

Multi-criteria Comprehensive Optimization of CCHP System

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Abstract. Based on the study of combined cooling, heating and power (CCHP), this page constructs penalty function under the constraints of energy saving and emission reduction. It is a overall optimization system combining energy saving effect, emission reduction effect and economic effect in CCHP system in the form of objective function of least investment. A comparative case study was made between CCHP system and separate supply system in some area. It was indicated in the case study that the energy-saving and emission reduction effect of CCHP system is better than the separate system; CCHP system costs are less than the separate system when the ratio between electricity and natural gas price is greater than 0. 13.

1. Introduction

Combined cooling, heating and power (CCHP) is based on energy cascade utilization for the purpose, which recycles waste heat while generating electricity. It is a set of cooling, heating and power generation integrated system. CCHP system is increasingly recognized as an economic, energy-saving, low-carbon energy system [1]. It is an important part of the development of distributed power supply, which is also the development direction of the electric power industry in the 21st century. CCHP system which has been put into operation reflects the good economic and energy-saving effect. There are also a large number of domestic and foreign relevant theoretical researches. However, few studies combine 3 characteristics, which is used to reflect the superiority of the cogeneration systems compared with the independent systems. This article focuses on integrating all the 3 characteristics in the form of restriction condition and objective function, in order to avoid unilateral research previously and achieve overall optimization.

2. the CCHP programme

Fuel outputs electricity and heat at the same time, through the internal combustion engine, gas turbine or a fuel cell and so on. Electricity is used to supply the electrical load, while t heat generated supplies thermal load through waste heat utilization equipment [2]. When used in non-industrial areas, heat load generally includes heat load in winter, cool load in summer and hot water load. CCHP system can not provide all heat and electricity load, so it has to use the same way as common systems to provide part of the heat and electricity load that CCHP system can not afford. Therefore it often supplies heat source, and purchases electricity from outside grid to meet the load demand. Boiler is used as a supplementary heat, while power system is connected with power grid [3].

2.1 Economic effect theory

Economic effect refers to the effect of saving investment owned by CCHP system in comparison with traditional independent system. System investments are mainly composed of the initial investment and operating costs[4].

2.1.1 The analysis of the economic effect in CCHP system

Initial investment:

$$RMB_{CO} = r (W_{engine} PR_{engine} + W_{c-cool} PR_{c-cool} + W_{c-boiler} PR_{c-boiler}) + RMB_{oil}$$

$$r = \frac{1(1+i)^n}{(1+i)^n - 1} \quad (1)$$

RMB_{CO} ——initial investment of CCHP system; r ——investment recovery factor; W_{engine} ——gas internal combustion engine power generation; PR_{engine} ——the price of gas internal combustion engine; W_{c-cool} ——chiller power; PR_{c-cool} ——the price of chiller; $W_{c-boiler}$ ——auxiliary boilers power; $PR_{c-boiler}$ ——the investment of auxiliary boilers power; RMB_{cA} ——installation fee.

Gas consumption of gas internal combustion engine can be calculated by internal combustion engine power and power generation efficiency.

$$V_{nga} = \frac{W_{engine}}{\eta_{engine} \times HV_{ng}} \quad (2)$$

V_{ngc} ——gas consumption of gas internal combustion engine; η_{engine} ——power generation efficiency; HV_{ng} ——natural gas calorific value

Waste heat recovery of internal combustion engine in CCHP system

$$HR_{engine} = V_{nga} \cdot HV_{ng} \cdot \eta_{hr,engine} \quad (3)$$

Chiller cooling power

$$Repow_{ad} = Heat_{ad} \cdot COP_{ad} \quad (4)$$

Heat load provided by heat exchanger in CCHP system

$$Heat_{hex} = (HR_{engine} - Heat_{ad}) \cdot \eta_{hex} \quad (5)$$

η_{hex} ——Converter efficiency

Gas consumption of auxiliary fuel boiler in CCHP system

$$V_{nga-b} = \frac{Q_{heat-load} - Heat_{hex}}{\eta_{boiler} \cdot HV_{ng}} \quad (6)$$

$$Elc_{chiller} = \frac{Q_{cool-heat} - Repow_{ad}}{COP_{el-chiller-con}} \quad (7)$$

$Q_{cool-heat}$ ——cool load; COP_{el} - chiller - con ——cool coefficient

Power consumption of pumps and wind turbine owned by CCHP system

$$Elc_{pump} = \frac{\max(Repow_{ad}, 0)}{Repow_{ad}} \cdot 0.8 + \frac{\max(Repow_{ad}, heat_{hex}, 0)}{\max(Repow_{ad}, heat_{hex})} \cdot 0.37 \quad (8)$$

Electricity purchased by external public grid

$$Elc_{buy} = Elc_{power-load} + Elc_{chiller} + Elc_{pump} - W_{engine} \quad (9)$$

Operating costs include two parts, operating costs of natural gas and costs of purchasing electricity.

