Initiative Optimization Operation Strategy and Multi-objective Energy Management Method for Combined Cooling Heating and Power

Feng Zhao, Chenghui Zhang, and Bo Sun

***Abstract*—This paper proposed an initiative optimization operation strategy and multi-objective energy management method for combined cooling heating and power (CCHP) with storage systems. Initially, the initiative optimization operation strategy of CCHP system in the cooling season, the heating season and the transition season was formulated. The energy management of CCHP system was optimized by the multi-objective optimization model with maximum daily energy efficiency, minimum daily carbon emissions and minimum daily operation cost based on the proposed initiative optimization operation strategy. Furthermore, the pareto optimal solution set was solved by using the niche particle swarm multi-objective optimization algorithm. Ultimately, the most satisfactory energy management scheme was obtained by using the technique for order preference by similarity to ideal solution(TOPSIS) method. A case study of CCHP system used in a hospital in the north of China validated the effectiveness of this method. The results showed that the satisfactory energy management scheme of CCHP system was obtained based on this initiative optimization operation strategy and multi-objective energy management method. The CCHP system has achieved better energy efficiency, environmental protection and economic benefits.**

***Index Terms*—Multi-objective optimization, energy management, initiative optimization, distributed energy sources, combined cooling heating and power (CCHP), operation strategy.**

I. INTRODUCTION

ENERGY shortage, environmental pollution and climate change are important factors that restrict the sustainable development of the world economy and society. Therefore, energy and environmental issues have become the major strategic issues in many countries with high attention. Combined cooling heating and power (CCHP) is an advanced and highly efficient energy technology based on the concept of temperature counterparts and cascade utilization. CCHP can not only achieve energy cascade utilization and improve energy efficiency, but also show great advantages in reducing CO_2 and $PM_{2.5}$ emissions, which has better economic, environmental and social benefits. CCHP has been an important development trend of future energy technology, and it has been a research focus for scholars of many countries.

The operation strategy and energy management method play a key role in improving the energy utilization ratio and the economic and environmental benefits of CCHP system. Many scholars have obtained some results by using different intelligent optimization methods to optimize the energy management and the operation of CCHP system. A detailed mixed integer linear program (MILP) optimization model for combined cooling, heating and power system operation planning was presented by Bischi et al.[1]. Jing et al.[2] introduced a multi-objective optimization design and operation strategy analysis of a solar combined cooling heating and power system. Wang et al.[3] proposed a general modeling method for optimal dispatch of combined cooling, heating and power microgrid. Zhou et al.[4−5] introduced a multi-objective optimization model for low carbon scheduling and energy saving scheduling of CCHP system respectively. A multi-objective optimization design and operation strategy analysis of building cooling heating and power (BCHP) system based on life cycle assessment was presented by Jing et al.[6]. Wang et al.[7] proposed a life cycle assessment optimization of solar-assisted hybrid CCHP system. The operation and dispatch of CCHP system was optimized by using linear programming, nonlinear programming and dynamic programming method respectively in [8−11]. An environmental economic dispatch considering equal emission performance coefficient for CCHP was applied in [12]. A probability constrained multi-objective optimization model for CCHP system operation decision support was proposed in [13]. Fang et al.[14] introduced a novel optimal operational strategy for the CCHP System based on two operating modes. An improved operation strategy of combined cooling heating and power system following electrical load was introduced in [15]. A new operation strategy for CCHP systems with hybrid chillers was proposed in [16]. A novel operation strategy for CCHP systems based on minimum distance was presented in [17]. Wu et al.[18] proposed a multi-objective optimal operation strategy study of micro-CCHP system. However, the operation characteristics of CCHP system and the load characteristics of heat, cooling and electricity load were not considered in the

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operation strategy and energy management of CCHP system in [1−18]. Simultaneously, CCHP system with the heating storage system and cooling storage system were not considered in [1−18].

As is known to all, the ratio of heat (cooling) load power to electrical load power of buildings is random, however the ratio of heat (cooling) energy power to electrical energy power generated by CCHP system is relatively fixed, therefore the energy generated by CCHP system and the loads of building have a natural mismatch. Meanwhile, energy storage system is an important part of CCHP system, it has many advantages such as ability of peak load shifting. Consequently, a CCHP with the heating storage system and the cooling storage system is designed. The initiative optimization operation strategy of CCHP system in the cooling season, the heating season and the transition season is formulated based on the load rate of natural gas engine generator, the ratio of heat (cooling) load power to electrical load power of buildings and the ratio of heat (cooling) energy power to electrical energy power of CCHP system. On the basis of this initiative optimization operation strategy, the energy management of the combined cooling heating and power system is optimized by the multi-objective optimization model with maximum daily energy efficiency, minimum daily carbon emissions and minimum daily operation cost. Furthermore, the Pareto optimal solution set is solved by using the niche particle swarm multi-objective optimization algorithm. Finally, the most satisfactory energy management scheme is obtained by using the technique for order preference by similarity to ideal solution (TOPSIS) method. The diagrams of initiative optimization operation strategy and multi-objective energy management method for CCHP system are shown in Fig. 1.

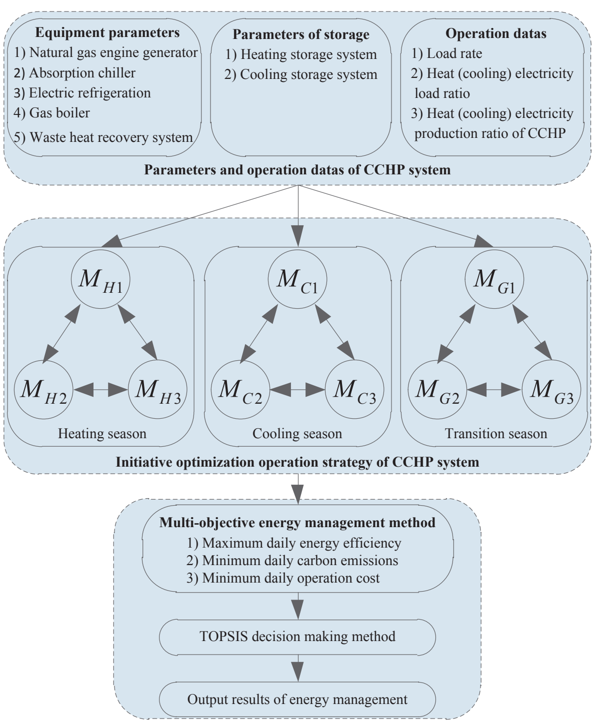

Fig. 1. Diagrams of initiative optimization operation strategy and multi-objective energy management method for CCHP system.

