Integrated Energy System Planning Based on Equipment Performance

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Abstract. The Integrated Energy System (IES) has the advantage of improving energy utilization and promoting energy flexibility. Its equipment configuration is one of the keys to Integrated Energy System planning. This paper takes equipment selection and capacity planning as the goal establishes the IES equipment selection and capacity planning model makes the minimum annual inclusive cost as the optimization goal and uses the mixed-integer linear programming algorithm to solve the practical problem. Finally, a typical southern park is taken as an example to analyze and verify the feasibility of the model and algorithm.

1. Introduction
With the rapid development of social economy, the contradiction between energy demand and energy reserves is becoming increasingly acute. Integrated energy system (IES) implements an integrated system that solves energy needs including heating, power supply, cooling, and heating by means of multi-energy complementarity. With the increase in the types of energy coupling, storage, conversion, and replacement equipment, the market mechanism has matured, and user participation has increased. We need to study the optimal configuration of IES further.

To determine the optimal type and capacity of large energy equipment, scholars at home and abroad have proposed various economic, environmental, and energy consumption objective functions. Ref.[1] conducted an in-depth analysis of the needs of IES and designed a multi-scenario planning method for regional-level IES. Ref.[2] takes a residential area as an example of a plan. The objective function contains the annual total investment cost and the yearly operating cost of the system. Ref.[3] uses the minimum total operating cost of electricity purchase and natural gas as the objective function. It establishes an optimized coordination model of combined cooling, heating, and power generation that considers different tariff structures and wind, light, gas, and storage complementary power generation. Ref.[4] proposed a IES planning method based on an improved Kriging model. Ref.[5] proposed a three-level collaborative overall optimization method for combined cooling, heating, and electricity supply systems. This paper optimizes the combination of device type and device capacity. Ref.[6] proposed a optimization of the capacity of the IES under the limited financial constraints, while reducing the annual total cost and carbon dioxide emissions. Ref.[7] proposed a method for selecting the best components of the IES, which uses multivariable linear regression technology and gradient descent algorithm. Ref.[8] considered the fluctuations on the supply and demand sides, introduced robust optimization theory, and...
established an IES planning optimization model using particle swarm optimization algorithms. Ref.[9] studied the planning costs under high prediction accuracy and low prediction accuracy, and verified the planning results by using the operation effect of IES. Ref. [10] constructed an alternative method based on the selection of IES components, which used multivariate linear regression for impact assessment and AHP for trade-off analysis;

However, the types of energy coupling equipment considered at home and abroad are few. Among the optimization variables, capacity optimization is performed only on equipment types. Combination optimization of equipment types and equipment capacities is not performed simultaneously.

2. Mathematical model of key equipment in IES

2.1. Lithium Bromide Refrigerator (LB)

\[
\begin{align*}
Q_{cw} &= \frac{P_{ret}(1-\eta_{net}-\eta_1)}{\eta_{net}}(1-x(t)) \cdot \eta_{reach} \cdot COE_{co} \\
\eta_{reach} &= \frac{T_{c1}-T_{c2}}{T_{c1}-T_w}
\end{align*}
\]

In the formula, \( Q_{cw} \) is the cooling capacity of the absorption chiller in the period; \( \eta_{reach} \) is the waste heat recovery coefficient of flue gas; \( COE_{co} \) is the refrigeration coefficient; \( T_{c1}, T_{c2} \) respectively represent the inlet and outlet temperature of the flue gas of the absorption chiller.

2.2. Electric Refrigerator (EC)

\[
Q_{ec} = E_{ec} \cdot COP_{ec}
\]

In the formula, \( Q_{ec}, E_{ec} \) are the cooling capacity and power consumption of EC, kWh; \( COP_{ec} \) is the cooling coefficient of EC.

2.3. Ice Storage Tank (IST)

\[
Q_i = V_i (C_w \rho_w \Delta t_i + \rho_i \gamma \cdot IPF)
\]

In the formula, \( Q_i \) is the cold storage capacity of the ice storage tank, kJ; \( V_i \) is the effective capacity of the ice storage tank; \( C_w \) is the specific heat capacity of water, kJ/(kg·℃); \( \rho_w, \rho_i \) are the density of water and ice, kg/m³; \( \Delta t_i \) is the temperature difference between the inlet and outlet; \( \gamma \) is the dissolution rate of ice, kJ/kg; \( IPF \) represents the ice storage rate, %.

