Research on optimal configuration of park-level multi-energy complementary system with multiple evaluation indexes

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Abstract

At present, the shortage of energy is becoming more and more serious, and the ecological environment is deteriorating. The proposal of the concept of park level multi energy complementary system (MECS) provides direction for achieving environmentally friendly and sustainable energy development. In recent years, how to set the capacity and scheduling methods of equipment to improve the economy and reliability of the system has become a hot research topic in this field. In this paper, a two-layer optimal scheduling strategy is proposed to allocate the capacity of various energy equipment in the park, considering the comprehensive energy self-sufficiency rate, comprehensive energy utilization rate and energy shortage expectation. The proposed capacity allocation scheme can effectively improve the economy of MECS in the park. Finally, the effectiveness and practicability of the algorithm are verified by simulation analysis.
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At present, the shortage of energy is becoming more and more serious, and the ecological environment is deteriorating. The proposal of the concept of park level multi energy complementary system (MECS) provides direction for achieving environmentally friendly and sustainable energy development. In recent years, how to set the capacity and scheduling methods of equipment to improve the economy and reliability of the system has become a hot research topic in this field. In this paper, a two-layer optimal scheduling strategy is proposed to allocate the capacity of various energy equipment in the park, considering the comprehensive energy self-sufficiency rate, comprehensive energy utilization rate and energy shortage expectation. The proposed capacity allocation scheme can effectively improve the economy of MECS in the park. Finally, the effectiveness and practicability of the algorithm are verified by simulation analysis.

Introduction: In recent years, there has been a significant shift in the global energy landscape towards renewable and sustainable energy, which has given rise to the concept of a MECS that integrates various renewable energy, storage technologies, and energy management strategies to improve the efficiency and reliability of the overall system[1]. As the deployment of such systems expands, optimizing their configuration becomes crucial for maximizing their benefits.

In recent years, many scholars have conducted research on the optimization scheduling problem of park level MECS. In reference [2], a risk constrained stochastic scheduling model was proposed to utilize the potential scheduling capabilities of multi energy systems, while maintaining the level of system operational risk, to seek solutions for economic operation in response to uncertain renewable energy generation. In reference [3], in order to obtain the minimum operating cost, an operational optimization model was established and the moth flame optimization algorithm was used to optimize the schedule of each unit in the hybrid energy system. In reference [4], an iterative solution was developed to arrange multiple energy conversion and storage devices within the hub to efficiently utilize available hybrid solar wind renewable energy.

However, most of the aforementioned references only consider economic and carbon emission costs, without considering issues such as comprehensive energy utilization and self-sufficiency [5, 6]. This study aims to address this urgent need and propose an innovative method to optimize the configuration of park level MECS, which considers multiple evaluation indicators. This article will adopt a holistic perspective and consider the interaction between different energy, storage technologies, and energy management strategies within the framework of a multi energy park. In addition, this article will explore various commonly used evaluation indicators in various energy system evaluations, including comprehensive energy self-sufficiency rate, comprehensive energy utilization rate, and energy shortage expectation. By examining multiple indicators simultaneously, it is possible to gain a more comprehensive understanding of system performance and determine the optimal configuration to achieve a balance between different evaluation criteria.

Modeling of Park Level MECS: The park level MECS includes links such as energy production, conversion, and storage. This paper uses an energy hub model to describe the energy flow coupling relationship of the park’s comprehensive energy new system, and constructs a typical park level MECS structure as shown in Figure 1.

![Structure of the Park’s MECS](image)

**Fig 1 Structure of the Park’s MECS**

1) Photovoltaic power generation model

   \[ P_{PV,t} = \begin{cases} \alpha_t P_{PV,N} / \alpha_N & 0 \leq \alpha_t \leq \alpha_N \\ \alpha_t \geq \alpha_N & \end{cases} \]

   where, \( P_{PV,t} \) represents the actual photovoltaic power during time \( t \), \( P_{PV,N} \) represents the rated photovoltaic power, \( \alpha_t \) represents the actual light intensity during time \( t \), and \( \alpha_N \) represents the rated light intensity.

2) Cogeneration model

   \[ P_{CHP,t}^h = \eta_{CHP}^{-1} P_{CHP,t}^g \]

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   where, \( P_{CHP,t}^h \) and \( P_{CHP,t}^g \) respectively represent the electric power and thermal power generated by Cogeneration in period \( t \), \( P_{CHP,t}^g \) represents the natural gas power absorbed by Cogeneration in period \( t \), and \( \eta_{CHP} \) and \( \eta_{CHP}^{-1} \) respectively represent the power generation efficiency and heat generation efficiency of Cogeneration.

