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Design and economic analysis of energy storage optimization allocation for campus microgrid

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Abstract. In the twenty-first century, the "double carbon" plan is advancing steadily. Energy saving and emission reduction is one of the key points of the plan. A power grid independent park, if energy storage equipment can be configured, it can greatly improve the park microgrid power utilization, in order to achieve the purpose of energy saving. Therefore, research on the optimization of the proportion of power grid and microgrid in the park and the optimization of the configuration of energy storage devices can greatly improve the energy utilization rate, so as to achieve the significance of environmental protection. After collecting and sorting the daily load, daily wind power generation and 12-month daily wind power generation data of the three parks A, B and C, and processing the data, a linear function model is established. After using linear programming, operations research and genetic algorithm, the research results are obtained when the three parks are combined and equipped with 50kW/100kWh energy storage devices.

Keywords: Economic analysis, Energy storage systems, Microgrids, linear programming.

1. Introduction:

Wind power generation technology continues to improve and the cost of decline, now has been favored by all walks of life. By the end of March 2024, China's installed wind power capacity of about 460 million kW, an increase of 21.5%; The installed capacity of photovoltaic power generation was about 660 million kW, up 55 percent year-on-year. The total installed capacity of wind power generation accounted for about 37.3% of the country's installed capacity of power equipment, accounting for more than one-third of the total. However, there is a problem that must be solved in wind power generation: wind power generation has time series fluctuation instability, there are quite a few researches on this issue, such as Ma Chao et al., Research on Hybrid energy Storage Allocation in Micro-grid Systems with multiple micro-Sources, and Fan Gangqiang et al., Research on Hybrid Energy Storage Capacity Optimization Allocation in wind-wind Complementary Systems. However, an exact and general research method, research direction and research conclusion on this issue still need to be supplemented. In this paper, the influence of two factors, the proportion of wind-wind power network and the degree of park connection, on the time-series fluctuation instability of wind-wind power generation is verified. In order to solve this problem, energy storage devices can be considered to smooth the output of renewable energy and improve the reliability and elasticity of the grid. This paper records the data of the three parks A, B and C, and sets two situations of the three parks in independent operation and joint operation respectively. Under this setting, in order to further refine the research direction and research object, it also sets whether the energy storage device is configured or not and the parameter difference of the energy storage device in each case, analyzes the purchased power, abandoned wind and light power, total power supply cost and average power supply cost per unit power of each park, etc., so as to make a relatively comprehensive data comparison. Analyze the impact of different conditions on the economy, and obtain the best optimization plan.

2. Research on energy storage configuration scheme of independent operation of each park

2.1. Objective function and model analysis

In this study, Park A, B and C are all connected to the main power grid. Based on this, it is stipulated that Park A is equipped with A photovoltaic power grid with an installed capacity of 750kW, and the maximum load value of Park A is 447kW. Park B is equipped with a 1000kW wind power grid with a maximum load of 419kW; Park C is equipped with a photovoltaic power grid with an installed capacity of 600kW and a wind power grid with a installed capacity of 500kW, and the maximum load of Park C is 506kW. The general structure of the three parks is as shown in FIG. 1 below:

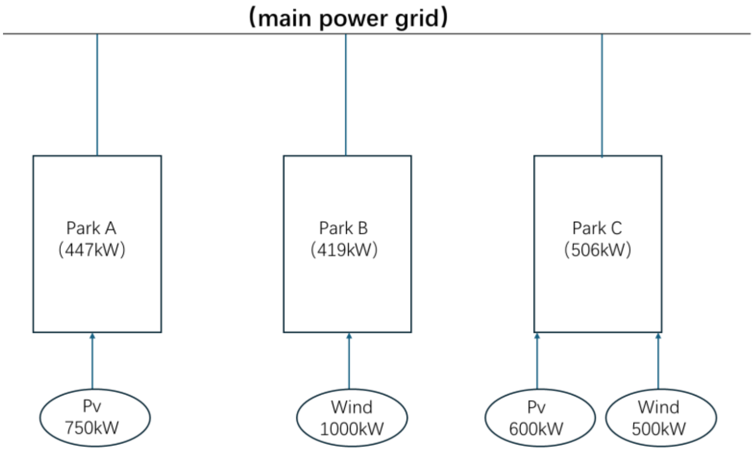

Figure 1. Structure diagram of the independent park

It is stipulated in this study that the scenic power grid of each park can only supply power to the region, and the insufficient part is purchased from the main power grid. Besides, the excess electricity of scenic power generation can only be stored in the energy storage device or abandoned, and cannot be sold to the main power grid.

Because the wind-power generation has the instability of time series fluctuation, in order to facilitate the research and data recording, this paper divides the whole day into 24 periods, and sets the percentage of the actual generation of wind-power generation in a certain period of time to the installed capacity as per unit value, that is, p.u. P.u. value. If it is necessary to use the actual power generation, take the corresponding per unit value and multiply the corresponding installed capacity of the park.

It is set that the total power purchased from the main power grid and the wind power grid just meet the load of the park at the corresponding time period, then the purchased power is the sum of the typical daily load of each time period.

Since the park has not been configured with energy storage devices at this time, the abandoned power is the part of the actual power generation that exceeds the park load in the corresponding period.

In order to facilitate a comparative study of the calculation results of the three parks, this paper introduces a unified treatment of the average power purchase cost per unit of electricity, which is the ratio of total power purchase cost and total load.

Based on the above analysis and MATLAB function, the following model can be established:

The corresponding abandoned energy in the i period of Park s is:

$$q_{si} = (Q_{si} - R_{si})H(Q_{si} - R_{si}), \quad (1)$$

Among which Q_{si} ,represents the actual generating capacity of wind power generation during i period of Park s,; R_{si} ,indicates the typical load value in i period of Park s. $H(x) = \begin{cases} 0, Q_{si} - R_{si} < 0 \\ 1, Q_{si} - R_{si} > 0 \end{cases}$.

The power supply cost during period i of Park s is:

$$C_{si} = Q_{si}P_k + (R_{si} - Q_{bi})H(Q_{si} - R_{si}), \quad (2)$$

Among them P_k ,the unit price of online shopping for wind power grid and photovoltaic power generation is k=1,2. $H(x) = \begin{cases} 0, Q_{si} - R_{si} > 0 \\ 1, Q_{si} - R_{si} < 0 \end{cases}$.

The total electricity purchased by the park in one day is the sum of the typical load of the park in each period：

$$P_s = \sum_{i=1}^{24} R_{si}, \quad (3)$$

The total abandoned electricity is:

$$q_s = \sum_{i=1}^{24} q_{si}, \quad (4)$$

Set the price of purchasing electricity from the main grid as 1 CNY /kWh, the price of online purchasing electricity from wind power is 0.5 CNY /kWh, and the price of online purchasing electricity from photovoltaic power is 0.4 CNY /kWh, then:

The total power supply cost is:

$$C_s = \sum_{i=1}^{24} C_{si}, \quad (5)$$

The cost of electricity supplied per unit time is:

$$C = \frac{C_s}{P_s}, \quad (6)$$

On this basis, each park is equipped with the same number of energy storage devices with technical parameters of 50kW/100kWh, 50kW is the transmission power of the battery, 100kWh is the battery capacity, and the unit price of the energy storage device is 800 CNY /kW, and the unit price of energy is 1800 CNY /kWh, in order to maximize the benefits, The allowable range of SOC(State of Charge) is limited to 10%~90%. On the basis of energy conservation, the charging/discharging efficiency of the device is 95%.

