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Thermal Economy Optimization of Distributed Energy System Combining Cooling, Heating and Power Based on Genetic Algorithm

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Abstract:

Optimization of the installed capacity and annual operating hours is one of the valid methods of improving energy efficient and economy performance of distributed energy system. Firstly, a hotel building thermodynamic system combined cooling, heating and power (CCHP) was proposed, which based on the annual energy demand. Multi-object optimization model of CCHP was established by means of combining exergy quantity, construction budget and economic returns. And then, Optimum power, energy supply and annual hours were calculated by adopting Fast- Elitist-Non-Dominated-Sorting-Generic-Algorithm(NSGA). Finally, the effects of the prices of different energy were compared and principles of installation and operation were analyzed.

Keywords: *Natural Gas Distributed Energy System, Combined Cooling, Heating and Power, Exergy, Thermal economy ,Multi-Object Optimization, Generic -Algorithm*

I. INTRODUCTION

Natural gas distributed energy system combined cooling, heating and power (CCHP) supply is one of the most typical forms of distributed energy. The exhaust heat discharged by natural gas power generation is used as energy resource for lithium bromide refrigeration unit or heat ex-changer, which supply cooling or heating to building. Energy cascade use improve the efficiency of fuel greatly. Natural gas distributed energy has been treated as the focus of energy development direction by China recent years. The total capacity of natural gas is planed 50 million kilowatts by 2020. Compared with the traditional coal-fired units, natural gas distributed energy units are more suitable for building or industrial park type energy users [1]. At present, there are many domestic units at preparatory stage. Economy and energy efficiency is the first concern [2], so the size of unit capacity and mode of operation are very important design tasks. In recent years, many scholars have conducted a number of

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preliminary studies on the design, operation and thermal economy of the system, and various technical solutions has been proposed to reduce the cost of CCHP[3-5].

Energy system index evaluation matrix of internal combustion engines, gas turbines, fuel cells, photovoltaic, absorption refrigeration systems, heat ex-changers was build by Zhang Tao, etc. according to the cold and heat load demand, energy prices and equipment technical information [7].The annual cost of the system was the objective function, and the nonlinear integer programming method was used to solve the optimal configuration, operation strategy and evaluation index value of different systems. According to the research conclusion of Lin Ruming, Jin Hongguang, it is considered that the use of exergy efficiency as the evaluation criterion is more reasonable than the thermal efficiency, and this view has also been adopted by other scholars [8] [9].

Optimization of CCHP by intelligent algorithms is another focus of the distributed energy system research. Genetic algorithms was adopted by Longxi Li et al. to optimize the capacity of residential and commercial building CCHP system for the lowest annual cost[10]. Jiangjiang et al. analyzed the economic impact of the price of the product, the investment of the energy system, the service cycle, the profit rate and the running time on the CCHP system by establishing the exergy use model [11].Genetic algorithms was used by Rong Zeng et al. to optimize energy efficiency, CO2 emission reduction and operating time and annual operating costs is adopted as the optimization variables for the CCHP system to optimize the capacity and operation of the unit[12]. In general, the energy efficiency or economy was often adopted to evaluate and optimize the system by most of the current research. In this paper, the natural gas distributed energy unit of a hotel building has been studied as the object, and the economic performance and exergy efficiency have been taken into account. The economic benefits maximization and the exergy utilization maximization generated by unit investment were adopted as multi- objects to optimize. The best combination of get cold, heat, and power unit capacity was calculated by genetic algorithm in this paper, as well as the best equipment running time, which determine the unit capacity and mode of operation.

II. STRUCTURE OF NATURAL GAS DISTRIBUTED ENERGY SYSTEM

The total area of the hotel building is about 80,000 square meters, and is divided into business area and hotel area. There is a large demand for cooling, heating and power load. The power system (including gas generator unit) and waste heat utilization system (including waste heat boiler, heat ex-changer and lithium bromide refrigeration unit) were combined into natural gas distribution energy units, which structure is shown in Figure 1. Gas-fired internal combustion engine power generation capacity in the deduction of the unit power consumption part of the system, the remaining power supply to the user. Cylinder water and high temperature flue gas of 500℃ or more set as heat source of plate heat ex-changer or flue gas hot water type lithium bromide unit. The temperature of cold water in

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generator set is generally 40 ~ 50℃, this part of heat can be considered as heat Water preheat heat source to be used. The final emission temperature of the internal combustion engine is about 100℃ and is discharged directly to the atmosphere. If the waste heat can not meet the building cold and heat load, conventional system of energy supply can be considered as supplement, such as electricity and air conditioning to be added into refrigeration. Electricity from the city power grid can also be provided by the gas generator.

