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A Reliability-Based Optimization Model for Operational Management of CCHP System

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ABSTRACT. The combined cooling, heating, and power (CCHP) system has been explored extensively due to its ability to reduce the carbon dioxide emission and improve the energy-utilization efficiency. However, the existing studies associated with CCHP system rarely concerned for the system reliability, although it was capable of enhancing the stability of operational patterns. In this study, predefined reliability coefficient (i.e., r) was incorporated innovatively into a CCHP system optimization model in order to examine the influence of reliability level on model results. A variety of solutions under different r values were obtained, which effectively reflected the trade-off between system economy and reliability. The CCHP system of a hotel in Shanghai, China, was used as a study case for demonstration. The generated results indicated that the system cost would increase with the increase of reliability level; meanwhile, the user requirements in cooling, heating and electricity were ensured greatly. The successful application of proposed optimization model in real case is expected to be a good example for CCHP system management.

Keywords: reliability evaluation, CCHP system, optimization model

1. Introduction

At present, the energy shortage has become main factor restricting the sustainable development of the country; meanwhile, the environmental pollution caused by traditional fossil energy combustion, greenhouse gas (GHG) emissions and extreme weather events are also problems that need to be solved urgently. It is critical to develop a distributed energy system, which used clean energy as raw material and realized the cascade utilization of energy in order to realize the goal of energy conservation and emission reduction. As an environment-friendly and high-efficiency energy system, combined cooling, heating and power (CCHP) system is capable of providing cooling, heating and electricity energy at the same time through utilizing the natural gas as main fuel. Firstly, the system uses natural gas as the main fuel, which releases heat through gas turbine, internal combustion engine or Sterling machine to drive power-generation equipment. Secondly, the waste heat flue gas with the high temperature generated by gas turbine or internal combustion engine will be provided to lithium bromide refrigeration unit and waste heat boiler to generate the cold energy and heat energy, respectively. When the quantity of cold, heat and electricity generated by the system is not enough to meet the users' needs, some auxiliary equipment such as exhaust heat boiler and electric chiller would be enabled; meanwhile, the insufficient electric quantity will be supplied through the power grid purchase.

Under rational structure composition and suitable operation strategy, the CCHP system exhibited the characteristics with the low cost and high-utilization efficiency. Therefore, it has been widely promoted and applied at the worldwide scale (Lin et al., 2007; Wei et al., 2007; Gu et al., 2010). For instance, Lin et al. (2007) analyzed the Sterling heat engine cycle and thermal efficiency and concluded that the combined cold, heat and electricity supply based on Sterling heat engine is a prospective choice for the energy system development in our country. Wei et al. (2007) studied the structure of CCHP system with micro gas turbine as the core and compared the economy between the combined and separate supply system through a practical case. It is proved that the combined supply system has great advantages. Gu et al. (2010) introduced the characteristics and system configuration of the co-generation system, and analyzed the research development of the triple generation system in the aspects of waste heat recovery and utilization, evaluation criteria of the triple generation system, optimization design and energy saving analysis. How to realize rational system structure design and generate optimal system operation pattern is a hotspot at present. Based on the operational research theory and the deep understanding of the system elements and structure, an optimization model aimed at the maximum revenue, minimum energy consumption and pollutants discharge was established and used in many countries and regions (Kong et al., 2005; Tan et al., 2014; Li et al., 2016). For example, Tan et al. (2014) proposed the multi-objective optimization model of CCHP system and appli-

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ed it for meeting the energy requirements in Guangdong higher Education Center. The best operation scheme under various system objectives is provided finally. Li et al. (2016) proposed a fuzzy optimization method, which calculates the weight values of different objectives in CCHP system more reasonably and converts the multi-objective optimization model into single-objective one in order to find the optimal strategy. Kong et al. (2005) used a linear programming model to determine the output strategy of gas turbine, absorption refrigerator and auxiliary boiler in CCHP system in order to minimize the total energy cost of the system. The above results show that based on the predetermined model objectives such as improving the energy efficiency and maximizing the economic benefit according to the optimization algorithm, the CCHP system owns a good economy while meeting the load needs of users, which lays a good foundation for future research. However, the cooling and thermoelectric load was fluctuated in a large range subjected to the influence of external meteorological factors (including temperature, humidity and radiation) and users themselves (including scale change and production activity arrangement). If it is not concerned in the design and implementation of the system operation scheme, it will have a great impact on the reliability of the system operation and will lead to poor user experience. The reliability analysis and evaluation of the CCHP system can effectively identify the potential adverse factors, avoid system-failure risk and promote the system performance. On the contrary, if the system reliability was not incorporated into the decision-making process, it means that the operation scheme is unreasonable and the user requirements may not be fully met, which leads to the reduction of system economy and user-satisfaction degree. Currently, the research related to the reliability of CCHP system is limited, and most of them are the qualitative analysis (Cui and Tang, 2017; He et al., 2019). For example, He et al. (2019) proposed a Monte Carlo method combined with important sampling method to evaluate the system reliability. Cui and Tang (2017) proposed an optimization model of the CCHP system with the objective function of minimum operating cost. Finally, the optimal operational patterns in different periods were identified and their respective reliability was evaluated.

Above studies were incapable of realizing the quantitative analysis to the system reliability level, which led to the difficulty in the decision maker's scheme design. Therefore, taking a five-star hotel in Shanghai as an example, this paper developed a CCHP optimization model based on reliability evaluation, which defines and quantifies reliability into a series of numerical values and effectively combines it into constraint conditions. Based on the predetermined reliability level, the facilities' output and economic costs of CCHP system under different reliability conditions are identified. Compared with the traditional optimization model, the proposed model can effectively provide more stable energy supply services for users with the costs as low as possible.