3) Gas boiler model

   \[ P_{GB,t}^h = \eta_{GB} P_{GB,t}^g \]

   where, \( P_{GB,t}^h \) is the heat generation power of the gas boiler, \( \eta_{GB} \) is the heat generation efficiency of the gas boiler, and \( P_{GB,t}^g \) is the natural gas consumption power of the gas boiler during time \( t \).

4) Electric boiler model

   \[ P_{EB,t}^h = \eta_{EB} P_{EB,t}^g \]

   where, \( P_{EB,t}^h \) is the heat generation power of the electric boiler at time \( t \), \( \eta_{EB} \) is the heat generation efficiency of the electric boiler, and \( P_{EB,t}^g \) is the electric power consumed by the electric boiler at time \( t \).

5) Electric energy storage model

   \[ S_{ES,t+1} = S_{ES,t} + P_{ES,t}^e \Delta t - \frac{P_{HS,t}^h}{\eta_{ES}} \Delta t \]

   where, \( \Delta t \) is the optimized time interval, \( S_{ES,t} \) is the energy of electric energy storage equipment in period \( t \), \( P_{ES,t}^e \), and \( P_{ES,t}^h \) are respectively the charging and discharging power of electric energy storage equipment in period \( t \), and \( \eta_{ES} \) and \( \eta_{ES}^{-1} \) are respectively the charging and discharging efficiency of electric energy storage equipment.

6) Thermal energy storage model

   \[ S_{HS,t+1} = S_{HS,t} + P_{HS,t}^h \Delta t - \frac{P_{HS,t}^h}{\eta_{HS}} \Delta t \]

   where, \( S_{HS,t} \) is the energy of thermal energy storage equipment in period \( t \), and \( P_{HS,t}^h \) are respectively the charging and discharging power of thermal energy storage equipment in period \( t \), and \( \eta_{HS} \) and \( \eta_{HS}^{-1} \) are respectively the charging and discharging efficiency of thermal energy storage equipment.

7) Photovoltaic system model

   \[ P_{PV,t}^r \]

   \[ 0 \leq \alpha_t \leq \alpha_{rated} \]

   where, \( P_{PV,t}^r \) is the actual power of the PV during period \( t \), \( P_{rated} \) is the rated power of the PV, \( \alpha_{rated} \) is the rated light intensity during period \( t \), and \( \alpha \) is the rated light intensity.

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Evaluation Indicators for Park Level MECS: This paper suggests evaluation indicators to assess the sustainability, efficiency, and reliability of the park’s MECS. The proposed indicators include the comprehensive energy self-sufficiency rate, comprehensive energy utilization rate, and energy shortage expectation.

The comprehensive energy self-sufficiency rate can be quantified as

$$\mu_{CESR} = \frac{E_{es}}{E_{es} + \frac{E_b}{\nu_k} + v_{LHV}E_g}$$  (9)

where, $\mu_{CESR}$ represents the comprehensive energy self-sufficiency rate, $E_{es}$, $E_b$, and $E_g$ represent the electricity, heat, and natural gas output from the MECS in the park, $v_{LHV}$ representing the low calorific value of natural gas, $\nu_k$ represents the unit conversion coefficient of electricity and heat energy, and $E_{es}$ represents the electricity produced by renewable energy equipment.

The comprehensive energy utilization rate can be expressed as

$$\mu_{CEUR} = \frac{E_b + \frac{E_b}{\nu_k} + v_{LHV}E_g + E_e^r}{E_{es} + E_b^r + v_{LHV}E_g^r}$$  (10)

where, $\mu_{CEUR}$ is the comprehensive energy utilization rate, $E_b^r$ is the electricity purchased by the park level MECS from the superior power grid, $E_g^r$ is the electricity sold by the park level MECS from the superior power grid, and $E_e^r$ is the natural gas purchased by the park level MECS from the superior natural gas grid.

The energy gap expectation of $\beta$-type energy is an important indicator of the reliability of $\beta$-type energy supplied by the slow-occupancy energy Internet. The smaller the gap, the better the gap expectation of $\beta$-type energy is, the smaller the burden of $\beta$-type energy that needs to be removed when the equipment is installed with $N$-1 failure scenario, the gain of $\beta$-type energy supplied by the Park Energy Internet.

