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An optimization method for design and operation of combined cooling, heating and power (CCHP) systems towards a smart grid

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Abstract

Combined cooling, heating and power (CCHP) systems are regarded as efficient, reliable and environmentally technologies for energy utilization. Besides, smart grid is an intelligent electricity delivering system brings benefits to utilities and consumers as well as improves the energy efficiency and reliability on the grid. The combination of the two provides a promising energy solution for future distributed energy system. An optimization method was proposed for design and operation of CCHP systems towards a smart grid. The program can optimize the sizing of components, hourly demand of biogas and electricity from grid. So the program serves the smart grid from demand side response. A sewage treatment plant (STP) in Hong Kong was selected for the case study as it needs simultaneous heating, cooling and power with self-generated biogas. The simulation was conducted under different sizing criteria and biogas prices. The CCHP system can avoid the dependency on utility if the peak-load-sizing is adopted. For STP, it is more economically attractive to adopt a larger system. The optimized strategy shows the CHP should operate longer at full load when the biogas price is cheaper and operate at part load only to satisfy the heating load when the biogas is expensive.

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1. Introduction

Distributed energy systems are regarded as efficient, reliable and environmentally alternative energy systems compared with conventional large centralized power plants [1]. Among all of the distributed energy systems, the combined cooling, heating and power (CCHP) system is broadly identified as a promising system for energy saving [2,3]. The CCHP systems can utilize recoverable waste heat for space heating, cooling and domestic hot water purposes while electrical power is generated [4]. It has drawn widely attentions for the following reasons. Firstly, the CCHP systems enjoy high energy efficiency owing to cascade utilization of energy and integrated primary energy conversion technologies. Secondly, the CCHP systems can meet simultaneous demand of cooling, heating and electricity. Thirdly, it reduces the investment and energy loss of the distribution system as most of the CCHP systems are located close to the load. So it is more reliable and environmentally friendly [5].

Due to the above advantages, the CCHP systems have been successfully implemented in many different sectors [6]. One of its applications is in the sewage treatment plants, where the waste water is collected and treated centrally while the biogas is produced. The biogas can be used as fuel to drive the CHP units for generating power and heat [7-9]. An absorption chiller driven by the waste heat can be used for cooling. Biogas fueled CCHP systems have been found suitable to be used in subtropics areas where the cooling demand is large around the year [10].

Many studies have been conducted to improve the design and operation of the biogas fueled CHP and CCHP systems. Bruno et al. [11] analyzed the performance of biogas-driven micro gas turbine cogeneration system with various integrated configurations. The best configurations are adopting a trigeneration plant that uses all the available biogas and additional natural gas to completely cover the plant's heating demand. Lian et al. [12] formulated a calculation process to evaluate the thermo-economic potential of a biomass driven steam-turbine plant for trigeneration based on the second law of exergy. It reveals that the price of electricity and fuel have significant impact on the overall production cost ($/h)). Huang et al. [13] carried out the modeling, simulation and economic analysis of small scale biomass trigeneration applications. The results show that the maximum efficiency and the best breakeven electricity price in the case is 71.7% and 103 £/kWh. Daniel et al. [14] focused on the evaluation of small-scale biomass CCHP systems in terms of thermodynamic feasibility and energy efficiency. Some guidelines were put forward for more efficient biomass combustion. To sum up, the biogas fueled CCHP systems are still at an early stage of development and more studies are required before their wide applications [15].

On the other hand, many countries are trying to update their utility grids towards smart grids for energy efficient networks [16]. A smart grid is defined to be an intelligent, digitized network delivering electricity in an optimal way from source to consumption [17]. One of the most beneficial parts of a smart grid is to reduce the peak power demand. It is realized by some demand response programs, such as critical peak pricing, which encourages customers to reduce their consumption by charging high price during peak load period [18]. Another benefit of a smart grid is initial investment saving. Electricity is an instantaneous commodity which needs to be consumed as it is generated. To guarantee every moment of sufficient supply to the customers, utilities must keep excess generation of 8%-16% for backup, which wastes lots of energy. By lower the peak power demand, it is expected about 20% of the entire grid capacity can be reduced [19]. In sum, a smart grid brings radical change to the role of demand side [20]. So for realizing the smart grids, relevant demand response program is indispensable. The recent researches on smart grid focus on load prediction [21~22], real-time pricing [23], measurement method [24] and system's design and control [25~28].

Through the above statement, it was noticed that it was a promising application field and energy solution for combination of CCHP and smart grids in the sewage treatment plant. However, the intensive research on this application has not been found in existing literatures. The biogas produced in the sewage treatment process can be used as fuel for the CHP unit. The CHP unit generates electricity and thermal energy for heating and cooling. A smart grid can be connected to the CCHP region for balancing the dynamic electricity load through the demand side response. The combined CCHP and smart grid can improve the energy utilization efficiency, power supply reliability and reduce the peak load of electricity production and distribution of a utility grid.

In this paper, a sewage treatment plant in Hong Kong was selected as a study case for careful design and operation of a CCHP system towards a smart grid. The operating principle is described briefly as follows. The produced biogas is used to drive a CHP unit, generating power to facilitate the electricity demand in the plant. If the generated electricity is beyond requirement, the surplus part is uploaded to the smart grid. If not, the supplementary power is obtained from the smart grid. The produced thermal energy, on one hand, heats the digesters, on the other hand, drives an absorption chiller for district cooling. If the produced cooling capacity fails to satisfy the load, the split-type air-conditions driven by electricity will be used.

To maximize the benefits of the system, optimization of the design and operation is necessary. In design stage, oversizing of the CCHP system can result in a huge investment while under-sizing can lower the benefits. In operation stage, it is critical to forecast the supplementary utility demand from the smart grid, as the electricity demands in the sewage treatment plant are changing monthly and hourly. In addition, the biogas is burned to satisfy different load demands of heating, cooling and electricity demands. So optimization should be conducted for dynamic distribution of the biogas for driving the CHP and boiler as well as the thermal energy for digester heating and absorption cooling. To solve the problems, an optimization method was proposed. Two main objectives were achieved on the basis of the study. One is to optimize the sizing of the major components for maximum economic benefits. The other one is to predict the hourly optimized power exchange with the utility grid and distribution strategy for biogas and thermal energy.

Nomenclature	
C_{absorp}	Cooling capacity of absorption chiller, kW
$C_{absotp,nom}$	Nominal cooling capacity of absorption chiller, kW
C_{load}	Cooling load, kW
$C_{split,AC}$	Cooling capacity provided by split-type air-conditions, kW
$Cost_{investemt}$	Initial investment of equipment, HKD
$Cost_{maintain}$	Maintenance cost of equipment, HKD/year
$Cost_{operation}$	Operation cost of equipment, HKD/year
E_{CHP}	Electricity generated by CHP , kW
$E_{CHP,nom}$	Nominal electricity generated by CHP, kW

E_{grid}	Electricity demand from the utility grid, kW
E_{load}	Electricity load, kW
$E_{split,AC}$	Electricity consumed by split-type air-conditions, kW
H_{fuel}	Combustion heat of biogas, kJ/Nm^3
$M_{fuel,CHP}$	Biogas consumption by CHP, Nm^3/s
$M_{fuel,CHP,nom}$	Nominal biogas consumption by CHP, Nm^3/s
$M_{fuel,boiler}$	Biogas consumption by the boiler, Nm^3/s
$Pri_{grid,i}$	Real-time price of electricity at the time of i, HKD/kWh
$Pri_{biogas,i}$	Real-time price of biogas at the time of i, HKD/Nm^3
$Q_{rad,nom}$	Heat released by the radiator under nominal condition, kW
$Q_{boiler,nom}$	Nominal heating capacity of the boiler, kW
Q_{CHP}	Utilized thermal energy generated by CHP unit, kW
$Q_{CHP,heating}$	Thermal energy generated by CHP for heating, kW
$Q_{CHP,cooling}$	Thermal energy generated by CHP for cooling, kW
Q_{boiler}	Heating capacity of the boiler, kW
Q_{load}	Heating load, kW
$Q_{radiator}$	Heat released by the radiator, kW
Q_{waste}	Heat wasted in CHP, kW
Q_{tower}	Cooling capacity of cooling tower, kW

2. The proposed CCHP system in a sewage treatment plant

In the sewage treatment plant, a mixture of thickened primary effluent and activated sludge is produced in the sewage treatment process. This mixture needs to be broken down by biochemical reaction, which takes place in digesters fully enclosed and insulated at 35℃ in anaerobic conditions. In the digestion process, biogas mainly consisting of 53% methane (CH_4) and 47% CO_2 is produced. In order to make full use of the biogas and improve the energy utilization efficiency, a CCHP is proposed for power generation, digester heating and space cooling simultaneously.