2. Case Study

2.1. Background

This study selected a hotel in Shanghai as the research object. The hotel is located in Pudong New area, covering an area of 53,330 m^2, with 32 floors, a total height of 99.15 meters, a landscaping ratio of 50% and 400 ecological parking spaces. Shanghai, as the economic center of coastal areas and Yangtze River Basin in China, has high passenger throughput. Pudong New area is located in the east of Shanghai. It is the intersection of the middle point of China's coast and the mouth of the Yangtze River. It has convenient transportation, broad hinterland and superior geographical location. For the above reasons, the hotel has the characteristics of large passenger flow, high occupancy rate (average monthly occupancy rate as high as 60%), a variety of energy-type requirements (including electrical, heating, cooling and domestic hot water), and high energy consumption (average cooling, heating and power consumption of 1,002.77, 1,542.83 and 1,112.03 MJ/m^3), as well as high reliability requirements for energy supply. Due to its subtropical monsoon climate, the four seasons in Shanghai are very distinct, where they are performed as warm in spring, hot in summer, cool in autumn and cold in winter, respectively. There is obvious cooling demand in the summer and heating demand in the winter. Conversely, the heating and cooling demand in other two seasons (i.e., spring and autumn) are relatively consistent. Therefore, the peak period of the hotel's cooling demand is mainly concentrated in the June to September of summer; the peak period of heating demand occurs in December to February of winter. Other months, including March, April, May, October and November, are uniformly defined as the transition season. Normally, the variation range of the hotel's annual power supply load demand is slight. However, when it comes to summer, the required power reaches the peak value owing to the long service time of air conditioners. Figure 1 shows the monthly average cooling and heating load of the hotel, which varies over the twelve seasons. Therefore, the acts that accurately estimate the energy demand of the hotel and continuously adjust the operation strategy of the CCHP system are capable of meeting the energy demand and reducing the system cost.

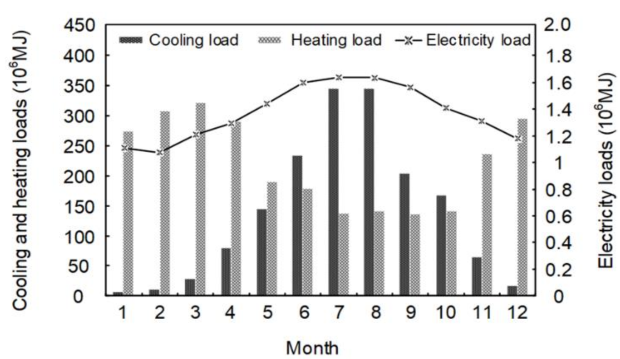

Figure 1. Schematic diagram of the hot, cold, and power load of a hotel in Shanghai.

The typical day in August of the summer is selected for analysis, since its average temperature is the highest and thus owns the largest cooling demand. The cold and hot load required for this typical day is shown in Figure 2. As shown in Figure 2, the cold demand of the hotel is highly volatile throughout the day, where the peak and valley periods occur at 14 o’clock in the afternoon and 5 o’clock in the morning, being 964,363.5 and 150,333.8 MJ, respectively. Compared with the cold load, the variations in electrical and thermal load are relatively stable. Among them, the highest and lowest electric demands were 2,930.2 kWh at 12 am and 1,272.4 kWh at 4 am, respectively. The highest and lowest heating demand were 404,323.8 MJ at 21 pm and 17,166.8 MJ at 3 am, respectively. Similarly, the typical day in March of the winter is considered as the representative with the highest heating requirement. Figure 3 described its energy requirements, where the heating demands varies from 195,620.4 MJ at 19 pm to 663,453.35 MJ at 3 am. The cooling energy is required only from 9 am to 22 pm all day, and the maximum cold load is 86,569.7 MJ at 12 am; the changes in the electric load is from 852.6 kWh at 4 am to 2,351.4 kWh at 17 pm. Correspondingly, the typical day in October of the transition season is chosen due to the smallest difference between cold and heat loads. The cold and heat energy required for this typical day is shown in Figure 4. As can be seen from it, the cold demand fluctuates between 14,535.9 MJ at 0 am and 508,756.2 MJ at 13 pm. The extreme values for the electric demand are 2497.7 kWh at 17 pm and 1029.0 kWh at 3 am, respectively. The highest and lowest heat requirements are 290,028.9 MJ at 17 pm and 62,346.2 MJ at 3 am, respectively.

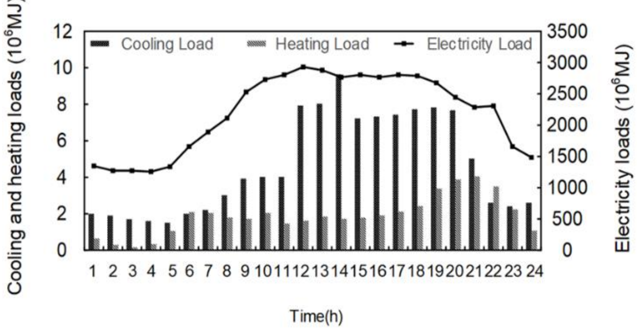

Figure 2. The cold, heat, and electricity load in a typical day of summer.

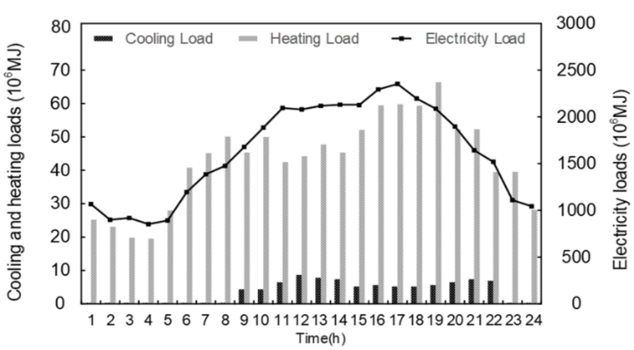

Figure 3. The cold, heat, and electricity load in a typical day of winter.

2.2. System Description

CCHP system is a typical distributed energy system which realizes the cascade utilization of energy and the integrated provision of cooling, heating and power. It is accompanied with the low cost, high energy-utilization efficiency and low pollutants emission. Figure 5 shows the structure and operation mechanism of CCHP system of targeted hotel. As shown in Figure 5, the hotel’s CCHP system consists of five parts: gas turbine, waste heat boiler, gas-fired boiler, heat exchange and lithium bromide refrigerator, respectively. Firstly, the gas turbine burns natural gas in its combustion chamber and converts part of fuel’s heat energy into the electric energy. At the same time, the waste heat flue gas with the high temperature generated in the conversion process is provided to the absorption chiller unit and the waste heat boiler through the heat recovery system for generating the cooling and heating energy, respectively. Under the context of utilizing the waste heat in priority, the gas-fired boiler is considered as the auxiliary cold and heat source when the cooling and heating capacity provided through above process are not enough to meet the users’ needs, where the flue gas generated by the gas-fired boiler directly provides the heat energy or was utilized by the absorption chiller to generate cool energy. As for insufficient electricity load, it can be supplemented by the power purchase of public power grid.