Operating costs of natural gas

$$RMB_{nga} = (V_{nga} + V_{nga-b}) \cdot t \cdot PR_{ng} \quad (10)$$

$$\text{Costs of purchasing electricity: } RMB_{elo} = Elc_{buy} \cdot t \cdot PR_{ng} \cdot EGCR \quad (11)$$

PR_{ng} ——the price of natural gas; RMB_{elo} ——costs of buying electricity; $EGCR$ ——the portion between electricity and natural gas.

$$\text{Total operation cost in CCHP system } RMB_{to} = RMB_{nga} + RMB_{elo} \quad (12)$$

$$\text{Total costs } RMB_t = RMB_{to} + RMB_{co} \quad (13)$$

2.1.2 Economic effect analysis of conventional separate systems of cold, heat and power

Conventional separate system is primarily compressed by the gas boilers and chiller. Heat load is provided by gas boiler which burns natural gas, while cool load is provided by chiller which is driven by electricity through public power grid.

Initial investment

$$RMB_{so} = r(W_{s-boiler}PR_{s-boiler} + W_{s-cool}PR_{s-cool}) + RMB_{sA} \quad (14)$$

Operating cost is derived as follows.

$$V_{ngs} = \frac{Q_{heat-load}}{\eta_{boiler} \times HV_{ng}} \quad (15) \quad Elc_{chiller} = \frac{Q_{cool-heat}}{COP_{el}} \quad (16)$$

Operating costs include two parts, operating costs of natural gas and costs of purchasing electricity. Natural gas cost of operation

$$RMB_{ngs} = V_{ngs} \cdot t \cdot PR_{ng} \quad (17)$$

Electricity cost of operation

$$RMB_{els} = PR_{ng} \cdot EGCR \cdot (ELC_{chiller} + ELC_{power-load}) \quad (18)$$

$$EGCR = \frac{PR_{el}}{PR_{ng}} \quad (19)$$

$$RMB_{ts} = PR_{ng} \cdot EGCR \cdot \left(\frac{Q_{c,load}}{COP_{el}} + ELC_{power-load} \right) \cdot t + \frac{Q_{h,load}}{\eta_{boiler} \cdot HV_{ng}} \cdot t \cdot PR_{ng} \quad (20)$$

Total cost of separated system

$$RMB_t = RMB_{ts} + RMB_{os} \quad (21)$$

$$\text{Cost saving} \quad \Delta RMB = RMB_c - RMB_s \geq 0 \quad (22)$$

2.2 Energy-saving effect analysis

Energy consumption of CCHP

$$E_c = \frac{Q_{heat-load}}{\eta_c^Q} + \frac{ELC_{buy}}{\eta_c^P} \quad (23)$$

η_c^Q ——rated waste heat recovery efficiency; η_c^P ——rated power generation efficiency Energy consumption of conventional separate system

$$E_s = \frac{Q_{heat-load}}{\eta_s^Q} + \frac{ELC_{chiller} + ELC_{power-load}}{\eta_s^P} \quad (24)$$

So, saving energy is

$$\Delta E = [(E_{sf} + E_{sp} \cdot EGCR) - E_{cf}] \cdot PR_{ng} \geq 0 \quad (25)$$

2.3 Emission reduction analysis

Carbon dioxide emissions in CCHP system

$$C_c = \frac{ELC_{buy}}{\eta_T^P} \cdot C_u + \frac{Q_{heat-load}}{\eta_{CF}^Q} \cdot C_f \quad (26)$$

C_f ——carbon dioxide emissions of unit fuel ; C_u ——carbon dioxide emissions of unit power supply

$$C_s = \frac{ELC_{chiller} + ELC_{power-load}}{\eta_T^P} \cdot C_u + \frac{Q_{heat-load}}{\eta_s^Q} \cdot C_f \quad (27)$$

so, carbon dioxide emission reductions

$$\Delta C = (C_s - C_c) \cdot \frac{1}{2} \cdot 49 \cdot a \cdot PR_{ng} \geq 0 \quad (28)$$

2.49 is carbon dioxide emission reduced by standard coal, a is conversion coefficient between natural gas and coal.