2.4. Gas Heat Pump (GHP)

\[
\begin{align*}
Q_{PH} &= G_p COP_p \\
Q_{PC} &= G_p COP_p
\end{align*}
\]

In the formula, \( Q_{PH}, Q_{PC} \) are the heating capacity and cooling capacity of GHP, kWh; \( G_p \) is the natural gas consumption of GHP, kWh; \( COP_p \) is the coefficient of performance of GHP.

2.5. Gas Turbine (GT)

\[
\begin{align*}
Q_{GT}(t) &= P_{GT}(t)(1-\eta_{GT} - k) / \eta_{GT} \\
Q_{WH}(t) &= Q_{GT}(t) COP_{GT} \\
Q_{SH}(t) &= Q_{GT}(t) COP_{GT} \eta_{WH}
\end{align*}
\]
In the formula, $Q_{GT}(t)$ is the heat generation power and electricity generation power of the gas turbine at any time $t$, kW; $\eta_{GT}$ is the power generation efficiency of GT,%; $k$ is 0.03 for the heat loss of the gas turbine; $Q_{W_H}(t), Q_{Sli}(t)$ are the heat generation power of GT at any $t$ Heating power, kW; $COP_{GT}$ is heating coefficient, value 1.2; $\eta_{W_H}$ is waste heat recovery rate, %.

2.6. Electric Boiler (EB)

$$Q_{EHB}(t) = \eta_{EHB}(1 - \mu_{loss})P_{EHB}(t)$$

In the formula, $Q_{EHB}(t)$ is the amount of heat supplied by the electric boiler at time $t$; $P_{EHB}(t)$ is the power consumption of electric boilers during period $t$; $\eta_{EHB}$ is electrothermal conversion efficiency; $\mu_{loss}$ is heat loss during time $t$.

2.7. Photovoltaic (PV)

$$P_{pv} = f_{pv}P_{r,pv}A \left[ 1 + \theta_p(T_{pv} - T_r) \right]$$

In the formula, $f_{pv}$ is the energy conversion efficiency of the photovoltaic power output, usually taken as 0.9; $P_{r,pv}$ is the actual radiation intensity; $A$ is the rated light intensity; $\theta_p$ is the temperature power coefficient; $T_{pv}$ is the actual temperature of the photovoltaic module; $T_r$ is the rated temperature of the photovoltaic module.

3. Optimization model

This article suggests taking the minimum annual comprehensive cost ($C^{\text{cos}}$) 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:

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

Initial investment cost

$$C^I = \frac{r(1+r)^y}{(1+r)^y - 1} \left[ c_{1,GT}P_{GT} + c_{1,GHP}P_{GHP} + c_{1,EB}P_{EB} + c_{1,LST}P_{LST} + c_{1,EB}P_{EB} \right]$$

System maintenance costs

$$C^M = \sum_{i=1}^{8760} \left[ c_{M,GT}(H_{i,GT} + P_{i,GT}) + c_{M,GHP}H_{i,GHP} + c_{M,EB}P_{EB} \right]$$

System operating costs

$$C^O = C^E + C^F = \sum_{i=1}^{8760} (P_{i,\text{SYS}} + P_{i,LST} + P_{i,EB} + P_{i,EB} + P_{i,EB})c_{i}$$

In formula (9), $c^I$ are the unit investment cost of the equipment; $p$ are the equipment planning capacity; $y$ is the service life of the equipment; $r$ is the discount rate.

In formula (10), $H_{i,GT}, P_{i,GT}, H_{i,GHP}, P_{i,EB}, C_{i,LST}, C_{i,EB}$ are the thermal and electrical power of the corresponding equipment; $c^M$ are the unit maintenance cost of the equipment.

In formula (11), $C^E, C^F$ are the electricity purchase cost and gas purchase cost of the system; $P_{i,\text{SYS}}, P_{i,LST}, P_{i,EB}, P_{i,EB}^E$ are the power provided by the grid to the electric load, the electric power required by the ice storage tank, the lithium bromide refrigerator and the electric boiler in the park at time $t$;
\( c^E_t \) is the electricity price at time \( t \); \( G^G_{GT}, G^G_{GHP} \) is the gas turbine and the gas heat pump input power at the time \( t \); \( c^G \) is the natural gas price.

IES planning constraints mainly include initial system investment cost constraints and IES maximum load constraints. System operation control constraints mainly include load supply and demand balance constraints, energy equipment operation constraints, etc.

4. Case analysis

4.1. Case introduction

This paper takes a southern park as an example. The operating parameters of each energy equipment are shown in Table 1. The typical daily load curve of the energy station supply area is shown in Figure 1 and Figure 2.