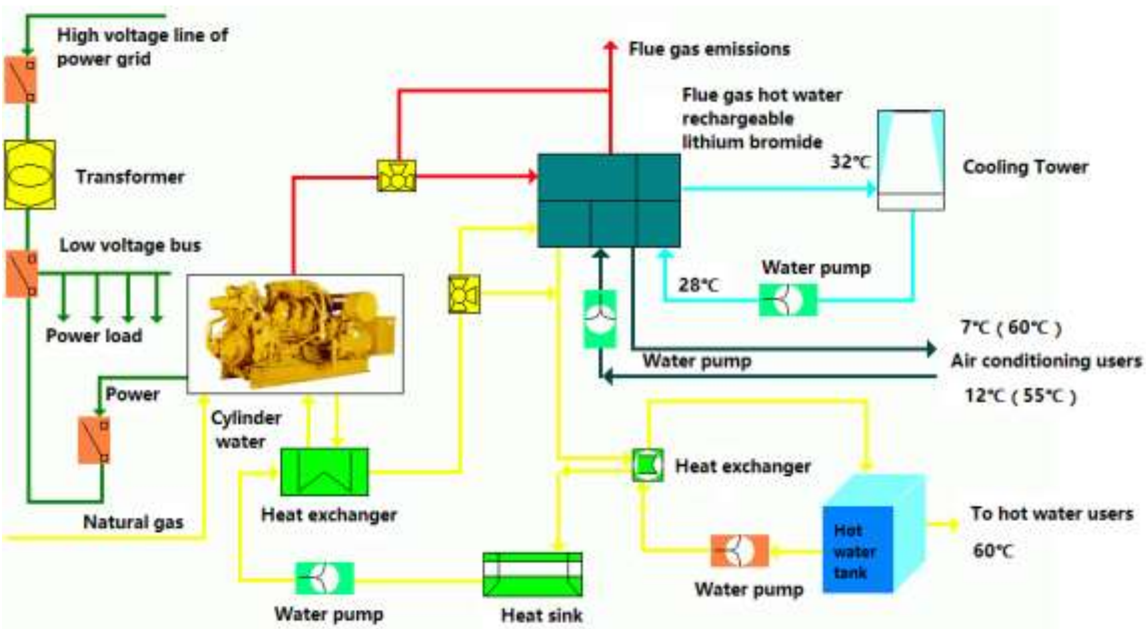

Fig 1: Structure of natural gas distributed energy system

The cooling, heating and power data of the hotel building are shown in Table I. Outdoor climatic conditions and indoor staff activities are the main factors affecting the cold and heat load. The heat load is mainly concentrated in the winter period, which continued about 100 days. The cooling load is mainly concentrated in the summer period, which continued about 120 days. the transition season is mainly concentrated in April to June in the spring ,and October to December in the fall. According to the local annual weather changes, and refer to the actual experience of the same type of hotel experience data. The cooling, heating load curves of the hotel were calculated by DEL software, as shown in Figure 2. All kinds of load changes frequently with the seasons, the magnitude of fluctuation is very obviously. The load demand is mainly concentrated in the daytime period, only a small amount of load produced at night.

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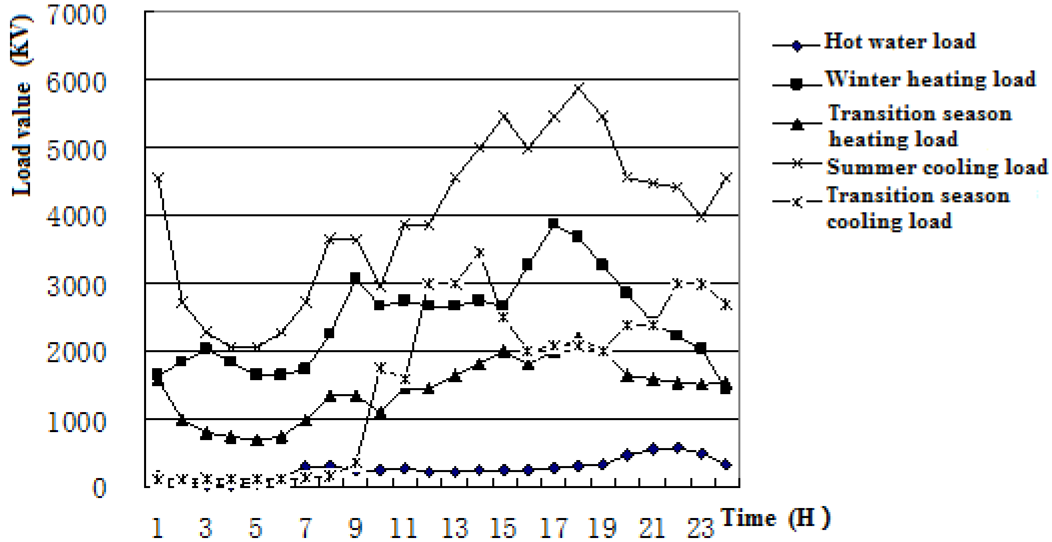