2.4 Penalty Function Model

In order to maximize economic of CCHP under constraints of energy saving and emissions mitigation, we build a function model with energy saving and emission reduction in the form of value.

$$\max F = \Delta RMB \quad (29)$$

$$\Delta E = [E_{sf} - E_{cf} + (E_{sp} - E_{cp}) \cdot EGCR] \cdot PR_{ng} \geq 0 \quad (30)$$

$$E_{sf} = \frac{Q}{\eta_s^Q} \quad E_{cf} = \frac{Q}{\eta_c^Q} \quad (31) \quad E_{sp} = \frac{P}{\eta_s^P} \quad E_{cp} = \frac{P}{\eta_c^P} \quad (32)$$

All variables are greater than zero.

According to constraints and objective function, we build penalty function as follows.

$$\min F = \frac{1}{\Delta RMB} + M(\min(0, \Delta E) + \min(0, \Delta C)) \quad (35)$$

$$\Delta RMB = RMB_T + RMB_S \quad (36)$$

$$\min RMB = \{[(V_{ngs} - V_{ngc-e} - V_{ngc-b}) + (ELs_{chiller} + ELs_{power-load} - ELc_{buy}) \cdot EGCR] + RMB_{so} - RMB_{co}\}^{-1}$$

The result of penalty function optimization must first meet that the effect of energy saving and emission reduction in CCHP system is better than that requirements in separate system., and then strive to maximize investment saving. Unknown parameters that enables the economy to achieve the best results can be calculated with certain parameters defined under the conditions of meeting energy saving and emission reduction. Considering the current state and the market price, energy consumption and emissions can be translated into the form of value, which is equivalent to increase investment.

3. Case analysis

We take a community in the north for example. As is shown in figure 1 and figure 2, CCHP system consists of gas engines, Waste heat absorption chillers, heat exchangers, gas boilers, electric compression chillers and other components [5]. electric compression chillers and power grid are regarded as auxiliary facility of CCHP system. Meanwhile, output can quickly make appropriate changes to meet load changes. Cool heat can be produced by gas engine and waste heat absorption chillers as same as electric compression chillers. Heat load can be obtained by recovering the waste heat of the gas engine and can also be provided by the gas boiler. Electricity comes from gas engine or power grid [6].

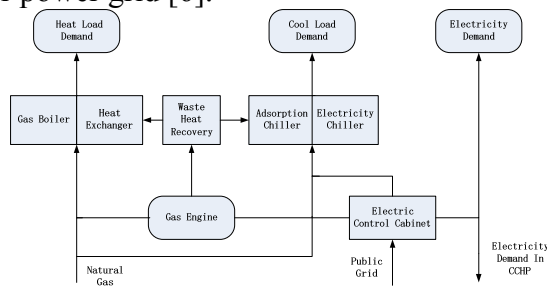


Fig.1 CCHP system

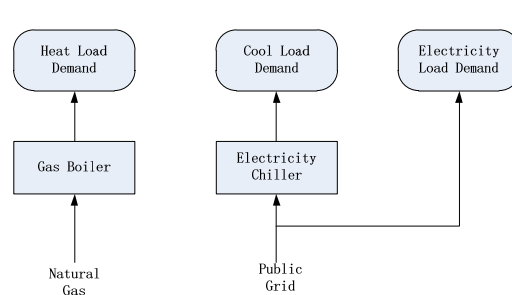


Fig.2 separate system

Selection of calculation parameters for gas turbine: Gas combustion engine power is 2000 kW, refrigeration coefficient of absorption chiller is 5.8, generator combustion efficiency is 85%, combustion efficiency of gas boiler is 85%, electricity chiller refrigeration coefficient is 1.2, generation efficiency of power grid is 30%, waste heat recovery efficiency of Heat recovery boiler and absorption chiller is respectively 77.6% and 69.5%. Initial investment of CCHP system: waste heat absorption chiller is 1 029 yuan/kW, electricity chiller is 971 yuan/kW, Gas turbine is 5533yuan/kW, waste heat boiler is 108kW/yuan. Natural gas calorific value is 10kW·h/m³.

Load in the community is shown in table 1. Economic effect in CCHP system is mainly reflected in its operating costs. Although the initial investment of equipment in CCHP is higher than that in separate system, operating costs of CCHP system are far lower than that of the separate system, which reflects its economy. The contrast between CCHP and separate system is shown in table 2.