A Double Layer Optimization Configuration Model for Park Level MECS: This paper takes into account the above evaluation indicators and constructs a two-layer optimization configuration model for the park level multi-energy complementary system. The objective function of the upper level planning model is the annual comprehensive cost, expressed as

$$\min C = C_{inv} + 365\sum_{n=1}^{N} p_n C_{op}$$  (11)

where, $C$ is the annual comprehensive cost, $C_{inv}$ is the equivalent annual investment cost of all equipment, $p_n$ is the probability of the occurrence of typical day, $N$ is the total number of selected typical days, and $C_{op}$ is the operating cost of the system under typical day $n$.

$$C_{inv} = \sum_{k=1}^{K} \sum_{j=1}^{J} I_k I_{inv} \eta_{crf}$$  (12)

where, $I_k$ is the 0-1 logical variable indicating the installation status of the $k$-th class of energy equipment (including class 1 energy conversion equipment, class 2 energy storage equipment, and class 3 renewable energy equipment). When installing this equipment, $I_k = 1$, otherwise $I_k = 0$, $I_{inv}$ is the investment cost of class $j$ energy equipment, and $\eta_{crf}$ is the equivalent annual fund recovery rate of class $\tau$ energy equipment. The specific description is as follows

$$\eta_{crf} = \frac{r(\nu + 1)}{(\nu + 1)^{\gamma} - 1}$$  (13)

where, $r$ is the discount factor, and $\gamma$ is the service life of Class $\tau$ energy equipment.

The lower level planning model aims to minimize the operating cost of a typical daily park level MECS. In addition to meeting the operational constraints of the park level comprehensive energy system, this paper also considers the constraints of comprehensive energy self-sufficiency rate, comprehensive energy utilization rate, and energy shortage expectations.

(1) Constraints on comprehensive energy self-sufficiency rate

In order to meet the energy sustainability requirements of the park level MECS, the corresponding constraints are expressed as

$$\omega_{CESR} \geq \omega_{CESR}^{\min}$$  (14)

where, $\omega_{CESR}^{\min}$ is the lower limit of the comprehensive energy self-sufficiency rate.

(2) Constraints on comprehensive energy utilization rate

In order to achieve the required efficiency of the park level MECS, the corresponding constraints are expressed as

$$\omega_{CEUR} \geq \omega_{CEUR}^{\min}$$  (15)

where, $\omega_{CEUR}^{\min}$ is the lower limit of the comprehensive energy utilization rate.

(3) Energy deficiency expectation constraint

The corresponding energy deficiency expectation constraint is

$$E_{EES}^B \leq E_{EES}^{\bar{B}}$$  (16)

where, $E_{EES}^{\bar{B}}$ is the expected upper limit of energy shortage for Class $\beta$ energy.

The solution process for the hybrid strategy is as follows:

Algorithm 1 Catastrophic Genetic Algorithm - CPLEX Hybrid Strategy

1: Data initialization: Input data on photovoltaic lighting and electrical, thermal, and gas loads.
2: Make the population algebra $g=0$ to generate the initial population
3: Determine whether the catastrophic conditions are met. If so, perform a population catastrophic operation and perform CPLEX to solve the lower level programming model; If not, proceed directly to CPLEX to solve the lower level programming model.
4: Calculate the objective function value and fitness value of the upper level planning
5: Determine whether it converges or reaches the maximum algebraic value, and if so, obtain the optimal configuration plan; If not, perform population selection, crossover, and mutation operations until $g=g+1$, and then return to step 3.

Example Analysis: This paper takes a typical park level MECS as the research object, and its structure is shown in Figure 1. The typical daily load curve is shown in Figure 2-4. Among them, the probability of typical days appearing in spring and autumn is 45%, and the probability of typical days appearing in summer and winter is both 20%. This paper adopts a three-stage electricity price from peak to flat to valley, with a peak hour electricity price of 1.15 yuan/(kW · h), a regular electricity price of 0.85 yuan/(kW · h), and a valley hour electricity price of 0.35 yuan/(kW · h). The electricity price curve is shown in Figure 6.

The price of natural gas is 3.25 yuan/m³. The CO₂ emission coefficients of natural gas and traditional power plants are 1.88kg/m³ and 1.0kg/kWh.
0.82kg/(kW · h), respectively, with a carbon tax price of 0.3 yuan/kg. The optional energy equipment parameters are shown in Tables 1 and 2.