The CCHP system mainly consists of a CHP generator and an absorption chiller. There are different CCHP systems according to different prime movers (gas turbine, steam turbine, internal combustion engine) and absorption chillers (single/double effect, hot water driven/fuel gas driven/steam driven/direct-fired). In this paper, the widely-applied reciprocating internal combustion engine was used as an example prime mover to illustrate how the proposed program can be applied for design and optimization of the CCHP system. According to previous research, the double effect absorption chiller driven by bypass of 450°C flue gas was found to be the optimized CCHP system in sewage treatment plants in subtropical regions [29]. The schematic diagram of the system is shown in Fig.1.

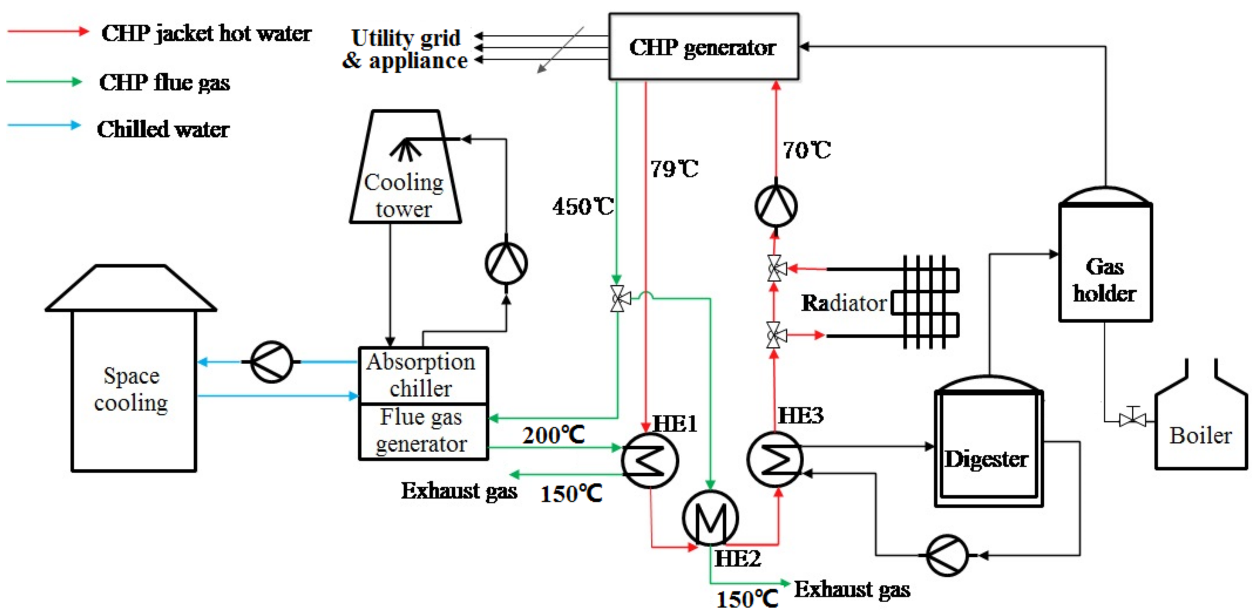

Fig.1 Schematic diagram of the tri-generation system in sewage treatment plant [29]

Power generation from the CHP is given the priority to meet the electricity demand in the CCHP region and any excess part is supplied to the utility grid for extra profit. The generated thermal energy consists of two parts: a part is taken away by the 450°C fuel gas and the other part is stored in the jacket water. The jacket water circulates in the CHP system so as to, on one hand, cools the generator to maintain its normal working state; and on the other hand, provides hot water as a byproduct. As it can be seen from Fig.1, one part of the 450℃ flue gas from the generator is supplied to the HE2 for heating the digester and the other part is transported to the double-effect absorption chiller for producing chilled water. The cooling/heating outputs are regulated by distributing the flue gas according to the demands. In cold days, the jacket hot water is firstly heated by the exhaust gas from the chiller and then reheated by the 450℃ bypassed flue gas. If the thermal energy provided by the CHP unit can not meet the heating demand of the digester, the auxiliary boiler will be turned on by burning the biogas.

3. The modeling and optimization program for CCHP system

A mathematical model of the CCHP system connected with smart grid was firstly established before an optimization program was proposed.

3.1 System modeling

The aim of the proposed program is to minimize the cost of the CCHP system by reasonable distribution of the biogas and thermal energy at one hour step. So the objective function can be proposed as Equ (1), in which the optimal value *fval* is achieved when the total cost for electricity, biogas, initial investment, maintenance and operation is minimal. Each term in Equ (1) refers to the cost within an hour.

$$fval = \min(\mathrm{Cost}_{electricity} + \mathrm{Cost}_{fuel} + \mathrm{Cost}_{investment} \cdot R / m + \mathrm{Cost}_{maintain} / m + \mathrm{Cost}_{operation} / m) \tag{1}$$

where, R is the capital recovery factor for the initial investment of the equipment; m is the total operation hours in a year. The detail model for each term is introduced as follows.

The capital recovery factor R is defined as:

$$R = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where, i is the interest rate and n is the service life for the equipment, which is supposed to be 2.0% (Hong Kong Data in 2014 [30]) and 20 years, respectively. It was assumed that i and n are the same to all the equipment in CCHP system.

The hourly electricity cost can be calculated as Equ (3):

$$\mathrm{Cos}\,t_{electricity} = E_{grid} \times Pri_{grid,i} \tag{3}$$

where E_{grid} is the electricity demand from the utility grid, kW. Positive value means power is taken from the grid while negative value means excess power is transported to the grid.

The hourly biogas cost can be calculated as Equ (4):

$$\mathrm{Cos}\,t_{fuel} = (M_{fuel,CHP} + M_{fuel,boiler}) \times Pri_{biogas,i} \tag{4}$$

The initial investment of the CCHP system mainly includes the investment of the CHP unit, absorption chiller, gas boiler and cooling tower, as shown in Equ (5):

$$\mathrm{Cos}\,t_{investment} = \mathrm{Cos}\,t_{investment,CHP} + \mathrm{Cos}\,t_{investment,chiller} + \mathrm{Cos}\,t_{investment,boiler} + \mathrm{Cos}\,t_{investment,tower} \tag{5}$$

The maintenance cost of the CCHP system mainly includes the maintenance cost for the absorption chiller and CHP, which is expressed as Equ (6):

$$\mathrm{Cos}\,t_{maintain} = \mathrm{Cos}\,t_{maintain,absorption} + \mathrm{Cos}\,t_{maintain,CHP} \tag{6}$$

The fuel expense accounts for the main operation cost of the CHP and boiler, which has been taken into considering in biogas cost $Cost_{\mathrm{fuel}}$. Besides, the operation cost of the absorption chiller can be ignored because the main energy input is the waste thermal energy. So the total operation cost mainly consists of electricity consumption by the chilled water pumps and cooling water pumps in the cooling system, given by Equ (7):

$$\mathrm{Cos}\,t_{operation} = \mathrm{Cos}\,t_{operation,tower} + \mathrm{Cos}\,t_{operation,absorp} \tag{7}$$

- Investment, maintenance and operation

The cost of investment, maintenance and operation of the CCHP system will be elaborated as follows. The initial investment of the CHP unit consists of the cost for purchasing the equipment and the cost for installation on site. The correlation between the capital costs (HKD) of a typical gas fueled reciprocating engine and nominal electric capacity (kW) is given as Equ (8), by considering the currency exchange rates (1€=8.4HKD) and 25% installation cost [31].

$$\mathrm{Cos}\,t_{investment,CHP} = (9332.6 \times E_{CHP,nom}{}^{-0.4611}) \times E_{CHP,nom} \times (1+25\%) \times 8.4 \tag{8}$$

The correlation between the capital costs (HKD) of the absorption chiller and nominal cooling capacity (kW) is given as Equ (9), by considering the currency exchange rates (1€=8.4HKD) and 25% installation cost [32].

$$Cost_{investment,absorption} = (4671.1 \times C_{absorp,nom}{}^{-0.47}) \times C_{absorp,nom} \times (1+25\%) \times 8.4 \quad (9)$$

The correlation between the capital costs (HKD) of the high efficiency (80%) gas boiler and nominal heating capacity (kW) is given by Equ (10), by considering the currency exchange rate (1$=8HKD) and 25% installation cost [33].

$$Cost_{investment,boiler} = 34 \times Q_{boiler,nom} \times (1+25\%) \times 8 \quad (10)$$

The typical construction cost for normal cooling tower application provided by 'TRANE quick reference for efficient chiller system design' is 20$/gpm to 40$/gpm [34]. In this paper, the investment of cooling tower is estimated on the basis of 30$/gpm. The correlation between the capital costs (HKD) of the cooling tower and nominal cooling capacity (kW) can be derived as Equ (11):

$$Cost_{investment,tower} = 150.7 \times Q_{tower,nom} \quad (11)$$

The heat balance between the cooling tower and absorption chiller can be written as Equ (12):

$$Q_{tower,nom} = Q_c + Q_a = Q_e + Q_g = C_{absorp,nom} + C_{absorp,nom} / COP_{absorp} \quad (12)$$

where, Q_e, Q_g, Q_c and Q_a represent the load of the evaporator, generator, condenser and the absorber, respectively, kW. The coefficient of performance of the absorption chiller (COP_{absorp}) was supposed to be 1.2.

