Research on Key Technology and Operation Mode of Integrated-Energy Services to Adapt to the New Environment of Power Market

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Abstract. The optimal configuration of the integrated energy system directly affects investment benefits and operating efficiency, which is one of the keys to the planning of the integrated energy system. This article models wind power generation, photovoltaics, combined cooling-heat-electricity, electric refrigeration and electric heating equipment for the park-level integrated energy system. On this basis, a multi-energy complementary capacity configuration optimization model was established. And taking a certain park as an example, the system capacity optimization configuration example analysis was carried out, and a reasonable optimization configuration plan was proposed to provide technical support for comprehensive energy system planning.

1. Introduction
The construction of an integrated energy system is an important way to promote the consumption of renewable energy, realize the coordinated operation of various forms of energy, and improve energy efficiency. By building a platform for the comprehensive utilization of various types of energy systems such as electricity/gas/heat/cold, the complementary characteristics and synergistic effects of different energy forms can be fully utilized to achieve optimal allocation of energy system resources, improve system flexibility, and increase renewable energy consumption and comprehensive energy efficiency.

At present, there exist problems such as low energy utilization rate, inability to exert its own high-efficiency advantages, limited operation and increased costs in the integrated energy system. To solve those problems, experts and scholars have achieved preliminary results in this regard. Literature [2] proposed a framework for coordinated optimization planning of multi-energy systems, and pointed out the objective function and constraint factors of multi-energy system optimization planning. Literature [3] analyzes and discusses the planning of energy Internet from the basic planning model, planning of energy production links, collaborative planning of source-network links, planning of energy consumption links, and solution methods of planning models. Literature [4] conducts an in-depth analysis of integrated energy system requirements. Based on the concept of multi-scenario planning, a planning method for regional integrated energy systems is designed; literature [5] proposed an integrated energy system planning method based on an improved Kriging model. Literature [6-9] also proposed a framework for joint planning of power-natural gas systems, considering the planning and operation of distribution lines and gas pipelines.
Existing research results have comprehensively considered various factors in the comprehensive energy planning, but there are few studies that consider the uncertainties of wind power, photovoltaics and cogeneration at the same time. This paper establishes models for wind power generation, photovoltaics, combined heating and power generation, electric heating, and battery cooling equipment. The optimization goal is to minimize the total operating cost of the system, and the penalty costs of abandoning wind and solar are considered. Genetic algorithm is used to obtain capacity optimization configuration and operation results.

2. Integrated energy supply output model

First of all, establish a wind power output model. Fan output is related to wind speed, cut-in wind speed, rated wind speed, and cut-out wind speed, whose output model is:

\[
P_{WT}^0(t) = \begin{cases} 
0 & 0 \leq v(t) < v_{in}, v(t) > v_{out} \\
\left[\frac{v(t)}{v_{in}}\right]^3 - \frac{v_{in}^3}{v_{rated}^3} \times P_{WT}^0 & v_{in} \leq v(t) \leq v_{rated} \\
P_{WT}^0 & v_{rated} < v(t) \leq v_{out}
\end{cases}
\]

(1)

Wherein, \(P_{WT}^0(t)\) represents the maximum output power of the wind turbine in period \(t\); \(v(t)\) is the wind speed in period \(t\); \(v_{in}\) is the cut-in wind speed; \(v_{rated}\) is the rated wind speed; \(v_{out}\) is the cut-out wind speed.

Then, build a photovoltaic power generation model. The principle of photovoltaic power generation is using photovoltaic modules to convert solar energy into electrical energy based on the photovoltaic effect. The output of photovoltaic units is related to solar radiation intensity and temperature. The output model is:

\[
P_{PV}^0(t) = P_{PV,\text{stc}} \times \frac{I(t)}{I_{\text{stc}}} \times \left[1 - \alpha \times (T(t) - T_{\text{stc}})\right]
\]

(2)

Formatting \(P_{PV}^0(t)\) represents the maximum output power of the photovoltaic unit; \(P_{PV,\text{stc}}\) represents the output power of the photovoltaic unit under standard conditions; \(I_{\text{stc}}\) represents the solar radiation intensity under standard conditions, and the value generally is 1000W/m²; \(T_{\text{stc}}\) represents the standard condition temperature, and the value generally is 25°C; \(I(t)\) is the solar radiation intensity during the period \(t\); \(T(t)\) is the temperature during the period \(t\); \(\alpha\) is the power temperature coefficient of the photovoltaic cell, generally 0.0039°C⁻¹.

