Planning Method for Power-Gas-Heat-steam Integrated Energy System in Industrial Park Considering Annual Comprehensive Cost

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Abstract. The current energy system in industrial parks have the problem of poor investment efficiency and low energy utilization rate. A planning method for the park's power-gas-heat-steam integrated energy system (IES) considering annual comprehensive cost is proposed. Firstly, based on the uncertainty of renewable energy and the characteristics of energy supply and consumption in the park, the structure of the integrated energy system is established. Papersons the minimum annual comprehensive cost including investment, operation, maintenance cost and environmental protection cost as the optimization goal. The mixed integer linear programming (MILP) algorithm is used to optimize the equipment selection, capacity planning and equipment operation mode at the same time. Through the example simulation, the planning scheme under different scenarios is given, and the effectiveness of the method is verified.

1. Introduction
Industrial parks represented by economic and technological development zones (ETDZ) have high demand for energy. The existing energy system of the parks have high construction and operation costs, low energy utilization rate, and neglect of environmental benefits. IES can realize the coordination and integration of multiple energy sources and optimize integration. It is of great significance for improving energy efficiency and building an environment-friendly society [1-3].

Whether the IES of the ETDZ can operate efficiently, economically and environmentally depends on the equipment type and capacity planning as well as the system operation mode under the corresponding planned capacity. In order to determine the optimal type and capacity of equipment in the park integrated energy system (PIES), scholars have conducted relevant research. Geidl et al. proposed the concept of energy hub (EH), and established a capacity expansion planning model for power and natural gas systems with the objective function of energy hub loss [4]. Mehleri et al. takes the annual total investment cost and the annual operating cost of the system as the objective function [5]. An optimized coordination model of cogeneration with different rates and wind, light, gas and storage for power generation was established [6]. In terms of algorithm, Bischi et al. uses a mixed integer linear programming algorithm to plan the short-term operation of the cogeneration system based on the EH model [7]. Guo Li et al. proposed a two-stage optimization planning design method. The upper layer uses multi-objective genetic algorithm to solve equipment selection and capacity optimization problems, and the lower layer uses...
mixed integer linear programming algorithm to optimize operation mode[8]. However, there is a lack of analysis and modeling of electro-gas-heat-steam coupling systems that meet the actual needs of industrial parks. In the optimization goal, there is a lack of consideration for environmental benefits. In the optimization variable, the device type is often determined first, and then the capacity optimization is performed, and the combination optimization of the device type and the device capacity is not considered at the same time.

This paper focuses on the PIES combined power-gas-heat-steam, fully considers the coupling and operation constraints of various types of energy conversion equipment in the system, and proposes an annual comprehensive costs including investment, operation, maintenance costs and environmental protection. The minimum cost is the optimization model of the objective function, and the mixed integer linear programming algorithm is used to optimize the equipment selection, capacity planning and equipment operation mode at the same time. Taking an ETDZ as an example, the calculation scheme of the integrated energy system of the park is given, and the effectiveness of the method is verified.

2. Basic structure of the PIES
The types of loads that can be included in the PIES studied are electric, gas, cold, heat and steam loads. The energy coupling relationships are gas-electric-thermal-steam coupling, electric-steam coupling, electro-thermal coupling, electricity-Cold coupling, steam-thermal coupling, steam-cold coupling, energy storage types include electrical energy storage, cold storage energy and steam energy storage. In addition, photovoltaic power can be arranged in the park, and primary energy can be purchased through the external power grid, gas network and steam network to meet the demand. The basic structure of the system's power supply is shown in Figure 1.

![Figure 1. The basic structure of the PIES](image)

3. PIES Optimization Model

3.1. Objective function
This paper takes the minimum annual comprehensive cost $C^{COM}$ as the objective function, including investment equivalent annual cost $C^I$, system annual operating cost $C^O$, system annual maintenance cost $C^M$ and annual environmental cost $C^{ENV}$.