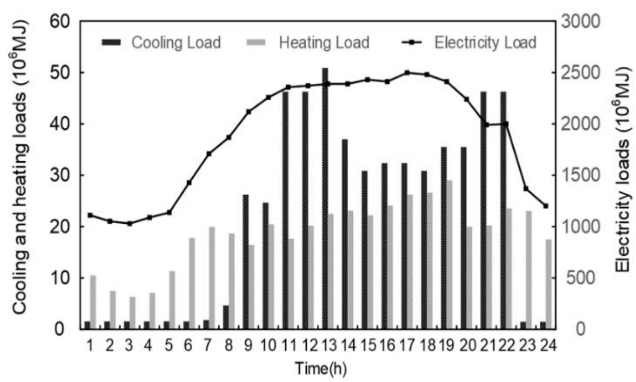

Figure 4. The cold, heat, and electricity load in a typical day of transition.

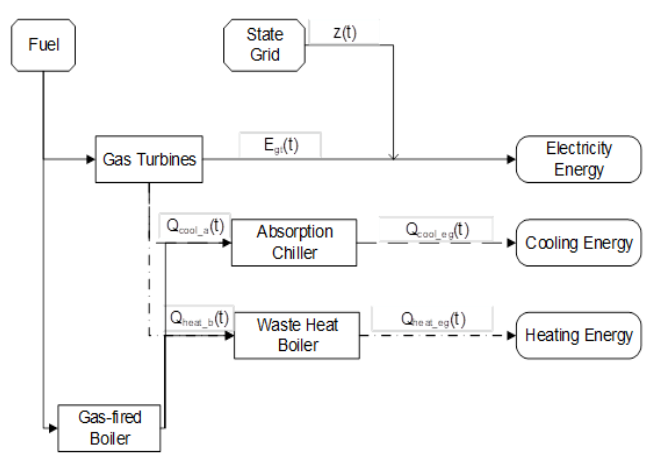

Figure 5. The structure and components of the CCHP system.

3. Methodology

3.1. The Formulation of CCHP System Operation Optimization Model

As mentioned in the section "Introduction", the operation strategy of CCHP system has a vital impact on the system performance, so it is of great practical significance to optimize the operation strategy and achieve the system targets. In this paper, the minimization of total system cost is considered as the objecttive function, which included the operation cost, equipment maintenance cost and environmental cost. Major constraints are the balance between energy supply and demand and the limitations in the equipment capacity.

3.1.1. Objective Functions

$$Minimize\ f = f_1 + f_2 + f_3$$

$$f_1 = \sum_{t=1}^{n} C_{ng}(t) \times \left[V_{ng}(t) + \alpha \times V_{ng\_a}(t) + \beta \times V_{ng\_b}(t)\right] + \sum_{t=1}^{n} \delta \times C_{ele}(t) \times E_{sg}(t)$$

$$f_2 = C_{gt}\sum_{t=1}^{n} E_{gt}(t) + \mu C_b \sum_{t=1}^{n} Q_b(t) + \mu C_{ac}\sum_{t=1}^{n} C_a(t)$$

$$f_3 = \sum_{j=1}^{m} V_j \times Q_j \tag{1a}$$

where f_1 is annual operational cost; f_2 is annual maintenance cost; f_3 is annual environmental cost; n is the number of hours throughout the year, being 8,760; $C_{ng}(t)$ is the price of natural gas during the t period, ¥/m³; $V_{ng}(t)$ is the amount of natural gas consumed by the gas turbine during the t period, m³; α is 0 or 1, where it equals to 1 when the recovery waste gas is allocated to the absorption refrigerator, otherwise 0; $V_{ng\_a}(t)$ is the natural gas quantity consumed by the absorption refrigerator during the t period, m³; β is 0 or 1, the value "1" occurs at that the natural gas is utilized by the waste heat boiler, otherwise take 0; $V_{ng\_b}(t)$ is the amount of natural gas supplemented to the gas-fired boiler during the period, m³; δ is 0 or 1, where it is 1 when the system buys electricity from the public power grid, otherwise 0; $C_{ele}(t)$ is the electricity selling price of the public power grid during the t period, ¥/kWh; $E_{sg}(t)$ is the electricity requirement at the t period, kWh; C_{gt} is the maintenance cost of the gas turbine, ¥/kW; $E_{gt}(t)$ is the electricity-generation amount of the gas turbine at t period, kW; μ is the conversion coefficient between MJ and kWh, i.e. 1 MJ = 0.278 kWh; C_b is the maintenance cost of the boiler, ¥/kW; $Q_b(t)$ is the heat supply of the boiler at t period, kW; $C_{ac}(t)$ is the maintenance cost of the absorption refrigerator, ¥/kW; $C_a(t)$ is the cooling capacity of absorption refrigerator at t period, kW; m is the type of the pollutants; V_j is the charge cost caused by the discharge of j pollutants, ¥/kg; Q_j is the discharge magnitude of j pollutant, kg. Objective function (1a) represents total cost of CCHP system, which includes annual operating cost f_1, annual maintenance cost f_2 of main equipments, and annual environmental cost f_3. Among them, f_1 included two parts: (i) operational cost of two facilities, i.e., $C_{ng}(t) \times [V_{ng}(t) + \alpha \times V_{ng\_a}(t) + \beta \times V_{ng\_b}(t)]$ and (ii) the purchase cost of the electricity from the power grid, i.e., $\delta \times C_{ele}(t) \times E_{sg}(t)$; f_2 mainly includes annual maintenance costs of gas turbine, boiler, and lithium bromide refrigerator (i.e., $C_{gt}\sum_{t=1}^{8760} E_{gt}(t)$, $\mu C_b \sum_{t=1}^{8760} Q_b(t)$, and $\mu C_{ac}\sum_{t=1}^{8760} C_a(t)$); f_3 is the total charge of emission discharge $\sum_{j=1}^{m} V_j \times Q_j$.