In addition, the cold-heat-electricity trigeneration system using natural gas is generally composed of gas turbines, absorption chillers and waste heat boilers. It can supply cold, heat and electricity at the same time. Its output model is:

\[
P_{MT,WH}(t) = \frac{P_{MT,e}(t)}{\eta_{MT,e}} \times \left(1 - \eta_{MT,e} - \eta_{HL}\right)
\]

(3)

\[
P_{MT,H}(t) = P_{MT,WH}(t) \times \eta_{WHR} \times O_H
\]

(4)

\[
P_{MT,C}(t) = P_{MT,WH}(t) \times \eta_{WHR} \times O_C
\]

(5)

\[
V_{NG} = \sum_t \left[\frac{P_{MT,e}(t) \times \Delta t}{\eta_{WT,e} \times q_{NG}}\right]
\]

(6)
Wherein, $P_{MT,WH}(t)$ represents the waste heat power of the cold-heat-electricity trigeneration system during the period $t$; $P_{MT,e}(t)$ represents the output electric power of the cold-heat-electricity trigeneration system during the period $t$; $\eta_{MT,e}$ is the power generation efficiency; $\eta_{HL}$ is the coefficient of heat dissipation loss, usually taken as 0.03; $P_{MT,H}(t)$ refers to the output heat power of the cold-heat-electricity trigeneration system during the period $t$; $\eta_{WHR}$ is the waste heat recovery efficiency; $O_H$ is the heating coefficient, usually taken as 1.20; $P_{MT,C}(t)$ represents the output cold power of the cold-heat-electricity trigeneration system during the period $t$; $O_C$ is the coefficient of refrigeration, usually 0.95; $V_{NG}$ is the consumption of natural gas; $q_{NG}$ is the low heating value of natural gas.

Last, heat energy can be produced by electric heating equipment such as heat pumps, and cold energy can be produced by electric refrigeration equipment. The output model is:

$$P_{EH}(t) = \eta_{EH} \times P_{EH,e}(t)$$ (7)

$$P_{EC}(t) = \eta_{EC} \times P_{EC,e}(t)$$ (8)

Wherein, $P_{EH}(t)$ represents the output thermal power of the electric heating equipment during the period $t$; $\eta_{EH}$ is the electrothermal conversion efficiency; $P_{EH,e}(t)$ is the input electric rate of the electric heating equipment during the period $t$; $P_{EC}(t)$ is the output cold power of the electric refrigeration equipment in period $t$; $\eta_{EC}$ is the conversion efficiency of electric to cold; $P_{EC,e}(t)$ represents the input electric rate of the electric refrigeration equipment during the period $t$.

3. Multi-energy complementary capacity configuration optimization model

3.1. The proposed objective function

The output of renewable energy sources such as wind power and photovoltaics has a strong uncertainty, which can be dealt with using scenario analysis. The scenario analysis method can clearly describe the probability characteristics of the uncertainty, and its model calculation is relatively simple. Assuming a total of $S$ scenarios of renewable energy output, the probability of scenario $s$ is $\rho$. Taking the lowest total operating cost of the system as the optimization goal, and in order to increase the rate of renewable energy consumption, the penalty cost of abandoning wind and light is considered. The objective function is as follows:

$$\min \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{R} \sum_{j=1}^{N_{MT}} \left( c_i^{MT} \left( P_{MT,r,i,j}^{s}, H_{MT,r,i,j}^{s} \right) + \rho_1 \left| P_{MT,r,i,j}^{s} - P_{MT,r,i,j}^{0} \right| + \varphi \rho_{buy,r,t}^{s} \right)$$

