Method of multi-objective optimal operation for combined cooling, heating, and power system

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Abstract. In order to give full play to the advantages of energy saving, high efficiency, economy, and low carbon of combined cooling, heating, and power (CCHP) system, it is necessary to seek an optimal operation mode. In this paper, a CCHP system model including energy storage equipment and ground source heat pump is established. To ensure the control accuracy, the unit commitment problem is considered in the programming. The optimal operation mode of CCHP system is obtained by taking the minimum annual operation cost, including pollutant treatment cost and the maximum primary energy utilization rate as the objective, and discussing the weight value of the above two purposes. Compared with the single objective optimization method, this optimal operation mode can provide more diversified and refined choices for the actual operation of CCHP system.

1. Introduction
The growing demand for energy poses a great challenge to social development. The energy demand presents the trend of distribution [1]. The Combined cooling, heating, and power system (CCHP) has the advantages of decentralized layout and nearby utilization [2], which has received widespread attention recently. Modeling, planning, operation optimization and performance evaluation of CCHP is a hot topic in academic circles [3, 4]. The operation control of CCHP system is a complex, and improper operation mode that will cause many problems, such as its deviation from the optimal operating point, declining efficiency and so on [5]. Therefore, it is of great significance to study the operation optimization of CCHP system in detail. Intelligent algorithm can be used to get Pareto front solution set, and then determine the optimal solution from Pareto solution set [6,7]. The multi-objective function can also be transformed into a single objective function. Then the optimal solution of the objective function can be obtained by traditional methods or intelligent algorithms [8]. Hongbo et al. [9] established a multi-objective optimization model, taking energy consumption minimization and environmental impact minimization as multi-objective optimization, and analysed the impact of the optimal operation strategy of the system on carbon dioxide emissions. Wang et al. [10] considered the three optimization objectives of annual total cost, saving carbon dioxide emissions, and the reduction primary energy saving, of which the weights were all taken as 1/3. The subjective weighting method is often used to determine the weight coefficient of each sub-objective, but the weakness of this method is too subjective.
In this paper, the multi-objective function of the operation cost and primary energy utilization rate of CCHP system coupled ground source heat pump (GSHP) is modelled, and the weight of the multi-objective function is discussed. This method effectively solves the problem that the weight of objective function is too subjective. The optimal weight of the multi-objective function and the operation strategy of the system under this optimal mode are obtained, which provided references and data support for the optimization of the CCHP system.

2. CCHP system description and equipment modeling

2.1. Description of the CCHP system
This study focuses on the CCHP system. The sketch map of the CCHP coupled GSHP is shown in Figure 1. This system can gain power from the grid, but it cannot transmit power to the grid.

![Figure 1. Sketch map of the CCHP system](image)

2.2. Model for equipment

2.2.1. Model of energy production equipment. The energy production subsystem consists of gas internal combustion engine (ICE) and gas boiler (GB).

The relationship between natural gas input power and power generation of ICE is shown as:

\[ G_{in} = 2.25P_{ICE} + 165.8 \] (1)

where \( G_{in} \) represents natural gas input power, KW; \( P_{ICE} \) is power generation of internal combustion engine, kW.

The natural gas consumption of ICE is expressed as follows:

\[ V_{ICE} = \frac{G_{in}}{H} \] (2)

where \( V_{ICE} \) represents natural gas consumption of ICE, m³; \( H \) is 9.778KWh/m³ as the low calorific value of natural gas.