3.1.2. Constraints

(i) Constraints of equipment capacity:

$$E_{gt}(t) = y(t) \times P_{gt} \times t \tag{1b}$$

$$V_{ng}(t) = \frac{\lambda \times E_{gt}(t)}{\eta_{gt} \times H_u} \tag{1c}$$

$$Q_{eg}(t) = \frac{\lambda \times E_{gt}(t) \times (1 - \eta_{gt} - \eta_{loss})}{\eta_{gt}} \tag{1d}$$

$$Q_{cool\_eg}(t) = Q_{eg}(t) \times x(t) \times \eta_{a\_hr} \times COP_a \tag{1e}$$

$$V_{ng\_a}(t) = \frac{Q_{cool\_a}(t)}{COP_a \times \eta_{a\_c} \times H_u} \tag{1f}$$

$$Q_{heat\_eg}(t) = Q_{eg}(t) \times (1 - x(t)) \times \eta_{b\_hr} \tag{1g}$$

$$V_{ng\_b}(t) = \frac{Q_{heat\_b}(t)}{\eta_{b\_c} \times H_u} \tag{1h}$$

where $E_{gt}(t)$ is the power generation provided by the gas turbine during the t period, kWh; P_{gt} is the rated power of gas turbine, KW; $y(t)$ is the operational state of gas turbine in t period, where the gas turbine runs at full load with $y(t) = 1$; conversely, $y(t) = 0$ means that the gas turbine stops running; $V_{ng}(t)$ is the amount of natural gas consumed by the gas turbine during the t period, m³; λ is the conversion coefficient between kWh and MJ, i.e., 1 kWh = 3.6 MJ; Hu is the calorific value of natural gas, MJ/m³; η_{gt} is rated power generation efficiency of gas turbine; $Q_{eg}(t)$ is the stem amount extracted from the gas turbine during the t period, MJ; η_{loss} is the heat-loss efficiency of gas turbine; $Q_{cool\_eg}(t)$ is the cooling amount produced by the absorption refrigerator through using the steam extracted from the gas turbine during the t period, MJ; η_{a_hr} is the heat recovery efficiency of absorption refrigerator; COP_a is the refrigeration coefficient of absorption refrigerator; $x(t)$ is the allocation ratio of the recovery steam between absorption refrigerator and boiler, where the condition $x(t) = 1$ occurs at all steam sourced from the gas turbine is allocated to the absorption refrigerator; $x(t) = 0$ means that all steam enters into the boiler; $V_{ng\_a}(t)$ is consumed natural gas volume of boiler when the cooling amount provided by CCHP system is not enough to meet the needs of the user, m³; $Q_{cool\_a}(t)$ is the capacity of absorption refrigerator in t period, MJ; η_{a_c} is the combustion efficiency of the absorption refrigerator; $Q_{heat\_eg}(t)$ is the heat amount produced by the boiler through using the steam extracted from gas turbine during the t period, MJ; η_{b_hr} is the operation efficiency of boiler; $V_{ng\_b}(t)$ is consumed natural gas volume of boiler when the heating amount provided by CCHP system is not enough to meet the needs of the user, m³; $Q_{heat\_b}(t)$ is the heat provision of boiler in t period, MJ; η_{b_c} is the combustion efficiency of boiler. Constraint (1b) calculates the electricity-generation amount of gas turbine; constraint (1c) reflects the relationship between the electricity generation and natural gas consumption of gas turbine; constraint (1d) provides recovery heat flue gas amount with the high temperature released by gas turbine; constraint (1e) determines the cooling amount generated by the absorption refrigerator through using the steam extracted from the gas turbine; constraint (1f) estimates the consumed natural gas amount for the supplement of the cooling amount; constraint (1g) reflected the relationship between heat generation amount of boiler; constraint (1h) estimates the consumed natural gas amount and generated heat of supplemental combustion.

(ii) Constraints of energy balance:

$$E_{gt}(t) + z(t) = E(t) \tag{1i}$$

$$z(t) < E(t) \tag{1j}$$

$$Q_{cool\_eg}(t) + Q_{cool\_a}(t) = Q_{cool}(t) \tag{1k}$$

$$Q_{cool\_a}(t) < Q_{cool}(t) \tag{1l}$$

$$Q_{heat\_eg}(t) + Q_{heat\_b}(t) = Q_{heat}(t) \tag{1m}$$

$$Q_{heat\_b}(t) < Q_{heat}(t) \tag{1n}$$

where $z(t)$ is purchased electricity amount sourced from the public grid, kWh; $E(t)$ is the electric requirement of users at t period, kWh; $Q_{cool}(t)$ is required cooling amount at t period, MJ; $Q_{heat}(t)$ is required heating amount at t period, MJ. The constraints (1i), (1k) and (1m) regulate the balance of electric, cold and heat requirement and their respective supply, respectively. Constraint (1j), (1l), and (1n) require that purchased electricity amount, supplementary cooling and heating amount should be lower than the required amount of users, respectively.

(iii) Constraints of facilities' capacity:

$$E_{gt\_\min} \le E_{gt}(t) \le E_{gt\_\max} \tag{1o}$$

$$Q_{ac\_\min} \le Q_{cool\_eg}(t) \le Q_{ac\_\max} \tag{1p}$$

$$Q_{rec\_\min} \le Q_{heat\_eg}(t) \le Q_{rec\_\max} \tag{1q}$$

where E_{gt_min} and E_{gt_max} represent the minimum and maximum electricity output of gas turbine during t period, respectively, kWh; Q_{ac_min} and Q_{ac_max} are the minimum and maximum cold output of absorption refrigerator during t period, respectively, MJ; Q_{rec_min} and Q_{rec_max} are the minimum and maximum heat output of boiler during t period, respectively, MJ; The constraints (1o) to (1q) regulate the range of the output of gas turbine, absorption refrigerator and boiler, respectively.

3.2. The Incorporation of Reliability Theory into the Optimization Model

The investigated results of targeted hotel (as shown in the section 2.1) demonstrated that the electric, cooling and heating requirements own the large variation trend, which leads to the difficulties in generating rational operational pattern of CCHP system and potential imbalance between energy supply and demand. Therefore, it is necessary to incorporate the reliability estimation of CCHP system into the optimization model developed in the section 3.1. In this study, the reliability coefficient r_i is predefined to reflect the reliability level, where i = 1, 2, 3 represents the type of the user demand. Equations (2) describe the reliability measures associated with the electric, cooling and heating provisions:

$$P\left\{E_{facility}(t) \ge E(t)\right\} \ge r_1 \tag{2a}$$

$$P\left\{Q_c(t) \ge Q_{cool}(t)\right\} \ge r_2 \tag{2b}$$

$$P\left\{Q_h(t) \ge Q_{heat}(t)\right\} \ge r_3 \tag{2c}$$

where $E_{facility}(t)$ is the total electricity amount provided by the system and the power grid, which equals to $E_{gt}(t) + z(t)$; $Q_c(t)$ is the supplied cooling amount of the system, MJ; $Q_h(t)$ the supplied heating amount of the system, MJ. Referring to Hu and Cho (2014), it can be seen that three types of energy requirements at t time are independent of each other and approximately follow the normal distribution as follows:

$$E(t) \sim N(\mu_1, \sigma_1^2) \tag{2d}$$

$$Q_{cool}(t) \sim N(\mu_2, \sigma_2^2) \tag{2e}$$

$$Q_{heat}(t) \sim N(\mu_3, \sigma_3^2) \tag{2f}$$

Based on existing data information of the user's energy demand, the mean value μ and standard deviation δ involved in the normal distribution are estimated. According to the stochastic optimization theory, the in Equations (2a) to (2c) are transformed their respective equivalents, being (2g) to (2i), respectively:

$$E(t)=\mu_1(t)+\phi^{-1}(r_1)\times\sigma_1(t) \tag{2g}$$

$$Q_{cool}(t)=\mu_2(t)+\phi^{-1}(r_2)\times\sigma_2(t) \tag{2h}$$

$$Q_{heat}(t)=\mu_3(t)+\phi^{-1}(r_3)\times\sigma_3(t) \tag{2i}$$

where φ^{-1} is the inverse function of standard normal distribution. The Equations (2g) to (2i) represent the electrical, heating and cooling amounts provided by system at different reliability levels, which is incorporated into the constraints (1i), (1k) and (1m) in the traditional optimization model in order to reduce the failure risk of CCHP system. Finally, the operational schemes under various reliability levels were obtained, which effectively reflected the trade-off between system economy and reliability.

In this study, the reliability-based optimization model for the CCHP system is coded and solved through software LINGO 12.0. This is mainly due to the facts that it owns many advantages, such as user-friendly interface, easy-to-edit language and a series of common equations and functions. The hardware facilities are listed as follows: (1) Operation System: Microsoft Windows 10; (2) CPU: Intel® Core™ i5-4210H @ 2.90GHz; (3) RAM: 4GB. And the calculation time for solving this optimization model is within the few minutes.

3.3. Data Collection and Parameter Analysis

The main components of the CCHP system are the gas turbines, lithium bromide refrigerator and boilers, respectively. Table 1 describes their performance parameters. The maintenance cost of the facilities is a major expenditure, which effectively enhances their safety and reliability. Many factors, including regional disparity, operators' experience and technical background and facilities' service time, would affect the repair and maintenance cost. In this study, based on the literature review (Gamou et al., 2002; Ruan et al., 2009; Yang et al., 2009; Zhou, 2014; Brown et al., 2015), designed unit maintenance cost of the main equipment is reflected in Table 1. The document "Regulations on the Administration of the Collection and Use of Sewage Charges", which has been implemented since 2003 in China, established the legal status of "pollution charge". Currently, the estimation of pollutant-discharge fees is mainly based on the expert survey method, willingness to pay method and alternative method for pollutant cost. According to local pollutant discharge standards, the fees charged by different pollutant discharges are determined through the pollutant cost substitution method, which are also shown in Table 1.

4. Result Analysis and Discussion

4.1. Result Analysis

Tables 2 to 4 demonstrate the output of main system equipments in the typical day over three seasons generated by reliability-based CCHP system optimization model, respectively. Referring to previous studies (Wang and Singh, 2008; Cho et al., 2009; Mago and Chamra, 2009; Ren et al., 2010; Zhou et al., 2013), in this study, the reliability level is designed as 0.85, 0.90 and 0.95, respectively. It can be seen that different reliability levels will lead to a variety of operational scheme.

Table 1. Parameters Associated with CCHP System

Category	Parameter	Value
Gas turbine	Rated power P_{gt_n}	270 MW
	Power generation efficiency η_{gt}	30%
	Heat loss efficiency η_{loss}	8%
	Maintenance costs	0.03 ¥/kWh
Absorption chiller	Rated power P_{EC_n}	800 MW
	Coefficient of performance COP_a	1.2
	Generator combustion efficiency η_{a_c}	85%
	Maintenance costs	0.0008 ¥/kWh
Waste heat boiler	Rated power P_{REC_n}	900 MW
	Combustion efficiency η_{b_c}	85%
	Maintenance costs	0.00216 ¥/kWh
Economic parameters	Electricity price of peak period	0.98 ¥/kWh
	Electricity price of flat period	0.61 ¥/kWh
	Electricity price of valley period	0.31 ¥/kWh
	Natural gas prices	2.74 ¥/m^3
Parameters related to pollutants discharge	Discharge amount of pollutant SO_2	11.6 kg/10^6 m^3
	Charged cost of pollutant SO_2	1.00 ¥/kg
	Discharge amount of pollutant NO_x	0.0062 kg/10^6 m^3
	Charged cost of pollutant NO_x	2.00 ¥/kg
	Discharge amount of pollutant CO_2	2.01 kg/$10^6$$m^3$
	Charged cost of pollutant CO_2	0.01 ¥/kg
	Discharge amount of pollutant CO	0 kg/10^6 m^3
	Charged cost of pollutant CO	0.16 ¥/kg

4.1.1. Electric Supply

According to the definition and measure of the system reliability, as the increase in the reliability level, users' requirements in the electricity, cool and heat amount would increase. Correspondingly, the energy output of major equipment also increases. For example, as the reliability level increases from 85 to 95%, average power outputs of gas turbines throughout the day of summer are 2,201, 2,395 and 2,573 kWh, respectively. Similarly, those of gas turbines throughout the day of winter are 1,687, 2,057 and 2,312 kWh, respectively. The electricity-generation amounts of transitional season were 1,964, 2,263 and 2,447 kWh, respectively. In fact, not only the reliability level exerts the influence on the operational scheme, but also the variations in the user's requirements at various time points. For example, in the summer, the minimum user demand occurs at 4 pm, leading to the minimum output of gas turbine. As the reliability level increases from 85 to 95%, the electricity output is 1,307, 1,621 and 2,073 kWh, respectively. Conversely, in the summer, the maximum user demand occurs at 12:00, leading to

Table 2. Operational Pattern of CCHP System in a Typical Day of the Summer Season