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

(1)

3.1.1. Equivalent annual cost of investment. The annual cost of investment in the park's integrated energy system is determined by the configured capacity of each device:
\[ C^l = \frac{r(1+r)^y}{(1+r)^y-1} \left( c^{l, PV} \cdot W^{PV} + c^{l, BAT} \cdot W^{BAT} + c^{l, HS} \cdot W^{HS} + c^{l, CS} \cdot W^{CS} \right. \\
\left. + c^{l, CHP} \cdot W^{CHP} + c^{l, EB} \cdot W^{EB} + c^{l, EH} \cdot W^{EH} + c^{l, EC} \cdot W^{EC} \right) \]
\[ + c^{l, HC} \cdot W^{HC} + c^{l, AC} \cdot W^{AC} \]  

(2)

\[ c^{l,k} = \sum_{j=0}^{k} \frac{c^{0}}{(1+r)^{jy_k}} \]  

(3)

\[ n_k = \text{INT} \left( \frac{y}{y_k} \right) \]  

(4)

Where \( y \) indicates the operating period of the integrated energy system of the park; \( r \) indicates the discount rate; \( W^{PV} \), \( W^{BAT} \), \( W^{HS} \), \( W^{CS} \), \( W^{CHP} \), \( W^{EB} \), \( W^{EH} \), \( W^{EC} \), \( W^{HC} \), \( W^{AC} \) indicate the rated capacity of photovoltaic units, electric energy storage, steam energy storage, cold energy storage, cogeneration unit, electric boiler, the rated capacity of electric auxiliary heat unit, electric refrigeration unit, heat exchanger, and lithium bromide refrigeration unit; \( c^{l,k} \) indicates the \( k \) unit's investment cost of the above-mentioned within the operating period of the park; \( c^{0} \) indicates the \( k \) unit's investment cost; \( y_k \) indicates the service life of the \( k \) unit; the largest integer \( < x \) calculated by the rounding function \( \text{INT} (x) \); \( n_k \) used to calculate the number of replacements of the \( k \) unit in the operating period of the PIES.

3.1.2. Annual operating cost. The annual operating cost of the system includes the electricity purchase cost \( C^E \), the gas purchase cost \( C^G \), and steam purchase cost \( C^S \) during the year. The calculation method is as follows:

\[ C^O = C^E + C^G + C^S \]  

(5)

\[ C^O = \sum_{t=1}^{8760} P^{SYS}_t \cdot c^E_t + \sum_{t=1}^{8760} G^{SYS}_t \cdot c^G_t + \sum_{t=1}^{8760} S^{SYS}_t \cdot c^S_t \]  

(6)

Where \( P^{SYS}_t \), \( G^{SYS}_t \), \( S^{SYS}_t \) indicate the electric power, gas power and steam power purchased by the PIES from the external energy network; \( c^E_t \) indicates the electricity price at the \( t \) moment; \( c^G \) and \( c^S \) indicate the natural gas price and the steam price.

3.1.3. Annual maintenance cost. The annual maintenance cost of the system is related to the output status of each device. The calculation method is as follows:

\[ C^M = \sum_{t=1}^{8760} \left[ c^{M, PV} \cdot P^{PV}_t + c^{M, BAT} \cdot P^{BAT}_t + c^{M, HS} \cdot S^{HS}_t + c^{M, CS} \cdot S^{CS}_t \right. \\
\left. + c^{M, CHP} \cdot P^{CHP}_t + c^{M, EB} \cdot S^{EB}_t + c^{M, EH} \cdot H^{EH}_t \right. \\
\left. + c^{M, EC} \cdot C^{EC}_t + c^{M, HC} \cdot H^{HC}_t + c^{M, AC} \cdot C^{AC}_t \right] \]  

(7)