In terms of maintenance cost, the typical range for an example reciprocating engine is 0.0075 ~ 0.015€/kWh [35]. In this paper, 0.01€/kWh was used for estimating the maintenance cost of the CHP unit. The correlation between the maintenance cost (HKD) of the CHP unit and nominal electric capacity (kW) is expressed as Equ (13), by considering the currency exchange rate (1€=8.4HKD).

$$\mathrm{Cost}_{maintain,CHP} = 0.01 \times E_{CHP,nom} \times 8.4 \tag{13}$$

Some companies offer constant cost maintenance and repair contracts for the absorption chiller so that the costs vary between 0.5% for large chiller (up to 700 kW) to 3% for small power machines. Repair contracts are even more expensive with 2% for large chiller and up to 12% for a 100 kW machine [32]. So in the calculation, 2.5% investment was used for estimating the annual maintenance cost for large chiller exceeding 700kW; while 15% was used for the small chiller less than 100 kW as shown in Equ (14):

$$\mathrm{Cost}_{maintain,absorption} = \begin{cases} 0.15 \times \mathrm{Cost}_{investment,chiller} & (C_{absorp,nom} < 100\,\mathrm{kW}) \\ [0.15 - 0.0002083 \times (C_{absorp,nom} - 100)] \times \mathrm{Cost}_{investment,chiller} & (100 \le C_{absorp,nom} \le 700\,\mathrm{kW}) \\ 0.025 \times \mathrm{Cost}_{investment,chiller} & (C_{absorp,nom} > 700\,\mathrm{kW}) \end{cases} \tag{14}$$

The annual operation cost for the electrical pumps can be estimated to be 3% of the initial investment according to other research and field measurement results [32,36]:

$$\mathrm{Cost}_{operation} = 0.03 \times (\mathrm{Cost}_{investment,tower} + \mathrm{Cost}_{investment,absorp}) \tag{15}$$

A summary of the investment, maintenance and operation cost for each component in CCHP system was shown in Table 1.

Table 1 Summary of investment, maintenance and operation cost for each component

Component	Cost	Unit	Equ	Ref
CHP unit	Investment	HKD	$Cost_{investment,CHP} = (9332.6 \times E_{CHP,nom}{}^{-0.4611}) \times E_{CHP,nom} \times (1+25\%) \times 8.4$	[31]
	Maintenance	HKD/y	$Cost_{maintain,CHP} = 0.01 \times E_{CHP,nom} \times 8.4$	[35]
	Operation	HKD/y	Decided by fuel cost	
Absorption chiller	Investment	HKD	$Cost_{investment,absorption} = (4671.1 \times C_{absorp,nom}{}^{-0.47}) \times C_{absorp,nom} \times (1+25\%) \times 8.4$	[32]
	Maintenance	HKD/y	$Cost_{maintain,absorption} = \begin{cases} 0.15 \times Cost_{investment,chiller} \ (C_{absorp,nom} < 100\,\mathrm{kW}) \\ [0.15 - 0.0002083 \times (C_{absorp,nom} - 100)] \times Cost_{investment,chiller} \\ (100 \le C_{absorp,nom} \le 700\,\mathrm{kW}) \\ 0.025 \times Cost_{investment,chiller} \ (C_{absorp,nom} > 700\,\mathrm{kW}) \end{cases}$	[32]
	Operation	HKD/y	$Cost_{operation} = 0.03 \times (Cost_{investment,tower} + Cost_{investment,absorp})$ (whole cooling system)	[32, 36]
Boiler	Investment	HKD	$Cost_{investment,boiler} = 34 \times Q_{boiler,nom} \times (1+25\%) \times 8$	[33]
	Maintenance	HKD/y	NA	
	Operation	HKD/y	Decided by fuel cost	
Cooling tower	Investment	HKD	$Cost_{investment,tower} = 150.7 \times Q_{tower,nom}$	[34]
	Maintenance	HKD/y	NA	
	Operation	HKD/y	$Cost_{operation} = 0.03 \times (Cost_{investment,tower} + Cost_{investment,absorp})$ (whole cooling system)	[32,36]

- Component model and energy balance

The CHP operation data under three typical conditions was given in the operation manual of GE company (Operation and maintenance manual of GE Jenbacher GmbH&CO, Model: JMS 420 GS-B.L-B125), shown in Table 2. By fitting the correlation between the biogas consumption ratio and electrical output ratio (shown in Fig.2), the following relationship exists. It can be seen that the electrical output increases linearly with the fuel consumption.

$$\frac{E_{CHP}}{E_{CHP,nom}} = \frac{1.10348 \times M_{fuel,CHP}}{M_{fuel,CHP,nom}} - 0.10383 \tag{16}$$

Table 2 CHP operation parameters

	Full load (Nominal)	75% load	50% load
Gas consumption $M_{\text{fuel,CHP}}$ (Nm^3/hr)	519	401	282
Mechanical output (kW)	1451	1088	726
Electrical output E_{CHP} (kWe)	1409	1054	699
Total thermal output Q_{CHP} (kW)	1412	1114	808

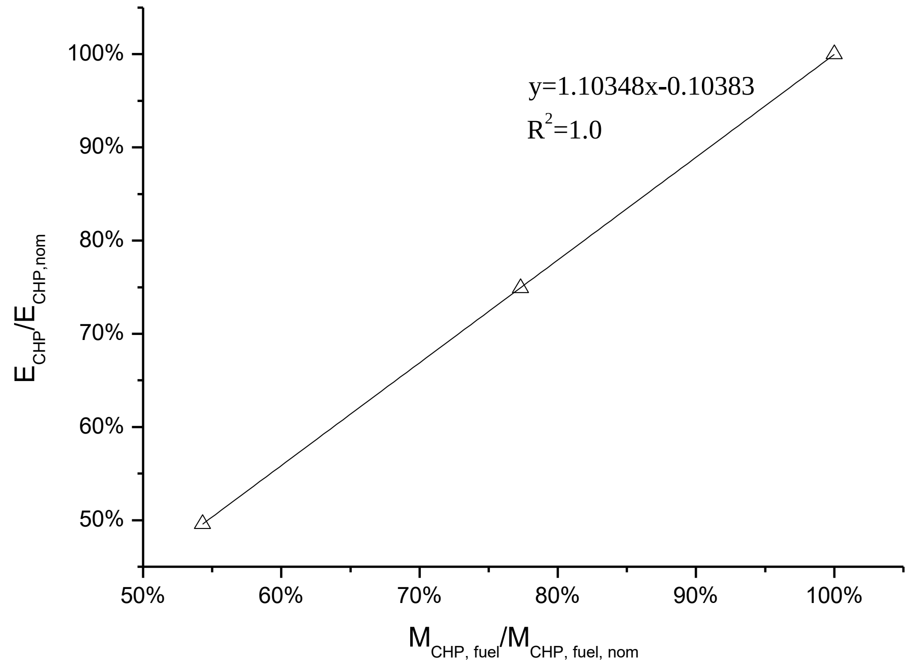

Fig.2 Relationship between biogas consumption and electrical output

Based on the energy balance of the CHP system, we obtain:

$$M_{fuel,CHP} \times H_{fuel} = E_{CHP} + Q_{CHP} + Q_{waste} \tag{17}$$

where, H_{fuel} is the combustion heat of the biogas, which is 22572 kJ/Nm^3.

By substituting the given data in Table 2 into Equ.(17), the waste energy in the CHP system under full load, 75% load and 50% load was calculated to be 261kW, 346kW and 433kW, accounting for 14.8%, 13.8% and 13.3% of the total energy input, respectively. So the average energy waste ratio in the CHP system can be calculated as 14%.

$$Q_{waste} = 14\% \times M_{fuel,CHP} \times H_{fuel} \tag{18}$$

By substituting the Equ (17) into Equ (16) and re-arranging the equation, we obtain:

$$M_{fuel,CHP} = \frac{1}{0.86 H_{fuel}} \times (E_{CHP} + Q_{CHP}) \tag{19}$$

The generated thermal energy is used for heating and absorption cooling, which is expressed as:

$$Q_{CHP} = Q_{CHP,cooling} + Q_{CHP,heating} \tag{20}$$

In the CCHP region, the energy generation and consumption should be balanced, including electricity balance, heating balance and cooling balance. The electricity balance can be expressed as:

$$E_{CHP} + E_{grid} = E_{load} + E_{split,AC} \tag{21}$$

where, E_{load} represents the electricity load except the power demand for the split-type air-conditions. Only the lighting, lift, computer, printer, etc are included. The heating balance in the CCHP region can be written as:

$$Q_{CHP,heating} + Q_{boiler} = Q_{load} + Q_{radiator} \tag{22}$$

The heating capacity of the boiler can be calculated as:

$$Q_{boiler} = \eta_{boiler} \times (M_{fuel,boiler} \times H_{fuel}) \tag{23}$$

where, η_{boiler} is the efficiency for the boiler. The typical efficiency for the high efficiency natural gas boiler is 80% [33,37].

