Integrated Evaluation Criteria of Economic Benefit and Energy Value Efficiency of Micro Grid

Xudong Wang 1, 2, a, Yan Qi 1, 2, b, *, Jinze Li3, Jingyu Nie3, Binyang Wu 3, c, Wanhua Su 3

1 State Grid Tianjin Electric Power Company, Tianjin 300010, China
2 State Grid Tianjin Electric Power Research Institute, Tianjin 300384, China
3 State Key Laboratory of Internal Combustion Engine, Tianjin University, Tianjin 300072, China

a xudong.wang@tj.sgcc.com.cn, *, b Corresponding author e-mail: qiyan_fly@163.com,
c tju_edu_cn@tju.edu.cn

Abstract. An evaluation criterion of micro grid is proposed from the perspective of economy, energy conservation and emission reduction. The heterogeneous energy such as cold, heat and electricity based on the micro grid taking combined cooling heating and power as the core was evaluated based on the energy value through the cascade utilization of energy, and the micro-grid optimization model including the micro-turbine, waste heat boiler, lithium bromide absorption chiller, fan and photovoltaic was established. As compared with the model of cost optimization only, its integrated optimization index increased by 11.547% and the efficiency of exergy increased by 14.651%.

Keywords: Combined Cooling Heating and Power, Integrated Energy Micro Grid, Energy Value, Evaluation Criteria, Exergy.

1. Introduction

The combined cooling, heating and power system (CCHP) is an energy supply system that combines primary energy sources such as natural gas, solar, wind, and hydropower that can directly generate heat and electricity to meet the needs of users with the combined supply of cold, heat and electricity. It can not only be distributed in the vicinity of power consumption sites, but also can be connected to the large power grid to meet different load requirements [1]. As of 2017, China's new energy micro-grid demonstration projects have reached 28, and "Internet +" smart energy demonstration projects have reached 55. The integrated energy field has received strong attention and support from the government [2]. In the era of increasingly depleted fossil resources and global warming, the integrated energy cascade utilization with CCHP as the core has become an important means to solve the problem of sustainable development. However, the current CCHP system has a complex structure and various equipment influences each other. A unified standard for the evaluation of the benefits of the integrated energy system has not yet been formed [3]. This paper proposes a new type of evaluation system that will comprehensively evaluate the integrated energy system based on both economic benefits and energy...
value, and study the improvement and promotion of system benefits after the introduction of energy value.

One of the core goals of the CCHP integrated energy system is to improve the efficiency of energy cascades. At present, experts and scholars have proposed many evaluation systems for the energy efficiency of the system. Based on the primary exergy efficiency index, energy efficiency index of non-renewable energy utilization level, primary energy saving rate index, exergy efficiency index, standard coal energy efficiency index of multi-energy complementary system and clean energy electricity proportion index [4-7], a combination of multiple indicators is used for evaluation. The above evaluation ideas based on the economics and the first and second laws of physics have some flaws due to different goals. Either it fails to consider the quality difference between heterogeneous energy sources, or its evaluation principle deviates from the actual use of users, or it is only applicable to the energy efficiency analysis of a single energy system without integrity, or the index parameters fail to change dynamically with the system operation [8]. Because none of the above evaluation systems comprehensively and accurately consider the energy levels of the three types of energy in the CCHP system, the input and output of these three types of energy have not been unified. Therefore, there is an urgent need for a new evaluation criterion that is suitable for comprehensive analysis of multiple energy efficiency and fair measurement of the conversion and loss of three types of energy in the CCHP system. At present, literature [9] has initially incorporated energy value parameters into the evaluation system, and assigns weights to heterogeneous energy. Through simulation analysis, it is verified that the optimized evaluation criteria can unify the quantification of energy efficiency, make the system fully reach the purpose of energy cascade utilization and provides a new idea for the evaluation of the integrated energy efficiency of the CCHP system.

This paper will take the CCHP microgrid as the research object, with the economic cost and energy value as the optimization direction, using the judgment matrix combined with the expert evaluation to obtain the weighting factors, and considering the corresponding energy value utilization weights of cold, heat and electricity respectively, which solves the problems of energy quality differences and usage differences between energies, and can be more accurately reflect the degree of energy utilization and loss, it provides a high-efficiency, low-carbon, and economic direction for the formulation and development of the optimal capacity planning and operation mode of the integrated energy triple-generation system.