The calculation formulas of the exhaust heat power and the cylinder liner water heat power of the internal combustion engine are as follows:

\[ Q_{ICE}^{eq} = 0.002(P_{ICE})^2 + 0.405P_{ICE} + 178.7 \] (3)

\[ Q_{ICE}^{Cyl} = -1.96 \times 10^{-5}(P_{ICE})^2 + 0.20(P_{ICE}) + 100.8 \] (4)

where \( Q_{ICE}^{eq} \) is the exhaust gas of ICE, kW; \( Q_{ICE}^{Cyl} \) is the cylinder liner water heat power of ICE, kW; t

The heat production of GB is related to boiler’s efficiency and gas consumption. In general, it can be considered as a linear relationship as shown in equation (5):

\[ Q_{GB}^H = HV_{GB}\eta_{GB} \] (5)

where \( Q_{GB}^H \) represents heating capacity of GB, kW; \( V_{GB} \) represents gas consumption of GB, m³; \( \eta_{GB} \) represents the efficiency of GB.
2.2.2. Model of energy recovery equipment. The mathematical model of cooling and heating capacity of absorption lithium bromide (ALB) refrigerator can be shown as:

\[
Q_{ALB}^C = (Q_{ICE}^{egC} + Q_{ICE}^{cryC}) \eta_{ALB}^C
\]

\[
Q_{ALB}^H = Q_{ICE}^{egH} \eta_{ALB}^H
\]

where \(Q_{ALB}^C\) represents the refrigerating capacity of ALB unit in summer, kW; \(Q_{ALB}^H\) represents the heating capacity of ALB in winter, kW; \(\eta_{ALB}^C\) represents the efficiency of ALB in summer; \(\eta_{ALB}^H\) represents the efficiency of ALB in winter.

The mathematical model of cooling and heating capacity of plate heat exchanger (PHE) is:

\[
Q_{PHE}^H = Q_{ICE}^{cryH} \eta_{PHE}^H
\]

where \(Q_{PHE}^H\) represents the heating capacity of PHE in winter, kW; \(\eta_{PHE}^H\) represents the efficiency of PHE in winter.

2.2.3. Model of energy conversion equipment. The refrigerating and heating capacity of GSHP can be calculated as follows:

\[
Q_{GSHP}^C = P_{GSHP}^C \eta_{GSHP}^C
\]

\[
Q_{GSHP}^H = P_{GSHP}^H \eta_{GSHP}^H
\]

Where \(Q_{GSHP}^C\) represents the refrigerating capacity of GSHP in summer, kW; \(Q_{GSHP}^H\) represents the heating capacity of GSHP in winter, kW; \(P_{GSHP}^C\) represents the input electric power of GSHP in summer, kW; \(P_{GSHP}^H\) represents the input electric power of GSHP in winter, kW; \(\eta_{GSHP}^C\) represents the efficiency of GSHP in summer; \(\eta_{GSHP}^H\) represents the efficiency of GSHP in winter.

Electric refrigeration unit (ER) is a kind of equipment that converts electric energy into cold energy and is widely used to meet the needs of users for cooling load.

The refrigerating capacity of ER can be calculated as:

\[
Q_{ER}^C = P_{ER} \eta_{ER}^C
\]

where \(Q_{ER}^C\) represents the refrigerating capacity of ER in summer, kW; \(P_{ER}\) represents the input electric power of ER in summer, kW; \(\eta_{ER}^C\) represents the efficiency of ER in summer.

2.2.4. Model of energy storage equipment. Energy storage includes heat storage (HS) and cold storage (CS).

The model of energy storage device is established as follows:

\[
SOC(t + 1) = (1 - \delta)SOC(t) - \left(\frac{\eta_{cha} P_{cha}(t)}{B} - \frac{P_{dis}(t)}{\eta_{dis} B}\right) \Delta t
\]

where \(SOC(t + 1)\) is the state of charge at the moment \(t+1\), \(SOC(t)\) is the state of charge at the moment \(t\); \(\eta_{cha}\) is the charging efficiency, \(\eta_{dis}\) is the discharging efficiency, \(B\) is the capacity of the ESS, kWh; \(\delta\) is the self-discharge rate; \(P_{cha}\) is the storage power at the moment \(t\), kW; \(P_{dis}(t)\) is the discharge power at the moment \(t\), kW.

