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Optimal Scheduling of CCHP With Distributed Energy Resources Based on Water Cycle Algorithm

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ABSTRACT In this paper, we deal with the optimal scheduling of a combined cooling, heating, and power (CCHP) system driven by distributed energy resources. First, a multi-objective optimization model is established based on three performance indexes, i.e., energy efficiency, economy, and environment. Then, we propose an optimal scheduling method based on the water cycle algorithm (WCA) and fuzzy mathematics optimization theory, which addresses the limitations in many traditional optimization algorithms such as local optimization, multiple iterations, and slow convergence speed. Moreover, aimed at showing the effectiveness of the proposed method, a case study has been carried out and the results show that the proposed method has better convergence performance, faster calculation, and higher precision compared with other algorithms such as genetic algorithm (GA), and particle swarm optimization (PSO), and the multi-objective model can reflect the operating state of the distributed energy resources CCHP system accurately.

INDEX TERMS Distributed energy resource, combined cooling, heating and power, water cycle algorithm, multi-objective optimization.

I. INTRODUCTION

In recent years, the demand for energy has been increasing and the ecological environment has deteriorated. In this context, microgrid technology has developed rapidly [1]–[3]. In order to improve energy efficiency, reduce greenhouse gas emissions, and protect the ecological environment, using distributed energy resources cooling and heating combined (D-CCHP) system is one of the solutions [4], [5]. The D-CCHP system consists of a CCHP system and a distributed energy resources system. The power generated by the distributed energy resources (such as wind power plant and solar photovoltaic generator) on the user side, the gas turbines and other power generation equipment are directly supplied to users. The waste heat generated by power generation will be recovered into hot water and high temperature steam by the regenerative system, and supplies heating and cooling to the users with the solar thermal plate. The D-CCHP system has obvious advantages compared with the traditional centralized power supply system [6]. For example, the energy utilization rate of D-CCHP has increased significantly, generally reaching 70%–90%, while the traditional centralized energy supply system is only 30%–45%. D-CCHP could use a variety of clean energy (such as hydrogen and natural gas) and renewable energy (such as wind and solar), which is a good way to solve energy crisis and energy security. It can also contribute to the protection of the environment and reduce the pollutant emissions. Distributed energy resources can also reduce the construction of large-scale, long-distance high-voltage transmission lines, which is conducive to environmental protection.

The components of the CCHP system mainly include generator units (internal combustion generator units, micro gas turbine generator units, gas turbine generator units, fuel cells, steam turbine generator units), heating equipment (gas boilers, waste heat boilers, heat exchangers), refrigeration equipment (electricity compression chillers, lithium bromide absorption chillers) and other equipment. The CCHP system is a typical complex energy system with multi-input, multi-output, multi-stage energy flow and information flow. Whether the CCHP system could be more efficient, more environmentally friendly, and more economical depends on the equipment model selection, equipment capacity and operational strategy for the system.

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At present, in order to improve the performance of the CCHP system, domestic and foreign researchers use different evaluation indicators and apply different intelligent optimization methods to optimize the equipment selection, equipment capacity and operation strategy of CCHP system with the goal of saving energy, reducing costs and reducing greenhouse gas emissions. For instance, Wu *et al.* [7] used an equation linearization method to solve the problem of the micro-grid economic optimization model with CHP system. Ameri and Besharati [8] described a mixed integer linear programming model for determining the optimal capacity and operating strategy of the CCHP system to reduce costs and CO_2 emissions. Moghimi *et al.* [9] used evolutionary algorithms to optimize CCHP system multi-objective optimization model in terms of energy, exergy, economy and environment. Ju *et al.* [10] built a CCHP system multi-objective optimization model driven by renewable energy and optimized it using entropy weight method. Yousefi *et al.* [11] used GA to optimize each single objective function, and AHP to obtain optimal scheduling by considering cost, energy saving, and emission reduction.

In terms of operational strategies, CCHP systems usually employ following the electricity load strategy (FEL) and following the thermal load strategy (FTL). In the FEL operation mode, the system determines the amount of power generated according to the size of the power demand, and then recovers the waste heat generated by the electric generation to meet the heat demand [12]. In the FTL operation mode, the system determines the boilers and generator units according to the heating demand and cooling demand, the power generated as a by-product of heating [13]. Since both operating strategies may lead to excess power or heat, some researchers have proposed some hybrid operating strategies [14]. For example, Mago *et al.* [15] proposed a strategy switching between FEL and FTL, called following a hybrid electric -thermal load (FHL). By calculating the case and analysis, the result shows that the FHL operation strategy is superior to the FEL strategy and the FTL strategy in terms of primary energy consumption, operating costs and CO_2 emissions. Huang *et al.* [16] proposed turbine inlet temperature (TIT) strategy and gas turbine inlet guide vanes (IGV) strategy to access the part load performance, which shows that the IGV strategy can improve the system performance. Liu *et al.* [17] proposed a new operation strategy based on the variational electric cooling to cool load radio, and adopted optimization algorithm to determine the optimal power generation unit capacity, where a case study is conducted to verify the feasibility of the optimal operation strategy.