The cooling balance in the CCHP region can be expressed as:

$$C_{absorp} + C_{split,AC} = C_{load} \tag{24}$$

The cooling capacity provided by the absorption chiller can be calculated as:

$$C_{absorp} = COP_{absorp} \times Q_{CHP,cooling} \tag{25}$$

where, COP_{absorp} is the coefficient of performance (COP) of absorption chiller. For the double effect absorption chiller driven by 450℃ flue gas, the typical value can be estimated as 1.2 [38].

The cooling capacity provided by the split-type air conditions can be calculated as:

$$C_{split,AC} = COP_{AC} \times E_{split,AC} \tag{26}$$

where, COP_{AC} is the coefficient of performance of split-type air conditions, which is set to be 3.0 in the study.

A schematic diagram was drawn to show the energy balances in CCHP system (Fig.3). In sum, the objective function of the optimization program was given as Equ.(1). The constrains include the 9 equality constraints and 12 inequality constraints. The equality constraints were given by Equ.(16) and Equ.(19)~(26). The inequality constraints were given on all the variables to restrict them in a normal range. For example, the cooling, heating and power generation rates should not excess the nominal capacity of each component. All the inequality constraints were listed as follows: $0 \le M_{fuel,CHP} \le M_{fuel,CHP,nom}$, $0 \le M_{fuel,boiler} \le M_{fuel,boiler,nom}$, $0 \le E_{CHP} \le E_{CHP,nom}$, $0 \le Q_{CHP} \le 0.86 M_{fuel,boiler,nom} \cdot H_{fuel}$, $0 \le Q_{CHP,heating} \le 0.86 M_{fuel,boiler,nom} \cdot H_{fuel}$, $-\infty \le E_{grid} \le +\infty$, $0 \le Q_{boiler} \le Q_{boiler,nom}$, $0 \le Q_{CHP,cooling} \le 0.86 M_{fuel,boiler,nom} \cdot H_{fuel}$, $0 \le C_{absorp} \le C_{absorp,nom}$, $0 \le Q_{radiator} \le Q_{radiator,nom}$, $0 \le E_{distric,AC} \le \dfrac{C_{load}}{COP_{AC}}$, $0 \le C_{distric,AC} \le C_{load}$.

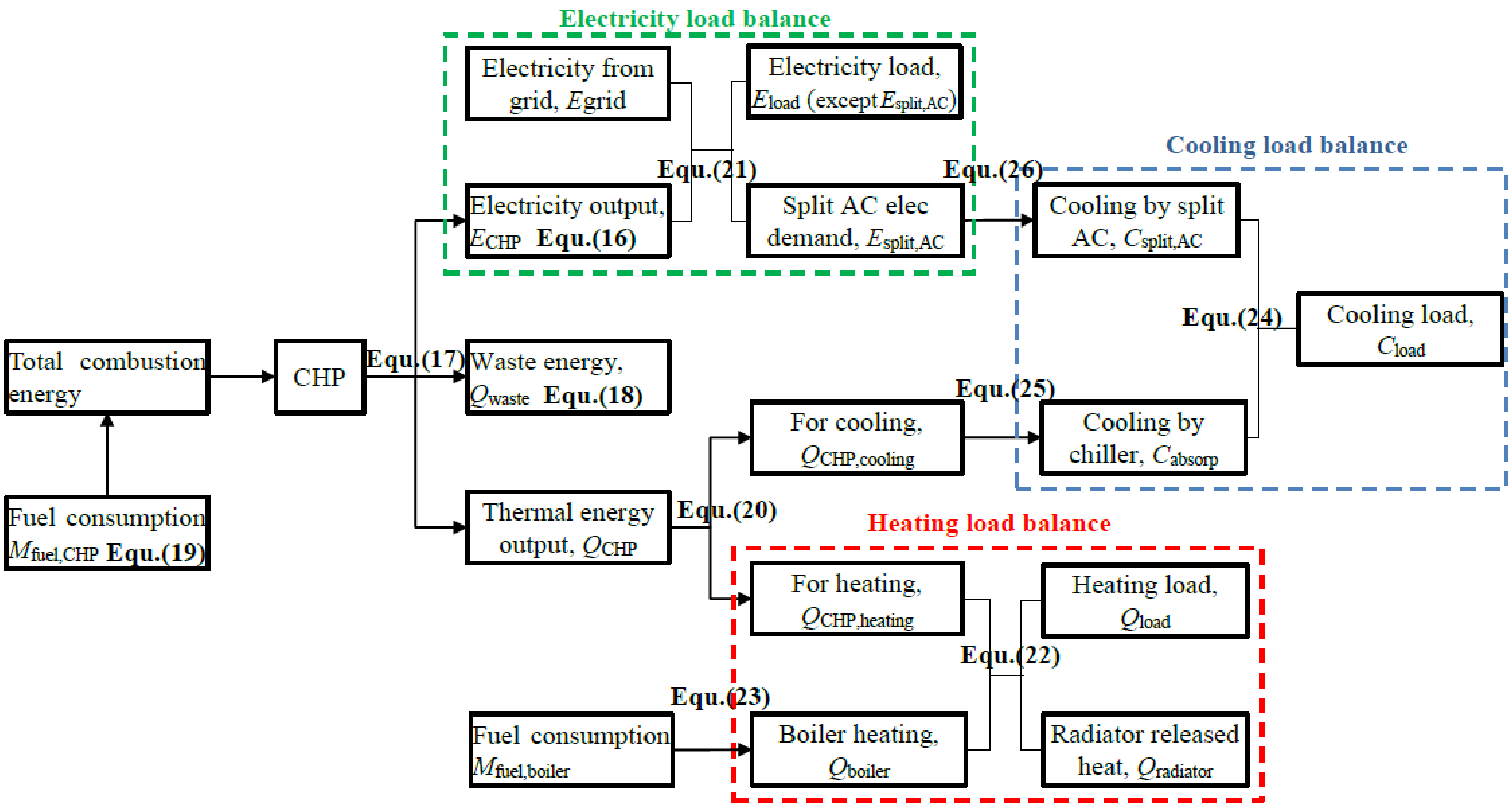

Fig.3 Schematic diagram of energy balance in CCHP system

3.2 Electricity price

The ‘ladder electricity price rate’ has been used in Hong Kong. According the tariff table provided by *CLP Power Hong Kong Limited* in 2015 [39], the electricity price for the non-residential user in Hong Kong was listed in Table 3. The electricity charge was set as the input for the optimization program.

Table 3 Electricity price in Hong Kong

Total monthly consumption block	Rate (Cents HKD/Unit)
Each of the first 5,000 units	97.0
Each unit over 5,000	96.2

3.3 Optimization program

The detailed optimization program of the CCHP system is shown in Fig.4. It can optimize the system from two aspects: sizing the main equipment in design stage and distribution of biogas and thermal energy in operation stage.

In the design stage of the CCHP system, the equipment needs to be carefully sized because it has great influence on $Cost_{investment}$, $Cost_{mantanence}$ and $Cost_{operation}$ in Equ(1). Larger capacity can bring more energy saving but lead to higher investment, maintenance and operation costs. By inputting different sizing configurations based on different design criteria in the program, the optimal objective function values can be obtained. In the operation stage of the CCHP system, the capacity of all the equipment is determined. So the optimal objective function value is only decided based on $Cost_{electricity}$ and $Cost_{fuel}$ in Equ(1). The optimal solution can be achieved by reasonable distribution of the biogas supplied to CHP and boiler, and thermal energy for heating and absorption cooling. Under optimized solution, the heating, cooling and electricity load can be satisfied with minimum overall cost (*fval*). The constrained optimization toolbox provided by the MATLAB was used for solving the problem.