II. CCHP SYSTEM

The system diagram of the CCHP system with the heating storage system and the cooling storage system is shown in Fig. 2. It mainly includes natural gas engine generator, gas boilers, waste heat recovery system, absorption chiller, electric refrigeration, heating storage system, cooling storage system and other devices. Operation principles of this CCHP system are as follows: natural gas engine generator provides electricity for electrical load of the user, if the electricity generated by CCHP system exceeds the electrical load, CCHP system will sell the excess electricity to the grid. Otherwise, CCHP system will buy electricity from the grid. High temperature flue gas and jacket water waste heat can be recycled by the waste heat recovery system, this waste heat can be transported to the absorption chiller and heat exchangers satisfy the user's cooling and heat load demand. If the cooling energy produced by the absorption chiller cannot meet cooling load demand of the user, then the electric refrigerator or the cooling storage system will provide the cooling energy. Otherwise, the excess cooling energy will be stored in the cooling storage system. If the heat energy produced by the waste heat recovery system cannot satisfy heat load of the user, then the gas boilers or the heating storage system provide the heat energy. Otherwise, the excess heat energy will be stored in the heating storage system.

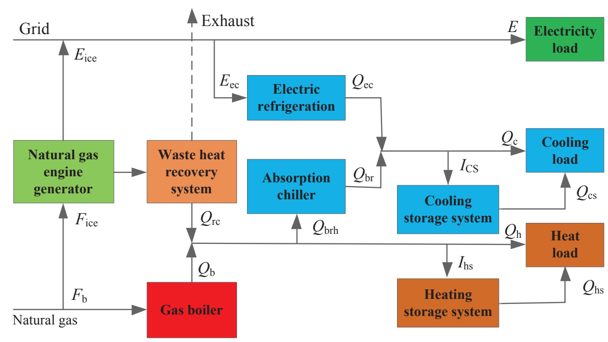

Fig. 2. Schematic of CCHP system with storage equipment.

A. Natural Gas Engine Generator

Natural gas engine generator has the advantages of mature technology, high electrical efficiency, excellent performance and better part load characteristics etc. The waste heat of natural gas engine generator mainly includes the high temperature flue gas waste heat and the jacket water waste heat. The electrical power and waste heat output power generated by the natural gas engine generator can be calculated as follows:

$$G_{\rm ice}^t = \frac{Q_{\rm ice}^t}{\eta_{\rm ice}^e}, \tag{1}$$

$$H_{\rm ice}^t = \frac{Q_{\rm ice}^t \cdot \eta_{\rm ice}^h}{\eta_{\rm ice}^e}, \tag{2}$$

where $G_{\rm ice}^t$ is natural gas consumption power of the natural gas engine generator in kW; $Q_{\rm ice}^t$ is electrical power of the natural gas engine generator in kW; $H_{\rm ice}^t$ is waste heat output power of the natural gas engine generator in kW; $\eta_{\rm ice}^h$ and $\eta_{\rm ice}^e$ are thermal efficiency and electrical efficiency of the natural gas engine generator, respectively.

B. Absorption Chiller

Absorption chiller utilizes the waste heat as driving heat source to produce cooling water, the cooling output power of the absorption chiller can be estimated as follows:

$$Q_{\mathrm{br}}^{t} = H_{\mathrm{br}}^{t} \cdot \eta_{\mathrm{br}}^{c}, \tag{3}$$

where Q_{br}^{t} is cooling output power of the absorption chiller in kW; H_{br}^{t} is heat input power of the absorption chiller in kW; η_{br}^{c} is absorption chiller efficiency.

C. Electric Refrigeration

Electric refrigeration utilizes the electricity as driving source to produce cooling water, the cooling output power of the electric refrigeration can be estimated as follows:

$$Q_{\mathrm{ec}}^{t} = E_{\mathrm{ec}}^{t} \cdot \eta_{\mathrm{ec}}^{c}, \tag{4}$$

where Q_{ec}^{t} is cooling energy power of the electric refrigeration in kW; E_{ec}^{t} is electrical power of the electric refrigeration in kW; η_{ec}^{c} is electric refrigeration efficiency.

D. Gas Boiler

The heat power of the gas boiler can be estimated as follows:

$$Q_{\mathrm{b}}^{t} = G_{\mathrm{b}}^{t} \cdot \eta_{\mathrm{b}}^{h}, \tag{5}$$

where Q_{b}^{t} is output power of the gas boiler in kW; η_{b}^{h} is gas boiler efficiency; G_{b}^{t} is natural gas consumption power of the gas boiler in kW.

E. Waste Heat Recovery System

The heat power of the waste heat recovery system can be estimated as follows:

$$Q_{\mathrm{rc}}^{t} = H_{\mathrm{rc}}^{t} \cdot \eta_{\mathrm{rc}}^{h}, \tag{6}$$

where Q_{rc}^{t} is output power of the waste heat recovery system in kW; H_{rc}^{t} is input power of the waste heat recovery system in kW; η_{rc}^{h} is waste heat recovery system efficiency.

F. Heating Storage System

The state of heat of the heating storage system can be estimated as follows:

$$S_{\mathrm{h}}^{t} = S_{\mathrm{h}}^{t-1} + (I_{\mathrm{hs}}^{t} - Q_{\mathrm{hs}}^{t}) \cdot \Delta t, \tag{7}$$

where S_{h}^{t} and S_{h}^{t-1} are the states of heat of the heating storage system in t and $t-1$ hour in kW·h, respectively; Q_{hs}^{t} is output power of the heating storage system in kW; I_{hs}^{t} is input power of the heating storage system in kW; Δt is time interval in hour.

G. Cooling Storage System

The state of cooling of the cooling storage system can be estimated as follows:

$$S_{\mathrm{c}}^{t} = S_{\mathrm{c}}^{t-1} + (I_{\mathrm{cs}}^{t} - Q_{\mathrm{cs}}^{t}) \cdot \Delta t, \tag{8}$$

where S_{c}^{t} and S_{c}^{t-1} are the states of cooling of the cooling storage system in t and $t-1$ hour in kW·h, respectively; Q_{cs}^{t} is output power of the cooling storage system in kW; I_{cs}^{t} is input power of the cooling storage system in kW; Δt is time interval in hour.