Where \( c^{M, PV} \), \( c^{M, BAT} \), \( c^{M, HS} \), \( c^{M, CS} \), \( c^{M, CHP} \), \( c^{M, EB} \), \( c^{M, EH} \), \( c^{M, EC} \), \( c^{M, HC} \), \( c^{M, AC} \) indicate the unit maintenance cost of photovoltaic units, electrical energy storage, steam energy storage, cold storage
energy, cogeneration units, electric boilers, electric auxiliary heat units, electric refrigeration units, heat exchangers, the steam lithium bromide refrigeration. $P_{t}^{PV}$, $P_{t}^{BAT}$, $S_{t}^{HS}$, $C_{t}^{CS}$ indicate the electric power output by the photovoltaic unit, the electric power exchanged by the electric energy storage, the steam power exchanged by the steam storage energy, and the cold power exchanged by the cold storage energy at $t$ moment; $P_{t}^{CHP}$, $S_{t}^{CHP}$, $S_{t}^{EB}$, $H_{t}^{EH}$, $C_{t}^{EC}$, $H_{t}^{HC}$, $C_{t}^{AC}$ indicate the electric power, heat power, steam power of the electric boiler, the heat power of the electric auxiliary heat unit, the cold power of the electric refrigeration unit, the heat power of the heat exchanger, and the cold power of the steam lithium bromide refrigeration unit at $t$ moment.

3.1.4. Annual environmental cost. Annual environmental cost in the traditional thermal power plant power generation, steam generation and natural gas combustion process, emissions of pollutants including CO2, CO, SO2, NOx and other pollutants will cause environmental degradation and ecological damage. In order to quantify the environmental protection benefits generated by the integrated energy system of the park, it is considered that part of the environmental cost should be paid to punish the environmental impact of the system operation, as follows:

$$C_{ENV} = \sum_{t=1}^{8760} \sum_{h=1}^{H} \sum_{c=1}^{C} \gamma_{E}^{h} P_{t}^{SYS} + \gamma_{G}^{h} G_{t}^{SYS} + \gamma_{S}^{h} S_{t}^{SYS}$$

(8)

Where $H$ indicates the collection of different types of pollutants, usually including CO2, CO, SO2, NOx, etc.; $c_{ENV,h}$ indicates the penalty value for the unit discharge of the $h$ pollutant; $\gamma_{E}^{h}$, $\gamma_{G}^{h}$, $\gamma_{S}^{h}$ indicates the unit emissions of $h$ pollutant produced by the production or use of electric, gas or steam.

3.2. Equipment operation constraints
The operational constraints of various equipment in the park's integrated energy system are as follows.

3.2.1. Photovoltaic unit operating constraints.

$$P_{t}^{PV} = W_{t}^{PV} \cdot \frac{K_{t}}{K_{stc}} \cdot (1 + \varepsilon (T_{t} - T_{stc}))$$

(9)

$$0 \leq P_{t}^{PV} \leq W_{t}^{PV}$$

(10)

Where $P_{t}^{PV}$ indicates the electric power output of the photovoltaic unit at $t$ moment; $K_{t}$ indicates the actual light intensity on the photovoltaic cell; $T$ indicates the surface temperature of the photovoltaic cell; $K_{stc}$, $T_{stc}$ indicates the output rated power under standard test conditions respectively and Light intensity and surface temperature; $\varepsilon$ indicates the temperature coefficient of the photovoltaic cell.

3.2.2. Energy storage equipment. The energy storage equipment in the system includes electric energy storage, steam energy storage and cold energy storage. Although these devices have different working principles, they have similar storage and discharge characteristics:

$$W_{t+1}^{ES} = W_{t}^{ES} (1 - \mu_{loss}^{ES}) + \left( \eta_{eh}^{ES} \cdot \max \left( P_{t}^{ES}, 0 \right) - \min \left( P_{t}^{ES}, 0 \right) / \eta_{dis}^{ES} \right) \cdot \Delta t$$

(11)

$$\beta_{min}^{ES} \cdot W_{t}^{ES} \leq W_{t}^{ES} \leq \beta_{max}^{ES} \cdot W_{t}^{ES}$$

