Optimal planning of multiple energy flows for microgrid with renewable energy sources

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Abstract. With the gradual depletion of fossil energy and the increasingly serious environmental pollution problems, the combined cooling heating and power (CCHP) microgrid with renewable energy sources which with high energy efficiency, less pollution emissions and flexible operation control have become research hotspots. In this paper, the optimal planning of CCHP microgrid with renewable energy sources is studied, and the mathematical model of optimal configuration of the system is established with the minimum total cost as the objective function, then the separated production (SP) system is used as a reference to compare the optimal configuration results of the CCHP microgrid system under the two modes of following the thermal load (FTL) and following the electric load (FEL). After that, the optimization configuration results of the two schemes of whether the CCHP microgrid system is equipped with the thermal storage tank (TST) in the same operating mode are compared. The simulation result shows that the system with TST under the FEL mode is more economical, energy-saving and environmentally friendly. Finally, the effects of natural gas price and electricity price on the optimal configuration results of the system in two operating modes are studied.

1. Introduction
The gradual depletion of the traditional fossil fuels and the increasing attention to environmental pollution issues have led to the rapid development of the combined cooling heating and power (CCHP) microgrid with renewable energy sources which can achieve energy cascade utilization and integrate renewable energy better [1]. As we all know, a reasonable planning is an important prerequisite and guarantee for stable and efficient operation of the CCHP microgrid system. The economic benefits, the environmental benefits and the energy utilization efficiency of CCHP microgrid will be greatly affected by its planning and design [2]. A large number of research on CCHP system planning has been carried out until now.

Three evaluation indicators including the primary energy saving, the CO₂ emission reduction and the annual total cost saving were established to optimize the equipment capacity and operation strategy of CCHP system in the literatures [3,4]. In the literature [5], the intermittent and random nature of renewable energy is considered, and then the improved bacterial foraging algorithm is used to obtain the optimal configuration of the microgrid under island operation with wind/solar/storage based on the reliability constraints of different users. However, the CCHP microgrid system interacts with the grid to provide reserve, peak shaving and demand response services with the ability to integrate renewable energy better. The impact of natural gas price, electricity price and distributed energy investment on the
optimal configuration of CCHP microgrid is analyzed in the literature [6]. In the literature [7], the optimal configuration, planning, sizing and operation of the hybrid renewable energy microgrid are studied, and four different microgrid structures are optimally designed. A two-stage optimal planning model for CCHP microgrid is proposed in the literature [8], which optimizes the equipment type and capacity and solves the optimal dispatch problem. In the literature [9], a model to find the optimal capacity and operation strategy of a user-oriented CCHP, auxiliary boiler, heat and electrical storage unit is proposed from the comprehensive perspective of power and natural gas network.

Based on the above existing research results, in this paper, the capacity of photovoltaic cell (PV), battery (BT), gas turbine (GT), gas boiler (GB), thermal storage tank (TST), absorption chiller (AC) and electric chiller (EC) in CCHP microgrid system with renewable energy sources under different operating strategies is optimally configured, and the impact of natural gas price and electricity price on the optimal configuration of the system is analyzed.

2. Model of components

2.1. PV
The actual output power of PV is related to the solar irradiance and the ambient temperature. It can be derived from the test parameters in a standard test environment:

\[ P_{PV}(t) = f_{PV} \cdot P_{STC} \cdot \frac{G(t)}{G_{STC}} \cdot (1 + k(T(t) - T_{STC})) \]  

where \( P_{PV}(t) \) is the actual output power of PV during the \( t \) period, \( f_{PV} \) is the output power derating factor, generally \( f_{PV} \) is set to 0.95, \( P_{STC} \), \( G_{STC} \) and \( T_{STC} \) are the maximum output power, irradiance, and the ambient temperature at standard test condition. \( k \) is a coefficient that relates power output with the temperature, \( T(t) \) is the ambient temperature during the \( t \) period.

