Integrated energy system planning method considering electric-heat-gas coupling

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Abstract. In order to determine the optimal configuration of energy equipment types and capacities in an integrated energy system, this paper proposes a method of equipment selection and capacity planning for an integrated energy system (IES) that considers the coupling of electricity, heat, and gas. Starting from the type of optional equipment and the form of input energy, the basic structure of IES is established. On this basis, for the equipment selection and capacity planning, an optimization model with the minimum annual comprehensive cost as the objective function is established, and the mixed integer linear programming algorithm is used to optimize the equipment type and capacity at the same time. Finally, taking an IES park as an example, the planning schemes in different scenarios are given, and the effectiveness of the proposed method is verified.

1. Introduction
With the increasingly severe energy and environmental issues, how to improve energy efficiency and minimize environmental pollution caused by energy use has become an important issue in the energy field. The integrated energy system IES (integrated energy system) integrates cooling, heating and power generation. It can not only improve the utilization of primary energy through the cascade use of energy, but also show a large advantage in reducing emissions [1]. Therefore, IES has become an important development trend of energy technology in the future, and its planning and operation are hot research topics.

IES is mainly composed of integrated energy stations and cooling, heating, and electric pipe networks. Whether IES can operate efficiently, economically, and environmentally depends on the equipment selection and capacity planning of integrated energy stations. The basic idea of comprehensive energy station planning is to first determine the basic structure of the comprehensive energy station and the connection relationship between equipment and load according to the park load, optional equipment type, energy form and other factors; second, to run simulations for different goals, The combination of the type of comprehensive energy equipment and capacity configuration that optimizes the target is selected.

Literature [2] proposed the concept of energy hub EH (energy hub), and established the comprehensive planning model of multi-region power and natural gas system expansion with the minimum cost of energy hub loss as the objective function. Reference [3] takes a residential area as an example for planning, and the objective function contains the annual total investment cost and the annual operating cost of the system. In [4], the minimum total operating cost of electricity purchase...
and natural gas was taken as the objective function, and an optimal coordination model for combined cooling, heating, and power generation considering different tariff structures and complementary power generation of wind, light, gas, and storage was established. Reference [5] considered various optimization models of combined heat and power CHP (combined heat and power) units, and gave the optimal CHP unit planning scheme with the goal of economic and environmental sustainability. Reference [6] optimized the system with the goal of minimum system operating cost and minimum CO2 emissions. In terms of algorithms, mathematical programming and intelligent optimization algorithms are widely used in IES planning research. Reference [7] proposed a three-level collaborative overall optimization method for cold, heat, and electricity co-generation system, which uses discrete particle swarm optimization and particle swarm optimization to combine equipment selection, equipment capacity, and thermoelectric load ratio. Variable stratification is optimized in turn to obtain the optimal operating parameters. However, at present, there is still a lack of detailed analysis and modeling of electricity, heat, and gas coupling systems at home and abroad, and fewer types of energy coupling equipment are considered. In the optimization variables, the combination optimization of the equipment type and equipment capacity is not considered at the same time, and the equipment type is often determined, and the capacity optimization is carried out only on this basis. In addition, existing studies do not consider the coupling between energy sources enough. The analysis of coupling between energy sources focuses on qualitative discussions and lacks quantitative analysis, making it difficult to accurately assess the complementary benefits of multi-energy coupling during system operation.

This article focuses on the IES including electric boilers, electric refrigeration units, ground source heat pumps and CHP units that are electrically, thermally, and gas-coupled. Based on solving the selection of equipment in IES and the determination of corresponding capacity, it is proposed that the annual comprehensive cost is the minimum Function optimization model. Fully considering the operation constraints and power balance constraints of various energy conversion equipment of IES, the mixed integer linear programming method is used to solve, and finally the equipment selection results and capacity allocation scheme are obtained. Taking an IES park as an example, the equipment selection and capacity configuration scheme of the integrated energy station is given, which verifies the accuracy of the algorithm.

2. The basic structure of the park IES
The optional equipment in the IES studied in this paper includes electric boilers, electric refrigeration units, ground source heat pumps, and CHP units. Electric boilers and electric refrigeration units, as electric heating and electric cooling equipment, can supply heat load and cooling load in the park respectively. The ground source heat pump can use the shallow heat energy of the land, through the input of electric energy to achieve the purpose of cooling or heating. The CHP unit uses natural gas as fuel and can be combined heat and power to supply the heat load and electricity load in the park. In addition, the park can meet the electrical load in the park by purchasing electricity from the external grid.

3. IES equipment selection and capacity planning model
3.1. Objective function
This paper takes the minimum annual comprehensive cost $C^{COS}$ as the objective function, including the initial investment cost $C^I$, system maintenance cost $C^M$, and system operating cost $C^O$. The objective function formula is as follows

$$\min C^{COS} = C^I + C^M + C^O$$

(1) Electric power balance

3.2. Constraints of electric heating and cooling power balance in IES
This paper considers the power balance constraints of electricity, heat and cold.
\[ P^{ld}_t = P^{sys}_t + P^{chp}_t \]  

\[ P^{ld}_t \] is the electrical load in the park at time \( t \).

(2) Thermal power balance

\[ H^{ld}_t = H^{gb}_t + H^{chp}_t + H^{hp}_t \]  

\[ H^{ld}_t \] is the heat load in the park at time \( t \). 

(3) Cold power balance

\[ C^{ld}_t = C^{ac}_t + C^{hp}_t \]  

\[ C^{ld}_t \] is the cooling load in the park at time \( t \).