Chen *et al.* [18] proposed a linear model of wind power, regenerative electric boilers and heat storage tanks, which showed that both the heat storage tank and the electric boiler can improve the flexibility of the CHP system. Wang *et al.* [19] presented a multi-objective optimization of a solar-powered CCHP system based on organic Rankine cycle. He adopted NSGA-II algorithm to achieve the best solutions for the multi-objective optimization of the system operating in three modes: namely power mode, CHP mode and CCP mode. Su *et al.* [20] proposed a new CCHP system driven by the synthetic utilization of biogas and solar energy, and optimized the saving ratios of CCHP FEL operation mode by GA. Reference [21] proposed a CCHP system with condensation heat recovery. The hot water is generated from the condensation heat of the chiller and the heat pump. The energy, economy and environment are the optimization objectives. Based on the typical daily load curve of a hotel, the genetic algorithm is adopted to verify the superiority of the purposed method. Tan *et al.* [22] established a CCHP system optimization model driven by gas turbines and steam turbines, proposed three optimized operating modes, and evaluated the performance of the system in each mode. Javan *et al.* [23] used a developed multi-objective genetic algorithm to optimize a CCHP system in a residential area, maximized energy efficiency and minimized cost while meeting constraints. Olamaei *et al.* [24] developed a heuristic and deterministic algorithm for solving a CCHP-thermal-heat only system optimization problem and reducing the total cost of the system and CO_2 emissions.

Based on the above observation, we can see that CCHP system driving energy has already contained natural gas, solar photo-voltaic, wind energy and biomass energy except for solar photothermal, and the CCHP system driven by multiple renewable energy has been rarely considered. Meanwhile, since the water cycle algorithm (WCA) is superior to other algorithms in terms of global optimization, the number of iterations, accuracy, and convergence speed, we propose a CCHP system driven by multiple distributed energy sources that includes solar thermal energy, and establish a multi-objective optimization mathematical model to design the optimal scheduling strategy. Based on the fuzzy mathematics optimization theory, the results obtained by WCA are compared with the results acquired by the GA and PSO. The superiority of the proposed method has been verified in several case studies.

The rest of the paper is organized as follows: Section 2 introduces the D-CCHP system mathematical model, each subsystem and each unit. The objective function and the constraints are given in Section 3. Section 4 introduces the water cycle algorithm, maximum fuzzy satisfaction method and the basic data. In Section 5, numerical analysis is given. Finally, the conclusion is drawn in Section 6.

II. SYSTEM DESCRIPTION

The D-CCHP system consists of a CCHP system, a distributed energy resource generation system, and a thermal system, as shown in Fig. 1.

A. DISTRIBUTED ENERGY RESOURCES GENERATION SYSTEM

The distributed energy resources (DER) generation system is composed of a wind power plant (WPP), a solar photovoltaic power generation (PV), and a gas turbine (GT).

Abbreviations		**Variable**	
CCHP	Combined Cooling, Heating and Power	$F_{WPP,R}$	Rated power of WPP
E	Energy efficiency	V	Wind speed
C	Total operation cost	F_{PV}	Energy input of PV
CE	Carbon dioxide emission	θ	Solar irradiant
DER	Distributed energy resources	F_{PT}	Output of PT
PV	Solar photovoltaic generator	I_C	Radiation of PT flat
WPP	Wind power plant	T_a	Environment temperature of PT
GT	Gas turbine	F_B	Electricity purchasing from grid
HRSG	Heat recovery steam generator	E_{WPPS}	Output of WPP selling electricity to grid
ST	Steam turbine	E_{PVS}	Output of PV selling electricity to grid
ECC	Electricity compression chiller	E_{GTS}	Output of GT selling electricity to grid
AC	Absorption chiller	M_{GT}	Natural gas consumption
HE	Heating exchanger	C_M	Maintenance cost of system
PT	Solar photovoltaic thermal	F_{WPP}	Energy input of WPP
TST	Thermal storage tank	γ	CO_2 emission of unit natural gas
RE	Regenerative electric boiler	φ	CO_2 emission of unit power energy
		H_{RE}	Heat energy generated by RE
Parameter		H_{ST}	Heat energy generated by ST
v_{in}	Cut-in speed	H_{HR2}	Heat energy generated by HRSG for TST
v_{out}	Cut-off speed	H_{PT1}	Heat energy generated by PT for TST
v_R	Rate speed	H_{TSTC}	Heat energy for AC
η_{PV}	Efficiency of PV	H_{TSTH}	Heat energy delivered to HE by TST
S_{PV}	Area of PV	H_{HE}	Heat energy generated by HE
A_P	Area of PT	H_{CC}	Cooling energy generating by ECC
p_B	Electricity price purchasing from grid	H_{AC}	Cooling energy generating by AC
p_{WPP}	Price of WPP selling electricity to grid	E_g	Total generated electricity
p_{PV}	Price of PV selling electricity to grid	E_{CC}	Electricity for ECC
p_{GT}	Price of GT selling electricity to grid	E_{RE}	Electricity for RE
p_{NG}	Price of natural gas	E_{WPP1}	Electric load provided by WPP
e	Price of natural gas	E_{PV}	Electricity generated by PV
η_{ES}	Transporting efficiency of extracted steam	E_{GT}	Electricity generated by GT
η_r	Transporting efficiency of pipeline	E_{ST}	Electricity generated by ST
η_{STg}	power generation efficiency of ST	H_{PT2}	Heat energy generated by PT for HE
η_{STl}	Heat energy loss ratio of ST	H_{fg}	Waste heat energy from GT
η_{HE}	Efficiency of HE	H_{HR1}	Heat energy generated by HR for ST
η_{GTg}	Power generation efficiency of GT	H_{HR3}	Exhaust gas of HRSG
η_{GTl}	Heat energy loss ratio of GT	E_{WPP2}	WPP output for RE
η_{HR1}	Radio of heat energy delivered to ST by HRSG	P_{CL}	Cooling load
η_{HR2}	Radio of heat energy delivered to TST by HRSG	P_{EL}	Electric load
η_{HR3}	Exhaust gas ratio of HRSG	P_{HL}	Heating load
q_{ng}	Calorific value of natural gas	H_{TST}	Heat energy input of TST
δ	Extraction steam ratio of ST	F_{GT}	Energy input of GT

Wind energy is a renewable, clean energy resource with large wind energy reserves and wide distribution, but its energy density is low and unstable. Unpredictability and the high cost of renewable energy technologies are major challenges for renewable energy technologies [19], [25], [26].