2.2. GT
GT which can generate electricity and heat simultaneously plays a critical role in CCHP microgrid system. The electrical efficiency, thermal efficiency, and the pollutant gas emission characteristics of GT are decided by its capacity and its load factor. A model based on the electrical efficiency and thermal efficiency of GT is established in this paper:

\[ \eta_{GT}^E = \left[ a \times \left( \frac{P_{GT}}{P_{cap,GT}} \right)^b + c \times \frac{P_{GT}}{P_{cap,GT}} + d \right] \times \eta_{GT}^{nom,E} \]  

\[ Q_{GT}^H = P_{GT} \times \eta_{GT}^{nom,H} \times \eta_r \]  

\[ F_{GT} = \frac{P_{GT}}{\eta_{GT}^E} \]  

where \( \eta_{GT}^{nom,E} \) and \( \eta_{GT}^{nom,H} \) are the nominal electrical efficiency and thermal efficiency of GT, respectively, which related to the rated capacity \( P_{cap,GT} \) of GT, and the expression is detailed in the literature [10]; \( \eta_{GT}^E \) is actual electrical efficiency, in the formula (2), \( a=0.8264 \), \( b=-2.334 \), \( c=2.329 \), \( d=0.1797 \); \( P_{GT} \) is the actual output power of GT; \( Q_{GT}^H \) is the output heat of GT; \( \eta_r \) is the waste heat recovery rate; \( F_{GT} \) is fuel consumption.

2.3. AC
AC is fed by thermal energy and produces cooling energy, and the relationship can be expressed as:

\[ Q_{AC} = \frac{COP_{AC}}{\eta_{AC}} \]  

where \( COP_{AC} \) is the cooling coefficient of performance; \( Q_{AC} \) is the cooling output; \( \eta_{AC} \) is the actual electrical efficiency. The parameter \( COP_{AC} \) and \( \eta_{AC} \) can be obtained from the experiment.
where \( Q_{h,AC} \) and \( Q_{c,AC} \) are the heat consumed and the cool produced by AC. \( COP_{AC} \) is the coefficient of performance of AC.

2.4. EC
EC is fed by electricity and produces cooling energy, and the relationship can be expressed as:

\[
Q_{EC} = COP_{EC} \cdot P_{EC}
\]

where \( Q_{EC} \) and \( P_{EC} \) are the electricity consumed and the cool produced by EC. \( COP_{EC} \) is the coefficient of performance of EC.

2.5. GB
GB is fed by natural gas and produces thermal energy with a certain efficiency, which can be expressed as:

\[
Q_{GB} = \eta_{GB} \cdot F_{GB}
\]

where \( F_{GB} \) and \( Q_{GB} \) are the natural gas consumed and the heat produced by GB. \( \eta_{GB} \) is the efficiency of GB.

The model established in this paper selects BT as the electricity storage device and TST as the heat storage device. The model is shown in the literature [11].

3. The operation strategy of the CCHP microgrid
In this paper, the equipment capacity of the CCHP microgrid system is optimized for the two modes of operation: following the thermal load (FTL) and following the electric load (FEL), and the separated production (SP) system is used as a reference.

When CCHP microgrid system is operating at FTL mode, GT adjusts its actual electrical efficiency according to the heat load demand in the CCHP microgrid system, if GT could not meet the heat load demand, the shortfall is supplemented by TST and GB. When the power output of PV and GT is greater than the electric load demand, the excess power is stored by BT or sold to the grid; when the electric load demand cannot be satisfied, the shortfall would be purchased from the grid or BT discharge to meet; if AC could not meet the cooling load demand, and the shortage is supplemented by EC.

When CCHP microgrid system is operating at FEL mode, GT adjusts its actual electrical efficiency according to the electric load demand in the CCHP microgrid system, if PV and GT could not meet the electric load demand, the shortfall is supplemented by BT or purchased from the grid; if GT could not meet the heat load demand, the shortfall is supplemented by TST and GB; if AC could not meet the cooling load demand, and the shortage is supplemented by EC.

SP system consists of EC and GB, the electrical demand in the system is satisfied by the grid, the cooling load demand is all satisfied by EC, and GB meets all the heat load demand [8].