III. Initiative Optimization Operation Strategy of CCHP System

In order to make the natural gas engine generator work efficiently in rated permissible working area and improve overall efficiency of CCHP system, the initiative optimization operation strategy of CCHP system in the cooling season, the heating season and the transition season was formulated based on the load rate of natural gas engine generator, the ratio of heat (cooling) load power to electrical load power of buildings and the ratio of heat (cooling) energy power and electrical energy power of CCHP system.

$$K_{\mathrm{ice}} = \frac{\eta_{\mathrm{ice}}^{h}}{\eta_{\mathrm{ice}}^{e}}, \tag{9}$$

where K_{ice} is the ratio of heat energy power to electrical energy power of natural gas engine generator;

$$K_{\mathrm{hload}}^{t} = \frac{H_{\mathrm{hload}}^{t}}{E_{\mathrm{hload}}^{t}}, \tag{10}$$

where K_{hload}^{t} is the ratio of heat load power to electrical load power of buildings in the heating season; H_{hload}^{t} and E_{hload}^{t} are the heat load power and the electrical load power of buildings in kW in the heating season, respectively.

$$K_{\mathrm{cload}}^{t} = \frac{H_{\mathrm{cload}}^{t} + \frac{C_{\mathrm{cload}}^{t}}{\eta_{\mathrm{br}}^{c}}}{E_{\mathrm{cload}}^{t}}, \tag{11}$$

where K_{cload}^{t} is the ratio of heat (cooling) load power to electrical load power of buildings in the cooling season; H_{cload}^{t}, C_{cload}^{t} and E_{cload}^{t} are the heat load power, the cooling load power and the electrical load power of buildings in kW in the cooling season, respectively.

$$K_{\mathrm{gload}}^{t} = \frac{H_{\mathrm{gload}}^{t}}{E_{\mathrm{gload}}^{t}}, \tag{12}$$

where K_{gload}^{t} is the ratio of heat load power to electrical load power of buildings in the transition season; H_{gload}^{t} and E_{gload}^{t} are the heat load power and the electrical load power of buildings in kW in the transition season, respectively.

A. Operation Strategy in the Heating Season

1) Operation Mode M_{H1}: If $K_{\mathrm{hload}}^{t} > K_{\mathrm{ice}}$ and $Q_{\mathrm{ice}}^{t}/P_{\mathrm{ice}} > L_{\mathrm{ice}}^{\min}$, the heat load power H_{hload}^{t} is satisfied by the waste heat recovery system output power Q_{rc}^{t}, the heating storage system output power Q_{hs}^{t} and the gas boiler output power Q_{b}^{t}. If $Q_{\mathrm{ice}}^{t} < E_{\mathrm{hload}}^{t}$, CCHP system will buy electrical energy power E_{bg}^{t} from the grid. Otherwise, CCHP system will sell the excess electrical energy power E_{sg}^{t} to the grid, where E_{bg}^{t} and E_{sg}^{t} are the purchased electrical power and the sold electrical power of CCHP system in kW, respectively; $L_{\mathrm{ice}}^{\min}$ is the permissible load rate of natural gas engine generator specified by the manufacturer.

2) Operation Mode M_{H2}: If $K_{\mathrm{hload}}^{t} < K_{\mathrm{ice}}$ and $Q_{\mathrm{ice}}^{t}/P_{\mathrm{ice}} > L_{\mathrm{ice}}^{\min}$, the electrical load power E_{hload}^{t} is satisfied by the natural gas engine generator output power Q_{ice}^{t} and the purchased electrical power E_{bg}^{t} from the grid. If $Q_{\mathrm{rc}}^{t} < H_{\mathrm{hload}}^{t}$, the heat load power H_{hload}^{t} is satisfied by the waste heat recovery system output power Q_{rc}^{t}, the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$. If $Q_{\rm rc}^t > H_{\rm hload}^t$, the excess heat energy power $I_{\rm hs}^t$ will be stored in the heating storage system.

3) Operation Mode M_{H3}: If $Q_{\rm ice}^t/P_{\rm ice} < L_{\rm ice}^{\min}$, the electrical load power $E_{\rm hload}^t$ is satisfied by the purchased electrical power $E_{\rm bg}^t$ from the grid. The heat load power $H_{\rm hload}^t$ is satisfied by the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$.

B. Operation Strategy in the Cooling Season

1) Operation Mode M_{C1}: If $K_{\rm cload}^t > K_{\rm ice}$ and $Q_{\rm ice}^t/P_{\rm ice} > L_{\rm ice}^{\min}$, the heat load power $H_{\rm cload}^t$ is satisfied by the waste heat recovery system output power $Q_{\rm rc}^t$, the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$. The cooling load power $C_{\rm cload}^t$ is satisfied by the absorption chiller output power $Q_{\rm br}^t$, the cooling storage system output power $Q_{\rm cs}^t$ and the electric refrigeration output power $Q_{\rm ec}^t$. If $Q_{\rm ice}^t < E_{\rm cload}^t$, CCHP system will buy electricity from the grid. Otherwise, CCHP system will sell the excess electricity to the grid.

2) Operation Mode M_{C2}: If $K_{\rm cload}^t < K_{\rm ice}$ and $Q_{\rm ice}^t/P_{\rm ice} > L_{\rm ice}^{\min}$, the electrical load power $E_{\rm cload}^t$ is satisfied by the natural gas engine generator output power $Q_{\rm ice}^t$ and the purchased electrical power $E_{\rm bg}^t$ from the grid. If $Q_{\rm rc}^t > H_{\rm cload}^t$, the excess heat energy power $I_{\rm hs}^t$ will be stored in the heating storage system. If $Q_{\rm rc}^t < H_{\rm cload}^t$, the heat load power $H_{\rm cload}^t$ is satisfied by the waste heat recovery system output power $Q_{\rm rc}^t$, the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$. If $Q_{\rm br}^t < C_{\rm cload}^t$, the cooling load demand power $C_{\rm cload}^t$ is provided by the absorption chiller output power $Q_{\rm br}^t$, the cooling storage system output power $Q_{\rm cs}^t$ and the electric refrigeration output power $Q_{\rm ec}^t$. Otherwise, the excess cooling energy power $I_{\rm cs}^t$ will be stored in the cooling storage system.