Time	Operation Loads in a Typical Summer Day																	
	r = 85%						r = 90%						r = 95%					
	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f
1:00	1400	0	8688	199775	0	67186	1737	0	10776	247798	0	83336	2221	0	13784	316951	0	106592
2:00	1323	0	8211	189829	0	30069	1641	0	10185	235461	0	37297	2099	0	13027	301171	0	47706
3:00	1323	0	8211	168982	0	17853	1641	0	10185	209603	0	22145	2099	0	13027	268097	0	28325
4:00	1307	0	8109	158662	0	34298	1621	0	10058	196801	0	42542	2073	0	12865	251723	0	54414
5:00	1389	0	8620	147727	0	110410	1723	0	10692	183239	0	136951	2204	0	13676	234375	0	175169
6:00	1724	0	10698	197765	0	218001	2139	0	13270	245304	0	270405	2700	35	16753	313981	0	345866
7:00	1966	0	12197	217112	0	212832	2438	0	15129	269302	0	263994	2700	419	16753	347054	0	337667
8:00	2196	0	13628	300224	0	186522	2700	24	16753	372544	0	231359	2700	785	16753	481186	0	295924
9:00	2630	0	16320	391341	0	178535	2700	562	16753	488903	0	221452	2700	1473	16753	630016	0	283253
10:00	2700	139	16753	401330	0	211893	2700	821	16753	501831	0	262829	2700	1804	16753	646553	0	336176
11:00	2700	216	16753	401330	0	152694	2700	917	16753	501831	0	189400	2700	1926	16753	646553	0	242255
12:00	2700	347	16753	807833	0	168669	2700	1080	16753	1006051	0	209214	2700	2135	16753	1291485	0	267599
13:00	2700	293	16753	818256	0	191690	2700	1012	16753	1018980	0	237769	2700	2048	16753	1308021	0	304124
14:00	2700	177	16753	986185	0	178535	2700	869	16753	1227276	0	221452	2700	1865	16753	1574446	0	283253
15:00	2700	216	16753	734871	0	185582	2700	917	16753	915550	0	230194	2700	1926	16753	1175728	0	294434
16:00	2700	177	16753	745294	0	198738	2700	869	16753	928479	0	246511	2700	1865	16753	1192264	0	315305
17:00	2700	216	16753	755717	0	219880	2700	917	16753	941407	0	272736	2700	1926	16753	1208801	0	348848
18:00	2700	199	16753	786987	0	251828	2700	896	16753	980194	0	312364	2700	1900	16753	1258411	0	399535
19:00	2700	84	16753	797410	0	351432	2700	753	16753	993122	0	435911	2700	1717	16753	1274948	0	557560
20:00	2542	0	15775	782175	0	402643	2700	453	16753	973011	0	499432	2700	1333	16753	1249224	0	638809
21:00	2378	0	14753	507563	0	420497	2700	249	16753	631118	0	521578	2700	1072	16753	811920	0	667134
22:00	2400	0	14889	256113	0	363647	2700	276	16753	319393	0	451063	2700	1107	16753	413201	0	576941
23:00	1724	0	10698	239457	0	233035	1737	0	13270	297019	0	289053	2700	35	16753	380128	0	369719
24:00	1543	0	9574	261428	0	111819	1641	0	11875	324271	0	138699	2448	0	15189	414765	0	177406

Note: The terms *a*, *b*, *c*, *d*, *e* and *f* represent the model results, being the outputs of gas turbine, purchased electricity amounts, the outputs of absorption chiller, supplementary cooling amount, the outputs of gas-fired boiler and supplementary heating amount, respectively.

Table 3. Operational Pattern of CCHP System in a Typical Day of the Winter Season

Time	Operation Loads in a Typical Winter Day																	
	r = 85%						r = 90%						r = 95%					
	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f
1:00	1109	0	911	0	5557	256015	1376	0	1130	0	6893	317558	1760	0	1446	0	8816	406178
2:00	935	0	911	0	4552	235492	1160	0	1130	0	5646	292101	1484	0	1446	0	7222	373617
3:00	956	0	911	0	4669	200929	1185	0	1130	0	5791	249230	1516	0	1446	0	7407	318782
4:00	887	0	911	0	4271	199174	1100	0	1130	0	5298	247052	1407	0	1446	0	6777	315997
5:00	927	0	911	0	4505	286131	1150	0	1130	0	5588	354912	1471	0	1446	0	7148	453958
6:00	1243	0	911	0	6328	417785	1542	0	1130	0	7850	518214	1972	0	1446	0	10040	662832
7:00	1441	0	911	0	7474	461850	1788	0	1130	0	9270	572871	2287	0	1446	0	11858	732742
8:00	1535	0	911	0	8011	512981	1903	0	1130	0	9937	636293	2435	0	1446	0	12710	813863
9:00	1745	0	10828	34279	0	471476	2165	0	13431	42520	0	584812	2700	69	16753	54811	0	748015
10:00	1960	0	12159	32948	0	519916	2431	0	15082	40868	0	644895	2700	409	16753	54811	0	824866
11:00	2178	0	13516	54191	0	441336	2700	2	16753	67229	0	547427	2700	756	16753	90666	0	700197
12:00	2162	0	13416	76617	0	459636	2682	0	16640	95035	0	570125	2700	730	16753	126087	0	729229
13:00	2203	0	13667	67527	0	496234	2700	32	16753	83958	0	615521	2700	794	16753	112063	0	787295
14:00	2215	0	13742	62986	0	471476	2700	47	16753	78419	0	584812	2700	814	16753	104979	0	748015
15:00	2211	0	13717	40412	0	541444	2700	42	16753	50387	0	671599	2700	807	16753	69124	0	859022
16:00	2385	0	14797	43888	0	617871	2700	258	16753	56039	0	766397	2700	1083	16753	76353	0	980276
17:00	2445	0	15174	38955	0	621100	2700	333	16753	50387	0	770403	2700	1180	16753	69124	0	985399
18:00	2284	0	14169	39960	0	616794	2700	132	16753	50387	0	765062	2700	923	16753	69124	0	978568
19:00	2170	0	13466	45219	0	689991	2692	0	16703	56089	0	855855	2700	743	16753	76353	0	1094698
20:00	1972	0	12235	55472	0	543597	2446	0	15176	68806	0	674269	2700	428	16753	90666	0	862438
21:00	1709	0	10602	66126	0	543597	2119	0	13150	82022	0	674269	2700	11	16753	104979	0	862438
22:00	1579	0	9798	62283	0	410120	1959	0	12153	77255	0	508706	2505	0	15545	98814	0	650671
23:00	1154	0	911	0	5814	405382	1431	0	1130	0	7212	502830	1831	0	1446	0	9224	643154
24:00	1085	0	911	0	5417	287372	1346	0	1130	0	6719	356452	1722	0	1446	0	8594	455927

Note: The terms a, b, c, d, e and f represent the model results, being the outputs of gas turbine, purchased electricity amounts, the outputs of absorption chiller, supplementary cooling amount, the outputs of gas-fired boiler and supplementary heating amount, respectively.

