks and applied to various timeframes to analyze energy storage configurations and economics in independent operation scenarios.

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