3) Operation Mode M_{C3}: If $Q_{\rm ice}^t/P_{\rm ice} < L_{\rm ice}^{\min}$, the electrical load power $E_{\rm cload}^t$ is satisfied by the purchased electrical power $E_{\rm bg}^t$ from the grid. The cooling load power $C_{\rm cload}^t$ is satisfied by the cooling storage system output power $Q_{\rm cs}^t$ and the electric refrigeration output power $Q_{\rm ec}^t$. The heat load power $H_{\rm cload}^t$ is satisfied by the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$.

C. Operation Strategy in the Transition Season

1) Operation Mode M_{G1}: If $K_{\rm gload}^t > K_{\rm ice}$ and $Q_{\rm ice}^t/P_{\rm ice} > L_{\rm ice}^{\min}$, the heat load power $H_{\rm gload}^t$ is satisfied by the waste heat recovery system output power $Q_{\rm rc}^t$, the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$. If $Q_{\rm ice}^t < E_{\rm gload}^t$, CCHP system will buy electrical power $E_{\rm bg}^t$ from the grid. Otherwise, CCHP system will sell the excess electrical power $E_{\rm sg}^t$ to the grid.

2) Operation Mode M_{G2}: If $K_{\rm gload}^t < K_{\rm ice}$ and $Q_{\rm ice}^t/P_{\rm ice} > L_{\rm ice}^{\min}$, the electrical load power $E_{\rm gload}^t$ is satisfied by the natural gas engine generator output power $Q_{\rm ice}^t$ and the purchased electrical power $E_{\rm bg}^t$ from the grid. If $Q_{\rm rc}^t < H_{\rm gload}^t$, the heat load power $H_{\rm gload}^t$ is satisfied by the waste heat recovery system output power $Q_{\rm rc}^t$, the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$. If $Q_{\rm rc}^t > H_{\rm gload}^t$, the excess heat energy power $I_{\rm hs}^t$ will be stored in the heating storage system.

3) Operation Mode M_{G3}: If $Q_{\rm ice}^t/P_{\rm ice} < L_{\rm ice}^{\min}$, the electrical load power $E_{\rm gload}^t$ is satisfied by the purchased electrical power $E_{\rm bg}^t$ from the grid. The heat load power $H_{\rm gload}^t$ is satisfied by the heating storage system output power $Q_{\rm hs}^t$ and the gas boiler output power $Q_{\rm b}^t$.

IV. MULTI-OBJECTIVE ENERGY MANAGEMENT METHOD

A. Optimization Variables

The optimization variables of multi-objective energy management method for CCHP system with heating storage and cooling storage are as follows: $Q_{\rm ice}^t$, $Q_{\rm br}^t$, $Q_{\rm ec}^t$, $Q_{\rm b}^t$, $Q_{\rm rc}^t$, $Q_{\rm hs}^t$, $Q_{\rm cs}^t$, $I_{\rm hs}^t$, $I_{\rm cs}^t$, $E_{\rm bg}^t$ and $E_{\rm sg}^t$.

B. Objective Function

In order to make CCHP with storage system to achieve high efficiency, high environmental benefits and economic benefits, the energy management of the combined cooling heating and power system is optimized by the multi-objective optimization model with maximum daily energy efficiency, minimum daily carbon emissions and minimum daily operation cost[3, 5].

1) Maximum Daily Energy Efficiency:

$$\max\ \eta_{\rm per} = \frac{\sum_t C_{\rm cchp}^t + \sum_t H_{\rm cchp}^t + \sum_t E_{\rm cchp}^t}{\sum_t F_{\rm cchp}^t}, \tag{13}$$

where $\eta_{\rm per}$ is the daily energy efficiency of CCHP system; $\sum_t F_{\rm cchp}^t$ is the daily gas energy consumption of CCHP system in kW·h; $\sum_t E_{\rm cchp}^t$ is the daily electricity production of CCHP system in kW·h; $\sum_t H_{\rm cchp}^t$ is the daily heat production of CCHP system in kW·h; $\sum_t C_{\rm cchp}^t$ is the daily cooling production of CCHP system in kW·h.

2) Minimum Daily Carbon Emissions:

$$\min\ \eta_{\rm cde} = G_{\rm f}\left(\sum_t F_{\rm g}^t + \sum_t F_{\rm b}^t\right) + G_{\rm e}\sum_t E_{\rm be}^t, \tag{14}$$

where $\eta_{\rm cde}$ is the daily CO_2 emissions of CCHP system in kg; $\sum_t F_{\rm g}^t$ and $\sum_t F_{\rm b}^t$ are the daily natural gas consumption of natural gas engine generator and the gas boiler in kW·h, respectively; $\sum_t E_{\rm be}^t$ is the daily purchase electricity of CCHP system from the grid in kW·h; $G_{\rm f}$ and $G_{\rm e}$ are the CO_2 emissions conversion factor of natural gas and purchase electricity in kg/kW·h, respectively.

3) Minimum Daily Operation Cost:

$$\min\ \eta_{\rm npv} = \frac{\rho C_{\rm inv} + C_{\rm om}}{365} + C_{\rm pur}, \tag{15}$$

where $\eta_{\rm npv}$ is the daily operating cost of CCHP system in yuan;

$$\rho = \frac{l(1+l)^n}{(1+l)^n - 1}, \tag{16}$$

where ρ is the capital recovery factor; l is the annual interest rate; n is the life of equipment;

$$\begin{aligned} C_{\rm inv} = {} & P_{\rm ice}R_{\rm ice} + P_{\rm br}R_{\rm br} + P_{\rm ec}R_{\rm ec} + P_{\rm b}R_{\rm b} \\ & + P_{\rm rc}R_{\rm rc} + P_{\rm es}R_{\rm es} + P_{\rm hs}R_{\rm hs} + P_{\rm cs}R_{\rm cs}, \end{aligned} \tag{17}$$

where I_{inv} is total investment of CCHP system in yuan; R_{ice}, R_{br}, R_{ec}, R_{b}, R_{rc}, R_{hs} and R_{cs} are the unit prices of natural gas engine generator, absorption chiller, electric refrigeration, gas boiler, waste heat recovery system, heating storage system and cooling storage system in yuan/kW, respectively;

$$C_{\mathrm{pur}} = P_{\mathrm{f}}\left(\sum_t F_{\mathrm{g}}^t + \sum_t F_{\mathrm{b}}^t\right) + P_{\mathrm{be}}\sum_t E_{\mathrm{be}}^t - P_{\mathrm{se}}\sum_t E_{\mathrm{se}}^t, \tag{18}$$

where C_{pur} is the annual total cost of the gas and electricity consumed by CCHP system in yuan; P_{f} is the natural gas price in yuan/kW·h; P_{be} and P_{se} are the purchased electricity price and the sold electricity price in yuan/kW·h, respectively; $\sum_t E_{\mathrm{se}}^t$ is the daily total sold electricity of CCHP system to the grid in kW·h.