(12)

$$-\mu_{min}^{ES} \cdot W_{t}^{ES} \leq P_{t}^{ES} \leq \mu_{max}^{ES} \cdot W_{t}^{ES}$$

(13)
Where $W_t^{ES},W_{t+1}^{ES}$ indicates the energy stored in the energy storage device at moment $t$ and $t+1$; $\mu_{ES}$ indicates the self-consumption rate of the energy storage device; $\eta_{ES}^{ch},\eta_{ES}^{dis}$ indicates the energy storage efficiency and the energy dissipation efficiency of the energy storage device; $P_t^{ES}$ indicates the switching power of the device; $\Delta t$ indicates the time interval usually takes 1h; $P_t^{ES}$ indicates the exchanges power between the $i$-type energy storage device and the system at time $t$; $\beta_{ES}^{min}$ indicates the minimum energy storage ratio of the energy storage device; $\beta_{ES}^{max}$ indicates the maximum energy storage ratio of the energy storage device; $\mu^{ES}$ indicates the maximum charge and discharge energy rate of the device; $ES$ indicates a collection of electric energy storage, steam energy storage and cold energy storage.

### 3.2.3. Cogeneration unit.

\[
P_t^{CHP} = G_t^{CHP} \cdot \eta_t^{CHP}
\]

\[
S_t^{CHP} = G_t^{CHP} \cdot \eta_t^{CHP}
\]

\[
0 \leq G_t^{CHP} \leq W^{CHP}
\]

Where $P_t^{CHP},S_t^{CHP}$ indicates the output electric power and steam power of the cogeneration unit at $t$ time; $\eta_t^{CHP}$ indicates the gas-electricity conversion efficiency of the cogeneration unit; $\eta_t^{CHP}$ indicates the gas-steam conversion efficiency of the cogeneration unit; $G_t^{CHP}$ indicates the input natural gas power of the cogeneration unit;

### 3.2.4. Energy coupling equipment. In addition to the cogeneration unit, the energy coupling equipment in the system also includes electric boilers, electric auxiliary heat units, electric refrigeration units, heat exchangers, and lithium bromide refrigeration units. The conversion efficiency is also used to describe:

\[
P_{out,i}^{l} = \eta^{l} \cdot P_{in,i}^{l}
\]

\[
0 \leq P_{in,i}^{l} \leq W^{l}
\]

Where $P_{out,i}^{l}$ indicates the output power of the energy coupling equipment at time $t$; $P_{in,i}^{l}$ indicates the input power of the energy coupling equipment at time $t$; $W^{l}$ indicates the rated capacity of the energy coupling equipment; $\eta^{l}$ indicates the conversion efficiency of the energy coupling equipment; $l$ indicates the collection of electric boilers, electric auxiliary heat units, electric refrigeration units, heat exchangers, and lithium bromide refrigeration units.

### 3.3. System power balance constraints

The power balance constraints of electricity, cold, heat, steam, and gas are considered in the system. Considering that the main optimization object of the model is the device configuration, the transmission network loss is temporarily not considered.

### 3.4. Optimization solution
The above model belongs to the mixed integer nonlinear programming method, which can be solved by calling the Gurobi solver through the Yalmip toolbox in the MATLAB environment.

4. Case Analysis
In this paper, an ETDZ in China is selected as the object. In order to improve the speed of the model, the typical daily load curve with seasonal characteristics and the unit photovoltaic output power curve represent the load characteristics and illumination characteristics of the whole year. The paper selects four scenarios for analysis, and the equipment selection, capacity planning and corresponding annual comprehensive costs under different scenarios are shown in Table 1. The pollutant discharges of each scheme are shown in Table 2.