$$+ \rho_2 \left( P_{bur,r,t}^{s} - P_{buy,r,t}^{0} \right) + \rho_3 \left( P_{cut,r,t}^{s} \right) = \phi_{buy,r,t}^{s}$$ (9)

$$c_i^{MT} \left( P_{MT,r,i,j}^{s}, H_{MT,r,i,j}^{s} \right) = \alpha_{0,r,j} + \alpha_{1,r,j} P_{MT,r,i,j}^{s} + \alpha_{2,r,j} H_{MT,r,i,j}^{s} + \alpha_{3,r,j} \left( P_{MT,r,i,j}^{s} \right)^2$$ (10)

$$P_{cut,r,t}^{s} = P_{WT,r,t,max}^{s} + P_{PV,r,t,max}^{s} - P_{WT,r,t}^{s} - P_{PV,r,t}^{s} - P_{WTH,r,t}^{s} - P_{PVH,r,t}^{s}$$ (11)

Formula 9 is the total operating cost of the system, including the power generation cost of the cold-heat-generator unit and the penalty for deviating from the plan, the power purchase cost and the penalty fee for deviating from the planned power purchase, and the cost of abandoning wind and solar power. Formula 10 is the cold-heat-electricity unit Cost function. Formula 11 is the expression of abandoning wind and light.
Where, $r_{MT}$ is the number of natural gas cold-heat-generator units in $r$ area; $P^e_{MT,r,t}$, $H^s_{MT,r,t}$, and $P^s_{buy,r,t}$ respectively represent the electric output, heat output, and purchased power of the $i$-th cold-heat-electric unit at time $t$ in region $r$ under scene $s$; $P^s_{cut,r,t}$ is the power of abandoning wind and light; $P^s_{WT,r,t,max}$, $P^s_{PV,r,t,max}$, $P^s_{WT,r,t}$, $P^s_{PV,r,t}$, $P^s_{WH,r,t}$ and $P^s_{PVH,r,t}$ respectively represent the wind power, photovoltaic power generation, grid power and heating power; $\varphi$ is the unit price of electricity purchase; $\rho_1$, $\rho_2$ and $\rho_3$ are respectively the penalty price of the cold-heat-electricity generating unit deviating from the planned output, the penalty price of the purchased power deviating from the planned purchased power, and the penalty price of abandoning wind and abandoning light.

3.2. Constraints

3.2.1. Electric power balance constraint.

$$\sum_{i=1}^{l_r} P^s_{MT,r,t} + P^s_{buy,r,t} + P^s_{PV,r,t} + P^s_{WT,r,t} + \sum_{i=1}^{l_r} P^s_{tie,t} = P^s_{L,r,t} + P^s_{EC,r,t}$$

(12)

Wherein, $l_r$ is the set of tie lines between $r$ area and other areas; $P^s_{tie,t}$ is the transmission power of the tie line; $P^s_{tie,t} > 0$ means the tie line inputs power into the area at time $t$; $P^s_{tie,t} < 0$ means the tie line delivers power outside the area at time $t$; $P^s_{L,r,t}$ and $P^s_{EC,r,t}$ are electric load power and electric refrigerator power respectively.

3.2.2. Cold-heat-electricity unit constraints.

$$P^s_{MT,r,t} = \frac{H^s_{MT,r,t}}{K_{hp,r,t}}$$

(13)

$$P^s_{MT,r,t} \leq P^s_{MT,r,t} \leq P^s_{MT,r,t}$$

(14)

$$-U^e_{r,t} \times \Delta t \leq P^s_{MT,r,t} - P^s_{MT,r,t} \leq U^e_{r,t} \times \Delta t$$

(15)

Formula (13) is the restriction on the heat-to-electricity ratio of the natural gas cold-heat-power unit, formula (14) is the upper and lower limit constraints of the natural gas cold-heat-power unit output, and formula (15) is the natural gas cold-heat-power unit climbing constraint. Wherein, $K_{hp,r,t}$, $P^s_{MT,r,t}$, $P^s_{MT,r,t}$ and $U^e_{r,t}$ are the thermoelectric ratio, the lower limit of electric output, the upper limit of electric output, and the maximum power increase per unit time of the $i$-th cold-heat-electric unit in the region $r$.