$$\begin{aligned} C_{\mathrm{om}} = {} & P_{\mathrm{ice}}M_{\mathrm{ice}} + P_{\mathrm{br}}M_{\mathrm{br}} + P_{\mathrm{ec}}M_{\mathrm{ec}} + P_{\mathrm{b}}M_{\mathrm{b}} \\ & + P_{\mathrm{rc}}M_{\mathrm{rc}} + P_{\mathrm{es}}M_{\mathrm{es}} + P_{\mathrm{hs}}M_{\mathrm{hs}} + P_{\mathrm{cs}}M_{\mathrm{cs}}, \end{aligned} \tag{19}$$

where C_{om} is the annual total maintenance management cost of CCHP system in yuan; M_{ice}, M_{br}, M_{ec}, M_{b}, M_{rc}, M_{hs} and M_{cs} are annual maintenance management costs of natural gas engine generator, absorption chiller, electric refrigeration, gas boiler, waste heat recovery system, heating storage system and cooling storage system in yuan/kW, respectively.

C. Constraints

$$E_{\mathrm{load}}^t = Q_{\mathrm{ice}}^t + E_{\mathrm{bg}}^t - E_{\mathrm{sg}}^t, \tag{20}$$
$$H_{\mathrm{load}}^t = Q_{\mathrm{rc}}^t + Q_{\mathrm{b}}^t + Q_{\mathrm{hs}}^t - I_{\mathrm{hs}}^t, \tag{21}$$
$$C_{\mathrm{load}}^t = Q_{\mathrm{br}}^t + Q_{\mathrm{ec}}^t + Q_{\mathrm{cs}}^t - I_{\mathrm{cs}}^t, \tag{22}$$
$$P_{\mathrm{ice}}\lambda_{\mathrm{ice}}^{\min} \le Q_{\mathrm{ice}}^t \le P_{\mathrm{ice}}\lambda_{\mathrm{ice}}^{\max}, \tag{23}$$
$$P_{\mathrm{br}}\lambda_{\mathrm{br}}^{\min} \le Q_{\mathrm{br}}^t \le P_{\mathrm{br}}\lambda_{\mathrm{br}}^{\max}, \tag{24}$$
$$P_{\mathrm{ec}}\lambda_{\mathrm{ec}}^{\min} \le Q_{\mathrm{ec}}^t \le P_{\mathrm{ec}}\lambda_{\mathrm{ec}}^{\max}, \tag{25}$$
$$P_{\mathrm{b}}\lambda_{b}^{\min} \le Q_{\mathrm{b}}^t \le P_{\mathrm{b}}\lambda_{\mathrm{b}}^{\max}, \tag{26}$$
$$P_{\mathrm{rc}}\lambda_{\mathrm{rc}}^{\min} \le Q_{\mathrm{rc}}^t \le P_{\mathrm{rc}}\lambda_{\mathrm{rc}}^{\max}, \tag{27}$$
$$0 \le S_{\mathrm{h}}^t \le S_{\mathrm{h}}^{\max}, \tag{28}$$
$$0 \le I_{\mathrm{h}}^t \le I_{\mathrm{h}}^{\max}, \tag{29}$$
$$0 \le Q_{\mathrm{h}}^t \le Q_{\mathrm{h}}^{\max}, \tag{30}$$
$$0 \le S_{\mathrm{c}}^t \le S_{\mathrm{c}}^{\max}, \tag{31}$$
$$0 \le I_{\mathrm{c}}^t \le I_{\mathrm{c}}^{\max}, \tag{32}$$
$$0 \le Q_{\mathrm{c}}^t \le Q_{\mathrm{c}}^{\max}, \tag{33}$$

where E_{load}^t, H_{load}^t and C_{load}^t are the building electrical load power, the building heat load power and the building cooling load power in t hour in KW, respectively; P_{ice}, P_{br}, P_{ec}, P_{b}, P_{rc}, P_{hs} and P_{cs} are rated power of natural gas engine generator, absorption chiller, electric refrigeration, gas boiler, waste heat recovery system, heating storage system and cooling storage system in kW, respectively; $\lambda_{\mathrm{ice}}^{\min}$, $\lambda_{\mathrm{br}}^{\min}$, $\lambda_{\mathrm{ec}}^{\min}$, $\lambda_{\mathrm{b}}^{\min}$ and $\lambda_{\mathrm{rc}}^{\min}$ are minimum load factors of natural gas engine generator, absorption chiller, electric refrigeration, gas boiler and waste heat recovery system, respectively; $\lambda_{\mathrm{ice}}^{\max}$, $\lambda_{\mathrm{br}}^{\max}$, $\lambda_{\mathrm{ec}}^{\max}$, $\lambda_{\mathrm{b}}^{\max}$ and $\lambda_{\mathrm{rc}}^{\max}$ are maximum load factor of natural gas engine generator, absorption chiller, electric refrigeration, gas boiler and waste heat recovery system, respectively; $S_{\mathrm{h}}^{\max}$ and $S_{\mathrm{c}}^{\max}$ are maximum energy storage of heating storage system and cooling storage system in kW·h, respectively; $I_{\mathrm{h}}^{\max}$ and $I_{\mathrm{c}}^{\max}$ are maximum input power of heating storage system and cooling storage system in kW, respectively; $Q_{\mathrm{h}}^{\max}$ and $Q_{\mathrm{c}}^{\max}$ are maximum output power of heating storage system and cooling storage system in kW, respectively.