WPP is stochastic because of the air density is unstable, and the power generated by the wind power system can be calculated according to the wind speed [25], [26], as shown in (1):

$$F_{WPP} = \begin{cases} 0, & 0 \le v \le v_{in}, v > v_{out} \\ \dfrac{v - v_{in}}{v_r - v_{in}} \cdot F_{WPP,R}, & v_{in} \le v \le v_r \\ F_{WPP,R}, & v_r \le v \le v_{out} \end{cases} \tag{1}$$

Solar energy is also a renewable and clean energy resource. Because of PV is clean, safe, convenient and efficient, it has

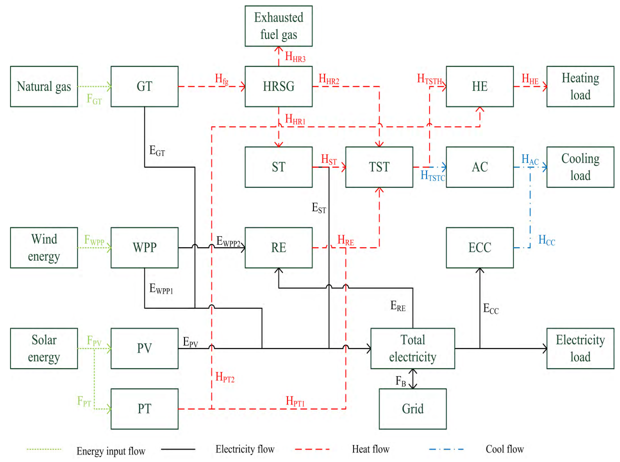

FIGURE 1. D-CCHP System.

become an emerging industry with universal attention and key development in the world [20], [27]. PV is one of the most widely used solar energy utilization technologies. At present, its efficiency can reach 24% [28]. It appears random in operation due to external environmental factors such as irradiance and temperature [27], [29]. The power of PV is related to the intensity of solar radiation [29], which can be calculated by

$$F_{PV} = \eta_{PV} \times S_{PV} \times \theta \tag{2}$$

B. THERMAL SYSTEM

The thermal system consists of a solar photovoltaic thermal system (PT) and a regenerative electric boiler (RE).

PT, whose model is given in [30], [31], collects solar thermal to meet the heat demand of the system. The energy collected by the PT could be expressed as

$$F_{PT} = A_{PT} I_C \left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) \right] \tag{3}$$

where T_s is the temperature of the sun center, which is generally 6000K [32].

RE uses the power generated by WPP to meet the demand of thermal. When the PT and the heat recovery steam generator supply insufficient thermal, RE becomes the backup thermal resource and supplies thermal energy to the load. Part of the thermal energy produced by RE is used to meet the heating demand, and the remaining heat is stored to meet future demands. The regenerative electric boiler model is introduced in the literature [18].

C. CCHP SUBSYSTEM

The CCHP subsystem consists of heat recovery steam generators (HRSG), steam turbines (ST), electric compression chillers (ECC), thermal storage tank (TST), absorption chillers (AC) and heat exchangers (HE). The operating principle of the CCHP subsystem is as follows: GT produces high-temperature steam while generating power. The fluid gas is recovered by the HRSG, and it is used to produce high pressure steam that enters ST and produces electricity. Moreover, ST can extract steam for thermal demand. The TST acts as a buffer for thermal transfer, and the heat generated by the ST, GT and thermal system is supplied to the heating load via TST. The HRSG can generate heat medium water for the heating and cooling load. The heat medium water is first used to supply hot water, and the remainder enters AC for meeting the cooling demand. The ST extracted steam can be used for heating through HE or for cooling by AC. The electricity generated by GT and ST is used to meet electrical loads. In addition, if the cooling demand can't be met, it is supplemented by ECC.

The CCHP operating strategy mainly includes FEL and FTL with shortcomings. Optimizing the operating strategy has an important impact on improving CCHP performance. This paper makes the following assumptions:

(1) The CCHP system can be connected to the grid. When the electricity generated by CCHP system is insufficient, the system can buy electricity from the grid, and can sell part of the power to the grid when electricity generation is excessive.
(2) The power efficiency of the grid, Coefficient of Performance (COP) of ECC and AC, efficiency of GT, ST, HRSG and HE are simplified as fixed values. The impact of external environmental conditions on equipment performance is also ignored during the calculation.
(3) The exhaust gas temperatures of GT, ST, HRSG and AC are assumed to be constant.

The system uses the electricity generated by WPP, PV, GT and ST to meet the electricity demand. If it is insufficient, it buys the remaining power from the electrical grid. For heating load, it is mainly supplied by ST, PT and RE. As for cooling load, it is mainly supplied by AC and ECC.

III. MULTI-OBJECTIVE OPTIMIZATION MODEL

The performance evaluation indexes were constructed to evaluate the operation effect of the D-CCHP system. Different optimization objectives are formulated to generate different operation results. To achieve the optimal operation performance, the multi-objective operation optimization model will be built.