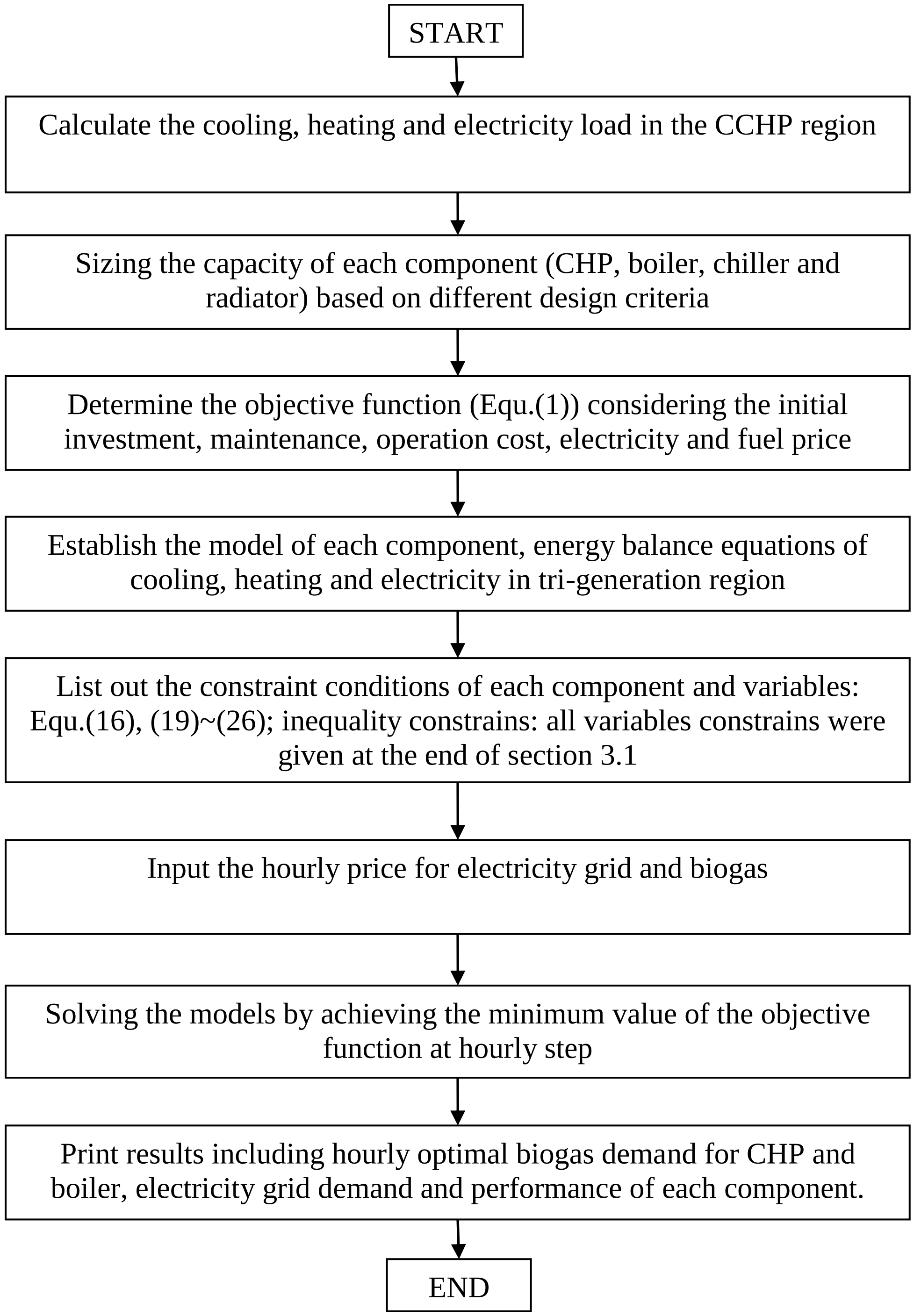

Fig.4 Flow chart of optimization programme of tri-generation system

4. Results and discussions

The following simulation results were obtained based on a practical engineering case in a sewage treatment plant in Hong Kong as introduced in Section 2. The annual cooling, heating and electricity load were simulated before the equipment can be sized. Three cases were then simulated based on different sizing criteria using the optimization program introduced in Section 3. At last, the influence of sizing criteria and biogas price were discussed.

4.1 Heating, cooling, and electricity loads in the sewage treatment plant

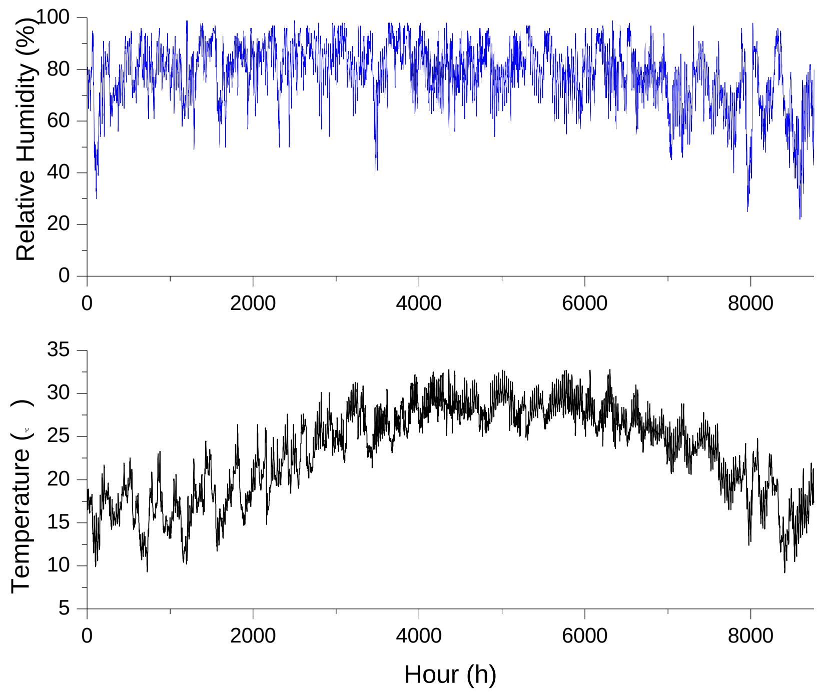

Fig.5 Hourly temperature and humidity in Hong Kong

The cooling and heating load have a close relationship with the climate. Hong Kong locates in subtropical area which owns hot and humid weather most of the year. The 20 years average weather data are shown in Fig.5. The temperature varies from 9.2℃ to 32.8℃ and the relatively humidity fluctuates from 22% to 99%.

As it was mentioned previously, a digester has to be operated at the design temperature of 35℃ to maintain a normal biogas production rate. The digester heating loads, varying with the ambient temperature, can be calculated by:

$$Q_{load} = \sum Q_{HL_i} = \sum F_{digester} \cdot K_i \cdot (t_{set} - t_{ambient}) \tag{27}$$

where, Q_{load} is the total heating load of the digesters, kW; Q_{HL_i} is the heating load for one particular digester, kW; t_{set} is the inside temperature of the digester which is set as 35℃; $t_{ambient}$ is the ambient air temperature, ℃.

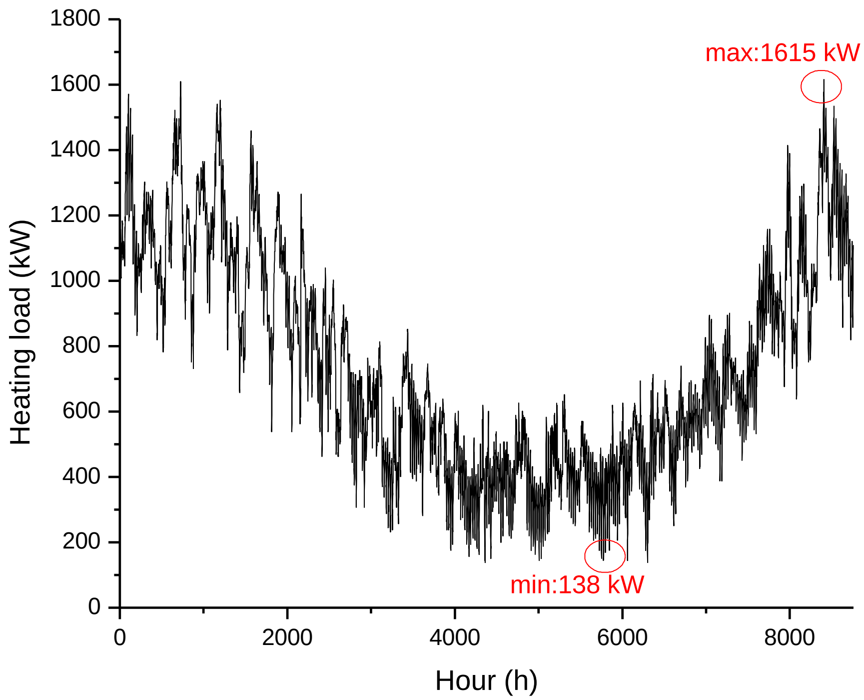

Fig.6 Annual heating load of the digesters

According to the data collection on site on 28th February 2014, the average $\sum F_{digester} \cdot K_i$ was calculated to be 62.6 W/℃. So the annual heating load of the digesters can be simulated by Equ (26) and the results are shown in Fig.6. It can be seen that the heating load varies greatly from season to season and even in a day. The maximum heating load is 1615 kW in December and the minimum load is only 138 kW in August.