D. Niche Particle Swarm Optimization

Supposing in a D dimension objective search space, PSO algorithm randomly initializes a swarm formed by N particles, then the position and flying velocity of k-th iterative m-th particle can be represented as:

$$X_m^k = \left(x_{m,1}^k, x_{m,2}^k, \ldots, x_{m,D}^k\right),\ m = 1, 2, \ldots, N, \tag{34}$$
$$V_m^k = \left(v_{m,1}^k, v_{m,2}^k, \ldots, v_{m,D}^k\right),\ m = 1, 2, \ldots, N, \tag{35}$$
$$p_{\mathrm{best},m}^k = \left(p_{m,1}^k, p_{m,2}^k, \ldots, p_{m,D}^k\right),\ m = 1, 2, \ldots, N, \tag{36}$$

where $p_{\mathrm{best},m}^k$ represents the best previous position of k-th iterative m-th particle;

$$g_{\mathrm{best}}^k = \left(p_{g,1}^k, p_{g,2}^k, \ldots, p_{g,D}^k\right), \tag{37}$$

where g_{best}^k represents the best position of the swarm.

Velocity and position are updated each time according to the formulas below

$$\begin{aligned} V_m^{k+1} = {} & V_m^k + c_1\varepsilon\left(p_{\mathrm{best},m}^k - X_m^k\right) \\ & + c_2\eta\left(g_{\mathrm{best}}^k - X_m^k\right), \end{aligned} \tag{38}$$
$$X_m^{k+1} = X_m^k + V_m^{k+1}, \tag{39}$$

where c_1 and c_2 are cognitive and social constants respectively; ε and η are quasi-random number generated within $(0, 1]$.

In this paper, we use a niche technology based on the fitness value sharing mechanism proposed by Goldberg and Richardson. The idea is to adjust the individual fitness by the sharing function, to limit the over growth of the similar individuals, and to create a stable environment for the evolution of the niche. It has the advantages of increasing the population diversity, avoiding the premature convergence of particle swarm optimization and improving the convergence speed[19]. The sharing mechanism of niche based on fitness value is as follows.

$$F_i = \frac{1}{S_i},\ i = 1, 2, \ldots, N_{\mathrm{s}}, \tag{40}$$
$$S_i = \sum_{j=1}^{N_{\mathrm{s}}} f_{\mathrm{sh}}(d_{ij}), \tag{41}$$
$$f_{\mathrm{sh}}(d_{ij}) = \begin{cases} 1 - \left(\frac{d_{ij}}{\sigma_{\mathrm{share}}}\right)^{\alpha}, & 0 \le d_{ij} < \sigma_{\mathrm{share}}, \\ 0, & d_{ij} \ge \sigma_{\mathrm{share}}, \end{cases} \tag{42}$$
$$d_{ij} = \|X_i - X_j\| = \sqrt{\sum_{l=1}^{D}\left(X_{i,l} - X_{j,l}\right)^2}, \tag{43}$$

where N_{s} is the number of individuals within the niche; S_i is sharing degree for individual X_i; $f_{\mathrm{sh}}(d_{ij})$ is shared function between individual X_i and X_j in the niche. α is the parameters for controlling the shape of shared function, whose general values are 1 or 2; $\sigma_{\rm share}$ is the shared distance in advance; d_{ij} is Euclidean distance between individual X_i and X_j.

The specific steps of the niche particle swarm optimization algorithm are as follows:

1) Initialize particle population $N_{\rm P}$, with randomly generated initial position X_0 and initial speed V_0, initial individual optimal position of particle $p_{\rm best} = X_0$, initial $N_{\rm s}$ is empty, initial k is zero.

2) Calculate the objective function of each particle and the non-dominated solution is deposited into the elite set.

3) Calculate the fitness of each individual in the elite set according to (40), randomly select the elite set of individuals as the global optimal position of particle $g_{\rm best}$ with the roulette method.

4) Update the position and velocity of the particle according to (38) and (39) and update $p_{\rm best}$;

5) Update the elite set with the non-dominated solution in the current particle swarm $N_{\rm s}$.

6) Select the non-dominated solutions in the particle swarm to join the elite set and remove the inferior solution, calculate the fitness of all non-inferior solution, if the number of the elite to focus more than the given maximum capacity, then delete the fitness value of the smallest individual.

7) If the end condition is met, the optimization is stopped, and the Pareto optimal solution set is set up from the elite set; otherwise, set $t = t + 1$ and go to Step 2.

E. TOPSIS Decision Making Method

The technique for order of preference by similarity to ideal solution (TOPSIS) is a multi-criteria decision analysis method. TOPSIS method is used to normalize the raw data, eliminate the influence of different parameters, and can make full use of the information of the original data, which can reflect the difference between the various schemes and reflect the actual situation objectively and realistically, with universal applicability, intuitiveness, reliability and precise advantages[20].

The TOPSIS process of energy management for CCHP system is carried out as follows.

1) Create an evaluation matrix consisting of m Pareto alternatives and n optimal objectives, with the intersection of each alternative and criteria given as g_{ij}, we therefore have a matrix $G = [g_{ij}]_{m\times n}$. The matrix G is then normalized to form the matrix $R = [r_{ij}]_{m\times n}$ using the normalization method (44).

$$r_{ij} = \frac{g_{ij}}{\sqrt{\sum\limits_{i=1}^{m} g_{ij}^2}},\ i = 1, 2, \ldots, m,\ j = 1, 2, \ldots, n. \tag{44}$$

2) Calculate the weighted normalized decision matrix $V = (v_{ij})_{m\times n} = (w_j r_{ij})_{m\times n}$, $i = 1, 2, \ldots, m$, where $w_j = W_j / \sum_{j=1}^{n} W_j$, so that $\sum_{j=1}^{n} w_j = 1$ and W_j is the original weight given to the indicator v_j, $j = 1, 2, \ldots, n$.

