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Assessment, Optimization and Validation Study of Integrated Energy System in Hot Summer and Warm Winter Zone#

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ABSTRACT

Aiming at the low operational efficiency and equipment redundancy of the energy system in an industrial park in a hot summer and warm winter zone of China, this paper firstly assesses the current state of the energy system, then based on the assessment results and the actual situation of the park, the energy system is optimized by using the typical day optimization, and finally, the operating benefits under the year-round scenario are verified. The results show that the optimized photovoltaic capacity is increased to the upper limit, the capacity of the energy storage equipment is increased accordingly, the capacity of the cooling equipment is reduced by 22.8%, and the dynamic payback period is 3.6 years, which can effectively reduce the redundancy of the equipment, improve the operational efficiency, and enhance the economy. However, under the year-round scenario validation, the typical day optimization does not consider enough the extreme cold load and PV output fluctuation, resulting in 2.9% of the cold load not being satisfied in the whole year. The dynamic payback period is extended to 7.1 years, with a significant decrease in the stability and economy of the system. This study provides a theoretical basis for the comprehensive energy system planning of industrial parks in hot summer and warm winter areas.

Keywords: hot summer and warm winter zone; integrated energy system; assessment and optimization; analysis of operational benefits

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
MIMLP	Mixed Integer Multi-Objective Linear Programming
TAC	Total Annual Cost
INV	Initial Investment
OP	Operating Cost
COP	Coefficient of Performance
Symbols	
In_i	Initial investment cost of equipment, yuan/kW
Cap_i	Capacity of equipment, kW
AF_i	Annualized investment factor of equipment
r	Fixed interest rate
n	Year
E_{grid}^{t}	Amount of electricity purchased from the grid at time step t, kW
E_{sell}^{t}	Amount of electricity sold to the grid at time step t, kW
$Price_{grid}^{t}$	Price of electricity sold from the grid at time step t, yuan/kWh
$Price_{sell}$	Price of electricity sold to the grid, yuan/kWh
E_{PV}^{t}	PV power at time step t ,kW
$E_{b}^{dis,t}$	Battery discharging power at time step t, kW
E_{demand}^{t}	Electrical load at time step t, kW
E_{c}^{t}	Power consumed by the chiller system at time step t, kW
$E_{b}^{ch,t}$	Battery charging power at time step t, kW
C_{c}^{t}	Cooling power of the chiller system at the time step t, kW
$C_{w}^{dis,t}$	Discharging power of the chilled water thermal storage system at the time step t, kW
C_{demand}^{t}	cold load at time step t, kW
$C_{w}^{ch,t}$	Charging power of the chilled water thermal storage system at the time step t, kW

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1. INTRODUCTION

With the increasing demand for energy consumption and the gradual progress of the "double carbon policy", reducing the energy consumption and carbon emissions of the whole society has become a key issue. Energy demand in 2040 is expected to be nearly 50% higher than it is today [1]. As the main body of high energy consumption and carbon emission, industrial parks in China account for 70% of the total energy consumption of the whole society and about 31% of the total carbon emission [2]. In addition, industrial parks in China's hot summer and warm winter zone have significant cooling needs. Still, the existing decentralised forms of energy supply in the parks often suffer from redundant equipment configurations and low operating efficiencies [3]. Even though some of the parks have introduced photovoltaic (PV) and energy storage technologies [4], the PV energy dissipation and optimization of the storage system still need to be improved. Therefore, the rational optimization of the energy system in industrial parks is of great significance for energy saving and emission reduction.

For the optimization methods of energy systems, existing studies often adopt optimization methods based on a single season or a typical day [5-7]. However, the existing studies lack the validation of year-round scenarios and the consideration of source-load uncertainty, which leads to over-idealized optimization results and poorer results in the actual operation process. The impact of typical day selection methods on the results and better selection methods have also been discussed in some studies. Amir et al. [8] revealed systematic biases in typical meteorological years when predicting building heating and cooling demand by comparing 10 years of actual meteorological data with typical meteorological year data. Gao et al. [9] proposed a typical day selection method based on k-means clustering and averaging, which significantly optimizes the operating cost of the system compared with the common typical day selection methods by reducing the dimensionality of the load data. Guo et al. [10] proposed a method based on Mixed Integer Multi-Objective Linear Programming (MIMLP), which significantly improves the robustness of standalone microgrid planning by constructing a system of evaluation indexes covering statistical features, temporal fluctuations, and extreme scenarios. Tian et al. [11] proposed a typical day extraction method based on key features, which is based on defining cumulative, extreme, and distributional indicators, and combining them with a mixed-integer linear programming model for typical day selection.