2. Integrated energy system network model

This paper establishes a CCHP network model to express the coupling relationship between different energy sources, and gives the definition and measurement methods of each parameter index in the model. As shown in Figure 1, the input of this model is gas, solar, wind, electric and other energy sources, and the output is the cold, heat, and electric loads that meet the needs of users. Split air conditioners and lithium bromide absorption refrigerating machine are used as cooling load energy equipment, waste heat boilers and heat storage tanks are used as heat load energy equipment, and micro gas turbines, storage battery, wind turbine, photovoltaics and large power grids are used as electric load energy equipment [10-13]. The operation mode adopts the combination of heat and electricity, which can avoid the generation of excess heat and electricity. The following will study the operating efficiency and energy consumption of the system in detail, and give the corresponding calculation methods:
2.1. Cooling equipment model
1) Split air conditioner
When the cooling capacity fails to meet the user's demand, the split air conditioner needs to be started. The electric energy purchased from the large power grid is used as input to output the cold energy. The power model is:

\[ P_{AC} = Q_{AC} \times \eta_{AC} \]  

(1)

In the (1), \( P_{AC} \) indicates the output power of the split air conditioner, \( Q_{AC} \) indicates its input electric power, \( \eta_{AC} \) indicates its cooling energy efficiency ratio.

2) Lithium bromide absorption refrigerating machine
Lithium bromide absorption refrigeration technology can make full use of all kinds of waste heat resources to achieve the purpose of energy saving and consumption reduction. The steam discharged from the waste heat boiler is directly used for absorption refrigeration. Its power model is:

\[ P_{AB} = Q_{AB} \times \eta_{COP} \]  

(2)

In the (2), \( P_{AB} \) indicates the cooling power output by the lithium bromide absorption refrigerating machine, \( Q_{AB} \) indicates the input heat of waste heat boiler steam, \( \eta_{COP} \) indicates its coefficient of performance.

2.2. Heating equipment model
1) Waste heat boiler
The waste heat boiler recovers the high-temperature flue gas discharged from the micro gas turbine, and heats the water to a certain temperature in the boiler to meet the heat load demand of the user. The excess steam can be used by lithium bromide absorption refrigerators. The power model is:

\[ P_{HRSG} = P_{GT} \times \frac{\eta_{GTH}}{\eta_{GTE}} \times \eta_{HRSG} \]  

(3)

In the (3), \( P_{HRSG} \) indicates the exhaust heat power of the waste heat boiler, \( \eta_{HRSG} \) indicates its efficiency, \( P_{GT} \) indicates the output power of the micro gas turbine, \( \eta_{GTH} \) indicates its heating efficiency, \( \eta_{GTE} \) indicates its power generation efficiency.

2) Heat storage tank
When the heat load provided is greater than the heat load required by the user, the microgrid will store the excess heat in the heat storage tank.

\[ E_{HST,t+\Delta t} = (1 - \phi_{EST}) \times E_{HST,t} + P_{HST,t} \times \Delta t \]  

(4)

In the (4), \( E_{HST,t} \) indicates the heat stored in the heat storage tank during the \( t \) time period, \( \phi_{EST} \) indicates the heat loss parameter of the heat storage tank, \( P_{HST,t} \) indicates the heat storage power in the heat storage tank during the \( t \) time period. When the heat storage tank is in the heat storage mode, \( P_{HST,t} \) is positive; when in the heat release mode, \( P_{HST,t} \) is negative.

2.3. Power supply equipment model
1) Micro gas turbines
As the most mature distributed power generation equipment, micro gas turbines are widely used in CCHP. The micro gas turbine uses natural gas as fuel to generate high-frequency alternating current and high-temperature flue gas to meet electrical and thermal loads. The power model is:

Heating efficiency:

\[ \eta_{GTH} = 4.08 \times 10^{-4} P_{GTe} + 0.107 R_{GT} -8.91 \times 10^{-5} P_{GTe} R_{GT} + 0.169 \]  

(5)

Power generation efficiency:
In the (5) (6), PGTe indicates the rated output power of the micro gas turbine, RGT indicates the load rate.

2) Wind turbine
Renewable energy power generation equipment has uncertainty. Therefore, the Weibull model is usually selected in wind power generation. The wind speed directly determines the output of the wind turbine. The power model is:

\[ P_W = \begin{cases} 0 & , v < V_{ci} \\ \\ Pe \frac{(v - V_{ci})}{V_e - V_{ci}}, V_{ci} \leq v < V_e \\ Pe & , V_e \leq v \leq V_{co} \\ 0 & , v > V_{co} \end{cases} \]  

(7)

In the (7). PW indicates the power output of the wind turbine, Pe indicates the rated power of the wind turbine, v, Ve, Vci, Vco indicates the current wind speed, rated wind speed, cut-in wind speed and cut-out wind speed respectively.

3) PV

\[ P_{PV} = P_{STC} \frac{G}{G_{STC}}[1 + m( T_e - T_{STC} + \frac{G}{800} (T_N - 20))] \]  

(8)

In the (8). PPV indicates the power output of the PV, GSTC, PSTC, TSTC indicates light intensity, output power and module surface temperature under specified standard conditions respectively, G indicates the actual light intensity, m indicates the power temperature coefficient, Te, TN indicates the ambient temperature and module rating temperature respectively. GSTC is 1000W/m², TSTC is 25°C.