3) Determine the best alternative S^+ and the worst alternative S^-

$$\begin{aligned} S^+ = {}& [(\max v_{ij}) | j \in J^+, (\min v_{ij})|,\\ & j \in J^- | i = 1, 2, \ldots, m] = [v_1^+, v_2^+, \ldots, v_m^+], \end{aligned} \tag{45}$$

$$\begin{aligned} S^- = {}& [(\min v_{ij}) | j \in J^+, (\max v_{ij})|,\\ & j \in J^- | i = 1, 2, \ldots, m] = [v_1^-, v_2^-, \ldots, v_m^-], \end{aligned} \tag{46}$$

where

$$\begin{aligned} J^+ = {}& [j = 1, 2, \ldots, n | j \text{ associated with the criteria}\\ & \text{having a positive impact}],\\ J^- = {}& [j = 1, 2, \ldots, n | j \text{ associated with the criteria}\\ & \text{having a negative impact}]. \end{aligned}$$

4) Calculate the distance D_i^+ between the Pareto alternative i and the best condition S^+ , the distance D_i^- between the Pareto alternative i and the worst condition S^-

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2},\ i = 1, 2, \ldots, m, \tag{47}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2},\ i = 1, 2, \ldots, m. \tag{48}$$

5) Calculate the similarity to the worst condition

$$C_i = \frac{D_i^-}{(D_i^+ + D_i^-)},\ i = 1, 2, \ldots, m. \tag{49}$$

6) Rank the alternatives according to C_i. Finally, the optimal scheme of energy management is obtained.

V. Case Study

In this paper, a CCHP with heating storage system and cooling storage system in a hospital in the north of China is used to verify the initiative optimization operation strategy and multi-objective energy management method. This CCHP system mainly includes: natural gas engine generator, gas boilers, waste heat recovery system, absorption chiller, electric refrigeration, heating storage system, cooling storage system and other equipments. Parameter values of this CCHP system are shown in Table I.

TABLE I
PARAMETER VALUES OF CCHP SYSTEM

Parameter	Value	Parameter	Value
$P_{\rm ice}$	9500	$P_{\rm br}$	10 100
$P_{\rm ec}$	4800	$P_{\rm b}$	18 000
$P_{\rm rc}$	7800	$S_{\rm cs}$	15 000
$S_{\rm hs}$	15 000	$\eta_{\rm ice}^h$	0.41
$\eta_{\rm ice}^e$	0.48	$\eta_{\rm ec}^c$	3.1
$\eta_{\rm br}^c$	1.41	$\eta_{\rm rc}^h$	0.95
$\eta_{\rm b}^h$	0.88	$R_{\rm br}$	1800
$R_{\rm ice}$	4750	$R_{\rm b}$	260
$R_{\rm ec}$	1000	$R_{\rm cs}$	10
$R_{\rm rc}$	160	$R_{\rm hs}$	10
$G_{\rm e}$	0.997	$G_{\rm f}$	1.96
$P_{\rm be}$	1	$P_{\rm f}$	4
$P_{\rm se}$	1	$Q_{\rm max}^h$	5000
$I_{\rm max}^h$	5000	$Q_{\rm max}^c$	5000
$I_{\rm max}^c$	5000	$L_{\rm ice}^{\rm min}$	0.3

According to the cooling, heat and electrical power load of the hospital, it will be divided into the cooling season (June, July, August), the heating season (January, February, March, November, December) and the transition season (April, May, September, October). Figs. 3-5 are the typical daily load data of this hospital in the cooling season, the heating season and the transition season, respectively.

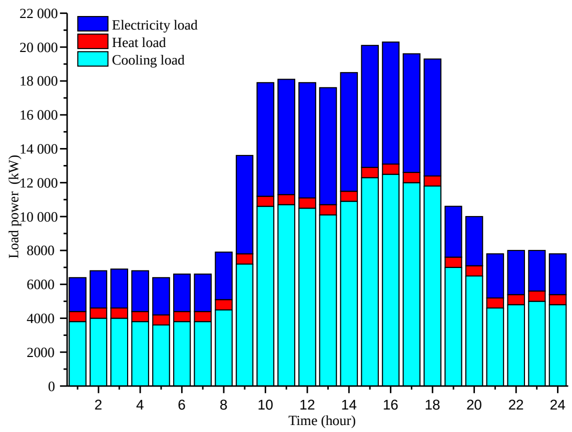

Fig. 3. Typical daily cooling, heat and electrical load in the cooling season.

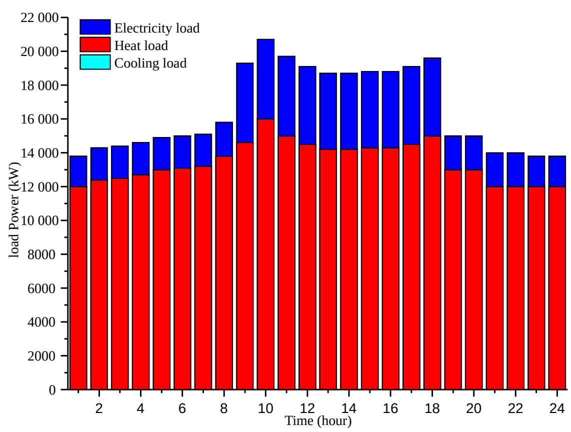

Fig. 4. Typical daily heat and electrical load in the heating season.

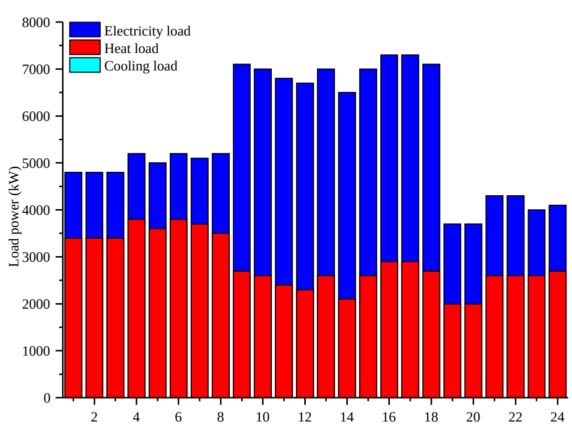

Fig. 5. Typical daily heat and electrical load in the transition season.

Figs. 6-8 are the optimal energy management results of CCHP system in the cooling season, the heating season and the transition season based on this initiative optimization operation strategy and multi-objective optimization method, respectively. In order to distinguish and compare the diagrams, the power value of sold electricity to the grid is expressed as negative, the power value of purchased electricity from the grid is expressed as positive, the output power value of the energy storage system is expressed as positive, and the input power value of the energy storage system is expressed as negative. Optimal objective results of CCHP systems in three typical seasons are shown in Table II.