3.2.3. Purchase electricity power constraints.

$$P^s_{buy,r,t} \geq 0$$

(16)

Formula (16) indicates that only electricity purchase is allowed in the system, and electricity sale is not allowed.

3.2.4. Wind power and photovoltaic constraints.

$$P^s_{PV,r,t} \geq 0$$

(17)

$$P^s_{WT,r,t} \geq 0$$

(18)
\[ P_{WTH,r,t}^s \geq 0 \]  \hspace{1cm} (19)  
\[ P_{PVH,r,t}^s \geq 0 \]  \hspace{1cm} (20)  
\[ 0 \leq P_{PV,r,t}^s + P_{PVH,r,t}^s \leq P_{PV,r,t,\text{max}}^s \]  \hspace{1cm} (21)  
\[ 0 \leq P_{WT,r,t}^s + P_{WT,r,t}^s \leq P_{PV,r,t,\text{max}}^s \]  \hspace{1cm} (22)  

3.2.5. Electric boiler constraints.

\[ P_{EB,r,t}^s = P_{WTH,r,t}^s + P_{PVH,r,t}^s \]  \hspace{1cm} (23)  
\[ H_{EB,r,t}^s = \eta_{EB,r,t} P_{EB,r,t}^s \]  \hspace{1cm} (24)  
\[ 0 \leq H_{EB,r,t}^s \leq H_{EB,r,t,\text{max}}^s \]  \hspace{1cm} (25)  

Formula (23) is to ensure that the electric boiler in region \( r \) only consumes wind power and photovoltaic power in region \( r \). Formula (24) is the restriction on the electric-heat conversion relationship of the electric boiler, and formula (25) is the output restriction of the electric boiler. Where, \( H_{EB,r,t}^s \) is the heat output of the electric boiler at time \( t \) in region \( r \) under scene \( s \); \( \eta_{EB,r,t} \) and \( H_{EB,r,t,\text{max}}^s \) are respectively the point conversion efficiency and the upper limit of heat output of the electric boiler in \( r \) area.

4. Solving algorithm

The mathematical model of capacity allocation optimization is essentially a typical multi-constraint multi-objective linear programming problem. Because of the conflicts between the goals, the multi-objective planning problem usually just seeks its relatively superior non-inferior optimal solution set to guide the final implementation of the planning problem.

Genetic algorithm is an optimization algorithm derived from biological natural selection and genetic mechanism. It provides a universal and easy-to-implement optimization solution idea for solving various complex optimization problems. At the same time, it has simple solution, strong robustness, and global optimization. Moreover, it has advantages such as good performance and good parallel processing conditions, and it has fewer restrictions on solving the problem without requiring continuous differentiability of the objective function.

The core elements of genetic algorithm mainly include fitness evaluation, genetic operator settings, basic operation parameter settings, etc. The flowchart of genetic algorithm is shown in Figure 1:
5. Example analysis
Take an industrial park power supply system in a certain area as a simulation example.

5.1. Basic data
Typical daily load curves in heating season, cooling season and transition season are shown in Figure 1. According to typical daily wind speed and light intensity, the power generation output of renewable energy is shown in Figure 2.
Comparing the three energy use scenarios, we can acquire: During the heating season, there is little cooling load demand in the park, and the domestic hot water load demand has increased significantly compared with other seasons, and the heating load and electric load demand are large. During the cooling season, the heating load and domestic hot water load demand within the park are at a low level, but the demand for cooling load and electric load is relatively high. During the transition season, the demand for cooling load in the park is relatively small, and the demand for electricity load and domestic hot water load is at the annual average level.