4) Storage battery

When the power provided is rich or insufficient, the battery can enter the charging and discharging state respectively, which can effectively suppress the fluctuation of the microgrid power load. The electric quantity model of the state of charge of the battery at a certain moment is:

\[ SOC = \frac{C_{rec}}{C_{max}} \]  

(9)

In the (9), SOC indicates the remaining capacity of the battery, Crec indicates its remaining capacity, Cmax indicates the total battery capacity.

The power model of the battery in a certain time period is:

\[ SOC_{t+\Delta t} = SOC_t - \frac{P_B \times \Delta t}{C_{max}} \]  

(10)

In the (10), PB indicates the discharge and charging power of the battery, positive when discharging and negative when charging.

3. Objective optimization model and algorithm

3.1. Objective Function

From the perspective of achieving the optimal economic and energy value of the micro grid, the system is planned and capacity is configured. Among them, economic optimization includes operating costs and pollution control costs [14-16].

1) Operation cost model:
\[ M_{1,1} = \min \sum_{j=1}^{24} \left( C_{\text{gas}} P_{\text{out}}^{\text{GTE}} + \sum_{i=1}^{n} \frac{1}{2} \left( C_{j} + P_{j} \right) \left( C_{j} - C_{i} \right) \right) \]  

(11)

where, \( M_{1,1} \) denotes the total cost of running the system for 24 hours, \( C_{\text{gas}} \) denotes the price of natural gas, \( P_{\text{out}} \) denotes the output power per unit hour of each equipment, \( C_{j} \) denotes the operation and maintenance cost per unit hour of each equipment, \( C_{i} \) denotes the electricity purchase price, \( C_{s} \) denotes the price of electricity sold. \( P_{j} \) denotes the power interaction between the power grid and the micro grid. The sale of electricity is negative, the purchase is positive.

The pollution of micro grid mainly comes from micro gas turbine and large power grid, and the pollution gases include CO2, SO2 and NOX.

\[ M_{1,2} = \min \sum_{j=1}^{24} \sum_{k=1}^{n} \left( W_{\text{GT},k} P_{\text{GT}} + W_{\text{D},k} P_{\text{P},k} \right) C_{k} \]  

(12)

where, \( M_{1,2} \) denotes the total cost of pollution control for 24 hours, \( k \) denotes the type of polluted gas, \( n \) denotes the total number of pollutant gas categories, \( W_{\text{GT},k} \) denotes the emission coefficient of the polluted gas produced by the gas turbine, \( W_{\text{D},k} \) denotes the emission coefficient of polluted gas generated by the large power grid, \( P_{\text{P},k} \) denotes the power purchased from the large power grid. \( C_{k} \) denotes the treatment cost per unit of polluted gas. If it is in the state of selling electricity, \( P_{\text{P},k} \) is zero.

The total cost of micro grid is the sum of operation cost and pollution control cost:

\[ M_{1} = M_{1,1} + M_{1,2} \]  

(13)

2) Energy efficiency model of micro grid based on energy value:

The differences of heterogeneous energy sources and the principle of energy cascade utilization are incorporated into the comprehensive energy efficiency assessment of micro grid, and the energy efficiency model of micro grid was built:

\[ M_{2} = \min \left( 1 - \frac{\beta E_{\text{h}} + \gamma E_{\text{e}} + \alpha E_{\text{c}}}{G_{\text{sec}}} \right) \]  

(14)

where, \( M_{2} \) denotes the energy efficiency index of the system. They are the cold, heat, and electricity output of the system, and \( \beta, \gamma, \) and \( \alpha \) denotes the energy value utilization weights corresponding to cold, heat, and electricity respectively, which can be obtained by the analytic hierarchy process (AHP). \( C_{\text{gas}} \) denotes the consumption of natural gas, \( H \) denotes the calorific value of natural gas, \( E \) denotes the total amount of electricity generated from renewable energy and purchased from the power grid.