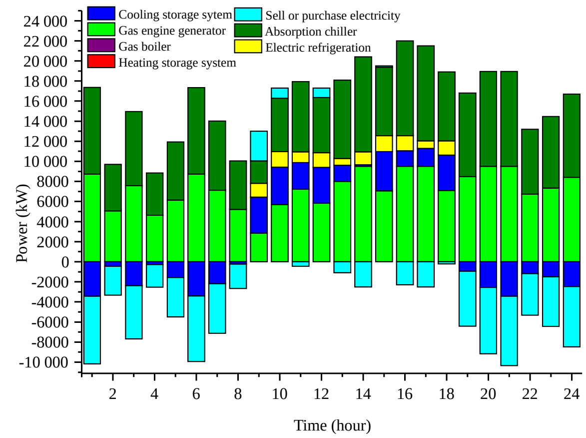

Fig. 6. Typical daily optimal results in the cooling season.

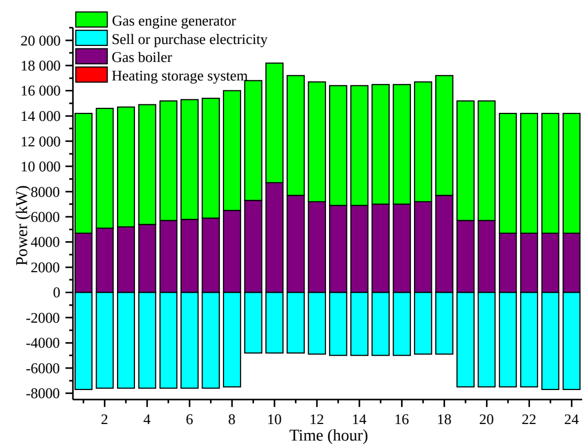

Fig. 7. Typical daily optimal results in the heating season.

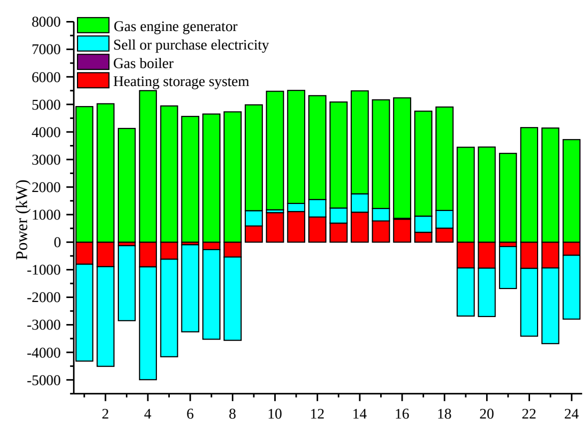

Fig. 8. Typical daily optimal results in the transition season.

TABLE II
OPTIMAL OBJECTIVE RESULTS OF CCHP SYSTEMS IN THREE TYPICAL SEASONS

Typical day	$\eta_{\rm per}$	$\eta_{\rm cde}$ (kg)	$\eta_{\rm npv}$ (yuan)
Cooling season	0.8665	355 600	466 800
Heating season	0.8571	127 500	294 700
Transition season	0.8469	59 700	137 000

As is shown in Fig. 3, the ratio of cooling (heat) load power to electrical load power of this hospital is far greater than the ratio of heat (cooling) energy power to electrical energy power of CCHP system during 1-8 hours and 19-24 hours, and the electrical load power is smaller than the allowable operating power in the cooling season. Meanwhile, the ratio of cooling (heat) load power to electrical load power of this hospital is slightly greater than the ratio of heat (cooling) energy power to electrical energy power of CCHP system during 9-18 hours in the cooling season. The optimal energy management results of CCHP system in the cooling season are shown in Fig. 6. CCHP system sell the excess electricity to the grid and store the excess cooling energy in the cooling storage system during 1-8 hours and 19-24 hours, meanwhile release the cooling energy from the cooling storage system during 9-18 hours to meet cooling load demand. Ultimately, the daily energy efficiency of CCHP system is 0.866, the daily CO_2 emissions of the system is 355 600 kg and the daily operating cost of the system is 466 800 yuan, in the cooling season.

As is shown in Fig. 4, the ratio of heat load power to electrical load power of this hospital is far greater than the ratio of heat energy power to electrical energy power of CCHP system, and the electrical load power is smaller than the allowable operating power during 1-8 hours and 19-24 hours in the heating season. At the same time, the heat load power fluctuation is slight and the heat load power is greater than the rated heat power of natural gas engine generator. The optimal energy management results of CCHP system in the heating season are shown in Fig. 7. Natural gas engine generator works at rated power and the excess electricity is sold to the grid, the insufficient heat energy power is supplied by the gas boiler. Ultimately, the daily energy efficiency of the CCHP system is 0.8571, the daily CO_2 emissions of the system is 127 500 kg and the daily operating cost of the system is 294 700 yuan, in the heating season.

As is shown in Fig. 5, the ratio of heat load power to electrical load power of this hospital is far greater than the ratio of heat energy power to electrical energy power of CCHP system, and the electrical load power is smaller than the allowable operation power during 1-8 hours and 19-24 hours in the transition season. However, the ratio of heat load power to electrical load power of this hospital is smaller than the ratio of heat energy power to electrical energy power of CCHP system during 9-18 hours in the transition season. The optimal energy management results of CCHP system in the transition season are shown in Fig. 8. This CCHP system sells the excess electricity to the grid and stores the excess heating energy in the heating storage system during 1-8 hours and 19-24 hours, meanwhile it buys electricity from the grid and releases the heating energy from the heating storage system during 9-18 hours to meet load demand. Ultimately, the daily energy efficiency of the CCHP system is 0.8469, the daily CO_2 emissions of the system is 59 700 kg and the daily operating cost of the system is 137 000 yuan, in the transition season.

VI. CONCLUSIONS

A novel initiative optimization operation strategy of CCHP system with heating storage and cooling storage system was presented in the cooling season, the heating season and the transition season. The multi-objective energy management of CCHP system was optimized with maximum daily energy efficiency, minimum daily carbon emissions and minimum daily operation cost based on the proposed initiative optimization operation strategy. The most satisfactory energy management scheme was obtained by using TOPSIS method.

CCHP system used in a hospital in the north of China has obtained better energy efficiency, environmental protection and economic benefits in accordance with this initiative optimization operation strategy and multi-objective energy management method. Meanwhile, this CCHP with storage system designed in this paper can stabilize fluctuations in cooling and heat load and achieve peak load shifting.

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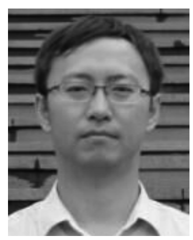

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