When configuring the energy storage cost, the park should comprehensively compare the cost of power abandonment and the cost of the energy storage device, that is, if the energy storage cost is larger than the cost of power abandonment, at this time, the calculation should choose to abandon power rather than store excess power. And because the energy storage device can eliminate the time series fluctuation instability of the wind-power grid to a certain extent, that is, the energy storage device has the characteristics of cross-time operation, at this time the abandoned power is:

$$q_{si} = (Q_{si} - \max\{E_i + R_{si}, P_{L\max s}\})H(Q_{si} - \max\{E_i + R_{si}, P_{L\max s}\}), \tag{7}$$

Among them E_i For the remaining battery capacity of the energy storage device during the i period, $\max\{E_i + R_{si}, P_{L\max s}\}$,it means that when the power supply of the wind power grid exceeds the rated value, the excess power will also be used; $P_{L\max s}$, indicates the maximum load value of Park s.

Total power supply cost:

$$C_s = \sum_{i=1}^{24} C_{si}, \tag{8}$$

Storage cost:

$$C_e = \sum_{i=1}^{24} 1800E_i, \tag{9}$$

Total cost per unit of probability:

$$C_p = \sum_{i=1}^{24} 800E'_i, \tag{10}$$

Among them E'_i ,it is discharging quantity.

Average power supply cost per unit of electricity:

$$C = \frac{C_s}{Q_s}, \tag{11}$$

Aiming at the minimum total cost of electricity purchase, an optimization model is established, and the objective function can be obtained:

$$\min C_s = \sum_{i=1}^{24} (C_{si} + C_e + C_p), \tag{12}$$

At this time, the energy storage device with technical parameters of 50kW/100kWh is the initial value. If you want to verify whether the scheme is the best scheme, you can consider the battery transmission power and battery capacity as variables, that is, the transmission power makes it fluctuate up and down at 50kW, and the battery capacity makes it fluctuate up and down at 100 kWh, and observe different results. Find the optimal battery technical parameter results. By modifying the parameters of the above optimization model objective function, we can get:

$$\min C_s = \sum_{i=1}^{24} (C_{si} + C_e + C_p) = \sum_{i=1}^{24} Q_{si}P_k + \sum_{i=1}^{24} \alpha E'_i + \sum_{i=1}^{24} \beta E_i, \tag{13}$$

Among which α indicates the battery transmission power; β indicates the battery capacity.

2.2. Constraints

The situation at the beginning of the power rejection is the key to discuss the constraints of the research model. When the park is not equipped with energy storage devices, the power supply of the wind power grid must be guaranteed not to exceed the park load value, and the wind power grid and photovoltaic power grid have installed capacity constraints, then when the energy storage device is not configured, the purchased power should meet the following constraints:

For Park A:

$$0 < Q_{Ai} \leq \delta_{Agi} P_{Ag} \text{ ,} \tag{14}$$

For Park B:

$$0 < Q_{Bi} \leq \delta_{Bfi} P_{Bf} \text{ ,} \tag{15}$$

For Park C:

$$0 < Q_{Ci} \leq \delta_{Cfi} P_{Cf} + \delta_{Cgi} P_{Cg} \text{ ,} \tag{16}$$

Among them δ_{sgi} represents the per unit value of PV power grid i period in Park s; δ_{sfi} represents the per unit value of wind power grid i period in Park s; P_{sg} represents the installed capacity of PV power grid in Park s; P_{sf} represents the installed capacity of wind power grid in Park s.

Where, represents the per unit value of PV power grid i period of Park s, represents the per unit value of wind power grid i period of Park s; Represents the installed capacity of PV power grid in Park s, and represents the installed capacity of wind power grid in Park s.

When the park is equipped with 50kW/100kWh energy storage device, the purchased power should meet the following constraints:

For Park A:

$$R_{Ai} \leq Q_{Ai} \leq P_{Ag} \text{ ,} \tag{17}$$

For Park B:

$$R_{Bi} \leq Q_{Bi} \leq P_{Bf} \text{ ,} \tag{18}$$

For Park C:

$$R_{Ci} \leq Q_{Ci} \leq P_{Cf} + P_{Cg} \text{ ,} \tag{19}$$

At this time, when the generating capacity of the wind-power grid in the park is less than the park load, the energy storage device does not work; when the generating capacity is greater than the park load, the power abandonment occurs, and the excess power is input to the energy storage device to make it work. Moreover, the allowable SOC(γ) range of the energy storage device is 10%~90%, and the charge/discharge efficiency (η) is 95%. Therefore, the energy storage capacity—E_i—of the battery in the i period is constrained by the remaining amount in the (i-1) period, that is:

$$E_i \leq \gamma (100 - \eta E'_i) \text{ ,} \tag{20}$$

In the battery discharge process should also meet this constraint condition, namely:

$$(R_{si} - Q_{si}) H (R_{si} - Q_{si}) \leq \eta E'_i \text{ ,} \tag{21}$$

That is, the power directly supplied by the energy storage device to the park should also be within its load value, then the load of park s in each time period can be satisfied and within a reasonable range, without damaging the microgrid of the park.

For verification function: $\min C_s = \sum_{i=1}^{24}(C_{si}+C_e+C_p) = \sum_{i=1}^{24} Q_{si}P_k + \sum_{i=1}^{24}\alpha E'_i + \sum_{i=1}^{24}\beta E_i$ the following constraints should be met at the same time:

$$\begin{cases} Rsi \le Qsi \le Ps \\ Ei \le \gamma(\beta - \eta E'_i) \\ (R_{si}-Q_{si})H(R_{si}-Q_{si}) \le \eta E'_i \end{cases}, \quad (22)$$

At this time, the capacity of the energy storage device is a variable β, and its value is uncertain. During period i, if the actual power generation is greater than the load, the energy storage device is input. During period (i+1), if the power generation is less than the load value, the energy storage device outputs— E'_i —power supply for the park; If it is greater than the load value, the energy storage device will continue to be input, and the total input should be less than 90% of the total capacity of the energy storage device, and the remaining power after output is not less than 10% of the total capacity of the energy storage device— β .

3. Research on energy storage configuration scheme for joint operation of each park

3.1. Objective function and model analysis

When the three parks form a joint park, the maximum load value of the joint park, the total installed capacity of photovoltaic power grid and the total installed capacity of wind power grid formed after the three parks are the sum of the three, and the structure is shown in Figure 2:

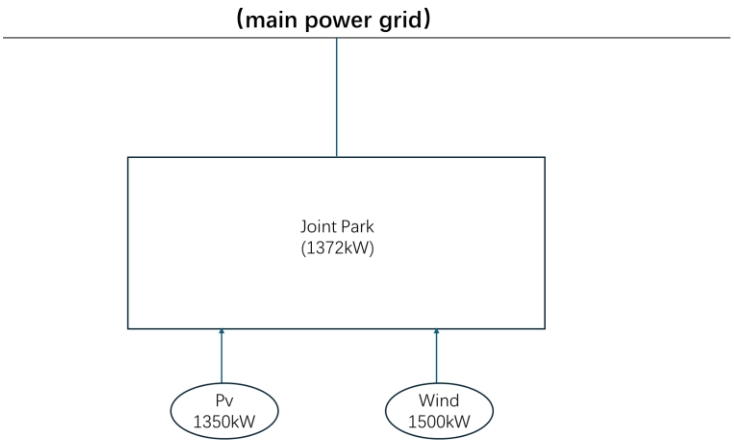

Figure 2. Structure diagram of the Joint Park

When the joint park is not equipped with energy storage devices, it is also based on the principle of consistency between power consumption and power supply, and the primary power grid and microgrid configuration of the original park are not changed in the three parks. Therefore, the typical daily load value of the joint park and the per unit value volatility of the wind-generated power grid are not changed, so the temporal volatility of the joint park is unchanged.

In the study of the joint park, the original landscape power grids of park A, B and C are merged together, and in principle, it is stipulated that the joint park still gives priority to purchasing electricity from the landscape power grid. If the generation capacity of the landscape power grid is not enough to maintain the normal operation of the microgrid of the joint park, the insufficient part will be purchased from the main grid.