Fig 2: Demand of hotel heating, cooling and power energy load in 24h

III. ENERGY SYSTEM OPTIMIZATION MODEL

3.1 Objective function

If the demand for energy load has been determined, the system can be optimized in different ways. From the point of view of energy utilization, the thermodynamic performance of the system is optimal when the net output and exergy efficiency are maximum. From the economic point of view, it is hoped that the system has the lowest investment cost, the largest revenue, the shortest period of project capital utilization. Taking into account the economic performance and energy efficiency of the system, the thermal and economic indexes are optimized simultaneously. The objective function of the optimization is as follows.

$$\max F_1 = \frac{w + q_0\left(1 - \frac{T_0}{Tg}\right) + q_1\left(\frac{T_0}{T_C} - 1\right) + q_2\left(1 - \frac{T_0}{T_w}\right)}{Z1} \tag{1}$$

$$\max F2 = \frac{Z_2}{Z1} \tag{2}$$

$$Z_1 = (K_1 * w + K_2 * q_1 + K_3 q_0 + K_4 q_2) \tag{3}$$

$$Z_2 = w * t_1 * P_1 + q_1 * t_2 * P2 + q_0 * t_3 * P3 + q_2 * t_4 * P4 - B * P5$$

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(4)

Where, Z1 represents the initial investment in the project,

Z2 represents the annual operating income, yuan,

w —— Power generation

q_0 ——Heating power (kW)

q_1 ——Cooling power (kW)

q_2 ——hot water power(kW)

According to the demand of energy users, hot water power averaged 523.7kW under different seasons within 24 hours .

Tg— Heat source temperature,Tg=1000℃

T0—Ambient temperature, T0=20℃

Tc—Cold source temperature, Tc=5℃

Tw—Hot water temperature, Tc=70℃

The thermal economic coefficient F1 is defined as an indicator of energy efficiency in this paper, which is the ratio of the total output energy consumption of the energy system to the total capital investment. This indicator can indicate the amount of fire available to the system under the unit investment, ie the useful work (kW /RMB yuan) that can be generated by the unit funds. The economic benefit coefficient F2 is defined as the measure of economic returns, which is the ratio of the annual income of the system to the total capital investment. This indicator means the economic return that can be generated by the unit investment. By the optimizing calculation, the thermal economic coefficient F1 and the economic benefit coefficient F2 can be optimized at the same time. According to this principle, the power generation, heating and cooling power of the unit are arranged to meet the dual requirements of energy efficient use and economic benefit.

The initial investment Z1 mainly includes power generation equipment, heating equipment, refrigeration equipment investment. According to engineering experience, distributed energy equipment investment and equipment power approximation desirable linear relationship [13], k1 = 0.45 million yuan/ kW, k2 = 0.2 million yuan/ kW, k3 = 0.1 million yuan/ kw, k4 = 0.05 million yuan/ kW.

Annual operating income Z2 includes power generation, heating income, cooling revenue, and minus the cost of natural gas consumed by energy systems. Reference to the current price of energy in Zhejiang Province of China, the sale price P1 by 1.08 yuan / kWh, for the price of P2 by 0.3 yuan / kWh, heating steam price P3 by 0.4 yuan / kWh, heating water price P4 by 0.4 yuan / kWh, and natural gas price P5 by 3.1 yuan / Nm3.

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3.2 Restrictions

3.2.1 Design variable constraints

In order to determine the size and operation of the energy system unit, the power generation, heating power, cooling power, and running time of CCHP system have been adopted as optimization variables. According to energy demand and climate and other factors, the cooling, heating and power load, as well as supplying time are shown in the TABLE I.