Consider 3 configuration options:

Case 1: Choose the gas-fired heat and power combined supply system combined with dual-mode cooler, lithium bromide refrigerator, and gas heat pump as candidates for energy station planning.

Case 2: Based on Case1, it is considered to configure photovoltaics with an installed capacity of 1MW at the energy station.

Case 3: Based on Case2, it further configures ice storage tank.

We calculate the proportion of equipment maintenance costs based on 3% of the total equipment value. The initial capacity of the energy storage equipment is set to 50% during the operation, and the maximum depth of charge and discharge of the battery is 50%.

| Equipment                | Effectiveness                        | Price per unit (yuan/kW) |
|-------------------------|--------------------------------------|--------------------------|
| Gas Turbine             | Gas to electricity: 0.26; Gas to heat: 0.63 | 4000                     |
| Lithium Bromide Refrigerator | Hot to cold: 1                   | 1200                     |
| Electric Boiler         | Electric to heat: 0.98             | 700                      |
| Gas Heat Pump           | Gas to heat: 3.8                   | 1000                     |
| Ice Storage Tank        | Ice storage: 0.89; Melting ice: 0.91 | 160                      |
| Electricity price       | Peak: 1.3345 yuan/kWh; Flat section: 0.8205 yuan/kWh; Valley: 0.4252 yuan/kWh |                |
| Photovoltaic power generation price | 0.85 yuan/kWh               |                          |
| Natural gas prices      | 3.50 yuan/m³                     |                          |

4.2. Planning results and analysis

From Table 2 and Table 3, we can analyze the capacity allocation and cost under different scenarios to get the most economical situation.
Table 2 Results of optimal configuration of energy station equipment capacity (kW)

| Case  | GT   | LB   | EB   | GHP  | EC   | IST  | PV |
|-------|------|------|------|------|------|------|----|
| Case1 | 4000 | 7000 | 2000 | 7000 | 2000 | -    | -  |
| Case2 | 3000 | 5000 | 5000 | 5000 | 3000 | -    | 1000|
| Case3 | 4000 | 4000 | 4000 | 4000 | 2500 | 8000 | 1000|

Table 3 Economic analysis of energy station equipment configuration (yuan)

| Case  | Annual comprehensive cost | Construction cost | Annual operation and maintenance costs | Energy purchase cost |
|-------|---------------------------|-------------------|---------------------------------------|----------------------|
| Case1 | 2474.0                    | 317.3             | 9.5                                   | 2147.2               |
| Case2 | 2274.9                    | 286.8             | 8.6                                   | 1979.5               |
| Case3 | 2304.5                    | 283.2             | 8.5                                   | 2012.8               |

Table 2 shows the equipment selection and capacity planning scheme for the comprehensive energy station. Comparing Case 1 and Case 2, the optional equipment is added with photovoltaic power generation equipment. Photovoltaic power generation does not consume primary energy, and it can meet a part of electrical load demand. Therefore, the use of photovoltaic can reduce installation. The lithium bromide refrigerator capacity with a higher cost is reduced from 10000kW to 7000kW, which reduces the demand for gas heat pumps. And the size of the electric boiler is increased from 2000kW to 5000kW.

Comparing Case 2 and Case 3, the optional equipment includes ice storage tank. The cold storage device is converted into raw energy for storage by electric refrigerator, and the maximum can reach 8000kW. The situation is subject to technical and economic evaluation before configuration.

All kinds of costs corresponding to the three planning schemes are shown in Table 3. Comparing Case 1 and Case 2, the overall annual cost is reduced by 199.1 yuan, decreasing the number of 8.05%. Among them, equipment construction costs and system operation and maintenance costs were reduced by 30.5 yuan and 0.9 yuan. It shows that the use of photovoltaic power generation can realize the effective use of clean energy and save the cost of operation and maintenance and energy purchase of energy stations. Comparing Case 2 and Case 3, the cold storage purchases electricity from the external power grid at the time of the valley of electricity price to reduce the demand for electrical power at the time of peak electricity price. However, this will increase the cost of purchasing additional electricity. Besides, the use of energy storage equipment can make the system's energy supply operation more flexible. To a certain extent, reduce the system's operation and maintenance costs. It is recommended to configure based on actual conditions.

5. Conclusion
In this paper, with capacity and cost as the optimization goal, we have established the IES equipment selection and capacity planning model, using a mixed-integer linear programming algorithm. This paper takes an energy station in a park in southern of China as an example for analysis. By comparing the configuration results of different schemes, we analyze the impact of energy storage equipment on the configuration results of the energy station, which provides reference for the equipment configuration of the energy station.

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