Table 4. Operational Pattern of CCHP System in a Typical Day of the Transition Season

Time	Operation Loads in a Typical Transition Day																	
	r = 85%						*r* = 90%						*r* = 95%					
	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f
1:00	1155	0	7167	9070	0	109000	1432.7	0	8889	11250	0	135202	1832	0	11370	14390	0	172933
2:00	1094	0	6787	9451	0	77992	1356.6	0	8417	11722	0	96739	1735	0	10767	14994	0	123737
3:00	1070	0	6640	9597	0	65776	1327.4	0	8236	11903	0	81587	1698	0	10535	15226	0	104356
4:00	1131	0	7021	9217	0	73763	1403.4	0	8708	11432	0	91494	1795	0	11138	14622	0	117028
5:00	1183	0	7342	8895	0	117927	1467.7	0	9107	11032	0	146274	1877	0	11649	14112	0	187096
6:00	1485	0	9215	7023	0	184643	1842.0	0	11429	8710	0	229027	2356	0	14619	11142	0	292943
7:00	1777	0	11028	8008	0	207194	2204.5	0	13679	9933	0	257000	2700	120	16753	13449	0	328722
8:00	1942	0	12052	36099	0	194039	2409.2	0	14949	44777	0	240683	2700	382	16753	59641	0	307851
9:00	2202	0	13661	259011	0	171018	2700	30.845	16753	321464	0	212127	2700	793	16753	415851	0	271326
10:00	2348	0	14568	241867	0	212832	2700	212.12	16753	301324	0	263994	2700	1025	16753	390090	0	337667
11:00	2451	0	15211	465744	0	183233	2700	340.76	16753	579815	0	227279	2700	1189	16753	746300	0	290707
12:00	2466	0	15299	465656	0	210013	2700	358.31	16753	579815	0	260497	2700	1212	16753	746300	0	333194
13:00	2484	0	15416	513690	0	233975	2700	381.70	16753	639542	0	290218	2700	1242	16753	822694	0	371210
14:00	2484	0	15416	369236	0	240083	2700	381.70	16753	460363	0	297794	2700	1242	16753	593512	0	380900
15:00	2527	0	15679	305144	0	231156	2700	434.33	16753	381190	0	286722	2700	1309	16753	492245	0	366737
16:00	2508	0	15562	320938	0	250419	2700	410.94	16753	400636	0	310615	2700	1279	16753	517118	0	397299
17:00	2598	0	16118	320382	0	272501	2700	522.04	16753	400636	0	338005	2700	1421	16753	517118	0	432333
18:00	2579	0	16001	304822	0	276729	2700	498.65	16753	381190	0	343250	2700	1391	16753	492245	0	439041
19:00	2508	0	15562	353412	0	301630	2700	410.94	16753	440917	0	374137	2700	1279	16753	568639	0	478548
20:00	2329	0	14451	354524	0	207664	2700	188.73	16753	440917	0	257583	2700	995	16753	568639	0	329467
21:00	2070	0	12842	468113	0	210483	2567.1	0	15928	580640	0	261080	2700	584	16753	746300	0	333940
22:00	2079	0	12900	468055	0	244781	2578.8	0	16001	580567	0	303622	2700	598	16753	746300	0	388354
23:00	1424	0	8834	6283	0	239613	1765.9	0	10957	7793	0	297211	1832	0	14016	9968	0	380155
24:00	1249	0	7752	7365	0	181824	1549.6	0	9615.3	9135	0	225531	1735	0	12299	11686	0	288470

Note: The terms a, b, c, d, e and f represent the model results, being the outputs of gas turbine, purchased electricity amounts, the outputs of absorption chiller, supplementary cooling amount, the outputs of gas-fired boiler and supplementary heating amount, respectively.

the maximum output of gas turbine, being 2,700 kWh under three reliability levels, respectively. Moreover, purchased electricity amounts are 347, 1,080 and 2,135 kWh due to the supplied amounts of the gas turbine are incapable of meeting user's requirement. It can be seen that the operational mode of CCHP system ensures the full utilization of gas turbine in priority; the electricity purchase is considered as the supplementary way. This is because the natural gas was utilized by the gas turbine for the electricity supply; meanwhile, the recovery waste gas, as the byproduct, is absorbed by the absorption refrigerator or boiler to generate the cooling or heating amounts. This energy-cascade utilization way is beneficial to realize the minimization of total system cost compared to the way purchasing the electricity from the public grid. Similar situation also appears at other two seasons. For example, in the winter, the minimum electric demand occurs at 4 pm, as the reliability level increases from 85 to 95%, the electricity output is 887, 1,010 and 1,407 kWh, respectively. The electricity requirement during this period is satisfied by the gas turbine and there is no need to purchase electricity from the grid. Conversely, under the maximum demand at 17 pm, the user's demand is satisfied by both gas turbine and public grid. As the reliability level increases from 85 to 95%, the output of gas turbines is 2,445, 2,700 and 2,700 kWh, respectively; the purchasing electricity is 0, 333 and 1,180 kWh, respectively.

4.1.2. Cold Supply

In the typical day of the summer, the high cold demand is satisfied by both absorption chiller and supplemental combustion facility, because the limited capacity of the gas turbine is incapable of supplying enough the waste gas to the absorption refrigerator for generating sufficient cooling amount. For example, the maximum user demand occurs at 14 pm, and along with the reliability level increased from 85 to 95%, the absorption chillers reach their maximum level, being 16,753 MJ. The gap can be filled by the boiler, where its cooling provisions were 986,185, 1,227,276 and 1,574,446 MJ, respectively. The absorption refrigerator is preferred for its characteristic of the low cost, where it utilizes the recovery waste gas as the raw material. Compared with those in the summer, the cold demands in the winter would remarkably decrease, leading to various energy provision patterns. For instance, the minimum demand at 23:00 ~ 8:00 is satisfied by the absorption refrigerator solely. Conversely, during the period from 9:00 to 22:00, user's cold demand exceeds the maximum capacity of the absorption refrigerator, the insufficient cooling amount was provided by the boiler's combustion. As the reliability level increased from 85 to 95%, the peak value of supplementary cooling amount appeared at 12:00, being 76,617, 95,035 and 126,087 MJ, respectively. In the transition season, the large cooling demand is satisfied by both two equipments. The peak demand at 11:00 ~ 22:00 needs more outputs of the boiler. At the three levels of 0.85, 0.9 and 0.95, the peak value of the supplementary amount appeared at 13 pm, being 529,106, 656,295 and 839,447 MJ, respectively.