The cooling load consists of three parts: cooling CHP inlet air to its nominal working temperature 25℃, air-condition cooling load in office building and air-conditioning cooling load in power house. In subtropical regions, the ambient temperature can exceed the nominal operation temperature of the CHP unit, especially in summer, which results in power output de-rating as reported. For example, power output de-rating can be determined for each project if the intake air temperature is greater than 30℃ for Jenbacher gas internal combustion engine [40]. For the gas turbine engine, the influence by high inlet air temperature is even larger [41,42]. So the intake air is cooled to 25℃ to maintain its normal working condition in this study. This part of cooling load can be calculated as:

$$C_a = m_a \cdot (h_{amb} - h_{nom}) \tag{28}$$

where, m_a is the mass flow rate of the intake air, which is designed to be 13.3 kg/s in this project. h_{amb} and h_{nom} are the enthalpy of the ambient air and cooled air, respectively, kJ/kg.

The office building in the sewage treatment plant is a 26th-floor building with gross area of 242,113 sq ft. The operation schedule for the air-conditioning system is from 7:00 to 24:00 in workdays and suspended on weekend. The powerhouse is the space for control centers, pump room and other equipment rooms. The dynamic cooling load of the office building and powerhouse were simulated by TRNSYS software. The simulation results for their annual cooling load are shown in Fig.7. The maximum total cooling load is 1117 kW in summer and minimum cooling load is zero in winter.

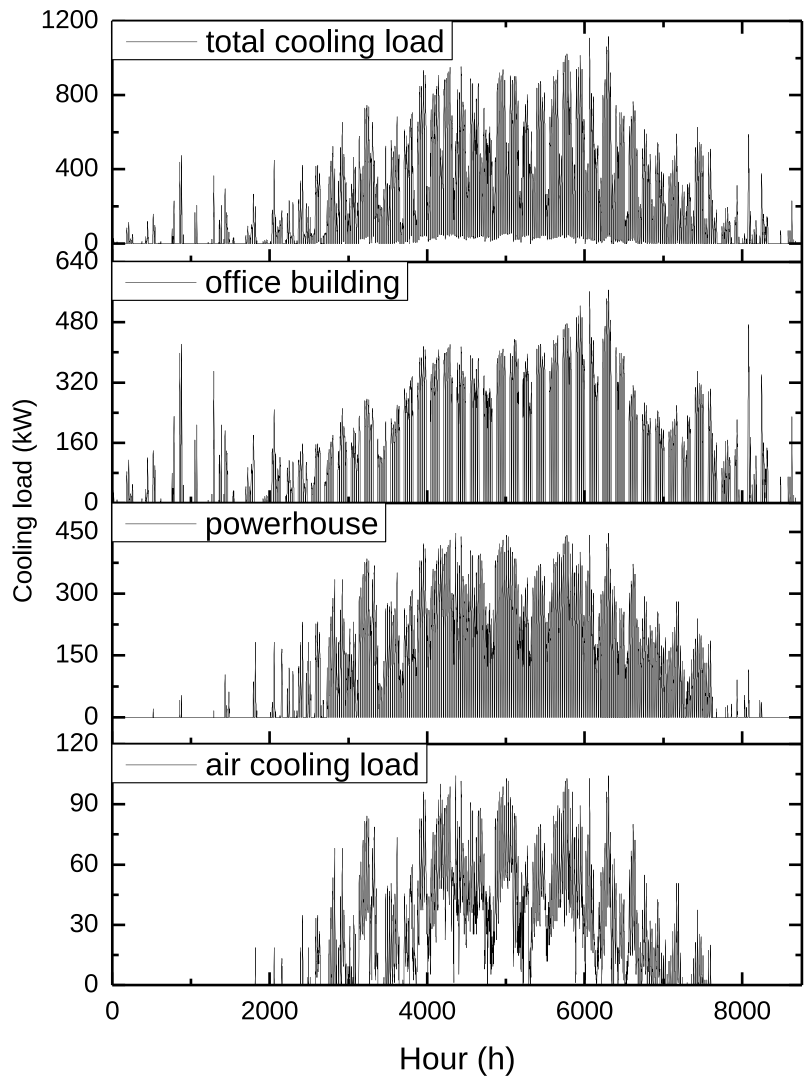

Fig.7 Annual cooling load in sewage treatment plant

The electricity load of the office building was calculated by the nominal power of each appliance and corresponding operation schedule. The appliances include lighting system and electrical equipment in car parks, lift lobby, floor corridor, entrance lobby, elevator lobby, public places, fire excape stairs, toilets and office. The annual electricity load, workday load and weekend load are ploted in Fig.8. The maximum cooling load is 1117 kW in summer and minimum load is 0 in winter. The peak electricity load is 168kW and minimal load is 73kW.

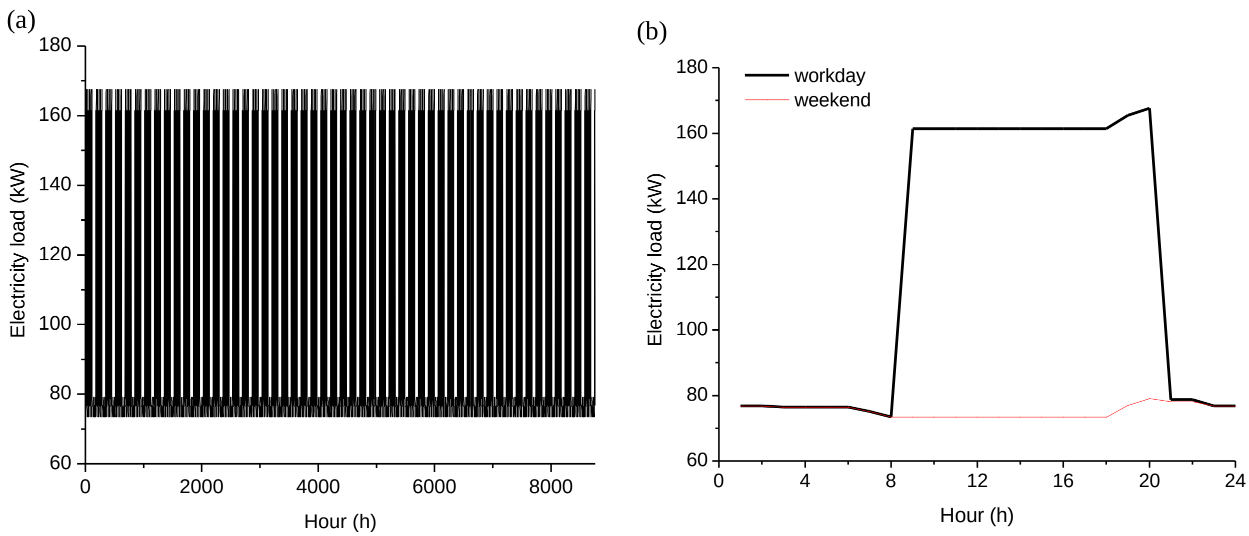

Fig.8 Electricity load in sewage treatment plant: (a) annual load (b) workday and weekend load

4.2 Simulation results under different sizing criteria

There is flexibility in sizing the CCHP system according to the customer's demand and budget. If the CCHP system is sized large enough to meet the peak thermal and electricity requirement, it can be disconnected from any grid so that the purchase of expensive on-peak power is avoided. However, this design needs big investment. If the CCHP system is sized only to meet the base thermal or electricity demand, extra electricity and thermal energy should be bought from the grid or generated by other auxiliary device. This system can avoid part-load operation of CHP and reduce investment, but the benefits are much less. For the sewage treatment plant, three simulation cases were conducted based on different sizing criteria: base heating load, 30% peak heating load and peak heating load. The following simulation results were based on the biogas price=0, because the biogas was not purchased but self-generated from the sewage treatment process.