Since the park is not equipped with energy storage devices at this time, the abandoned power refers to the part of the actual power generation that exceeds the load of the park during the corresponding period.

In the research process, the power purchase cost per unit of electricity can still be applied to the joint park, and the average power purchase cost per unit of electricity is introduced for unified treatment, that is, the ratio of total power purchase cost to total load.

Based on the above analysis, the following operation economic evaluation models, energy storage optimization configuration models and energy storage operation optimization models of the joint park are established:

In order to protect the normal operation of the microgrid of the park, the power of the wind-power grid larger than the load value of the park during the corresponding period should be abandoned, that is, the abandoned power is generated at this moment. The formula for the abandoned power can be expressed as:

$$q_i = (Q_{gi} + Q_{fi} - R_i) H(Q_{gi} + Q_{fi} - R_i) \, , \tag{23}$$

Thus, the total abandoned power is:

$$q = \sum_{i=1}^{24} q_i \, , \tag{24}$$

Among them... q_i denotes the abandonment of power in the i period of the joint Park; ... Q_{gi} represents the photovoltaic power generation of the joint park during the period i; Q_{fi} denotes the wind power generation of the joint park during period i; $H(x) = \begin{cases} 0, Q_{gi} + Q_{fi} - R_i < 0 \\ 1, Q_{gi} + Q_{fi} - R_i > 0 \end{cases}$.

Daily total electricity purchased:

$$P = \sum_{i=1}^{24} R_i \, , \tag{25}$$

Power supply cost during i period of the Joint Park:

$$C_i = Q_i P_k + (R_i - Q_i) H(R_i - Q_i) \, , \tag{26}$$

Among them Q_i is the total solar power generation of the Joint Park i period; P_k , the unit price of online shopping for wind power grid and photovoltaic power generation; The unit price for wind power grid and photovoltaic power generation online shopping, consistent with the content set in section 2, the price of wind power online shopping is 0.5 CNY /kWh, and the price of photovoltaic power online shopping is 0.4 CNY /kWh. When k=1, P_k =0.5, then $Q_i P_k$ calculates the total price of wind power online shopping; When k=2, P_k =0.4, then Q_iP_k calculates the total price of PV online shopping electricity; $H(x)=\begin{cases}0, R_i-Q_i>0\\1, R_i-Q_i<0\end{cases}$.

And that:

$$Q_i = Q_{gi} + Q_{fi} , \quad (27)$$

Total power supply cost:

$$C^{'} = \sum_{i=1}^{24} C_i , \quad (28)$$

In order to make the final result more convenient to compare with the calculation result of independent operation of each park, the formula of power supply cost per unit time is also used here, namely:

$$C = \frac{C^{'}}{P} , \quad (29)$$

When the joint park is equipped with energy storage devices, the power abandonment cost and energy storage configuration cost should also be considered. At this time, the power abandonment in the i period of the Joint Park:

$$q_i = (Q_i - \max\{E_i + R_i, P_{L\max}\})H(Q_i - \max\{E_i + R_i, P_{L\max}\}) , \quad (30)$$

Where E_i is the remaining capacity of the device, R_i is the load value of period i of the joint park, and $P_{L\max}$ is the maximum load value of the joint park.

At this moment, because the three parks have been combined with each other, the occurrence of power abandonment will be reduced due to the complementary effect of power generation to a certain extent.

According to the analysis in Section 2, the optimization model of minimum total power purchase cost can be established:

$$\min C^{'} = \sum_{i=1}^{24}(C_i + C_p + C_e) = \sum_{i=1}^{24} Q_iP_k + \sum_{i=1}^{24} \alpha E^{'}_i + \sum_{i=1}^{24} \beta E_i , \quad (31)$$

α transmit power for variable batteries; β is variable battery capacity.