The AHP model is easy to analyze according to Fig. 1. The comparison layer is the energy cascade utilization rate, and the index layer is the three heterogeneous energy sources of cold, heat and electricity. The judgment matrix [17] is constructed as shown in Table 1. According to the expert scoring method, each energy source in the index layer is assigned between 1 and 9 to evaluate the energy value of each energy source. According to the energy flow direction of the micro grid in Figure 1, it is easy to see that the energy flow flows in the direction of electricity, heat and cold. Therefore, according to the principle of energy volume utilization, it can be concluded that electric energy is more important than thermal energy, and thermal energy is slightly more important than cold energy. Based on this, the judgment matrix as shown in Table 1 can be given.

| Table 1. Judgment matrix |
|--------------------------|
| Electricity | Thermal energy | Cold energy |
| Electricity | 1 | 4 | 7 |
| Thermal energy | 1/4 | 1 | 2 |
| Cold energy | 1/7 | 1/2 | 1 |

The weights calculated by the judgment matrix are \( \alpha=0.7014, \beta=0.2132, \gamma=0.0853 \).
3) Comprehensive index model of microgrid economy-energy efficiency:
In conclusion, the objective function expressed by the microgrid economy-energy efficiency comprehensive index $\eta_e$ is as follows:

$$\eta_e = \sum_{i=1}^{2} \eta_i = \frac{M_1}{\min(M_1)} + \frac{M_2}{\min(M_2)} \quad (15)$$

Min (M1) and min (M2) represent the minimum values obtained by single objective optimization for M1 and M2 respectively.

4) Exergy efficiency model:

CCHP exergy efficiency $[18]$ is:

$$\eta_{ex} = \frac{W + E_h + E_c}{\sum H} \quad (16)$$

Where, $W$, $E_h$, $E_c$, $f$ and $H$ denote power generation, heat production, cold production, natural gas consumption and natural gas calorific value respectively.

The power grid exergy efficiency $[19]$ is:

$$\eta_{eg} = \frac{\eta_{coal}}{\tau_{coal}} \quad (17)$$

Where, $\eta_{coal}$ and $\tau_{coal}$ are the average efficiency of pure coal-fired power generation in China and the ratio between chemical exergy of coal in China and maximum calorific value respectively. The two are usually 35% and 96%.

Exergy efficiency of split air conditioning $[19]$ is:

$$\eta_{ac} = \sum Q_c \left( \frac{T_0}{T_c} - 1 \right) \frac{\tau_{coal}}{\eta_{coal}} \frac{Q_c}{COP_c} \quad (18)$$

Where, $Q_c$, $T_0$, $T_c$ and $COP_c$ are the cooling capacity, ambient temperature, refrigeration temperature and energy efficiency ratio of refrigeration cycle respectively.

The total exergy efficiency of the microgrid $[20]$ is:

$$\eta_{sys} = \frac{\varepsilon_e}{\varepsilon_c} \quad (19)$$

Where, $\varepsilon_e$ and $\varepsilon_c$ denote the total revenue exergy and total payment exergy of the microgrid respectively.

3.2. Constraints

1) Balance constraint of cooling load:
   The cooling capacity of split air conditioners and lithium bromide absorption chillers should meet the cooling load required by users. The balance equation is:
   $$P_{AC} + P_{AR} = P_c \quad (20)$$
   Where, $P_c$ denotes the cooling load required by users.

2) Balance constraint of thermal load:
   The heat supply of the waste heat boiler and the heat storage tank should meet the heat load required by users. The heat generated by the waste heat boiler is first used to supply the heat load demand of users, then the excess heat is transferred to the refrigerator, and finally the excess heat is stored in the heat storage tank. If the excess heat is greater than the maximum capacity of the heat storage tank, it will be discharged into the atmosphere.
   Heat storage model of heat storage tank:
Heat release model of heat storage tank:
\[ P_{\text{HRSG}} + \frac{P_{\text{HST}}}{\mu_{\text{in}}} \geq P_H \] (21)

Where, \( \mu_{\text{in}} \) and \( \mu_{\text{out}} \) denote the heat storage and heat release efficiency of the heat storage tank respectively, and \( P_H \) denotes the heat load required by users.

3) Balance constraint of electric load:
Micro gas turbine, wind turbines, photovoltaic, storage battery and large power grid together provide the electric load required by users. When the electricity generated by the power generation equipment is greater than the user’s demand, the excess heat is stored in the battery. If the power generated by the generating equipment is insufficient, it is necessary to discharge the battery and purchase power from the large power grid.

Electric load balance formula for battery charging:
\[ P_{\text{GT}} + P_W + P_{\text{PV}} + \frac{P_E}{\eta_{\text{in}}} + P_{jh} = P_E \] (23)

Electric load balance equation of battery discharge:
\[ P_{\text{GT}} + P_W + P_{\text{PV}} + P_{\text{E}} \eta_{\text{out}} + P_{jh} = P_E \] (24)

Where, \( \eta_{\text{in}} \) and \( \eta_{\text{out}} \) denote the charging and discharging efficiency of the battery respectively, and \( P_E \) denotes the electric load required by users.