The power of energy storage at the moment \(t\) can be expressed as:

\[
P_{ESS}(t) = \begin{cases} P_{dis}(t), & P_{ESS}(t) > 0 \\ 0, & P_{ESS}(t) = 0 \\ P_{cha}(t), & P_{ESS}(t) < 0 \end{cases}
\]
3. Multi-objective optimization operation of CCHP

3.1. Objective

3.1.1. Operation economy. The operation economy of CCHP system connected to a grid without power injection generally refers to the minimum operation cost, which is composed of fuel cost, power purchase cost, maintenance cost and pollutant emission cost. This paper mainly studies the emission cost of CO₂ and NOₓ, the annual CO₂ emissions are as follows [11]:

\[
C_{\text{CO}_2} = 0.002 \sum_{t=1}^{N_1} \sum_{t=1}^{T} (V_\text{ICE,1}(t) \Delta t) + 0.002 \sum_{t=1}^{N_2} \sum_{t=1}^{T} (V_\text{GB,1}(t) \Delta t) + 0.096 \sum_{t=1}^{T} P_{\text{buy}}(t) \tag{14}
\]

The reference method [7,8] is used to calculate NOₓ emissions and pollutant treatment cost. The objective function can be written as:

\[
C = C^H_O + C^C_O + C_M + C_{\text{CO}_2} + C_{\text{NO}_x}
\]

\[
C^H_O = \sum_{i=1}^{N_1} \sum_{t=1}^{T} (V_\text{ICE,1}(t) \Delta t) + \sum_{i=1}^{N_2} \sum_{t=1}^{T} (V_\text{GB,1}(t) \Delta t) + \sum_{t=1}^{T} C_{\text{environ}} P_{\text{buy}}(t) \tag{15}
\]

\[
C^C_O = \sum_{i=1}^{N_1} \sum_{t=1}^{T} (V_\text{ICE,1}(t) \Delta t) + \sum_{t=1}^{T} C_{\text{m},t} P_{\text{buy}}(t) \tag{16}
\]

\[
C_M = \sum_{i=1}^{N_1} \sum_{t=1}^{T} f_\text{ICE,1}(P_{\text{ICE,1}}(t) + f_\text{ICE,1}(Q_{\text{ICE,1}})) \Delta t + \sum_{i=1}^{N_2} \sum_{t=1}^{T} f_\text{GB} Q_{\text{GB,1}}(t) \Delta t + \sum_{t=1}^{T} f_\text{ER} Q_{\text{ER,1}}(t) \Delta t + \sum_{i=1}^{M_3} \sum_{t=1}^{T} f_\text{GSH,1}(Q_{\text{GSH,1}}^C(t) + f_\text{GSH,1}(Q_{\text{GSH,1}})) \Delta t \tag{17}
\]

where \(C\) represents total annual operation cost of the system; \(C^H_O\) is the operating cost in winter, \(C^C_O\) is the operating cost in summer; \(C_M\) is the maintenance cost; \(C_{\text{environ}}\) is the pollutant emission cost; \(M_1\) is the number of ALB, \(M_2\) is the number of ER, \(M_3\) is the number of GSHP; \(f\) is the equipment maintenance cost coefficient, $\text{kW}$.

3.1.2. Primary energy efficiency. Primary energy efficiency refers to the ratio of system output energy to primary energy consumption. The higher the primary energy efficiency is, the better the system energy saving will be[11].

\[
P_{\text{ER}} = \frac{Q_h + Q_c}{P_{\text{buy}} \eta + W_{\text{CCHP}}} \tag{19}
\]

where \(Q_h\), \(Q_c\) and \(Q_e\) represent the annual thermal, cooling and electric energy consumption respectively; \(\varphi\) represents the average efficiency of power plants; \(\eta\) is the transmission line loss rate of power grid.