TABLE I. Run time and energy load of heating, cooling and power

ENERGY TYPE	OPERATION TIME (DATE)	DAYS	MAXIMUM LOAD (KW)	MINIMUM LOAD(KW)	AVERAGE LOAD (KW)
HEATING LOAD IN HEATING SEASON	12.01 TO 3.10 OF NEXT YEAR	100	4305	2187	2992
HEATING LOAD IN TRANSITION SEASON	11.10 TO 11.30, AND 3.11TO 4.01	40	1854	820	1200
COOLING LOAD IN REFRIGERATION SEASON	6.01 TO 9.30	120	5654	1317	2200
COOLING LOAD IN TRANSITION SEASON	5.01 TO 5.30, AND 10.01 TO 10.15	45	2466	104	350
POWER LOAD IN REFRIGERATION SEASON	6.01 TO 9.30	120	4065	2187	2450
POWER LOAD IN TRANSITION SEASON	5.01 TO 5.30,AND 10.01 TO 10.15	45	2852	1160	1600
OPERATING DAYS PER YEAR	/	305			

3.2.2 Restrictions

The integrated energy system of the annual average energy efficiency should be greater than 70%, which described in China National Standard CJJ145-2010 clearly.Considering the co-generation industry

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regulations,the ratio of heating to power should be greater than 30% in gas-steam combined cycle co-generation. Therefore, the energy system parameters need to meet the following constraints.

$$\eta_1 = \frac{3.6W + Q_0 + Q_1 + Q_2}{B * Q_L} * 100\% > 70\% \qquad (5)$$

$$\eta_2 = \frac{Q_0 + Q_1 + Q_2}{3.6W} * 100\% > 30\% \qquad (4)$$

$$Q_0 + Q_1 + Q_2 + 3.6W \le B * Q_L \qquad (5)$$

Where,

η_1 —Annual Energy Efficiency of Energy Systems (%)

η_2 —Thermal ratio of energy systems (%)

W—Combined power generation capacity (kWh);

Q_0 —Annual Total Heating supply (MJ);

Q_1 —Annual total cooling supply (MJ);

Q_2 —Annual total hot water supply (MJ);

B —Annual total natural gas consumption (Nm3);

Q_L —Natural gas low calorific value (MJ/Nm3), taken as 36.3MJ/Nm3.

In this paper, the TCG model internal combustion engine is selected to use in the natural gas distributed energy system. The main performance indexes of the internal combustion engine are shown in Table Ⅱ.

TABLE Ⅱ PERFORMANCE INDEX OF GAS INTERNAL COMBUSTION ENGINE

INTERNAL COMBUSTION ENGINE MODEL	UNIT	TCG (2016 V16 C)	TCG (2020 V16)	TCG (2016 V08 C)
ENGINE POWER	kW	415	827	1605
ROTATING SPEED	r*min-1	1500	1500	1500
AVERAGE EFFECTIVE	bar	19	18.9	18.1

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PRESSURE				
EXHAUST GAS TEMPERATURE	°C	442	448	447
EXHAUST GAS FLOW	Kg*h-1	2147	4295	8447
HIGH TEMPERATURE CYLINDER WATER TEMPERATURE	℃	92	92	92
LOW TEMPERATURE CYLINDER WATER TEMPERATURE	℃	44	44	44
ELECTRIC POWER	kW	400	800	1560
CYLINDER WATER RESIDUAL HEAT	kW	222	461	970
FLUE GAS WASTE HEAT	kW	197	402	815
FUEL CONSUMPTION	kW	941	1882	3745
ELECTRICAL EFFICIENCY	%	42.2	42.3	43.3
THERMAL EFFICIENCY	%	45.0	45.2	44.8
TOTAL EFFICIENCY	%	87.2	87.5	87.1

Ⅳ OPTIMIZATION ALGORITHM DESCRIPTION

In the multi-objective optimization, the optimization goals are conflicting and mutually constrained in most cases.The improvement of a certain target performance may lead to the decline of other target performance, and it is impossible to achieve all the objectives at the same time. Compromise, coordinate, balance, and make all the objective functions as optimal as possible. Therefore, for the multi-objective optimization problem, the optimal solution is not a single optimal solution. Usually a solution set is obtained as a result of multi-objective optimization, which is called the Pareto optimal set. Graphical representation of the objective function corresponding to the Pareto optimal set of non-inferior vectors is called the Pareto frontier. Multi-objective optimization is the Pareto optimal solution set by

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multi-objective optimization. Some Pareto optimal solutions are selected from the Pareto optimal solution set according to the actual conditions and the preference of decision makers. Fast non-dominated sorting genetic algorithm with elite strategy (NSGA-II) is one of the most widely used multi-objective optimization algorithms to date. It has the following advantages. it can reduce the computational complexity. Operators are compared and chosen by using crowded distances. Individual diversity is guaranteed to prevent premature convergence.Elite retention mechanism is introduced to help maintain good individuals and improve the overall evolutionary level of the population.