A. OBJECTIVE FUNCTIONS

The energy efficiency and cost of the system have been considered in existing studies. As the greenhouse effect exacerbates, reducing CO_2 emissions is increasingly important, and thus reducing CO_2 emission would become another objective. Therefore, we take C, E and CE as the optimization objectives. The detailed objective functions are as follows.

1) OPERATING COSTS UNDER PEAK AND VALLEY ELECTRICITY PRICES

The total operating cost of the system consists of three parts, i.e., DER generation costs, purchasing electricity costs from grid and natural gas consuming costs, which is given by

$$C = F_B \cdot p_B - M_{GT} \cdot p_{NG} + C_M - [E_{WPPS} \cdot p_{WPPS} + E_{PVS} \cdot p_{PV} + E_{GTS} \cdot p_{GT}] \quad (4)$$

where C_M is the operating cost of each unit, which can be expressed as

$$C_M = \sum F_i \cdot p_i \quad (5)$$

where F_i is the energy produced by the i-th equipment, and p_i is the operating cost to produce unit energy.

2) ENERGY EFFICIENCY

The energy efficiency of the system reflects the performance of the system. The energy efficiency of the D-CCHP system can be calculated by

$$E = \frac{[P_{HL} + P_{CL} + P_L] \cdot \Delta t}{F_{GT} + F_{PV} + F_{WPP} + F_{PT} + F_B} \quad (6)$$

3) CARBON DIOXIDE EMISSIONS

Since both natural gas combustion and electricity generation from grid produce carbon dioxide, the total CO_2 emissions from D-CCHP system can be expressed as

$$CE = \gamma F_{GT} + \varphi F_B \quad (7)$$

4) OBJECTIVE FUNCTION

In order to improve the performance of D-CCHP system, the system should be operated with low operating cost, high energy efficiency and low CO_2 emissions. Hence, the objective function is formulated as

$$f_1 = \min C = \min \sum_{t=1}^{T} \{F_B(t) \cdot p_B(t) - [E_{WPPS}(t) \cdot p_{WPP} + E_{PVS}(t) \cdot p_{PV} + E_{GTS}(t) \cdot p_{GT}] - M_{GT}(t) \cdot p_{NG} + C_M(t)\} \quad (8)$$

$$f_2 = \max E = \max \frac{\sum_{t=1}^{T} \{[P_{HL}(t)+P_{CL}(t)+P_{EL}(t)] \cdot \Delta t\}}{\sum_{t=1}^{T} [F_{GT}(t)+F_{PV}(t)+F_{WPP}(t)+F_{PT}(t)+F_B(t)]} \quad (9)$$

$$f_3 = \min CE = \min \sum_{t=1}^{T} [\gamma F_{GT}(t)+\varphi F_B(t)] \quad (10)$$

B. MAIN CONSTRAINT

The energy flowing through the system should be constant, and some other constraints are needed.

1) ENERGY BALANCE CONSTRAINTS

(1) heating balance

$$H_{RE}(t) + H_{ST}(t) + H_{HR2}(t) + H_{PT1}(t) = H_{TSTC}(t) + H_{TSTH}(t) \quad (11)$$

$$H_{HE}(t) \geq P_{HL}(t) \cdot \Delta t \quad (12)$$

(2) cooling balance

$$H_{CC}(t) + H_{AC}(t) \geq P_{CL}(t) \cdot \Delta t \quad (13)$$

(3) electricity balance

$$E_g(t)+E_{CC}(t)+E_{RE}(t) = [E_{WPP1}(t)+E_{PV}(t)+E_{GT}(t) + E_{ST}(t)]\,(1-e) \quad (14)$$

$$E_g(t) + F_B(t) = P_{EL}(t) \cdot \Delta t \quad (15)$$

2) HEATING MODULES CONSTRAINT

Steam turbine module:

$$H_{ST}(t) = \delta \cdot H_{HR1}(t) \cdot \eta_r \cdot \eta_{ES} \quad (16)$$

$$E_{ST}(t) = [H_{HR1}(t) - H_{ST}(t)] \cdot (1 - \eta_{STl}) \cdot \eta_{STg} \quad (17)$$

Gas turbine module:

$$H_{fg}(t) = \frac{E_{GT}(t)\left(1 - \eta_{GTg} - \eta_{GTl}\right)}{\eta_{GTg}} \quad (18)$$

Heat recovery steam generator module:

$$H_{HR1}(t) = H_{fg}(t) \cdot \eta_{HR1} \quad (19)$$

$$H_{HR2}(t) = H_{fg}(t) \cdot \eta_{HR2} \quad (20)$$

$$H_{HR3}(t) = H_{fg}(t) \cdot \eta_{HR3} \quad (21)$$

$$\eta_{HR1} + \eta_{HR2} + \eta_{HR3} = 1 \quad (22)$$

Regenerative electric boiler module:

$$0 \leq H_{RE}(t) \leq E_{WPP2}(t) + E_{RE}(t) \quad (23)$$

Thermal storage tank:

$$H_{TST}(t) = H_{TSTC}(t) + H_{TSTH}(t) \quad (24)$$

3) OTHER MODULES CONSTRAINTS

Electric compression chillers:

$$H_{CC}(t) = E_{CC}(t) \cdot COP_{CC} \quad (25)$$

Absorption chillers:

$$H_{AC}(t) = H_{TSTC}(t) \cdot COP_{AC} \quad (26)$$

Heat exchangers:

$$H_{HE}(t) = [H_{TSTH}(t) + H_{PT2}(t)] \cdot \eta_{HE} \quad (27)$$

Output of wind power plant:

$$0 \leq E_{WPP1}(t) + E_{WPP2}(t) + E_{WPPS}(t) \leq F_{WPP}(t) \quad (28)$$

Output of solar photovoltaic thermal:

$$F_{PT}(t) = H_{PT1}(t) + H_{PT2}(t) \quad (29)$$

Output of solar photovoltaic generator:

$$0 \leq E_{PVS}(t) + E_{PV}(t) \leq F_{PV}(t) \quad (30)$$

IV. OPTIMIZATION APPROACH

In order to solve the multi-objective optimization problem, this paper resorts to the fuzzy theory and water cycle algorithm.

A. MAXIMUM FUZZY SATISFACTION METHOD

This paper transforms the multi-objective function into a single objective function using the maximum fuzzy satisfaction method. The idea of the solution is finding the optimal solution of each single objective under all constraints firstly. Then these optimal solutions will be used to fuzzify each single objective function (determine the membership function). Thirdly, we will find the solution when the intersection of the membership function takes the maximum value, which is the optimal solution to the multi-objective optimization problem.

Fuzzy mathematics represent and solve actual objective fuzzy phenomenon by using precise mathematical methods [33]. In order to achieve this goal, we must first determine the membership function u, where the size of u reflects the satisfaction of the optimization results, $u = 1$ represents the most satisfied, and $u = 0$ represents the most dissatisfied.

The multi-objective optimization of this paper is for reducing the operating cost, the CO_2 emissions, and improving the energy efficiency. For the above three objectives, the membership function obeys the half-gamma distribution as

$$U_k(t) = \begin{cases} 1, & f_k \le f_{kmin} \\ \exp\left(\dfrac{f_{kmin}(t) - f_k(t)}{f_{kmin}(t)}\right) & f_k > f_{kmin}, \quad k = 1, 2, 3 \end{cases} \tag{31}$$

In order to facilitate the membership function, f_2 can be changed to:

$$\begin{aligned} f_2 &= \max E = \min E^{-1} \\ &= \min \frac{\sum_{t=1}^{T} [F_{GT}(t) + F_{PV}(t) + F_{WPP}(t) + F_{PT}(t) + F_B(t)]}{\sum_{t=1}^{T} \{[P_{HL}(t) + P_{CL}(t) + P_{EL}(t)] \cdot \Delta t\}} \end{aligned} \tag{32}$$

The multi-objective optimization function can be transformed into single-objective optimization function as:

$$f = \max u(t), \quad s.t. \begin{cases} u(t) \le u_1(t) \\ u(t) \le u_2(t) \\ u(t) \le u_3(t) \\ (11) - (30) \end{cases} \quad t = 1, 2, \ldots T \tag{33}$$

where $u(t)$, $u_1(t)$, $u_2(t)$, and $u_3(t)$ are the satisfaction of fuzzy optimization, operating cost, energy efficiency and greenhouse gas emissions, respectively. $u(t) = \cap_{k=1}^{3} u_k(t)$.

B. WATER CYCLE ALGORITHM

In recent years, intelligent optimization algorithms have been widely used to solve constrained engineering problem optimization. However, due to the complexity of engineering structures, it is hard to implement for many practical engineering optimization problems [34]. This paper uses the water cycle algorithm (WCA) to solve the constrained problem.

The WCA is an intelligent algorithm derived from the evaporation and rainfall of water, the flow of streams and rivers into the sea and other water cycle process in the nature, which can solve the constrained problem [34]–[36]. The main steps of WCA are as follows:

(1) Form initial raindrops, streams, rivers, and sea;

(2) Calculate the value of each raindrops;

(3) Iterative calculation makes the stream flow to the rivers, and the rivers flows to the sea to find the best solution;

(4) If the evaporation condition is met, the raining process is carried out. This is a key step to prevent WCA from the local solutions.

The specific algorithm flow is described in [35].

V. CASE STUDY AND ANALYSIS

A. BASIC DATA

This paper selects a building in Guangzhou for the case study. The cooling, heating and electric loads of the building on the typical winter and summer days (July 15th and January 15th) are shown in Fig.2.

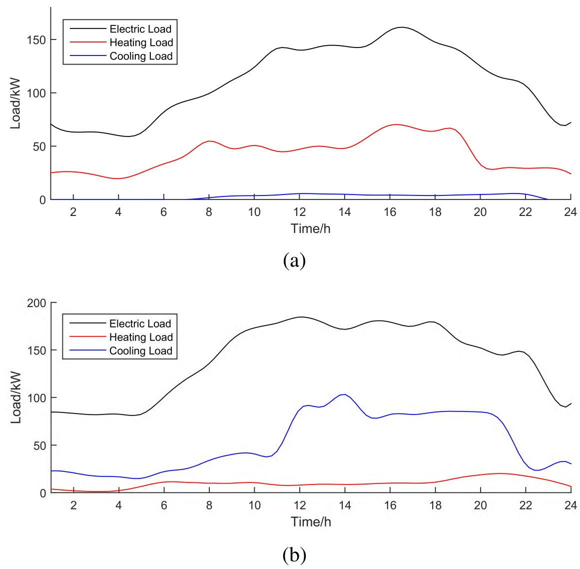

FIGURE 2. Typical loads of daily electricity, cooling, and heating. (a): Winter. (b): Summer.