In summary, although the typical day optimization method is the most common in energy system planning studies, the selection of typical days is often insufficient to achieve a comprehensive coverage of the year-round scenarios and to cope with the source-load uncertainty in actual operation. Therefore, it is necessary to select a more comprehensive typical day selection method on the one hand and verify the typical day optimization results on the other hand. In this paper, the typical day optimization of an industrial park in a hot-summer and warm-winter zone of China is carried out based on measured load data, and the optimization results are verified using year-round scenarios.

Chapter 1 provides an introduction and review of the study, Chapter 2 introduces the methodology, Chapter 3 describes the research object, Chapter 4 discusses the results, and Chapter 5 summarizes the conclusions.

2. METHODOLOGY

2.1 Research framework

The research framework of this paper includes an assessment of the current state of the park's energy system, the use of a typical daily planning method to optimize the energy system design, and the use of annual data to verify the actual operational benefits of the optimized design. Among them, typical day planning of the integrated energy system includes three parts: typical day selection, equipment capacity optimization, and equipment operation strategy optimization. Firstly, six typical days are selected according to the three seasons of summer, winter, and transitional season, which are working days and non-working days, respectively. Subsequently, the Gurobi solver is used to obtain the optimization results for each device. Finally, the capacity optimization results obtained from the typical day optimization are put into the year-round scenario to verify the optimization effect.

2.2 Objective function and constraints

In this study, the annualized investment cost and operating cost of the energy system are selected as the objective function, as shown in equation (1). The annualized investment cost considers the initial investment in the chiller system, the battery system, the chilled water thermal storage system, and the PV system, which are converted to the annualized investment cost, and the operating cost considers the cost of purchasing electricity from the grid.

$$minTAC = INV + \mathrm{OP} \tag{1}$$

where TAC is the sum of the annualized investment cost and operating cost of the energy system, yuan; INV is the annualized investment cost, yuan; OP is the annual operating cost, yuan.

The first stage cost, INV, is the annualized investment cost of the equipment installed in the system and can be expressed in equation (2):

$$INV = In_c * Cap_c * AF_c + In_b * Cap_b * AF_b + In_w * Cap_w * AF_w + In_{PV} * C_{PV} * AF_{PV} \quad (2)$$

where In_i is the initial investment cost of equipment i, yuan/kW; Cap_i is the capacity of equipment i, KW; AF_i is the annualized investment factor of equipment i; c is the chiller system; b is the battery system; w is the chilled water thermal storage system; PV is the PV system.

AF represents the annualized investment factor, which calculates the amount that would need to be paid each year given a fixed interest rate and number of years, as shown in equation (3):

$$AF = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \quad (3)$$

where r is the fixed interest rate; n is the number of years.

The second stage cost, OP, is the cost of purchasing electricity from the grid and proceeds from the sale of electricity to the grid, as shown in equation (4):

$$OP = \sum_{t \in T} (E_{grid}^t \times Price_{grid}^t - E_{sell}^t \times Price_{sell}) \quad (4)$$

where E_{grid}^t is the amount of electricity purchased from the grid at time step t, kW; $Price_{grid}^t$ is the price of electricity sold from the grid at time step t, yuan/kWh; E_{sell}^t is the amount of electricity sold to the grid at time step t, kW; $Price_{sell}$ is the price of electricity sold to the grid, yuan/kWh.

For the energy system, the energy supply at each operating moment must satisfy the load demand. In this study, since there is no heat load in the energy system, the electric and cold balances are considered, and the constraints are shown in equations (5) and (6).

$$E_{PV}^t + E_{grid}^t + E_b^{dis,t} = E_{demand}^t + E_c^t + E_b^{ch,t} + E_{sell}^t \quad (5)$$

where E_{PV}^t is the PV power at time step t, kW; $E_b^{dis,t}$ is the battery discharging power at time step t, kW; $E_b^{ch,t}$ is the battery charging power at time step t, kW; E_{demand}^t is the electrical load at time step t, kW; and E_c^t is the power consumed by the chiller system at time step t, kW.

$$C_c^t + C_w^{dis,t} = C_{demand}^t + C_w^{ch,t} \quad (6)$$

where C_c^t is the cooling power of the chiller system at the time step t, kW; $C_w^{dis,t}$ is the discharging power of the chilled water thermal storage system at the time step t, kW; C_{demand}^t is the cold load at time step t, kW; $C_w^{ch,t}$ is the charging power of the chilled water thermal storage system at the time step t, kW.