3.3. Optimal solution

From the mathematical point of view, solving the optimized operation model of the integrated energy system is actually a complex nonlinear problem solution. But at present, most of these problems are calculated by mixed integer linear programming (MILP). The principle is to linearize the nonlinear problem piece by piece in order to solve the nonlinear problem and obtain the optimal solution. Therefore, in the calculation process of this paper, the above method will also be adopted to solve the calculation of the established optimization model through MATLAB software and Cplex solver.

4. Example analysis

This article selects an IES park as the object. The relevant parameters of each equipment in the park, as well as the electricity price and natural gas price, are shown in Table 1. Among them, the natural gas price is converted into a unit calorific value of 0.2 yuan/(k Wꞏh). This article selects 4 scenes for comparative analysis.

| Equipment type       | parameter                              | Numerical value |
|----------------------|----------------------------------------|-----------------|
| Electric boiler      | Initial investment/(yuan. (kV*A)^{-1}) | 1000            |
|                      | Maintenance cost / (yuan. (kW)^{-1})   | 2               |
|                      | Electrothermal conversion efficiency   | 0.95            |
|                      | Initial investment/(yuan. (kV*A)^{-1}) | 1500            |
| Electric refrigeration| Maintenance cost / (yuan. (kW)^{-1})   | 1.2             |
|                      | Energy efficiency ratio                | 4               |
|                      | Initial investment/(yuan. (kV*A)^{-1}) | 7000            |
| Ground source heat pump | Maintenance cost / (yuan. (kW)^{-1})   | 1.5             |
|                      | Heating energy efficiency ratio        | 3.8             |
|                      | Cooling energy efficiency ratio        | 4.2             |
|                      | Initial investment/(yuan. (kV*A)^{-1}) | 7900            |
|                      | Maintenance cost / (yuan. (kW)^{-1})   | 1.5             |
| CHP unit             | Gas-heat conversion efficiency        | 0.45            |
|                      | Gas-electricity conversion efficiency  | 0.3             |
Scenario 1: Optional equipment includes electric boilers and electric refrigeration units, and the input energy form is electrical energy;

Scenario 2: Optional equipment includes electric boilers, electric refrigeration units, ground source heat pumps, and the input energy form is electrical energy;

Scenario 3: Optional equipment includes electric boilers, electric refrigeration units, CHP units, and the input energy forms are electrical energy and natural gas;

Scenario 4: Optional equipment includes electric boilers, electric refrigeration units, CHP units, ground source heat pumps, and the input energy forms are electrical energy and natural gas.

Table 2 shows the equipment selection and capacity planning scheme of the comprehensive energy station.

| Scenes | Electric boiler capacity | Electric cooling capacity | Ground source heat pump capacity | CHP unit capacity |
|--------|-------------------------|--------------------------|---------------------------------|------------------|
| 1      | 6300                    | 4500                     | --                              | --               |
| 2      | 2700                    | 4500                     | 900                             | --               |
| 3      | 4300                    | 4500                     | --                              | 4100             |
| 4      | 2700                    | 4500                     | 900                             | 0                |

The annual comprehensive costs corresponding to the four planning schemes are shown in Table 3. Comparing scenario 1 and scenario 2, due to the high energy conversion efficiency of the ground source heat pump, the annual comprehensive cost of the program has decreased by 79.153 million yuan, a decrease of 17.70%, of which equipment maintenance costs and system operating costs have been reduced by 3.733 million yuan and 4.704 million Yuan, but because of the high initial investment of ground source heat pump equipment, the system equipment investment cost increased by 198,700 yuan; comparing scenario 1 and scenario 3, because the price of natural gas is significantly lower than the electricity price, and the CHP unit can supply both electrical and thermal loads, the annual comprehensive cost was reduced by 1.3729 million yuan, a decrease of 3.07%, of which the system operating cost was reduced by 474.02 million yuan, but the initial investment of CHP units was high and the energy conversion efficiency was not high, resulting in an increase of 2.362 million in system investment costs and maintenance costs. Yuan and RMB 1.8365 million; the annual comprehensive cost of scene 4 and scene 2.

Table 3. Annual comprehensive expenses planned in different scenarios

| Scenes | total cost/ Ten thousand yuan | Equipment investment/ten thousand yuan | Equipment maintenance/ten thousand yuan | System operation/ten thousand yuan |
|--------|--------------------------------|----------------------------------------|----------------------------------------|-----------------------------------|
| 1      | 4472.72                        | 96.02                                  | 2119.30                                | 2257.38                           |
| 2      | 3681.19                        | 115.89                                 | 1781.94                                | 1783.36                           |
| 3      | 44335.43                       | 319.64                                 | 2302.95                                | 1712.84                           |
| 4      | 3681.19                        | 115.89                                 | 1781.94                                | 1783.36                           |

System Other parameter

| Discount Rate | 0.04 |
| Economical service life of equipment | 1.5 |
| Minimum planning unit/(kV*A) | 100 |
| Gas-to-electricity conversion efficiency | 0.45 |
| Electricity price / (yuan. (kW.h)$^{-1}$) | 0.47, 0.90, 0.35 |
| Gas price/(yuan. (kW.h)$^{-1}$) | 0.2 |
Through the comparison of the equipment planning results and the various costs in the above different scenarios, it can be seen that the rich energy forms and equipment types can reduce the overall annual comprehensive cost of the energy station and the amount of electricity purchased, making the energy station the most economical. Running under the configuration.

5. Conclusion
This paper proposes an electric, thermal, and gas-coupled IES equipment selection and capacity planning method. This method establishes the IES equipment selection and capacity planning model, takes the minimum annual comprehensive cost as the optimization goal, uses a mixed integer linear programming algorithm, and takes an IES park as an example to realize the electrical, thermal, and gas-coupled IES equipment selection and The overall optimization of capacity configuration provides a brand new overall design method for the optimal design of electric, thermal, and gas-coupled IES.

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