Scenario 1: Only consider cogeneration, energy storage equipment and energy coupling equipment;
Scenario 2: Only consider photovoltaic units, energy storage equipment and energy coupling equipment;
Scenario 3: Only consider photovoltaic units, cogeneration, energy storage equipment and energy coupling equipment;
Scenario 4: Consider photovoltaic units, cogeneration, energy storage equipment and energy coupling equipment;

| Equipment                             | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---------------------------------------|------------|------------|------------|------------|
| photovoltaic unit (MW)                | --         | 614.8      | 486.9      | 489.2      |
| cogeneration unit (MW)                | 379.1      | --         | 170.9      | 226.2      |
| electric boiler (MW)                  | 0          | 98.9       | 121.4      | 38.9       |
| heat exchanger (MW)                   | 104.3      | 104.3      | 104.3      | 104.3      |
| electric auxiliary heat (MW)          | 0          | 0          | 0          | 0          |
| lithium bromide refrigeration unit (MW)| 55.2       | 0          | 4.1        | 10.4       |
| electric refrigeration (MW)           | 48.6       | 110.1      | 58.2       | 89.8       |
| electric energy storage (MW)          | 0          | 573.7      | --         | 324.6      |
| steam energy storage (MW)             | 920.3      | 0          | --         | 264.6      |
| cold energy storage (MW)              | 0          | 1087.8     | --         | 762.4      |

annual comprehensive cost (10^4$) 140003.1 127728.3 127366.5 126444.7

| Pollutant | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|-----------|------------|------------|------------|------------|
| NOx       | 2920       | 2220       | 2280       | 2110       |
| CO2       | 714000     | 519000     | 546000     | 519000     |
| CO        | 343        | 190        | 232        | 255        |
| SO2       | 4260       | 3900       | 3670       | 3020       |

annual environmental cost (10^4$) 6872 5483.1 5449.6 4842.8

Comparing scenario 1 and scenario 4, when the photovoltaic unit is not considered in the system, because the cogeneration unit has higher energy comprehensive utilization rate, the system economy can be improved at the peak and peak price of electricity, and more thermoelectricity will be deployed in the system. Co-production units, and correspondingly equipped with more absorption refrigeration units, steam energy storage equipment, improve the overall energy efficiency of the system. Comparing scenario 2 and scenario 4, when the cogeneration unit is not considered in the system, the system will be equipped with more photovoltaic units, and at the same time, due to the improvement of the photovoltaic unit, more electric equipment such as electric boilers and electric refrigerators are put into the system, and More electric energy storage equipment stabilizes the volatility of renewable energy, and the cold storage equipment also stores the electric energy generated by the photovoltaic unit through cold energy conversion. Comparing scenario 1 and scenario 2, since the adjustment flexibility of the cogeneration unit is significantly higher than that of the photovoltaic unit, there is less energy storage
equipment required in scenario one. Comparing scenario 3 and scenario 4, the addition of energy storage equipment improves the economics and flexibility of the system. As the proportion of cogeneration units increases, the system energy efficiency and environmental protection level increase. In addition, since the photovoltaic unit can obtain cheap electric energy during operation and does not generate pollutants, the annual comprehensive cost and environmental protection cost of the scene one are significantly higher than the other three scenarios. Scene 3 is slightly lower than the annual comprehensive cost and environmental protection cost of scenario 2. The annual comprehensive cost and environmental protection cost of scenario 4 are the lowest.

Through the comparison of equipment planning results and cost and cost in the above different scenarios, it can be seen that the abundant energy forms and equipment types can effectively reduce the annual comprehensive cost of the park's integrated energy system and the emission of pollutant gases, making the park economic and environmentally friendly. Run under the same good configuration.

5. Conclusion
This paper propose a planning method for the park's power-gas-heat-steam integrated energy system considering annual comprehensive cost. The method fully considers the coupling and operation constraints of various types of energy conversion equipment in the system, optimize the annual comprehensive cost with MILP and the example verify the paper provides a new overall method for integrated energy system planning. In this paper, 4 energy forms and 10 energy coupling devices have been considered. In the future, the impact of the introduction of hydrogen energy and electricity-hydrogen coupling on the integrated energy system planning of the park can be further considered.

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