3. INTRODUCTION TO THE PARK AND ASSESSMENT OF THE CURRENT STATE

3.1 Introduction to physical Information of the park

The research object of this paper is an industrial park in China's hot summer and warm winter zone, which covers an area of 430,000 m^2 and a building area of 419,000 m^2, of which office buildings account for 25% and factories account for 75%. The energy use of the park is a single use of electricity, and in recent years, the annual electricity consumption is about 26.5 million kWh, and the overall load characteristics are relatively stable.

This industrial park is supplied by three sets of cooling systems, all of which are composed of chillers, split air conditioners, and VRVs. Fig.1 shows the detailed energy system form of one of the sets, and the remaining area is similar to it. The park is equipped with 10 MW of rooftop photovoltaic power generation, which is self-generated and self-consumed, and the surplus power is fed into the Internet. To consume the PV, the park is equipped with 600kW/1.2MWh electrochemical energy storage, with peak and valley arbitrage as the basic operation strategy, 2.5 charging and 2.5 discharging per day, with minor adjustments according to the PV output.

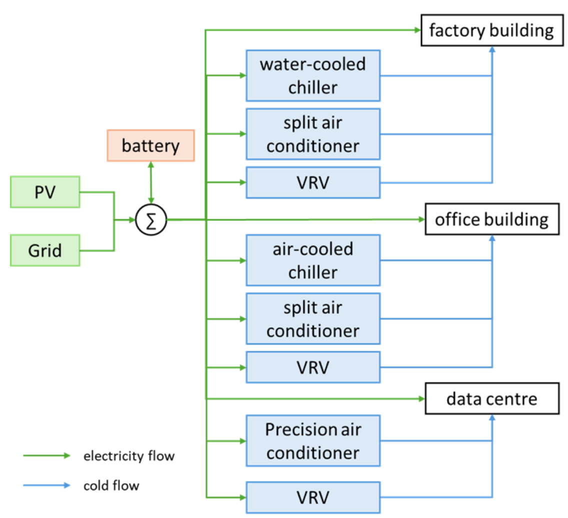

Fig. 1 Current energy system form

3.2 Assessment of the current state of the energy system

To assess the current situation of the cooling system in the park, the two sets of chiller units in Fig.1 were selected as research objects to analyze their annual operation and typical daily operation, and the operation conditions are shown in Fig.2. The annual operation hours of the three water-cooled chiller units in the factory building were 1900h, 950h and 40h (standby); the annual operation hours of the two air-cooled chiller units in the office building were 700h and 600h (not counting the standby chiller units), and the annual operation hours of the units are on the low side. The annual running hours of the two air-cooled chiller units in the office building are 700h and 600h, respectively (not counting the standby refrigeration units). The annual running hours of the units are low. The annual

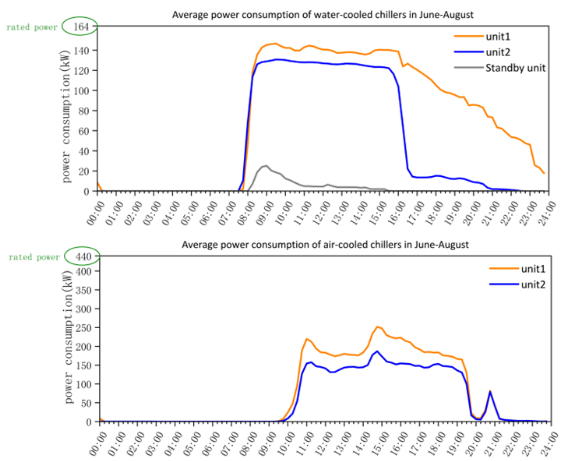

Fig. 2 Current chiller operation diagram

cooling power consumption of the park is calculated to be 9 million kWh, the cold load is 23 million kWh, and the COP of the park system is 2.6, which means that the system operation efficiency is low.

The solution to the above existing problems is: instead of a decentralised energy supply to all areas of the park, a centralized system is used to supply energy to the whole park to improve the efficiency of equipment operation and reduce energy consumption.