4) Constraint of energy storage device:
Energy storage equipment includes batteries and heat storage tanks, and the capacity constraints are:
\[ \begin{aligned}
\text{SOC}_{\text{min}} &\leq \text{SOC} \leq \text{SOC}_{\text{max}} \\
E_{\text{HST,min}} &\leq E_{\text{HST}} \leq E_{\text{HST,max}}
\end{aligned} \] (25)

Where, \( \text{SOC}_{\text{max}}, \text{SOC}_{\text{min}}, E_{\text{HST}}, \text{max} \) and \( E_{\text{HST}}, \text{min} \) denote the upper and lower limits of capacity of storage battery and heat storage tank respectively.

5) Operating power constraint of each device:
\[ P_{i,\text{min}} \leq P_i \leq P_{i,\text{max}} \] (26)

Where, \( P_{i,\text{max}} \) and \( P_{i,\text{min}} \) denote the upper and lower limits of each device respectively.

6) Constraint of unit ramp rate:
The ramp rate refers to the power that the unit is allowed to increase or decrease in a unit time interval. The ramp rate constraint equation of micro gas turbine is as follows:
\[ -R_{\text{down}} < P_{\text{GT}}(t) - P_{\text{GT}}(t-1) < R_{\text{up}} \] (27)

Where, \( P_{\text{GT}}(t) \) and \( P_{\text{GT}}(t-1) \) denote the power of the micro gas turbine at time \( t \) and time \( (t-1) \) respectively. \( R_{\text{up}} \) and \( R_{\text{down}} \) denote the maximum climbing and descending ramp rate of the gas turbine respectively.

7) Interactive power constraints with large power grid:
The power purchased and sold between the micro grid and the power grid should also be limited within a certain range to prevent excessive fluctuations from affecting the stability of the large power grid. The constraint equation is:
\[ P_{jh,\text{min}} \leq P_{jh} \leq P_{jh,\text{max}} \] (28)

Where, \( P_{jh,\text{min}} \) and \( P_{jh,\text{max}} \) denote the minimum and maximum interactive power allowed between the micro grid and the large power grid respectively.
3.3. Optimization algorithm

Grey Wolf optimization algorithm is a swarm intelligence optimization algorithm proposed by Australian scholar Mirjalili et al in 2014, inspired by the process of cooperative predation by wolves [20-23]. The predation process of gray wolves can be divided into three steps: tracking the prey, surrounding the prey and attacking and preying on the prey. In the process of hunting, gray wolves will cooperate with each other, and a few leading individuals will guide and distribute them, so as to complete the hunting task efficiently.

In the gray wolf optimization algorithm, the position of each gray wolf represents the potential solution of the problem. After the prey is found, wolves will surround it before attacking. In order to simulate this behavior, gray wolves use the following equation to update their position during the encirclements:

\[
D_i(k) = \left| C \cdot X_p(k) - X_i(k) \right|
\]

\[
X_i(k+1) = X_p(k) - A \cdot D_i(k)
\]

(29)

Where, \(X_p(k)\) is the current position of prey, and \(C\) and \(A\) denote the influence coefficients, which can be calculated according to the following equations:

\[
A = 2aR_1 - a
\]

\[
C = 2R_2
\]

(30)

(31)

Where, \(a\) decreases linearly as follows:

\[
a = 2 - \frac{k}{k_{\text{max}}} \times 2
\]

(32)

In the gray wolf population, most individuals act under the guidance of the leading individuals. The grey wolf optimization algorithm also divides the whole population into four levels, but the \(\alpha\), \(\beta\) and \(\delta\) individuals are set as one respectively. In the search process, the three best positions in the population are assigned to \(\alpha\), \(\beta\) and \(\delta\) successively in each iteration, and other individuals update their positions according to these three excellent individuals. The updating principle is defined as:

\[
D_\alpha = \left| C_1 \cdot X_\alpha(k) - X_i(k) \right|
\]

\[
D_\beta = \left| C_1 \cdot X_\beta(k) - X_i(k) \right|
\]

\[
D_\delta = \left| C_1 \cdot X_\delta(k) - X_i(k) \right|
\]

\[
X_1 = X_\alpha(k) - A_1 \cdot D_\alpha
\]

\[
X_2 = X_\beta(k) - A_1 \cdot D_\beta
\]

\[
X_3 = X_\delta(k) - A_1 \cdot D_\delta
\]

\[
X_i(k+1) = \frac{(X_1 + X_2 + X_3)}{3}
\]

(33)

In this paper, the number of gray Wolf individuals searched is 30, and the maximum number of iterations is 200.

4. Example analysis

4.1. Load forecasting

The load of microgrid is mainly borne by micro gas turbine, grid power, storage battery and renewable energy equipment (photovoltaic cell and wind turbine). Since the renewable energy devices output power with maximum predicted power, the power output of photovoltaic cell and wind turbine can be equivalent to the reduction of microgrid load. GWO was used to optimize the 24-hour output power of micro gas turbine, power grid and storage battery, and the rest output can be obtained through calculation. Each dimension coordinate of gray wolf position represents the output of a certain equipment per hour, so the 24-hour output power dimension of three equipment is 72. Fig. 2 shows the predicted output of
photovoltaic cell and wind turbine respectively, as well as the daily load of microgrid before and after the conversion of renewable energy.