Table 1 cool、 heat and electricity load in some area

Program	Load in winter	Load in summer	Load in spring and autumn
Operation hours/h	2640	3672	2448
Electricity load/kW	1400	1400	1400
Cool load/kW	0	3200	0
Heat load/kW	2906	960	960

Table 2 investment costs of CCHP and separate system ten thousand yuan

System	CCHP system	Separate system
Annual initial investment	173	62.8
Annual maintenance costs	55.9	43.4
Annual operating energy costs (gas)	659.3	143.9
Annual operating energy costs (electricity)	86.9	889.6
Annual investment	975.1	1139.7
Pay back period	6.5	

Take various parameters into equations, results come out

$$min F = \frac{1}{912.73 \cdot PR_e - 112.606 \cdot PR_{ng} - 16.46}$$

According to the above formula, power consumption of CCHP system reduces, and the natural gas consumption increases. So the higher electricity price, the lower price of natural gas makes CCHP system a better economic result. It needs to find an optimal ratio between electricity price and natural gas price within an acceptable range of the market.

Traditional cooling not only increases the burden of the large power grid, but also raises high operation cost of users. CCHP utilizes waste heat from generation electricity to heat and cool, which increases energy efficiency and its economic benefit, while energy supply cost is decreased. As long as the ratio between electricity and gas in winter is higher than 0.1233, that in summer is higher than 0.1116, that in spring and autumn is higher than 0.1159, the economic effect in CCHP system is always better than that in separate system, namely that the ratio is above 0.124.

Table 3 consumption of natural gas and electricity

festival	winter	summer	Spring and autumn
Natural gas consumption in separate system/ $N \cdot m^3$	349.933	548.8705	115.4818
Natural gas consumption in CCHP system/ $N \cdot m^3$	462.5399	115.4818	228.0878
Natural gas consumption difference/ $N \cdot m^3$	-112.606	-433.389	-112.606
Electricity consumption in separate system/ $kW \cdot h$	1400	4600	1400
Electricity consumption in CCHP system/ $kW \cdot h$	487.27	960	428.8
Electricity consumption difference/ $kW \cdot h$	912.73	3383.2	971.2

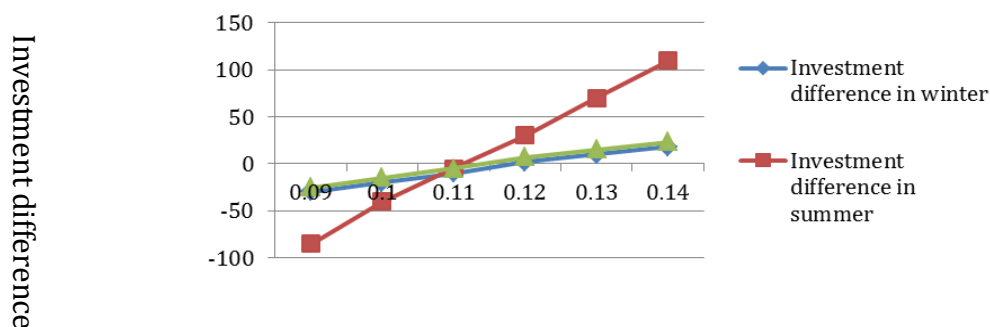


Figure 3 effect of EGCR on the investment difference between CCHP and separate system

4. Conclusion

In summary, this paper constructs penalty function under the constraints of energy saving and emission reduction. It is a overall optimization system combining energy saving effect, emission reduction effect and economic effect in CCHP system in the form of objective function of least investment.

From the case study, the following advantages can be obtained from CCHP system with respect to separate system.

(1) CCHP system has a good economic effect. Due to the increasingly tense power supply, state grid views the police of peak valley electricity price as effective management of power demand side. In a small CCHP system, as long as the electricity ratio is above 1.3, investment in CCHP is smaller than that in separate system.

(2) CCHP system has better environmental benefits. Natural gas belongs to clean energy. CCHP adopts natural gas to generate and heat. After its full combustion and taking certain measures, the harmful components in natural gas are far lower than the relevant environmental protection index.

(3) CCHP system improves the comprehensive utilization rate of energy. The efficiency of gas use can reach as high as 90%, while generating efficiency of large natural gas power plant is generally 35% ~ 55% and the efficiency of its terminal of the power generation can only be reached by 30 ~ 47%. Using waste heat of the generator to supply heat can improve the reliability of hot and cold supply.

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