The calculation process of NSGA-II include the following steps. Firstly, the initial population is produced, and then determine whether the algorithm can be withdrawn. Exiting means Pareto optimal solution was obtained. Not quitting means the evolution of the population generation can continue. In the evolutionary process, the choice means selecting the population of the fitness function value of a small number of individuals as a parent, to produce new population.Not all individuals can become a member of the parent. Those individuals whose fitness function is too large will be eliminated due to not adapting to the environment. The selection operation is based on the order value and the crowding distance. Specifically, when the order values of the two individuals are different, the individual with the smaller order value will be selected regardless of the crowding distance. When the order values are the same, individuals with large crowding distances will be selected because the larger the crowding distance is, the better the population diversity.

Ⅴ SIMULATION RESULTS AND ANALYSIS

In the calculation of this paper, the parameters are selected as follows.Population number is 100, crossover probability is 0.4, mutation probability is 0.05, maximum evolutionary algebra is 2000. The resulting Pareto frontier is shown in Fig.3, from which 10 sets of optimal calculation results is chosen and shown in the table Ⅲ.

How to choose a suitable solution in the multi-objective optimal solution set to meet the requirements of optimal design is a problem that must be solved by multi - objective optimization. For the multi-objective optimization of the distributed natural gas CCHP system, a set of more appropriate solutions are selected from all the Pareto optimal solutions obtained in the search space. By optimizing the allocation of cold, heat and power equipment, power and annual heating, annual cooling, annual power generation, and equipment running time, the overall performance of the energy system is best achieved. The results in Fig. 3 shows a set of Pareto optimal solutions, which is obtained by optimizing objective functions F1 and F2. As the coefficient F1 becomes bigger, that means the energy efficiency and the amount of fire available under the unit investment both increase. However at the same time the coefficient F2 and the economic benefit both decrease. the possibility of simultaneous optimization is very small because of the contradictory nature of these two objective functions. Therefore, it is only a

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decision process to select the optimal solution from the Pareto optimal solution set according to the actual requirements of the system. In fact, choosing the optimal solution is a decision process and this process relies heavily on engineering experience and preferences of decision makers. If the energy efficiency was taken as the main target, solution could be selected in the larger F1 program.If the economic benefits was taken as the main target, solution could be selected in the larger F2 program.

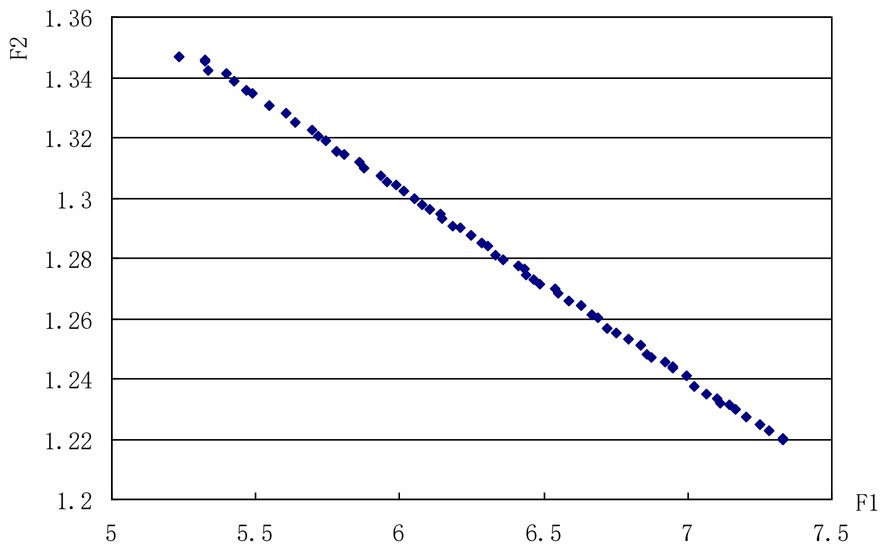

Fig 3: Pareto-optimal front of the NSGA-Ⅱ in the 2000th generation

TABLE Ⅲ. OPTIMIZATION RESULTS

HEATIN (kW)	COOLING(kW)	POWER(kW)	HEATING TIME (DAYS)	COOLING TIME (DAYS)	POWER GENERATION TIME (DAYS)	THERMAL ECONOMIC COEFFICIENT (F1)	ECONOMIC BENEFITS COEFFICIENT (F2)
1297.1	2250.0	1172.6	305	140	165	7.33	1.35
110.7	824.3	1160.6	305	140	165	5.23	1.25
633.5	824.3	1160.6	305	140	165	6.31	1.22
560.6	2250.0	1172.6	305	140	165	5.23	1.35
848.2	2015.2	1160.6	305	140	165	5.49	1.33