![Electric Load Graph](image)

**Figure 2.** Electric load forecasting

After the load forecasting with the equivalent conversion of renewable energy, the cold, heat and power load forecasting of microgrid is shown in Fig. 3

![Cooling and Heating Load Graph](image)

**Figure 3.** Cooling and heating load forecasting

### 4.2. Price parameters

Table 2 and Table 3 respectively list the parameters related to power grid transaction price and pollutant treatment.

**Table 2.** Transaction price with large power grid

| Price (CNY/kWh) | Time                  |
|-----------------|-----------------------|
| **purchase**    | **sale**              | **Time**          |
| 0.71            | 0.65                  | 10:00-14:00       |
|                 |                       | 18:00-20:00       |
| 0.47            | 0.39                  | 7:00-9:00         |
|                 |                       | 15:00-17:00       |
|                 |                       | 21:00-22:00       |
| 0.31            | 0.21                  | 00:00-6:00        |
|                 |                       | 23:00-24:00       |
Table 3. Pollutant emission coefficient and control cost

| Pollutants type | CO₂ | SO₂  | NOx  |
|----------------|-----|------|------|
| Control cost (CNY/kg) | 0.21 | 14.824 | 62.964 |
| Pollutant emission coefficient (g/kWh) | Micro gas turbine | 724 | 0.0036 | 0.2 |
| Power grid | 922 | 2.295 | 3.583 |

4.3. Equipment parameters

Table 4 shows the parameters of each equipment in the microgrid. The upper limit / lower limit of storage battery capacity is 480 / 160 kWh, the initial storage capacity is 160 kWh, and the storage efficiency is 95%. The capacity of the heat storage tank is 140 kwh, with an initial heat storage capacity of 100 kWh, and the heat storage efficiency is 60%. The fuel (natural gas) price of micro gas turbine is: Cgas = 0.175 CNY/kWh. The upper limit of each equipment is the rated power of the equipment.

Table 4. Equipment parameters

| Equipment        | Power limits /(kW) | Maintenance price /(CNY/kWh) |
|------------------|--------------------|------------------------------|
| Micro gas turbine| 100/0              | 0.04                         |
| Battery          | 40/-40             | 0.045                        |
| Photovoltaic cell| 80/0               | 0.01                         |
| Wind turbine     | 80/0               | 0.045                        |
| Power grid       | 150/-150           | 0.012                        |
| Absorption refrigerator| 100/0     | 0.01                         |
| Heat storage tank| 84/-84             | 0.02                         |
| Split air conditioner| 80/0            | 0.03                         |
| Waste heat boiler | 200/0              | 0.025                        |

4.4. Optimization analysis

Scenario 1: optimization aiming at system economy.

Fig. 4 shows the electric power output under the optimization aiming at system economy. It can be seen from the figure that the gas turbine works under practically full load between 11 ~ 14 and 18 ~ 20, which is basically consistent with the peak period of the purchase of power grid. The application of gas turbine in this period can greatly save the cost of electricity. In addition, the gas turbine realizes higher efficiency under high load. The operation of the gas turbine in high load area leads to higher efficiency and less cost.

![Figure 4. Electric power output in scenario 1](image)

Fig. 5 shows the cold and hot power output under the optimization aiming at system economy. During the period when the gas turbine is running at a certain power, the cooling and heating loads are basically...
borne by the lithium bromide absorption refrigerator and the waste heat boiler respectively. If the heating of the waste heat boiler exceeds the demand of the heating load, the heat storage tank will store the heat (that is, the heating power is negative). The lithium bromide absorption chiller and waste heat boiler cannot meet the cooling and heating load with low power grid price and power output of gas turbine, so the split air conditioner and heat storage tank are used to compensate.

![Figure 5](image)

**Figure 5.** Cooling and heating power in scenario 1

**Scenario 2:** optimization aiming at comprehensive optimization index.

Fig. 6 shows the electric power output under optimization aiming at comprehensive index. It can be seen from the figure that higher efficiency occurs with the gas turbine under high load. Due to the higher energy value of electric energy, if the cost optimization allows, the gas turbine is supposed to operate under high load (high efficiency) area as far as possible, and the transaction with the power grid is mainly power sales. The storage battery basically works in the state of power storage from 1 to 15 hours. When the gas turbine supplies insufficient power during the peak power consumption period from 17 to 20 hours, the storage battery starts to discharge.