4.1.3. Heat Supply

The limited capacity of gas turbine leads to the fact that the recovery waste gas utilized by absorption chiller and boiler is not enough to meet both cooling and heating demand. The determination of allocation proportion between two equipments is mainly dependent on the provision cost of cold and heat energy, where more waste gas is allocated to the absorption refrigerator in priority for generating the cooling amount. Correspondingly, the heat demand is mainly satisfied by the gas-fired boiler, rather than the waste heat boiler. For example, the high cooling demand in typical day of the summer leads to the fact that the gas-fired boiler is used to generate the heating energy. As the reliability level increased from 85 to 95%, the maximum heat supply of the boiler appeared at 21 pm, being 420,497, 521,578 and 667,134 MJ, respectively. Similarly, in the transition season, at the three levels of 0.85, 0.90 and 0.95, the peak value appeared at 19 pm, being 301,630, 374,137 and 478,548 MJ, respectively. On the contrary, the winter has the lowest cooling demand that the heat supply was satisfied by both two boilers. For example, as the reliability level increased from 85 to 95%, the maximum heat supply of the gas-fired boiler appeared at 8:00, being 8,001, 9,937 and 12,710 MJ, respecttively. Moreover, heating supply amounts from waste heat boiler are 512,981, 636,293, 813,863 MJ, respectively.

4.1.4. System Cost

In fact, the introduction of the reliability level not only affects the decision variables, but also the objective value, where the increase in the reliability level means that the high energy demand would occur, resulting in the high system cost. In addition, the difference in the energy demand over three seasons also leads to the large variation in the system cost corresponding to the typical day in three seasons. It is clear that the system costs of the summer and winter are high than those of the transition season. For example, as the reliability level increased from 85 to 95%, total system cost of typical day in the summer was 20.63, 25.67 and 32.93 × 10^6 RMB, respectively. The total system cost in the winter was 13.12, 16.28 and 20.89 × 10^6 RMB, respectively. As for the transition season, the system cost was 12.57, 15.63 and 20.08 × 10^6 RMB, respectively. With the increase in the reliability level, the variation in the system cost reflected the trade-off between system economy and reliability. The high reliability means user's energy demand was completely satisfied, although the high system cost was expected. Conversely, the low reliability was accompanied with the low system cost; however, the imbalance between the energy supply and demand may occur.

4.2. Discussion

In order to better reflect the advantage of the reliability estimation, the traditional optimization model of this CCHP system was formulated for comparison purpose. A variety of energy provision patterns under predetermined reliability levels at the typical day over three seasons were provided to the dispatcher, which ensured the balance between energy supply and demand; meanwhile, more decision spaces are beneficial to the generation of suitable schedule pattern according to the practical situation. On the contrary, the single solution is provided by the traditional model, where the operational cost in the summer, winter and transition season was 19.84, 12.62 and 12.09 × 10^6 RMB, respectively. Moreover, under the context of instable energy requirement, the low system cost may lead to the fact that the user's requirements were not satisfied and affect their experience (Xu et al., 2018; Wang et al., 2020).

However, proposed optimization model still needs to be improved, especially in following three aspects. Firstly, a more reasonable definition and estimation of reliability was necessary, which is capable of enhancing the stability of system operation and the satisfactory degree of the customers. Secondly, many interactive relationships involved in the CCHP system, including the consumed gas amount was how to correspond to the electricity generation and recovered waste gas quantity, were oversimplified subjected to limited data information and acquaintance in entire CCHP system. How to comprehensively and accurately describe the complex relationships associated with the CCHP system and incorporated them into the optimization model is very important. Thirdly, the on-off operation of gas turbine is an important step during the entire process of CCHP system. The energy consumption amounts and operational efficiency during this period are different from those in stationary phase, where they normally are calculated by aid of the piecewise function. Some successfully applications incorporating the on-off operation into the operation optimization models of the CCHP system have been reported recently, which provided well demonstration (Yong et al., 2008; Park et al., 2014; Cao and Dai, 2016). Therefore, the proposed optimization model could also reflect the influences of on-off operation on system economy and operational strategy in the future but additional computational efforts are required.

Finally, many system parameters are affected by socioeconomic, engineering, meteorological and environmental factors, and thus exhibit the uncertain characteristics. In the future, some uncertain optimization techniques, including random, fuzzy and interval optimization methods, should be incorporated into model to handle more-complex problems.

5. Conclusion

In this study, a reliability-based operation optimization model was developed for supporting the operational management of CCHP system, which had the advantages in following two aspects. In terms of methodology, the reliability measure was innovatively incorporated into traditional optimization model and effectively ensured the balance between energy supply and demand under the context of large fluctuation in users' energy requirement. In terms of practical application, a five-star hotel in Shanghai is taken as an example, which realized the first application of reliability-based optimization model in the CCHP system. A variety of the operational schemes of CCHP system under three reliability levels were provided to the dispatcher, which were capable of offering more stable energy-supply services and evaluating the trade-off between system economy and reliability. As shown in the obtained solutions, it could conclude that with the increase in the reliability level, user's demands in the electricity, cool and heat amounts would also increase, leading to the increase in the system cost. Total system cost was 46.33, 57.58 and 73.90 × 10^6 RMB under three levels from 0.85 to 0.95, respectively. Compared with the objective values and decision variables of reliability-based optimization model, total cost and the output of system facilities sourced from traditional optimization model were reduced. For example, annual total cost of the tradition optimization model is 44.54 × 10^6 RMB. In order to further enhance the accuracy and practicality of proposed model, it is necessary to determine more reasonable definition of reliability and truly reflect the operational situation of CCHP system as possible, such as the introduction of accurate input-output relations, on-off operation and the ramp constraint. Moreover, some uncertain optimization methods should be incorporated into the proposed optimization model for tackling more complex issues.

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