4.2.1 Base heating load

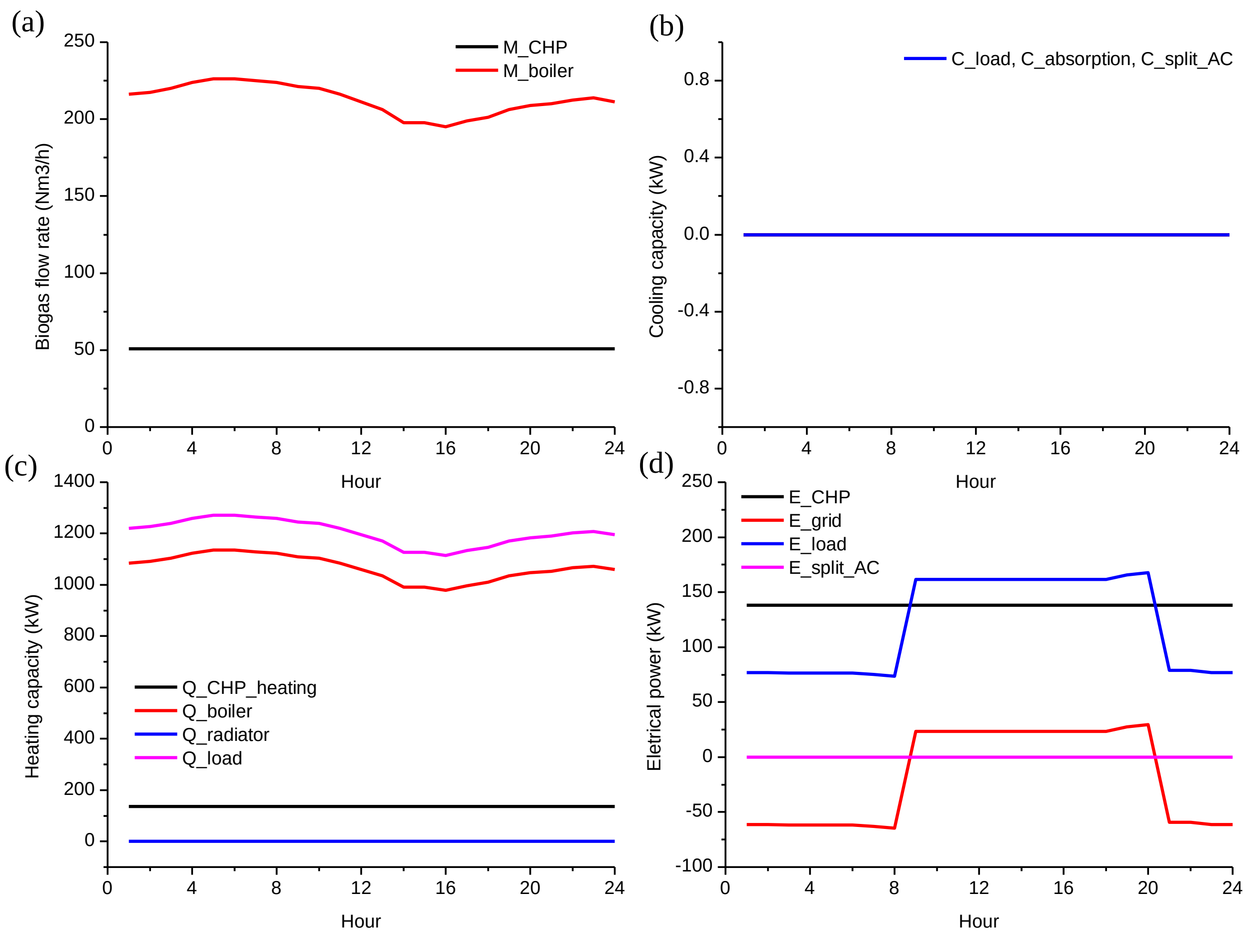

Fig.9 Performances of CCHP in winter under the sizing criteria of base heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

Fig.9 shows the winter performances of the CCHP system under the sizing criteria to meet the base heating demand. The nominal power output and heating capacity of the CHP unit are both 138kW. As it can be seen from Fig.10, the power and heating outputs of the CHP unit keep constant with steady nominal biogas supply. The auxiliary biogas boiler needs to be put into operation all the time in order to satisfy the digester’s heating demand. The biogas demand of the boiler changes according to the varying heating load. There is no cooling load in winter so that all the thermal energy output of the CHP is used for heating. In terms of electricity grid performance, the utility load is significantly lightened because of the extra generated power from CHP. During the period of high electricity demand in daytime working hours, only 23.4 kW power is needed from grid; while during low electricity demand from 8pm to 8am, there is even excess electricity can be sold to the utility grid.

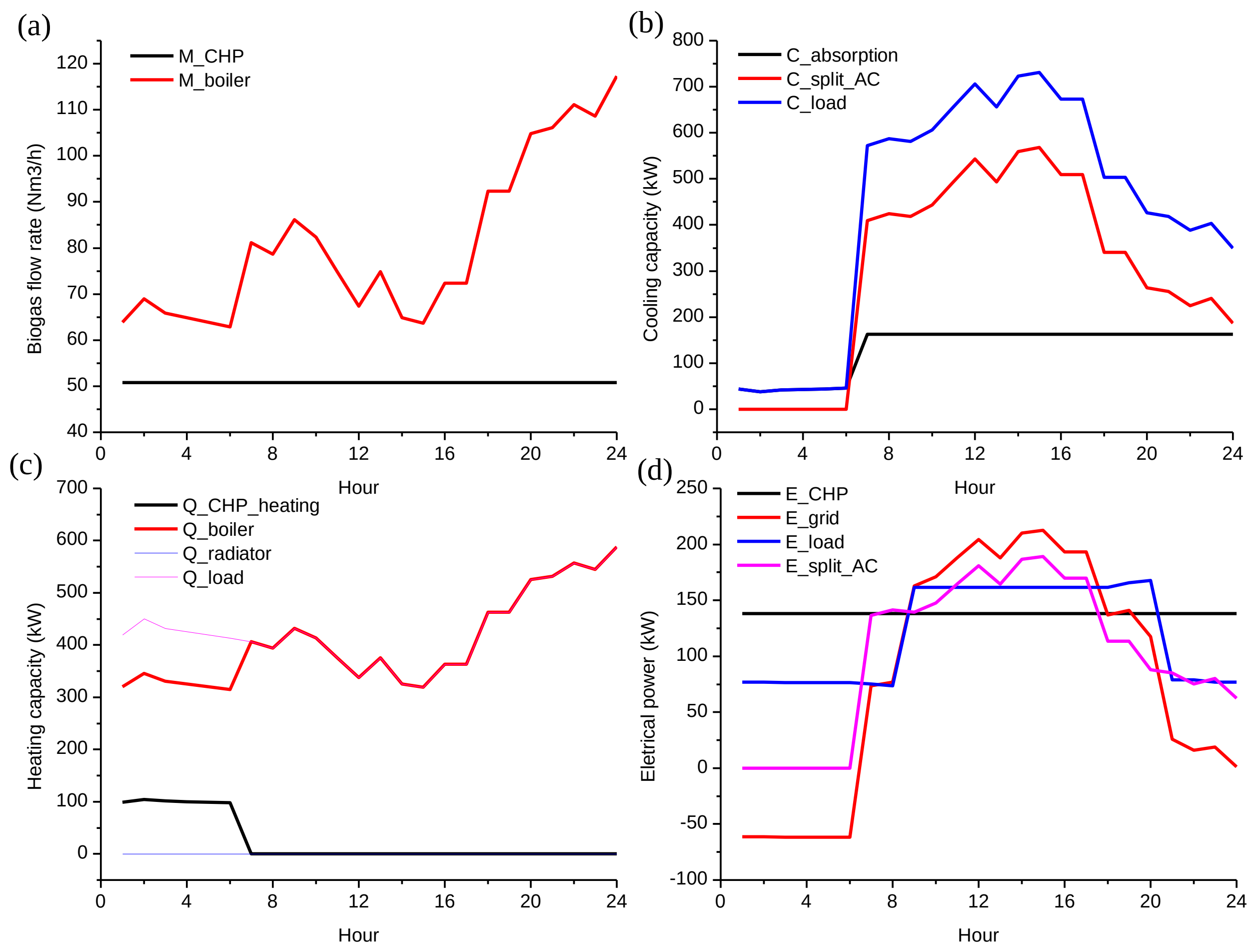

Fig.10 Performances of CCHP in summer under the sizing criteria of base heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

Fig.10 shows the summer performances of the CCHP system under the sizing criteria to meet the base heating demand. The summer performances are quite different from winter condition although the CHP unit remains operating at full load in a whole day. In summer, there is cooling demand all day with high demand between 8:00am to 6:00pm. So all the thermal energy produced by the CHP unit is distributed for cooling in the daytime, and the digester's heating load is satisfied by the biogas boiler. This is an economically effective practice for allocating the limited thermal energy because the self-produced biogas is 'free of charge' for burning, while the cooling by electricity-driven air-condition is much more costly. So it can be deduced that absorption cooling should be given the priority when the fuel gas price is extremely low. However, the cooling capacity provided by the absorption chiller is far below the demand because the absorption chiller capacity is too small under this design. The electricity-driven split-type air conditions should be used from 6:00am to 24:00pm. In terms of electricity grid, the utility grid load is much heavier in summer than in winter because of the usage of split-type air conditions. During peak hours from 8:00am to 18:00pm, more than 150kW power is needed from the grid.