![Figure 6](image)

**Figure 6.** Electric power output in scenario 2

**Table 5.** Comparison of two different scenes

| Scenario | Objective function | Cost (CNY) | Emission (kg) | Comprehensive optimization index | Exergy efficiency |
|----------|--------------------|------------|---------------|----------------------------------|-------------------|
| 1        | M1                 | 1445.4     | 406.91        | 3.0587                           | 50.836%           |
| 2        | M1+M2              | 1603.6     | 415.86        | 2.7055                           | 58.284%           |
| Difference |                  | -10.945%   | -2.1995%      | 11.547%                          | 14.651%           |
Fig. 7 shows the cold and hot power output under the optimization aiming at comprehensive index. As can be seen from the figure, due to the high load output of gas turbines, the cooling and heating loads are mainly supplied by lithium bromide absorption refrigerator and waste heat boiler in most periods. Only when gas turbine outputs less or peak load can they be compensated by split air conditioner and heat storage tank. During the period of 3-24 hours, a large amount of overflow heat is accumulated in the heat storage tank, which avoids the heat waste of gas turbine under too high load and can be advantage for additional productions.

Tab. 5 shows the optimization results in two different scenarios. Scenario 1 takes M1 as the objective function and regards the control of operation cost and emission control cost as the main purpose; while scenario 2 takes M1 + M2 as the objective function, which not only needs to ensure the cost control, but also needs to consider the comprehensive optimization of energy efficiency based on energy value.

As can be seen from the table, compared with scenario 1, scenario 2 increases the cost by 10.945%, but the comprehensive optimization index and efficiency are improved by 11.547% and 14.651% respectively. The slight increase in the cost of scenario 2 is expected, while the slight increase in emissions is due to the long-term operation of the gas turbine under high load in scenario 2. The power generation exceeds the microgrid power load, and its cumulative power sales is 4.16 times of that in scenario 1. As the emission per unit of electricity production by microgrid production is significantly lower than that of power grid, the sales of electricity to power grid can also reduce emissions in disguised form. Due to the limitation of the algorithm, this part of the calculation is not included in the scenario emissions, but even so, the emission of scenario 2 is only about 2% increased, so it can be inferred that the introduction of the objective function of scenario 2 plays a macro inhibitory effect on emissions.

In addition, the improvement of the comprehensive optimization index shows that the introduction of the objective function in scenario 2 is helpful to optimize the energy efficiency performance of the system. Considering the different energy values of cold, heat and electricity to microgrid, it is similar to the exergy analysis. Therefore, the comprehensive optimization index is verified through the comparison of exergy efficiency, and the verification results are in line with the expectations. Because the comprehensive optimization index considers the cost, and the cost is increased compared with scenario 1, the difference of the comprehensive optimization index should be lower than that of the efficiency.

5. Conclusions
Focus on the operation strategy of CCHP multi energy complementary microgrid, this paper puts forward the evaluation criteria of comprehensive economic benefits and energy value energy efficiency, constructs the operation strategy optimization model with comprehensive cost and energy efficiency based on energy value as the target, applying the classical GWO for solution. Combined with the optimization results and analysis, the following conclusions are obtained.
1) The introduction of energy efficiency index based on energy value can effectively lead the optimization to the direction of exergy efficiency improvement, and compared with the exergy efficiency which needs real-time temperature of each operating point, the index proposed can greatly reduce the amount of data required for optimization.

2) The results show that the cost, emission and energy efficiency of microgrid operation can be effectively adjusted by reasonably distributing the load of each equipment in microgrid.

3) There are constraints between emission reduction and the improvement of energy efficiency index based on energy value. However, from a macro point of view, micro grid electricity sales have a restraining effect on emissions.

4) The determination of energy value parameters and the measurement of operating point parameters can be flexibly adjusted and improved in practical work. The selection and development of intelligent algorithm is an important way to further improve the optimization range.

Acknowledgments
This paper is supported by the State Grid Tianjin electric power company's science and technology project (KJ19-1-17) and Tianjin key R & D program's science and technology support key project (18YFZCGX00570).

References
[1] Wu Fubao, Shi Ruxin, Sang Bingyu, Guo Xu, Zhang Shuzhi, Zhang Xiongwen. Optimal configuration of an integrated energy system considering energy costs and pollution emissions. Thermal power generation, pp. 1-9 August 2020.

[2] Kang Chongqing, Wang Yi, Zhang Jing, Wang Yongzhen, Gao Feng, Liu Yi. National Energy Internet Development Index System and Trend Analysis. Telecommunications Science, 2019, vol. 35, pp.2-14.

[3] Zhou Pengcheng, Wu Nannan, Zeng Ming. Comprehensive energy system modeling, simulation, planning, scheduling and benefit evaluation overview and prospects. Shandong Electric Power Technology, 2018, vol.45, pp.1-5.