4. RESULTS AND DISCUSSION

4.1 Forms of energy systems

According to the above assessment of the current situation of the industrial park and the corresponding solutions given, a centralized energy system is constructed to supply energy to the whole park, in which the cold load is met by the chiller, the electric load is met by the PV and the grid, and electrochemical energy

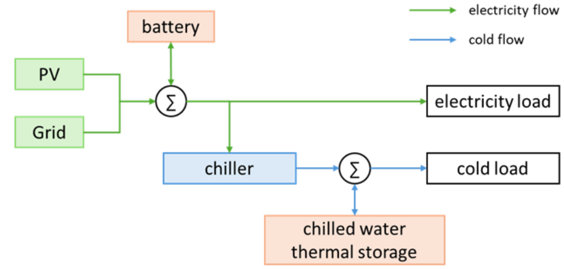

Fig. 3 Optimized energy system form

storage and chilled water thermal storage are configured to carry out PV energy dissipation and peak/valley arbitrage. The form of energy system after transformation is shown in Fig.3.

4.2 Optimization results based on typical days

Based on the annual load data of the park, a total of six typical days of corresponding weekdays and non-workdays in the three seasons of summer, winter and transition season are selected, and the time-of-use price for 10kV large industries are chosen respectively, and the results are shown in Fig. 4.

Table 1 Comparison of the capacity of each device before and after optimization

	Current	Optimized
PV	10MW	16MW
Chiller	18.4MW	14.2MW
Battery	1.2MWh/0.6MW	4.5MWh/2.3MW
Chilled water thermal storage	-	10.5MWh/2.6MW

As the PV system is more economical in this case, the optimized PV capacity has reached the upper limit of the roof PV capacity that can be installed in the park, which is 16 MW. A comparison of the system equipment before and after the optimization is shown in Table 1. It can be found that, due to the construction of the centralized energy station to improve the operating efficiency of the equipment and to reduce the redundancy of the equipment, the capacity of the refrigeration equipment has been reduced by 22.8%

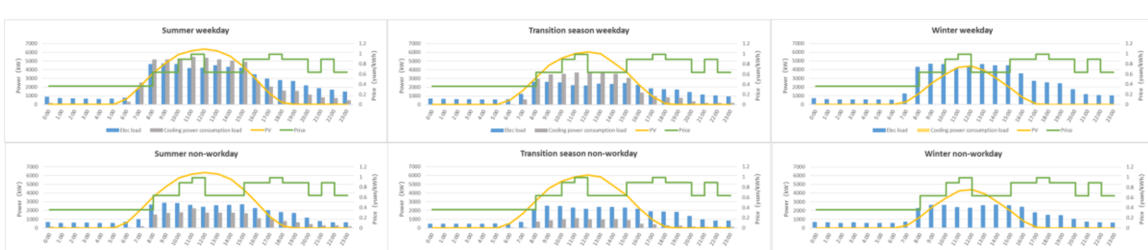

Fig. 4 Typical daily load and time-of-use price

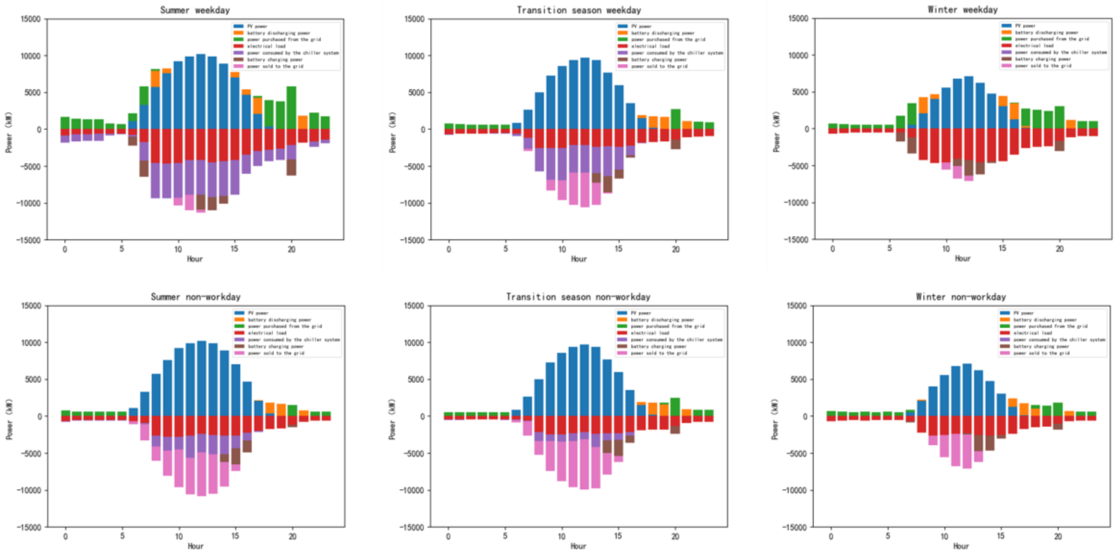

Fig. 5 Charging and discharging strategy of the battery system under a typical day

after the optimization. At the same time, due to the larger scale deployment of PV, the battery system and the chilled water thermal storage system are also increased accordingly for PV consumption.