3.1.3. Multi-objective optimization of CCHP system. In this paper, the two objectives of optimal management of CCHP system are the optimal economy and the highest efficiency of primary energy. The multi-objective optimization problem is transformed into a single-objective one by linear weighting method. Because the dimensions of the two objectives are different, the objective function should be standardized. The formula is as follows:

\[
\text{min} \ F = F_{\text{fee}} + F_{\text{ER}} \frac{P_{\text{ER}}^*}{P_{\text{ER}}} \tag{20}
\]

where \(F_{\text{fee}}\) is the weight coefficient respectively, and the overall weight coefficient is 1. \(C_{\text{st}}\) is the reference value of operation cost; \(P_{\text{ER}}^*\) is the reference value of primary energy efficiency.
3.2. Constraints

3.2.1. Equality constraints

(1) Electric Balance Constraint
\[ \sum_{i=1}^{N_1} P_{ICE,i}^H(t) + P_{buy}^H(t) = \sum_{i=1}^{M_1} P_{GSHP,i}^H(t) + Q_e^H(t) \] \[ \sum_{i=1}^{N_1} P_{ICE,i}^C(t) + P_{buy}^C(t) = \sum_{i=1}^{M_1} P_{GSHP,i}^C(t) + \sum_{i=1}^{M_2} P_{ER,i}^C(t) + Q_e^C(t) \] (21) (22)

(2) Thermal Power Balance Constraint
\[ Q_h(t) = \sum_{i=1}^{M_1} Q_{ALB,i}^H(t) + \sum_{i=1}^{M_1} Q_{GSHP,i}^H(t) + \sum_{i=1}^{N_2} Q_{GB,i}^H(t) + Q_{PHB}^H(t) \] \[ + P_{dis}^H(t) + P_{cha}^H(t) \] (23)

(3) Refrigerating Power Balance Constraint
\[ Q_c(t) = \sum_{i=1}^{M_1} Q_{ALB,i}^C(t) + \sum_{i=1}^{M_1} Q_{GSHP,i}^C(t) + \sum_{i=1}^{M_2} Q_{ER,i}^C(t) + P_{dis}^C(t) + P_{cha}^C(t) \] (24)

(4) Energy Storage Balance Constraint in one cycle
\[ SOC(0) = SOC(T) \] (25)

3.2.2. Inequality constraints

(1) Equipment Output Constraint
The electric power, heating power and cooling power of each equipment meet the requirements of upper and lower limits of power:
\[ P_{ICE,min}(t) \leq P_{ICE}(t) \leq P_{ICE,max}(t) \] \[ Q_{min}(t) \leq Q(t) \leq Q_{max}(t) \] (26) (27)
The minimum load rate of all equipment is set to 0.5.

(2) Energy Storage State Constraint
\[ SOC_{min}(t) \leq SOC(t) \leq SOC_{max}(t) \] (28)

3.3. Model solution
In order to ensure control accuracy, the unit commitment problem is considered in the programming. It is better to control the start-up and stop of each piece of equipment than to integrate multiple units into one equipment, and then distribute the optimized power to each unit equally. It uses commercial optimization software lingo19.0 platform to write the model program and ask the global solver to tackle it.

4. Case study

4.1. Primary data of the case
This paper takes a residential community in northern China as the research object. The typical cooling and thermal loads of the project are shown in Figure 2.
Figure 2. The typical cooling and thermal loads

The unit price of natural gas is ¥2.25/m³. The electricity pricing strategy of energy drawn from the grid adopts TOU pricing. The price of electricity is ¥1.435/kWh, ¥1.244/kWh, ¥0.9/kWh and ¥0.258/kWh, under the peak, top, plain, and valley periods.

The parameters of the energy supply equipment and energy storage equipment in the case are shown in Table 1 and 2.