[4] Gong Xundong, Xue Mingfeng, Mao Xiaobo. Research on the energy efficiency evaluation system of the integrated energy system in the park. Mechanical and Electrical Information, 2020, pp.100-101.

[5] Zhou Huan, Huang Longqiong, Wu Renjian, He Xianyu, Yuan Qitao, He Guanguyu. Comprehensive energy system value evaluation method based on green exergy economy. Automation of Electric Power Systems, 2020, vol. 44, pp.36-43.

[6] Guo Yanfei, Wu Qiang, Cheng Lin, Huang He, Gao Song. Energy efficiency analysis model of integrated energy system based on exergy efficiency. Renewable Energy, 2017, vol. 35, pp.1387-1394.

[7] Liu Xiaou, Ge Shaoyun. Energy efficiency definition of regional integrated energy system and its correlation analysis. Automation of Electric Power Systems, 2020, vol. 44, pp.8-19.

[8] Tian Liting, Cheng Lin, Li Rong, Sun Shumin, Shi Chao, Gao Wenzhong. Multi-scene energy efficiency evaluation method of park integrated energy system based on weighted directed graph. Proceedings of the Chinese Society of Electrical Engineering, 2019, vol. 39, pp.6471-6483.

[9] Wu Jingkai, Mu Yunfei, Jia Hongjie, Tian Zhe, Niu Jide, Xu Jing. Energy efficiency index based on energy value of multi-energy cooperative park. Automation of Electric Power Systems, 2019, vol. 43, pp.54-63.

[10] Liu Dunnan, Zhang Tingting, Li Hua, Qi Caijuan, Ma Yanxia, Zhang Weiqi, Xu Xiaofeng. Comprehensive energy system planning model for ubiquitous power Internet of Things. Power Generation Technology, 2020, vol. 41, pp.50-55.

[11] Xu Zhou, Sun Yonghui, Xie Dongliang, Wang Jianxi, Zhong Yongjie. Optimal configuration of regional integrated energy system energy storage considering electric/heat flexible load.
Automation of Electric Power Systems, 2020, vol. 44, pp.53-63.

[12] Wang Jun, Gu Wei, Lu Shuai, Zhang Chenglong, Wang Zhihe, Tang Yiyuan. Collaborative planning of multiregional integrated energy system based on heat network model. Power system automation, 2016, vol. 40, pp.17-24

[13] Wang Weiliang, Wang Dan, Jia Hongjie, Chen Zumayu, Guo Bingqing, Zhou Haiming, Fan Menghua. Summarization of steady-state analysis of typical regional integrated energy systems under the background of energy internet. Proceedings of the Chinese Society of Electrical Engineering, 2016, vol. 36, pp.3292-3306.

[14] Sun Qiang, Xie Dian, Nie Qingyun, Zhang Lihui, Chen Qian, Chen Jiejun. Research on Economic Optimal Dispatching of Park Integrated Energy System Including Electricity, Heating, Cooling and Gas Load. China Electric Power, 2020, vol. 53, pp.79-88.

[15] Li Na, Zhou Xichao, Wang Bing, Cong Lin, Jin Tai, Pan Chongchao. Summarization and prospect of integrated energy system optimization model. Shanghai Energy Conservation, 2020, pp.543-548.

[16] Jiang Shibai, Yang Lina, Liu Quan, Yang Liu. Research on comprehensive energy optimization of energy interconnected parks considering flexible load. Electrical measurement and instrumentation, pp.1-7, 2020.

[17] He Binbin, Duan Liqiang, Yang Yongping. A Study of New Evaluation Criteria for Combined Cooling-heating-power Cogeneration Systems. Thermal energy and power engineering, 2009, vol. 24, pp.592-596+680.

[18] Lv Jing, WANG Zhongzheng. A Review of evaluation Criteria for thermoelectric and cooling triple generation. Energy Conservation, 1998, pp.3-5.

[19] Zhou Yan. Research on the building heating and cooling system with exergy analysis. Hunan University, 2013.

[20] Liu Xiaodan. Optimization of Cooling Heat and Power Cogeneration System. Dalian University of Technology, 2007.

[21] Xu Xiandong, Jia Hongjie, Jin Xiaolong, Yu Xiaodan, Mu Yunfei. Research on electric/gas/heat mixed power flow algorithm of regional integrated energy system. Proceedings of the Chinese Society for Electrical Engineering, 2015, vol. 35, pp.3634-3642.

[22] Zhang Zhenzhong, Wang Pengxiao, Yang Xinhua. Coordinated control strategy for hybrid energy storage system of oil rig microgrid. Electrical Drive, 2020, vol. 50, pp.82-87.

[23] Mirjalili S, Mirjalili S M, and Lewis A. Grey wolf optimizer. Adv. Eng. Software, 2014, vol. 69, pp.46-61.