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890.1	1674.0	1160.6	305	140	165	5.88	1.31
1198.4	1674.0	1160.6	305	140	165	5.94	1.31
1284.6	1731.6	1160.6	305	140	165	5.86	1.31
1078.4	2124.2	1164.7	305	140	165	5.34	1.34
241.3	1331.6	1160.6	305	140	165	6.33	1.28

By comparing Table Ⅱ with Table Ⅲ, it shows that the optimal calculation results of cooling, heating and operation time of power generation system are the maximum time of actual energy load demand. This indicates that in order to achieve optimal thermal economy of the system, the equipment should be operated as much as possible and the equipment idle time should be reduced. From the optimization of the power of the equipment, it shows that the power generation value is lower limit, which indicates that for the natural gas distributed energy system, it is uneconomical to rely solely on increasing the amount of electricity at the present natural gas price. Unit parameter configuration should follow the principle of energy cascade utilization. Firstly meet the basic needs of the load, the appropriate increase in heating power, mainly rely on increasing the cooling power to replace the traditional electric refrigerator energy consumption. Through the unit cooling, heating and power reasonable distribution, exergy utilization efficiency and economic benefit of unit investment achieve comprehensive optimization.

Ⅵ THERMAL ECONOMY ANALYSIS

6.1 The effect of Energy Prices on Economic Benefit

When the refrigeration price, heating price, electricity price and natural gas price fluctuate with the market, the effect of the price factor on the thermal economic coefficient F1 and the return coefficient F2 of the distributed energy system is shown in figure 4 to figure 7. With the price increases, the coefficient F2 is significantly increased too, which indicates that the system's economic efficiency is improved.The results show that the effect of energy price on F2 is greater than that on F1, which reflect that the price factor mainly affects the future economic benefits of the energy system, and the influence on the initial investment and exergy efficiency of the system is smaller. The Specifically, when the cooling price increased from 0.5 yuan / kWh to 1.5 yuan / kWh, the maximum economic gain coefficient rose from 1.12 to 1.73, and the economic gain increased by 54%. When the heating price from 0.4 yuan / kWh High to 0.8 yuan / kWh, the maximum economic gain coefficient rose from 1.35 to 1.53, and economic gain increased by 13%. When the power generation price increased from 0.7 yuan / kWh to 1.4 yuan /

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kWh, the maximum economic yield coefficient from 1.02 Rose to 1.59, and economic gains increased by 55%. The optimization results show that the cooling price and the power supply price have a significant effect on the economic benefits of the distributed energy system. Unit in the parameter configuration should focus on increasing the cooling supply and running time, which will bring better economic benefits.

Fig. 7 shows that the thermal economic coefficient F1 is basically unchanged as the price of natural gas increases, but the benefit coefficient F2 is obviously reduced. This results indicates that the price of natural gas mainly affect the economic benefits of the energy supply system, but not affect the utilization rate of the exergy. The lower the price of natural gas, the higher the economic benefits of the energy supply system.

6.2 The interplay of thermal, economic, and economic returns

In Fig. 4 to Fig. 7, when the price of cold, heat, electricity and natural gas changes, the coefficient F2 decreases with the increase of coefficient F1.In other words, the exergy utilization rate is relatively small, the price factor on the energy system economy is relatively large. With the increasement of exergy efficiency, the impact of price factors on the economic benefits gradually decrease. When the coefficient F1 takes the maximum value, the F2 value at different prices is the closest. This shows that when energy prices are relatively low, they can also compensate for the effects of low prices through efficient energy efficiency.

However, the effects of three energy prices, such as cold, heat and electricity, on the rate of coefficient F2 decrease are different. In Figure 5, the rate of F2 decrease is the fastest. when F1 increases to the maximum, the three heating prices under the F2 value is close to the same. That is, the impact of heating price factors, the impact of the moment on the F2 has been ignored. In Figure 6 and Figure 7, as F1 increases, the values of F2 are slightly reduced, where the supply price has the least effect on F2 reduction. As can be seen from Fig. 7, when the supply price is 1.4 yuan / kWh, the decrease of F2 is the slowest as F1 increases. This shows that under the high electricity price, the improvement of the utilization of the exergy has little effect on the overall comprehensive benefit of the system. In this case, even if the exergy utilization rate is relatively low, the distributed energy construction unit can rely on the subsidy of high electricity price to obtain high of the economic benefits.