3.2. Constraints

According to the above analysis, the power consumption of the joint park at various periods should meet the constraints:

$$R_i \le \max\{Q_{gi} + Q_{fi}, P_{L\max}\} , \quad (32)$$

When the wind-landscape power generation of the joint park exceeds the load value of the corresponding period, the above model starts to analyze the work. At this moment, the model has the following constraints:

Due to the limitations of installed capacity of photovoltaic power grid and wind power grid, the constraints of wind power generation are as follows:

$$0 < Q_{gi} \le P_g \,, \tag{33}$$

$$0 < Q_{fi} \le P_f \,, \tag{34}$$

Where P_g is the installed capacity of photovoltaic power grid in the joint park, P_f is the installed capacity of wind power grid.

When the joint park is equipped with an energy storage device, and the SOC limit, charge/discharge efficiency, energy storage power unit price and energy unit price of the energy storage device are consistent with those set in Section 2, there are the following constraints:

$$Q = Q_g + Q_f < \mathrm{P_{Lmax}} \,, \tag{35}$$

Wind power grid and photovoltaic power online shopping should meet the following constraints:

$$0 \le Q_{gi} \le P_g \,, \tag{36}$$

$$0 \le Q_{fi} \le P_f \,, \tag{37}$$

In order to protect the energy storage device in the charging/discharging process will not cause irreversible damage due to overcharging or overdischarge, and extend the service life of the energy storage device, the constraint conditions of the energy storage device when charging are:

$$E_i \le \gamma(\beta - \eta E'_i) \,, \tag{38}$$

Where β is the total battery capacity variable.

The discharge process is also to protect the microgrid of the park and ensure the normal operation of the power grid. The energy storage device should meet the constraint conditions when discharging:

$$(R_i - Q_i)H(R_i - Q_i) \le \eta E'_i \,, \tag{39}$$

Therefore, for model functions, the following constraints should be met at the same time:

$$\min C' = \sum_{i=1}^{24}(C_i + C_p + C_e) = \sum_{i=1}^{24} Q_i P_k + \sum_{i=1}^{24} \alpha E'_i + \sum_{i=1}^{24} \beta E_i$$

$$\begin{cases} Q = Q_g + Q_f < \mathrm{P_{Lmax}} \\ 0 \le Q_{gi} \le P_g \\ 0 \le Q_{fi} \le P_f \\ E_i \le \gamma(\beta - \eta E'_i) \\ (R_i - Q_i)H(R_i - Q_i) \le \eta E'_i \end{cases} \tag{40}$$

4. Comparative analysis

4.1. Platform parameters

By recording meteorite data of microgrids in parks A, B and C, typical daily load data of each park can be obtained, as shown in Figure 3:

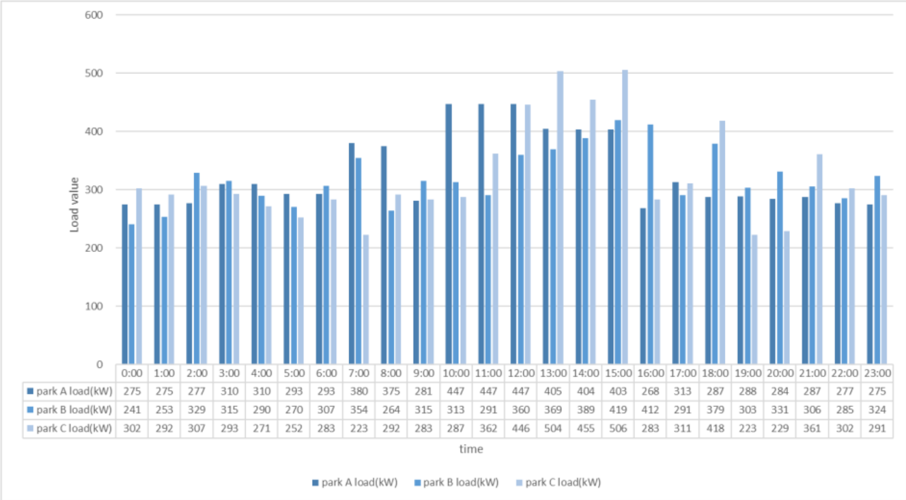

Figure 3. Typical daily load of the park

By recording the data of the power generation networks configured in parks A, B and C, the actual power generation capacity of each park in a day can be obtained. Because the installed capacity of power generation networks of each park is different, in order to facilitate the comparison and integration of the data of each park, the ratio of actual power generation and installed capacity is taken, that is, the per unit value, as shown in Figure 4:

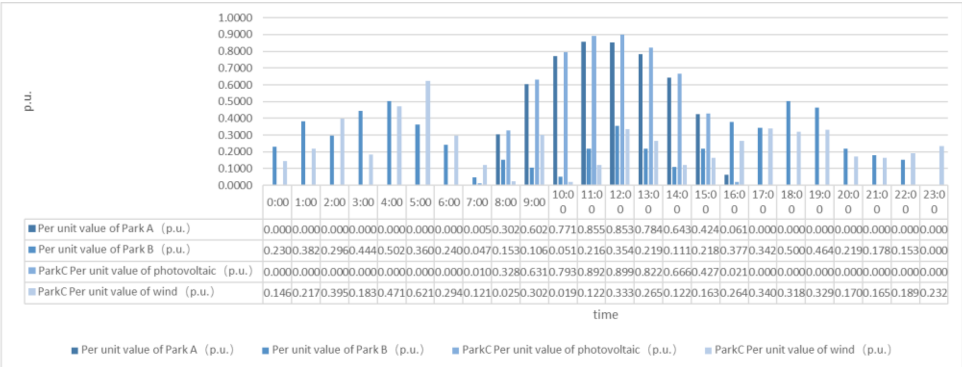

Figure 4. Typical solar power generation data

In order to ensure the change of microgrid load value and power generation value caused by climate change, the data records of this study should be collected for a long time, and the data collection period should not be less than 12 months. Within a certain deviation range, the median of the group of data with the most frequent occurrences should be taken as the typical data.

For the recorded data, a two-dimensional bar chart is first made, as shown in FIG. 3 and FIG. 4. In order to facilitate the preliminary comparison and seek some additional research directions, a line chart is then made, and the changing trend of the data can be clearly seen, as shown in FIG. 5 and FIG. 6:

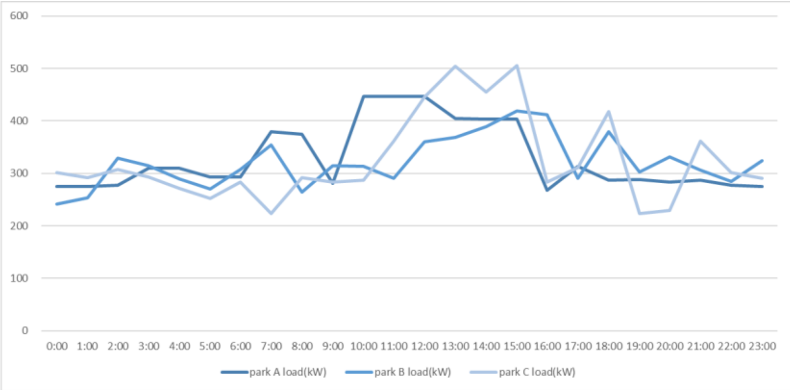

Figure 5. Typical daily load curve of the park

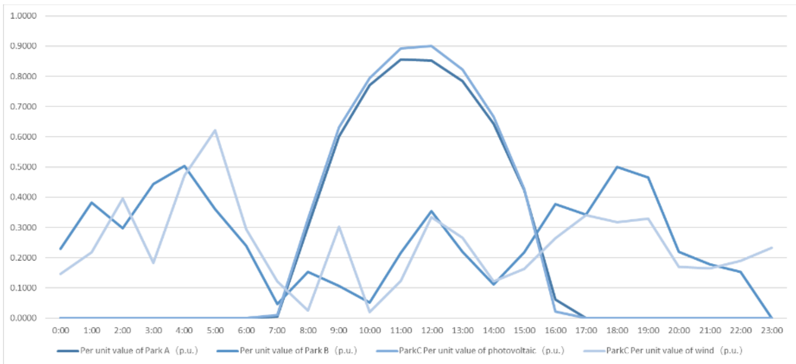

Figure 6. Typical solar power generation data curve

The microgrids of the three parks all reach the maximum load during the four time periods from 12:00 noon to 15:00 PM. As can be seen from Figure 6, during 24 time periods throughout the day, from 9:00 to 15:00, especially from 10:00 to 11:00, Per unit value of photovoltaic power generation is much greater than that of wind power generation.