The energy storage operation strategy under typical days is shown in Fig. 5 and Fig. 6. Under this optimization result, the battery is mainly used to dissipate the excess PV during daytime, and also makes use of the low valley time-of-use price to carry out the peak-valley arbitrage, which achieves some PV consumption effect under the premise of guaranteeing the economy. The chilled water thermal storage system is not only used to dissipate the excess PV during the daytime. It can also use the nighttime valley electricity for energy storage to meet the peak cold load, reduce the capacity of the chiller system, and improve the economy of the system.

Considering the existing PV 10MW with 1.2 MWh storage battery, the new equipment includes 6MW PV, 14.2MW chiller, 3.3 MWh storage battery, 10.5 MWh chilled water thermal storage, and the new investment of this system is 33.0 million yuan. After optimization, the annual grid power purchase cost is 3.2 million yuan, and the gain from power sales is 2.4 million yuan, which is 10.8 million yuan per year compared with the current situation (the annual grid power purchase cost under this is 12.3 million yuan, and the gain from power sales is 0.7 million yuan), and the system's dynamic payback period is about 3.6 years, which is good in terms of economy.

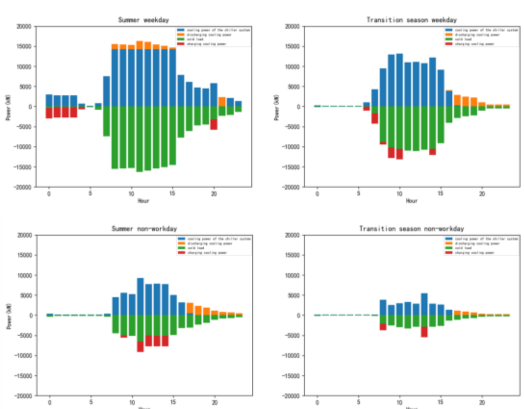

Fig. 6 Charging and discharging strategy of the chilled water thermal storage *system under a typical day*

4.3 Year-round scenario validation

To verify the validity of the typical day optimization results, the device configuration results obtained in Section 4.2 are put into the year-round scenario for verification. The typical day optimization results and the year-round scenario validation results are shown in Table 2.

Due to the lack of consideration of extreme cold load scenarios under typical day optimization, there will be 710,000 kWh of unmet cold load in the annual operation verification, accounting for 2.9% of the total cold load. At the same time, since the typical day optimization considers normal PV power generation, it lacks consideration of low PV power generation in the annual scenario, resulting in an increase of 3.7 million yuan in the annual grid power purchase cost, a decrease of 0.8 million yuan in the power sales revenue, a decrease of 4.5 million yuan in the annual revenue, and an increase in the dynamic payback period of the system from 3.6 years to 7.1 years.

It can be seen that the limitation of typical day selection leads to the lack of consideration of the source-load uncertainty and extreme cases, which will make the system less stable in actual operation, and the economy will be affected to a certain extent.

Table 2: Year-round scenario validation of optimization results for a typical day

	Typical day optimization results	Year-round scenario validation results
Annual cold load unsatisfied (million kWh)	0	71
Annual grid power purchase costs (million yuan)	315	683
Annual income from electricity sales (million yuan)	238	157
Annual earnings (million yuan)	1079	630
System dynamic payback period (years)	3.6	7.1

5. CONCLUSION AND OUTLOOK

5.1 Conclusion

In this paper, a typical day optimization of the energy system is carried out for an industrial park in the hot summer and warm winter zone of China and validated using year-round scenarios, and the following conclusions are obtained:

1. Centralized energy supply reduces the capacity of the chiller system by 22.8%, with a dynamic payback period of 3.6 years compared to the current situation, which effectively reduces equipment redundancy and improves equipment operating efficiency.

2. Under the year-round scenario validation, the typical daily optimization results do not meet the cold load in 2.9% of the years, with a decrease in stability; at the same time, the dynamic payback period of the system increases from 3.6 to 7.1 years, with a serious decrease in economy.

5.2 Outlook

There are still some deficiencies in this paper's research, and future research can go deeper in the following directions: to establish a more complete evaluation system for more reasonable selection of typical days; to consider the source-load uncertainty, and to make use of probabilistic models, stochastic planning and other optimization methods.

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