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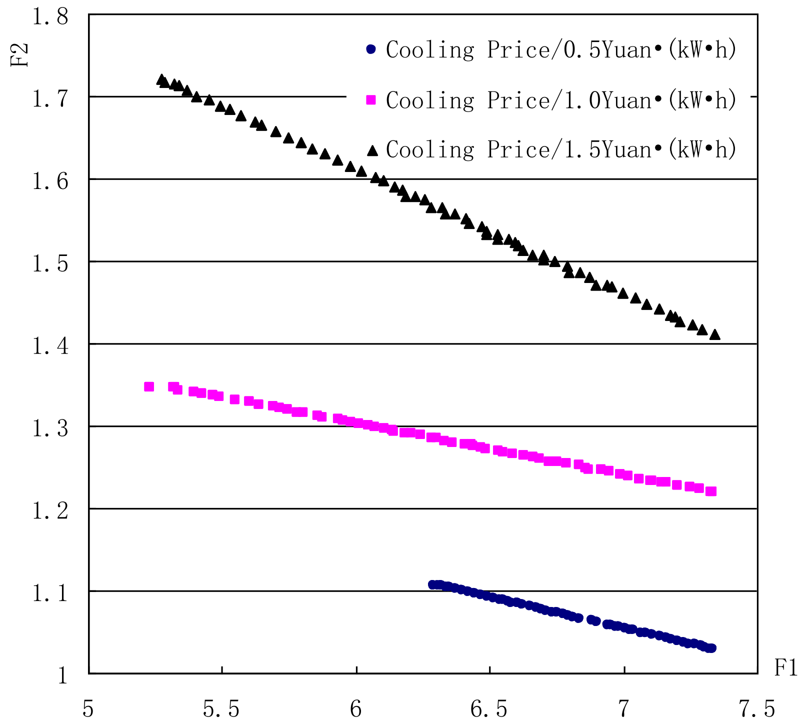

Fig 4: The effect of cooling energy price on optimization result

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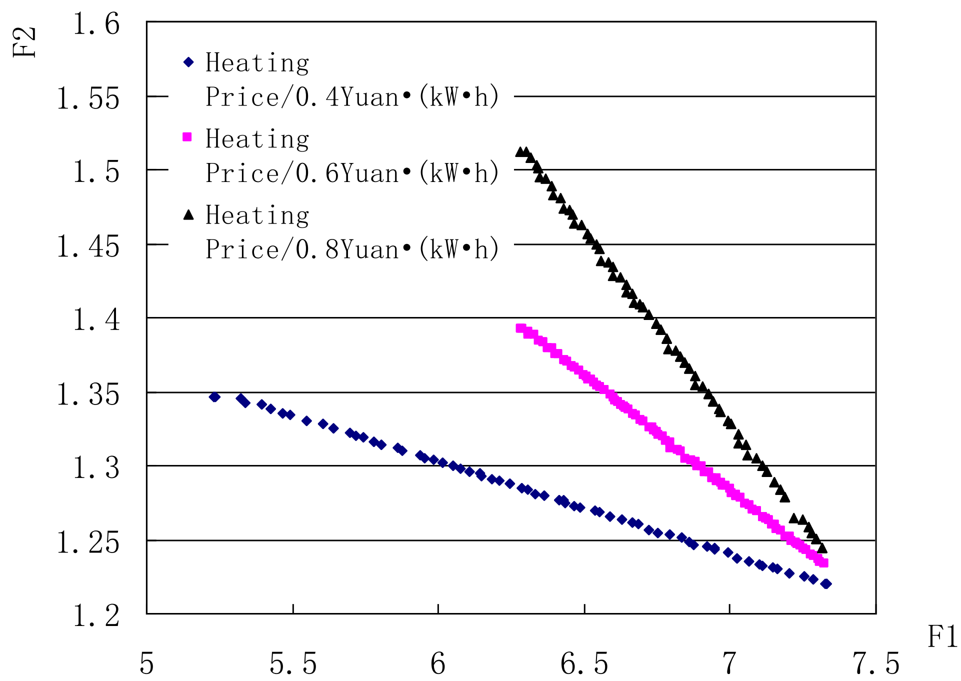