To verify the effectiveness and correctness of the method proposed in this article, four optimization configuration scenarios were set up, and the optimization configuration model in Scenario 1 did not consider any evaluation indicators; Scenario 2 adds evaluation indicators considering comprehensive energy self-sufficiency rate to Scenario 1; Scenario 3 adds evaluation indicators considering comprehensive energy utilization efficiency to Scenario 2; Scenario 4 has added indicators that take into account energy deficiency expectations on top of Scenario 3.

Through simulation verification, the configuration quantity of energy equipment in different scenarios is shown in Table 3, and the optimization results in different scenarios are shown in Table 4.

From the simulation results, it can be seen that after considering the evaluation indicators of comprehensive energy self-sufficiency rate and comprehensive energy utilization rate, the energy sustainability and efficiency of the system can meet the requirements, but correspondingly reduce the economic efficiency of the system. After considering the evaluation indicators of energy deficiency expectations, the reliability of the system can meet the requirements while also improving its economy. It can be seen that the proposed two-layer optimization configuration model, which takes into account multiple evaluation indicators, can pursue the economy of system operation costs on energy efficiency to Scenario 2; Scenario 4 has added indicators that take into account energy deficiency expectations on top of Scenario 3.

Table 1. Energy Conversion Equipment Parameters

<table>
<thead>
<tr>
<th>Energy conversion equipment</th>
<th>Capacity (kW)</th>
<th>Investment costs (yuan/kW)</th>
<th>Operation and maintenance (yuan/kW)</th>
<th>Ramp rate (kW/h)</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogeneration 1/2</td>
<td>2000/3800</td>
<td>4450/4000</td>
<td>0.158/0.154</td>
<td>1200/2400</td>
<td>25/25</td>
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<tr>
<td>Gas Boiler 1/2</td>
<td>1000/1900</td>
<td>2580/1820</td>
<td>0.038/0.038</td>
<td>620/1180</td>
<td>20/20</td>
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<tr>
<td>Electric Boiler 1/2</td>
<td>1000/1950</td>
<td>2410/1700</td>
<td>0.025/0.025</td>
<td>780/1590</td>
<td>20/20</td>
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Table 2. Energy Storage Equipment Parameters

<table>
<thead>
<tr>
<th>Energy storage equipment</th>
<th>Electricity storage</th>
<th>Heat storage</th>
<th>Energy storage equipment</th>
<th>Electricity storage</th>
<th>Heat storage</th>
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<tr>
<td>Operation and maintenance</td>
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<td>0.001</td>
<td>Upper and lower limits of energy</td>
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<td>2200/20</td>
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<td>Investment cost (yuan/kW)</td>
<td>580</td>
<td>460</td>
<td>Charging and discharging energy efficiency</td>
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<td>90%</td>
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<td>Power cap(kW)</td>
<td>510</td>
<td>500</td>
<td>Lifetime(years)</td>
<td>10</td>
<td>20</td>
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Table 3. Configuration Quantity of Energy Equipment in Different Scenarios

<table>
<thead>
<tr>
<th>Scene</th>
<th>CHP1</th>
<th>CHP2</th>
<th>GB1</th>
<th>GB2</th>
<th>EB1</th>
<th>EB2</th>
<th>ES</th>
<th>HS</th>
<th>PV</th>
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</thead>
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<tr>
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<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>11</td>
<td>6</td>
<td>14</td>
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<tr>
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<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>9</td>
<td>17</td>
<td></td>
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<tr>
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<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
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<td>0</td>
<td>3</td>
<td>1</td>
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<td>0</td>
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<td>11</td>
<td>7</td>
<td>17</td>
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Table 4. Optimization Results under Different Scenarios

<table>
<thead>
<tr>
<th>Scene</th>
<th>Annual penalty cost (10000 yuan)</th>
<th>Annual comprehensive cost (1000yuan)</th>
<th>Expected power shortage (kW)</th>
<th>Expected for thermal energy deficiency(MJ)</th>
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<tr>
<td>1</td>
<td>55.0</td>
<td>5980.7</td>
<td>26560</td>
<td>86399</td>
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<td>88372</td>
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<td>4</td>
<td>0</td>
<td>5878.9</td>
<td>0</td>
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References
5. Xu Chengyu, Cui Ziyong, Chen Ke, et al. Design and analysis of energy-efficient approximate Booth-folding squarers with precision recovery, ELECTRONIC LETTERS, 2022, 58(9): 349-351.