Table 1. The parameters of energy supply equipment

| Equipment | Parameters                  | Values   | Numbers | ƒ   |
|-----------|-----------------------------|----------|---------|-----|
| ICE       | Maximum power generated     | 850kW    | 2       | 0.13|
| ALB       | Rated refrigerating capacity| 825kW    | 2       | 0.001|
|           | Rated refrigerating efficiency| 1.4     |         |     |
|           | Rated heating capacity      | 895kW    |         |     |
|           | Rated heating efficiency    | 0.9      |         |     |
| ER        | Rated refrigerating capacity| 7280kW   | 3       | 0.01|
|           | Rated refrigerating efficiency| 5.03   |         |     |
| GSHP      | Rated refrigerating capacity| 1415kW   | 6       | 0.015|
|           | Rated refrigerating efficiency| 6.55   |         |     |
|           | Rated heating capacity      | 1440kW   |         |     |
|           | Rated heating efficiency    | 4.16     |         |     |
| GB        | Rated heating capacity      | 4200kW   | 2       | 0.003|
|           | Rated heating efficiency    | 0.92     |         |     |
| PHE       | Rated heating capacity      | 445kW    | 1       | 0.0005|
|           | Rated heating efficiency    | 0.9      |         |     |

Table 2. Parameters of energy storage equipment

|          | \( \eta_{cha/dis} \) | \( \delta \) | SOC(t)min | SOC(t)max | SOC(0) | SOC(T) |
|----------|-------------------|-------------|-----------|-----------|--------|--------|
| HS       | 0.88              | 0.001       | 0.25      | 0.80      | 0.50   | 0.50   |
| CS       | 0.88              | 0.001       | 0.25      | 0.80      | 0.50   | 0.50   |
4.2. Results and discussion
This optimization problem is a mixed integer nonlinear problem (MINLP). By changing the weight coefficients of $F_{fee}$ and $F_{ER}$, different optimization results are compared. The optimal results are obtained by changing the $F_{fee}$ and $F_{ER}$ weight coefficients of multi-objective functions. When the weights $F_{fee} = 0.9$ and $F_{ER} = 0.1$, the objective function value $F$ is the minimum of 1.20. Thus, this operation mode takes both energy efficiency and economy into account, which is called the optimal operation mode. The comparison of results under different operation modes is shown in Table 3.

Table 3. Results under different operation modes

| Objectives and units                  | Minimum operating cost model | Highest energy efficiency mode | Optimal operation mode |
|--------------------------------------|------------------------------|--------------------------------|------------------------|
| Annual operating cost/¥10000         | 2458                         | 2564                           | 2483                   |
| Annual carbon emissions/t            | 19590                        | 18814                          | 18829                  |

Under this optimal operation mode, the operation cost is increased compared with minimum operating cost mode ¥ 250000, less than highest energy efficiency mode ¥ 810000. The carbon emissions of optimal operation mode is 761t, lower than that of minimum operating cost mode, and 15t higher than that of highest energy efficiency mode. This optimal model takes into account the environmental protection, economy and energy saving at the same time. The method adopted in this paper is simple and effective, and solves the disadvantages of subjective valuation of objective function weight in the past.

Optimal thermal and cooling output power of each equipment are shown in the following Figures 3:

![Figure 3. Operation strategy on a typical day](image)

It can be seen that the energy storage equipment basically stores energy when the electricity price is low, and releases energy when the load is large. Energy storage equipment plays an effective role in the shifting peak and the filling valley. Moreover, it mainly uses GSHP and GB for heating in winter and uses GSHP and ER in summer. This optimal operation mode can consider both economy and energy efficiency.

5. Conclusions
In this study, a multi-objective optimization mode considering operation cost and primary energy efficiency was proposed in CCHP system, including ESS and GSHP. This optimization mode is studied in a realistic case of northern China. Compared with the single objective optimization method, the
optimal operation mode can provide more diversified and refined choices for the actual operation of CCHP system. The output model and operation mode of the equipment are simplified and linearized, and the off design and start-stop characteristics of some equipment are not considered. Therefore, more accurate modeling with intelligent algorithm will be the focus of future research.

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