The maximum capacity of GT and ST is 240kW and 72kW. The maximum heat output of RE, PT, TST and HRSG is 65 kW, 30 kW, 35kW and 53 kW. The maximum output power of WPP and PV is 120kW and 60kW. Besides, the station service power consumption rate of CCHP system is supposed to be 4%. The wind speed, solar radiation in typical days can be forecasted based on historical data, as shown in Fig.3.

The efficiency of HE is 0.8. AC uses lithium bromide as refrigerant, and its COP is generally 0.7-1.1. The COP is 0.7 in this paper. ECC is powered by electricity, and relies on compressor to increase the pressure of the refrigerant to perform the refrigeration cycle, and its COP is 5.8. Each DER can be connected to the grid; and sell electricity to the grid. The grid connection prices of WPP, PV and GT are \$0.0948/kWh, \$0.1554/kWh and \$0.08702/kWh. Natural gas

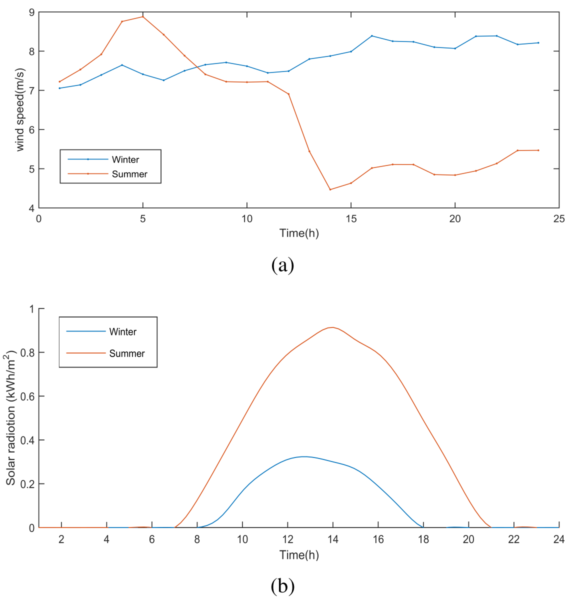

FIGURE 3. **Wind speed and solar radiation forecast of typical days. (a): Wind speed. (b): Solar radiation.**

price is \$0.3748/kg. Some parameters of ST, GT and HRSG are shown in Table 1.

TABLE 1. **Part of the unit parameters.**

ST		HRSG		GT	
parameter	value	parameter	value	parameter	value
η_{ES}	0.8975	η_{HR1}	0.7118	η_{GTg}	0.36
η_r	0.9948	η_{HR2}	0.2206	η_{GTl}	0.08
η_{STg}	0.9484	η_{HR3}	0.0676	q_{ng}	49200kj/kg
δ	0.6528				
η_{STl}	0.7942				

The price of electricity purchased from the grid varies over time. One day can be divided into three periods, i.e., valley period (0:00-8:00), the flat period (8:00-18:00) and the peak period (18:00-24:00). The specific price and other parameters of the models are shown in Table 2.

TABLE 2. **Electricity price and other model parameters.**

Period	Electricity purchase price	Other models
Valley Period	\$0.05208/kWh	$COP_{CC} = 5.8$
Flat Period	\$0.09937/kWh	$COP_{AC} = 0.7$
Peak Period	\$0.16086/kWh	$\eta_{HE} = 0.8$

Maintenance costs of some power sources are shown in Table 3.

TABLE 3. **Maintenance costs of some power sources.**

power source	WPP	PV	RE	PT	TST
maintenance cost	\$0.0031	\$0.0018	\$0.0013	\$0.0017	\$0.0004

B. OPTIMIZATION RESULTS FOR TYPICAL WINTER DAY

On a typical winter day, the total operating cost of D-CCHP system is \$57.19571, the energy efficiency is 79.33%, and the CO_2 emissions are 570.67kg. The DER generation capacity is 2385.69kWh, and the natural gas consumption is 180.29kg. The output of each unit in the cooling, heating and power load is shown in Fig.4. In winter, the solar radiation intensity is at its lowest point, the power generated by PV and the thermal collected by PT are low. DER generation systems rely mainly on WPP for power generation.

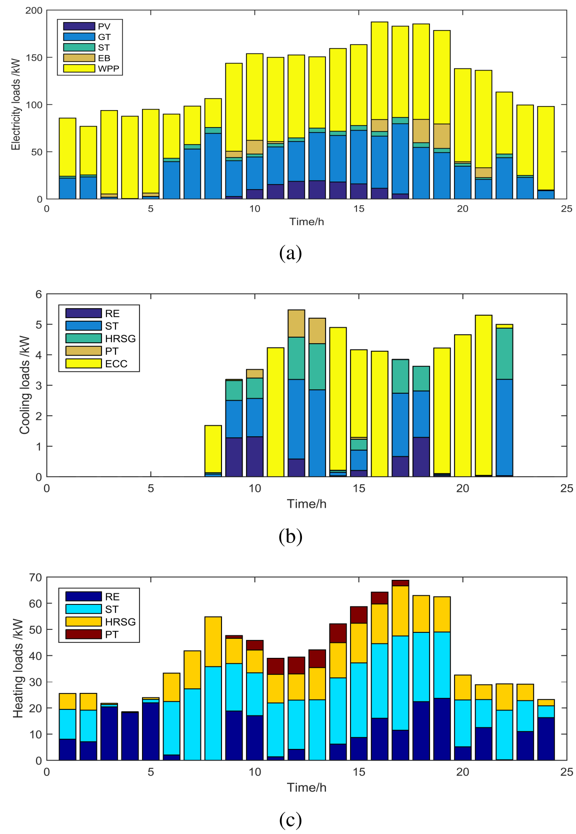

FIGURE 4. **Typical winter load of electricity, heating and cooling supply for optimization. (a): Electricity load. (b): Cooling load. (c): Heating load.**