4. The optimal planning model of the CCHP microgrid

4.1. Objective function
The total annualized cost is adopted as the objective function to be minimized, which including the initial investment costs of all equipment \( C_{inf} \), maintenance costs during operation \( C_{om} \), the costs of purchasing and selling electricity to the grid \( C_{grid} \), and natural gas costs \( C_f \):

\[
\min c = C_{inf} + C_{om} + C_{grid} + C_f
\]

The initial investment costs in the system can be expressed as:

\[
C_{inf} = \frac{r(1+r)^n}{(1+r)^n-1} \cdot (C_{GT} + P_{cap, PV} \cdot C_{inf, PV} + P_{cap, BT} \cdot C_{inf, BT} + Q_{cap, TST} \cdot C_{inf, TST} + Q_{cap, GB} \cdot C_{inf, GB} + Q_{cap, AC} \cdot C_{inf, AC} + Q_{cap, EC} \cdot C_{inf, EC})
\]
where $GTC$ is the initial investment cost of GT, which is closely related to the rated capacity of GT, and its relationship is as shown in formula (10). The subscript $\text{cap}$ is the rated capacity of the equipment; $C_{\text{inf}}$ is the initial investment cost per unit of equipment; $n$ is service life of equipment, and it is set to 20; $r$ is the interest rate, and it is set to 6.7%.

\[
C_{GT} = \begin{cases} 
(0.824 \times P_{\text{cap,GT}} + 6713.6) \times P_{\text{cap,GT}} & P_{\text{cap,GT}} < 4000kW \\
(-0.168 \times P_{\text{cap,GT}} + 4113.9) \times P_{\text{cap,GT}} & P_{\text{cap,GT}} \geq 4000kW
\end{cases}
\]  

(10)

$C_{\text{om}}$ can be calculated as follows:

\[
C_{\text{om}} = \sum_{j=1}^{N} \sum_{t=1}^{T} \left( C_{\text{om,GT}} \cdot P_{\text{GT,}j} + C_{\text{om,GB}} \cdot Q_{\text{GB,}j} + C_{\text{om,TST}} \cdot Q_{\text{TST,}j} + C_{\text{om,AC}} \cdot Q_{\text{AC,}j} \right)
\]

where $j$ and $t$ are the indexes for the day and the time period; $N$ and $T$ are the total number of days and the total number of time periods; $C_{\text{om}}$ is the unit operation maintenance cost of the equipment.

$C_{\text{grid}}$ can be expressed as follows:

\[
C_{\text{grid}} = \sum_{j=1}^{N} \sum_{t=1}^{T} \left( C_{i} \cdot P_{b,} - C_{i} \cdot P_{s} \right)
\]

(12)

where $C_{b}$ and $C_{s}$ are the price of purchasing and selling electricity to the grid during $t$ period; $P_{b,}^t$ and $P_{s,}^t$ are the purchase and sale of electricity by CCHP microgrid to the grid.

$C_{f}$ can be defined as follows:

\[
C_{f} = \sum_{j=1}^{N} \sum_{t=1}^{T} \left( F_{\text{GT,}j} + F_{\text{GB,}j} \right) \cdot c_{f}
\]

(13)

where $F_{\text{GT,}j}$ and $F_{\text{GB,}j}$ are the amount of natural gas required for GT and GB; $c_{f}$ is the natural gas price, and it is set to 0.253 yuan/kWh.

4.2. Constraints

4.2.1. The electrical energy balance constraint.

\[
P_{\text{PV,}j} + P_{\text{GT,}j} + P_{\text{BT,}j} + P_{\text{EC,}j} + P_{\text{AC,}j} + P_{\text{ac,}p} + P_{\text{ac,}s}
\]

(14)

4.2.2. The heat balance constraint.

\[
Q_{\text{GT,}j} + Q_{\text{GB,}j} + Q_{\text{TST,}j} \geq Q_{\text{AC,}j} + Q_{\text{es,}j}
\]

(15)

4.2.3. The cooling load balance constraint.

\[
Q_{\text{AC,}j} + Q_{\text{es,}j} \geq Q_{\text{c,}j}
\]

(16)

4.2.4. Constraints on the performance of the energy storage device.

\[
P_{\text{ch,}j} \leq P_{\text{ch,}j} \leq P_{\text{max,}j}
\]

(17)

\[
P_{\text{disch,}j} \leq P_{\text{disch,}j} \leq P_{\text{max,}j}
\]

(18)

\[
E_{\text{ES}} \leq E_{\text{ES,}j} \leq E_{\text{ES,}j}^\text{max}
\]