4.2. Simulation Results

In order to achieve the optimal solution, avoid falling into the local effective solution and find the global optimal solution, the simulated annealing algorithm can be used for part of the calculation of the above model, which is common and effective in power system optimization, and has a remarkable effect on improving the quality and reliability of the calculation results.

By substituting the load value of each period of the campus microgrid and the per unit value of each period of the campus power grid into the model established above, we can get:

When Park A, B and C operate independently and no energy storage device is configured, Park A purchases 7,901kwh of electricity, the total cost of purchasing power is 7897.8 CNY, and the average cost of purchasing power per unit of electricity is 0.9996 CNY /kWh. The purchased electricity of Park B is 7710kWh, the total cost of power purchase is 7706.9 CNY, and the average cost of power purchase per unit of power is 0.9996 CNY /kWh; The purchased electricity of Park C is 7776kWh, the total cost of purchasing power is 7769.8 CNY, and the average cost of purchasing power per unit power is 0.9992 CNY /kWh.

The park equipped with 50kW/100kWh energy storage device is the best, and the minimum cost of power purchase is 14481 CNY.

When Park A, B and C jointly operate and no energy storage device is configured, the total power purchased in the joint park is 23,387kwh, the total power purchase cost is 23,365 CNY, and the average power purchase cost per unit of power is 0.9991 CNY /kWh.

4.3. Comparative Analysis

For independent operation, the average power purchase cost per unit electricity of Park A and Park B is not much different, but Park C is less than the two. In the park introduction described above, Park C is different from Park A and Park B as follows: Park C is equipped with both the unique photovoltaic power generation equipment of Park A and the unique wind power generation equipment of Park B. Combined with Figure 5 and Figure 6, it can be seen that the peaks and troughs of photovoltaic power generation and wind power generation are complementary, namely: The time of day when wind power is weakest is the time when photovoltaic power is strongest. The two jointly supply power to a microgrid, which can effectively reduce the time series fluctuation instability of wind power generation, and reduce the operating cost of the microgrid by reducing the purchase of power from the main grid.

When parks A, B and C form A joint park, the average power purchase cost per unit of electricity decreases compared with the independent operation of parks A, B and C. At this time, the scale effect and wind and solar complementarity effect of microgrid play a role, reflecting the advantages of centralized configuration of microgrid. However, compared with the independent operation of Park C, the joint park has a lower average power purchase cost per unit of electricity. The average power purchase cost per unit of electricity does not change much, so the size of the microgrid network can play a certain role in reducing the operating cost, but its impact is not as great as the proportion of installed capacity of the coordinated wind power grid and photovoltaic power grid.

5. Conclusion

Joint operation can increase the mutual flow of resources to a certain extent and reduce costs. Therefore, the optimization method of park microgrid can be to coordinate the installed capacity ratio of wind power grid or expand the interconnection degree of microgrid. The characteristics of the independent operation of the park are convenient to coordinate the proportion of installed capacity of the wind-power grid and the management and maintenance of the micro-grid, but the overall utilization rate of wind-power energy is not as high as that of the joint operation, and the characteristics of the joint operation are vice versa. The limitation of the research in this paper lies in the limited data, so the research period can only take the data of a certain day, and the energy storage device is a long-term cost investment, so the model for calculating the length of a day does not use the energy storage device. The follow-up research can start from the directions of lengthening the collection period of research data, increasing the load of the park (without changing its volatility), investment return period and time-of-use electricity price.

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