Fig 5: The effect of heating energy price on optimization result

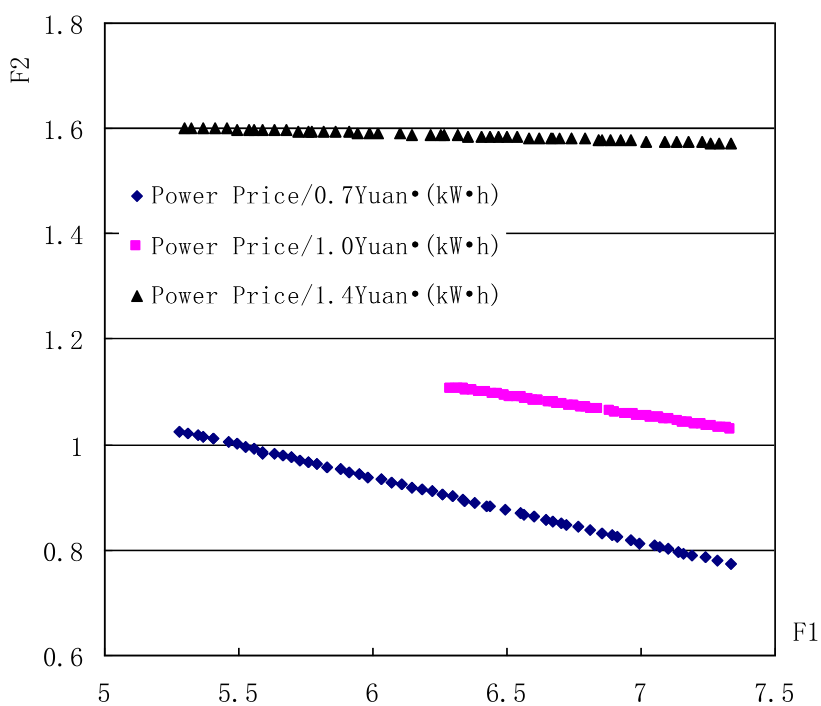

Fig 6: The effect of power energy price on optimization result

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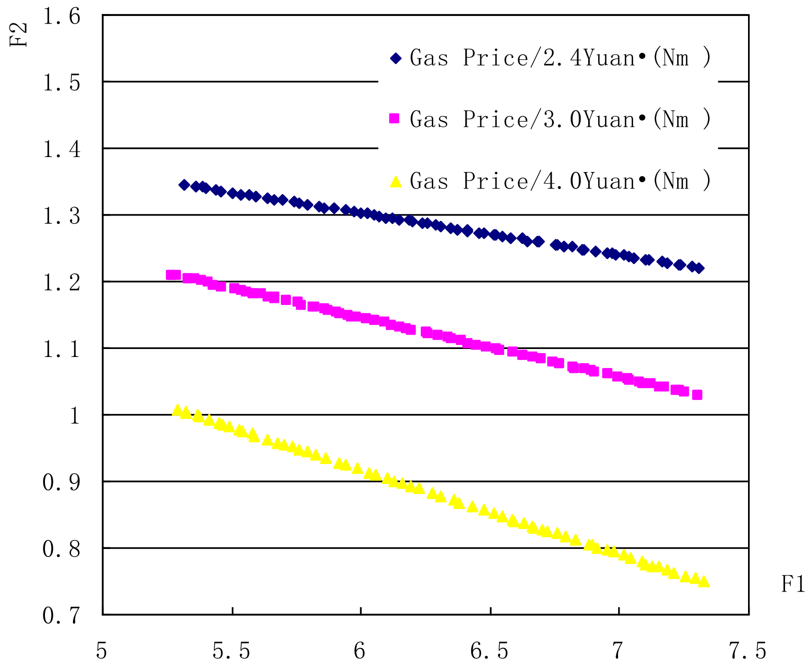

Fig 7: The effect of natural gas price on optimization result

Ⅶ. CONCLUSION

By optimizing the installed parameters and running time of the distributed energy system, the ratio of the income and input of the energy system can reach about 1.3, and the ratio of exergy consumption and investment can reach 7.3kW / Yuan. The economic performance of the system and the utilization efficiency of the energy cascade are optimized.

The calculation results of the load optimization of the refrigeration system are the average of the actual demand, and that of the power generation system is the minimum value of the actual demand. Natural gas distributed energy systems should increase the supply of hot and cold loads, not relying on power generation for profit.

The four energy prices of cooling, heating, power and natural gas significantly affect the investment income ratio of the distributed energy system. If the cooling price is increased to 1.50 yuan / kW, the system of income and investment in the proportion of funds up to 1.8. If the heating price is raised to 0.8 yuan / kW, the proportion of the proceeds and inputs will be up to 1.5. If the power generation price is increased to 1.4 yuan / kW, the proportion of the proceeds and inputs will be up to 1.6. If natural gas is

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reduced to 2.40 yuan / Nm3, the energy system revenue and investment ratio of funds can be increased to 1.35.

With the increasement of exergy efficiency, the impact of price factors on economic returns is gradually declined. In the case of maximum exergy utilization efficiency, the impact of energy prices is minimal. This suggests that energy efficiency can be improved to compensate for the impact of low energy prices on economic returns.

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