On a typical winter day, we have a strong heating demand but low cooling demand. In the peak period, the D-CCHP system preferentially uses DER and GT for meeting electricity demand. Insufficient part of the demand is met by the electricity that is purchased from the grid. In the valley period, the DER generation supply in the system is surplus, and the surplus is sold to the grid to obtain income. When the electricity demand can be satisfied by the DER, the heating load is mainly provided by RE. At other times, the steam generated by GT is transmitted to HRSG and ST to produce thermal for heating demand. Due to the cooling demand is too low in winter, it is mainly supplied by ECC.

C. OPTIMIZATION RESULTS FOR TYPICAL SUMMER DAY

On a typical summer day, the total cost is \$139.697, the energy efficiency is 79.57%, the CO_2 emissions are 953.99kg, the DER generation capacity is 2200.34kWh, and the natural gas consumption is 175.68kg. The output of each unit in the cooling, heating and power load on a typical summer day is shown in Fig. 5. In summer, we have high solar radiation intensity and low thermal demand. PT and TST can meet thermal demand in most of time, while at other times thermal demand is met by ST and RE. The system uses the electricity generated by DER and GT to meet the electricity demand, generate waste heat to supply cooling demand, and the insufficient demand is met by ECC.

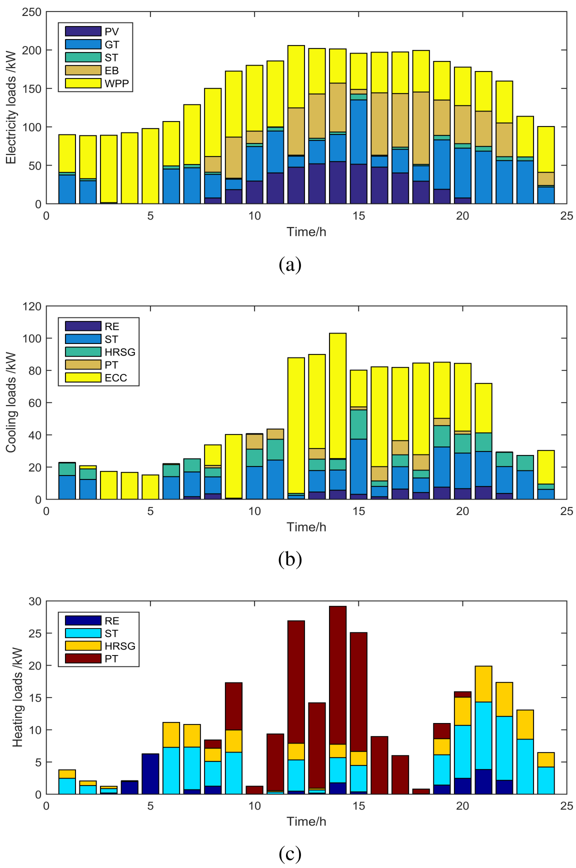

FIGURE 5. Typical summer load of electricity, heating and cooling supply for optimization. (a): Electricity load. (b): Cooling load. (c): Heating load.

D. THE SATISFACTION OF OPTIMIZATION RESULTS

Fig.6. shows the satisfaction of each objective and the satisfaction of fuzzy optimization on a typical winter day. It can be seen from the figure that the operating cost has most impact on the D-CCHP system operation and scheduling during 0:00-5:00, 6:00-8:00 and 21:00-24:00. In winter, the heating demand is high and it is satisfied by burning natural gas and RE. The system needs to purchase electricity from the grid while RE is operating, and natural gas consumption and purchasing electricity would increase the operating cost. During 8:00-9:00 and 10:00-21:00, the energy efficiency is most important. PT could meet part of heating demand, and DER could meet the electricity demand, the system needn't purchase electricity, the energy efficiency will reduce fast by burning natural gas. Although burning natural gas and electricity purchased from the grid will produce greenhouse gas, but most of the electricity comes from DER, the total CO_2 emissions are low.

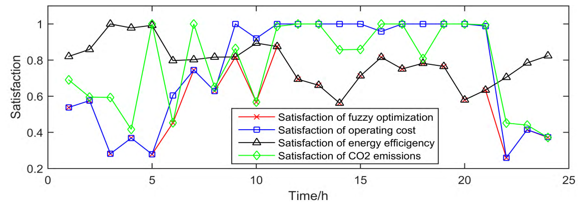

FIGURE 6. Satisfaction of each objective on the typical winter day.

Fig.7. shows the satisfaction of each objective and the satisfaction of fuzzy optimization on a typical summer day. In summer, the cooling demand is high and the heating demand is low. The cooling demand is mainly met by ECC. During 2:00-5:00 and 6:00-7:00, the system could sell some electricity to grid for reducing total cost, and during 7:00-9:00, 15:00-18:00, 19:00-21:00 and 23:00-24:00, the system purchases much electricity that will increase operating cost. Therefore, the operating cost has a greatest impact on system. The CO_2 emissions are most important for system during 0:00-1:00 and 11:00-12:00, because GT plays an important role in electricity, cooling and heating demand at that time, the natural gas consumption is too much, also system would purchase much electricity from grid at 11:00-12:00, the CO_2 emission will increase. At other times, the cooling and heating demand is mainly meet by PT and ECC, and the electricity is mainly meet by PV and WPP, the CO_2 emissions and operating cost are too low, and the energy efficiency has the greatest impact.