(19)

where $P_{\text{ch,}j}$ and $P_{\text{ch,}j}$ are the maximal and minimal charge limits in each period $t$; $P_{\text{max,}j}$ and $P_{\text{min,}j}$ are the maximal and minimal discharge limits in each period $t$; $E_{\text{ES}}^\text{max}$ and $E_{\text{ES}}^\text{min}$ are the maximum and minimum of the current energy of the energy storage device.
4.2.5. The facility capacity constraints.

\[ Q_{j}^{\min} \leq Q_{j}^{t} \leq Q_{j}^{\max} \]
\[ P_{i}^{\min} \leq P_{i}^{t} \leq P_{i}^{\max} \]  

(20) \hspace{1cm} (21)

where \( Q_{j}^{\max} \) and \( Q_{j}^{\min} \) are the upper bound and the lower bound of output cooling and heating power; \( P_{i}^{\max} \) and \( P_{i}^{\min} \) are the upper bound and the lower bound of output electricity.

4.3. Evaluation indicators

4.3.1. The Primary Energy Saving (PES). PES is defined as the ratio of the difference between the primary energy consumed by the CCHP system and the SP system and the primary energy consumption of the SP system at the same energy output.

\[ PES = \frac{(P_b \cdot \gamma_e + F_{GB} \cdot \gamma_g) - (P_b \cdot \gamma_e + (F_{GT} + F_{GB}) \cdot \gamma_g)}{P_b \cdot \gamma_e + F_{GB} \cdot \gamma_g} \]  

(22)

where \( P_b, F_{GT} \) and \( F_{GB} \) are the purchase of electricity, the natural gas consumption of GT and GB; \( \gamma_e \) and \( \gamma_g \) respectively represent the primary energy conversion rate of the grid and the natural gas primary energy conversion rate.

4.3.2. The Carbon Dioxide Emission Reduction (CDER). CDER is defined as the ratio of the difference between the CO2 emissions of the SP system and the CO2 emissions of the CCHP system and the CO2 emissions of the SP system.

\[ CDER = \frac{(P_b \cdot \beta_e + F_{GB} \cdot \beta_{GB}) - (P_b \cdot \beta_e + F_{GT} \cdot \beta_{GT} + F_{GB} \cdot \beta_{GB})}{P_b \cdot \beta_e + F_{GB} \cdot \beta_{GB}} \]  

(23)

where \( \beta_e, \beta_{GT} \) and \( \beta_{GB} \) are the CO2 emission conversion factor for the purchase of electricity, the natural gas required for GT and GB, respectively.

5. Case study

5.1. Basic information and data

| Table 1. Parameters of DGs. |
|----------------------------|
| Unit capacity investment | Unit operation and maintenance cost |
| cost (yuan/kW)            | (yuan/kWh)                      |
| PV                        | 23500                           | 0                                |
| GT formula (10)           | 2600                            | 0.025                            |
| BT                        | 200                             | 0.0016                           |
| TST                       | 970                             | 0.0016                           |
| GB                        | 300                             | 0.0027                           |
| AC                        | 1200                            | 0.0024                           |
| EC                        | 970                             | 0.0016                           |

The example in this paper is based on a typical hotel building in Beijing, the typical daily load including cooling, heat and electrical load data is selected for the simulation analysis of the case. Figures 1-3 show the typical daily load curves for summer, transition and winter, respectively. The electricity price is shown in Figure 4. According to the above established model and the principle of particle swarm algorithm, five schemes are developed including SP system, FTL operation mode with TST, FTL operation mode without TST, TEL operation mode with TST, and FEL operation mode.
without TST for optimal configuration of the system. The capacity of PV, GT, BT, TST, GB, AC and EC are made as optimal variables. Then write the optimization program in MATLAB to get the optimal configuration results. The parameter settings of the optimized configuration model are shown in Table 1.