The price of electricity purchased by the park from the grid is based on the time-of-use price, and the price of natural gas purchased by the park from the natural gas network is also based on the time-of-use price. The calorific value of natural gas is 9.7kWh/m³ for power conversion. The specific prices are shown in Table 1.

| Energy type       | Flat section | Peak  | Trough  |
|-------------------|--------------|-------|---------|
|                   | 6:00-8:00    | 8:00-12:00 | 22:00-6:00 |
|                   | 12:00-16:00  | 16:00-20:00 |
|                   | 20:00-22:00  |       |         |
| Electricity (yuan/kWh) | 0.66    | 0.92  | 0.41   |
| Natural gas (yuan/m³)    | 0.30     | 0.38  | 0.21   |

5.2. Optimize configuration and operation results
Using the solution algorithm proposed above, the optimized configuration results shown in Table 2 are obtained:
Table 2. Device configuration results

| Device                 | Capacity /kW | Device               | Capacity /kW |
|------------------------|--------------|----------------------|--------------|
| Photovoltaic generator set | 2160         | Waste heat boiler     | 6966         |
| Wind Turbine           | 1830         | Gas boiler            | 1409         |
| Gas turbine            | 13062        | Electric refrigerator | 701          |
| Absorption chiller     | 2000         | Electric heating machine | 179        |

The maximum electrical load on a typical day in the cooling season is 2095kW, the cooling load is 4413kW, and the heat load is 716kW. Solve and analyze the system efficiency and economic indicators in the typical day of the cooling season.

Table 3. Energy interaction cost

| Energy interaction cost | Power/kWh | Cost/yuan |
|-------------------------|-----------|-----------|
| Electricity             | 14017.6   | 8273.1    |
| Natural gas             | 71175.9   | 22013.2   |
| System operating cost   | /         | 30302.3   |

According to Table 3, it can be seen that when the system fully consumes renewable energy, the main cost of the system is the purchase of natural gas. Table 4 shows the energy supply, efficiency and required operating cost of each device on a typical day.

Table 4. Device operating cost

| Device                      | Power/kWh | Efficiency | Operating cost |
|-----------------------------|-----------|------------|----------------|
| Photovoltaic generator set  | 3895.6    | 7.5%       | 38.96          |
| Wind Turbine                | 6425.32   | 14.6%      | 385.52         |
| Gas turbine                 | 213520.8  | 68.0%      | 1259.81        |
| Absorption chiller          | 31902.1   | 66.5%      | 41.5           |
| Waste heat boiler           | 9360.23   | 55.9%      | 280.1          |
| Gas boiler                  | 1723.5    | 5.1%       | 91.4           |
| Electric refrigerator       | 5105.3    | 33.3%      | 23.7           |
| Electric heating machine    | 345.1     | 8.0%       | 12.8           |

The efficiency in the table shows the ratio of the energy supplied by the equipment to the energy that the equipment runs at maximum power throughout the day. It can be seen from Table 4 that the operating efficiency of new energy units is low. In the cooling season, the efficiency of gas turbines and refrigeration equipment is high, which corresponds to the large cooling load demand in the cooling season.

6. Conclusion

This paper focuses on the capacity planning of integrated energy system, establishes the capacity allocation optimization model, and makes an example analysis, which can provide reference for the comprehensive energy system planning of the park.

1) The model takes the lowest total operating cost of the system as the optimization goal, and considers the penalty cost of abandoning wind and light, which improves the rate of renewable energy consumption.

2) Considering that different load scenarios have different short-term energy demand, equipment operating efficiency is different. In the cooling season, the efficiency of gas turbines and refrigeration equipment is higher, which corresponds to the large cooling load demand in the cooling season.
Acknowledgments
The work is partly supported by National Social Science Foundation of China, Research on smart energy innovation mode and policy coordination mechanism for national energy security (No. 19ZDA081) and Research on key technology and operation mode of integrated energy services to adapt to the new environment of power market (CHDKJ19-01-40).

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