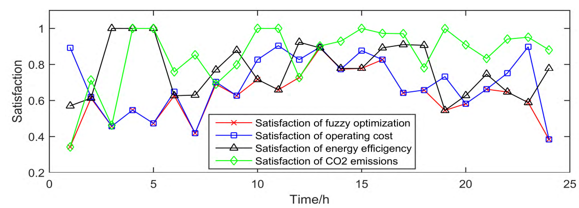

FIGURE 7. Satisfaction of each objective on the typical summer day.

Table 4 is the values of the three objective functions obtained by single-objective optimization and multi-objective optimization on the typical winter and summer day. From the table, we can see that in f_1 optimization, the energy efficiency is 18.5% and 17.2%, which is lower than the maximum energy efficiency on the typical winter and summer day, respectively. And the CO_2 emissions are 24.7% and 21.3%, which are higher than the minimum CO_2 emissions. In f_2 optimization, compared with the optimal value of f_1 and f_3, the operating cost has increased by 19.6% and 15.7%, and the CO_2 emissions have increased by 21.4% and 22.7%. The values of the operating cost and energy efficiency obtained by f_3 optimization differ from optimal values of f_1 and f_3 by

TABLE 4. The value of each objective functions by using single-objective and multi-objective optimization.

(a) On typical winter day.

	f_1(dollars)	f_2	f_3(kg)
f_1 Optimal	51.366	0.7252	630.32
f_2 Optimal	61.459	0.8902	613.45
f_3 Optimal	64.487	0.7554	505.32
Multi-objective optimization	57.195	0.7933	570.67

(b) On typical summer day.

	f_1(dollars)	f_2	f_3(kg)
f_1 Optimal	127.758	0.7386	1156.32
f_2 Optimal	147.459	0.8923	1033.54
f_3 Optimal	156.694	0.7114	842.32
Multi-objective optimization	139.697	0.7957	953.99

25.5% and 15.1% in winter, 22.8% and 20.3% in summer. In the single-objective optimization, the other two objectives are quite different from the optimal solution, and the performance of the system cannot be optimal. The results of multi-objective optimization in winter differ from the three single-objective optimal results by 11.3%, 10.9%, and 12.9%, and in summer, they are 9.3%, 10.8%, and 13.3%. It can be seen that multi-objective optimization coordinates the three objectives of operating cost, energy efficiency and CO_2 emissions to optimize system performance.

E. ALGORITHM PERFORMANCE COMPARISON

In order to verify the superiority of the proposed method in multi-objective optimization, it is compared with the Particle Swarm Optimization [37] (PSO) and Genetic Algorithm [20] (GA). Fig.8 demonstrates the comparison of the convergence rate, and it can be seen that the PSO and GA reach the best solution at 200 and 208 iterations respectively, while the WCA algorithm reaches the best solution at 180 iterations. The satisfaction obtained by WCA is 1.7% higher than PSO, 2.1% higher than GA. Table 5 shows the comparison of the best solutions for the three algorithms in terms of multi-objective optimization. From Table 5, we have that the proposed method detects the best solution with improvement compared with other algorithms. In summary, the proposed method could offer better scheme.

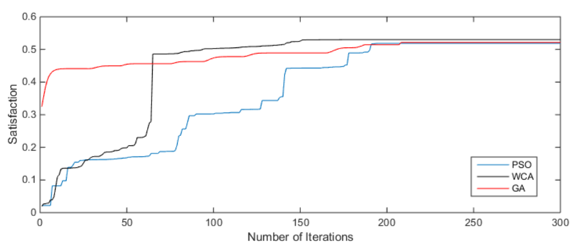

FIGURE 8. Convergence rate for the satisfaction using PSO, WCA and GA.

TABLE 5. Comparison of results using three algorithms.

	f_1(dollars)	f_2	f_3(kg)
WCA	57.195	0.7933	570.57
GA	59.948	0.7927	575.21
PSO	59.102	0.7925	604.2

VI. CONCLUSION

This paper proposes a D-CCHP system model consisting of three subsystems, namely DER generation system, thermal system and CCHP subsystem. In order to obtain the optimal operation strategy and analyze the corresponding performance, this paper selects the typical winter and summer days (July 15th and January 15th) as the representative, and establishes a multi-objective optimization model considering energy efficiency, operating cost and CO_2 emissions. Based on the fuzzy theory, the multi-objective problem is transformed into a single-objective problem based on the maximum fuzzy satisfaction method, and then WCA is used to optimize the single-objective function. The following conclusions are obtained:

(1) The D-CCHP system can improve energy efficiency and reduce CO_2 emissions.

(2) Compared with the single-objective optimization model, the multi-objective optimization model balances the result of each objective, and can better reflect the operating state of the D-CCHP system. The system performance is obviously improved by the multi-objective optimization.

(3) The maximum fuzzy satisfaction method can reduce the difficulty in solving the optimization model. Compared with the three different algorithms, WCA is superior to other algorithms in terms of global optimization, the number of iterations, accuracy, and convergence speed.

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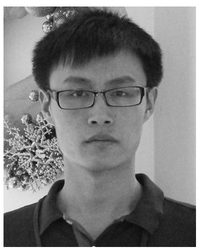

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