Table 2. Configuration results of five schemes.

| Operating mode | FTL With TST | FEL With TST | FEL Without TST | SP Without TST |
|----------------|-------------|-------------|----------------|---------------|
| Equipment capacity (kW) | | | | |
| PV | 3102 | 2853 | 1419 | 1244 | 0 |
| GT | 759 | 900 | 1030 | 1150 | 0 |
| GB | 2518 | 2255 | 2311 | 2133 | 4108 |
| EC | 526 | 269 | 260 | 351 | 3714 |
| BT | 2402 | 3518 | 6114 | 4603 | 0 |
| TST | 4121 | 0 | 18803 | 0 | 0 |
| AC | 3190 | 3445 | 3454 | 3363 | 0 |
| Cost (yuan) Initial investment costs | 8269800 | 7988400 | 5913400 | 4872800 | 445800 |
| Operation and maintenance costs | 338800 | 368400 | 241430 | 241400 | 142000 |
| Purchased and sold of electricity | -309700 | -508800 | 601100 | 410800 | 19187400 |
| Purchased natural gas | 8700400 | 9440600 | 9000700 | 10440000 | 3039800 |
| Total costs | 16998000 | 1728900 | 1575300 | 15965000 | 22815000 |
| PES | 27.95% | 23.93% | 28.05% | 19.15% | --- |
| CDER | 39.70% | 36.80% | 40.72% | 33.84% | --- |

5.2. Result and analysis

Table 2 shows the configuration results of the five schemes, as shown in this table, the total annual cost of the CCHP microgrid system in both FTL and TEL modes is lower than that of the SP system, and its PES and CDER are both greater than 0, indicating that the energy saving and environmental protection of the CCHP microgrid system are superior to the SP system. Compare the configuration results of the two schemes in the two operating modes: In the FTL and FEL operating modes, configuring TST in the system can effectively improve the economic, energy-saving and environmental protection of the system. At the same time, compared with the FTL and FEL operating modes, the total annual cost of system with the TST in the FEL operating mode is lower, and the PES and CDER are better than that in the system with TST under the FTL operating mode. All in all, the example system with TST operation in FEL mode is more economical, energy efficient and environmentally friendly.

Figure 1. Typical daily load curve in summer.

Figure 2. Typical daily load curve in the transition season.
5.3. Correlation factor analysis

5.3.1. Natural gas price. The CCHP microgrid system was optimally configured by setting different natural gas prices in FTL and FEL modes, and its impact on the optimal configuration of CCHP microgrid system was analysed.

Figure 3. Typical daily load curve in winter.

Figure 4. Time-of-use electricity price.

Figure 5. The optimal configuration capacity of each device under different natural gas price in FTL.

Figure 6. The annual total cost of the system under different natural gas price in FTL.

Figure 7. The optimal configuration capacity of each device under different natural gas price in FEL.

Figure 8. The annual total cost of the system under different natural gas price in FEL.
The optimal configuration capacity of each device in the system and the annual total cost of the system under different natural gas price are shown in Figure 5, Figure 6, Figure 7 and Figure 8. It can be seen that the change in natural gas price has similar effects on the equipment capacity configuration and the total annual cost of system in the two operating modes. When the natural gas price increases, the GT optimal configuration capacity decreases, and its waste heat recovery and output electric power decrease, resulting in an increase in the optimal configuration capacity of GB and PV.

5.3.2. Electricity price. The purchase price of electricity was increased by 10%, 20%, 30%, 40%, and 50%, respectively, and the impact on the optimal configuration results of the system under FTL and FEL operating modes was analysed.

The optimal configuration capacity of each equipment and total annual cost in the two operating modes when electricity price changes are shown in Figure 9, Figure 10, Figure 11, Figure 12. In the FTL operation mode, the increase of the electricity price leads to an increase in the total annual cost of the system, EC optimal configuration capacity is reduced, and its output cooling energy is reduced, so that the AC optimal configuration capacity is increased, and the required thermal power is increased which make the optimal configuration capacity of GT increase.
6. Conclusions
This paper mainly studies the optimal planning of CCHP microgrid with renewable energy sources, and the specific model of each micro-source is established. By comparing the optimal configuration capacity of each device in the system under the two operating modes of FTL and FEL, and optimal configuration results when the system without and with TST in the same operation mode, it is concluded that the system configuration TST in the FEL mode is more economical, energy-saving and environmentally friendly. In two modes of operation, both the natural gas price and electricity price affect the optimal configuration of the equipment capacity in the system, and the increase in natural gas prices and the reduction in electricity prices all weaken the advantages of the CCHP microgrid system.

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