4.2.2 30% peak heating load

In order to generate more energy, larger size of the equipment was selected to meet 30% of the peak heating load. Fig.11 shows the winter performance of the CCHP system. The nominal power and thermal outputs of the CHP are 485kW and 477kW, respectively. Similar with the case of base heating load, the CHP operates at full load with all the thermal energy used for heating the digester. Owing to much larger capacity of the CHP unit, the electricity load can be fully satisfied by the power output of the CHP unit. As much as 323kW to 409kW extra electricity can be sold to the utility for profit.

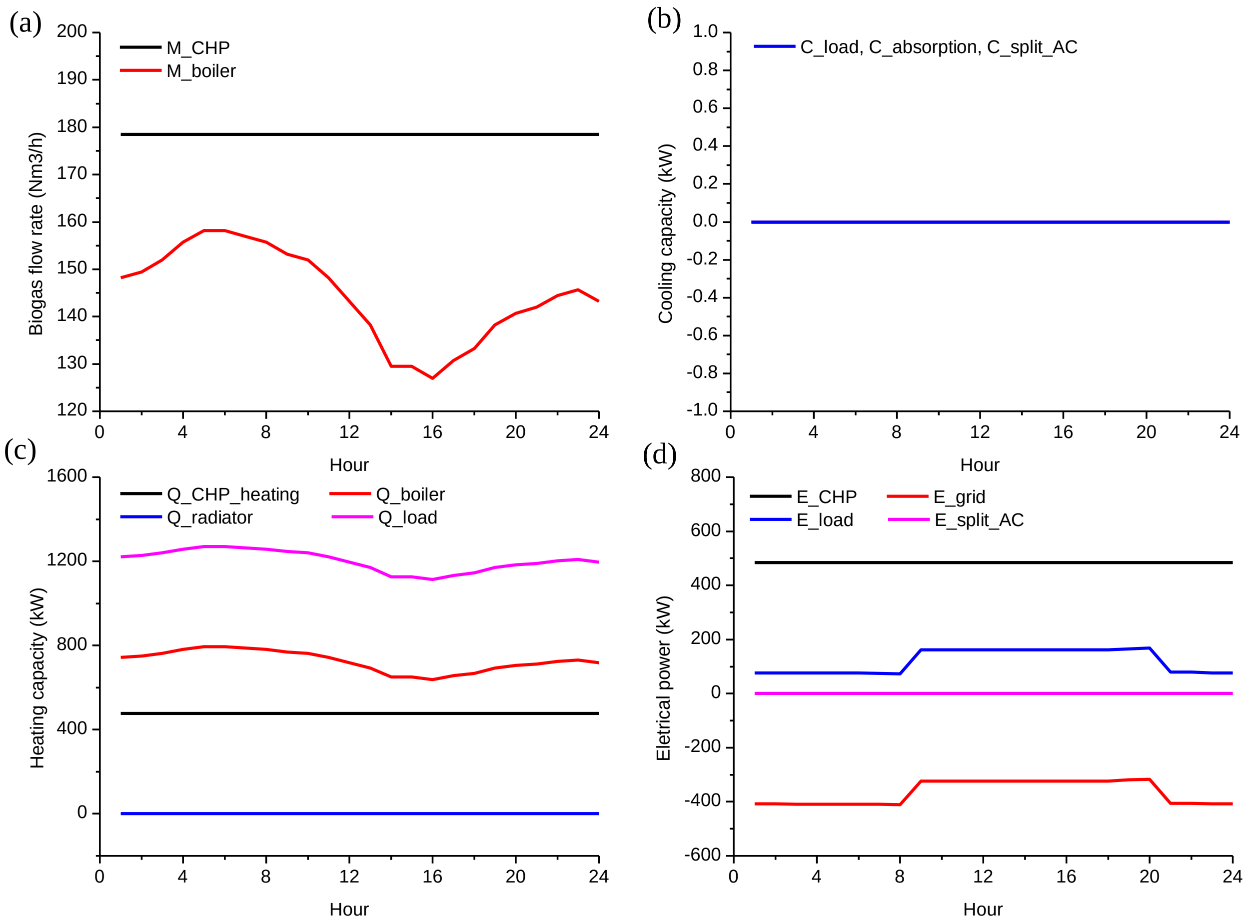

Fig.11 Performances of CCHP in winter under the sizing criteria of 30% peak heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

Fig.12 shows the summer performances of CCHP system under the sizing criteria to meet 30% peak heating demand. Similar with the case of base heating load, the CHP operates at full load all day long but distributes different proportion of thermal energy for cooling and heating within different time span. All the thermal energy is supplied to drive the absorption chiller from 7am to 17pm when the cooling load reaches the peak of the day. In other period, the thermal energy is also given the priority to meet the cooling demand and the surplus part will be used for heating. As the capacity of CHP is much larger than the last case, the generated electricity can cover all the electricity demand including the office building and split-type air-condition. In this way, no utility grid power is necessary, so peak load reduction is realized through the ‘self-sufficient’.

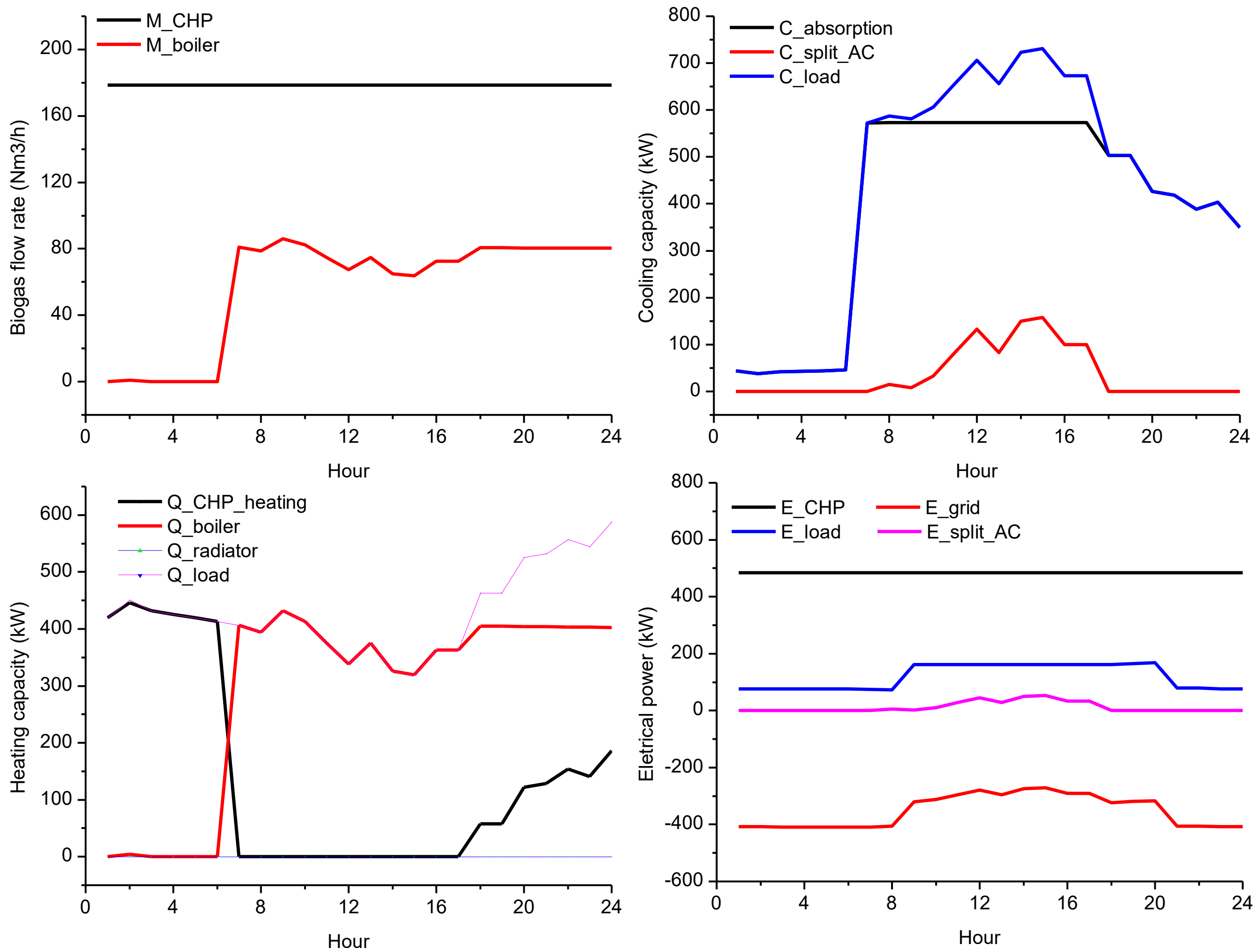

Fig.12 Performances of CCHP in summer under the sizing criteria of 30% peak heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

4.2.3 Peak heating load

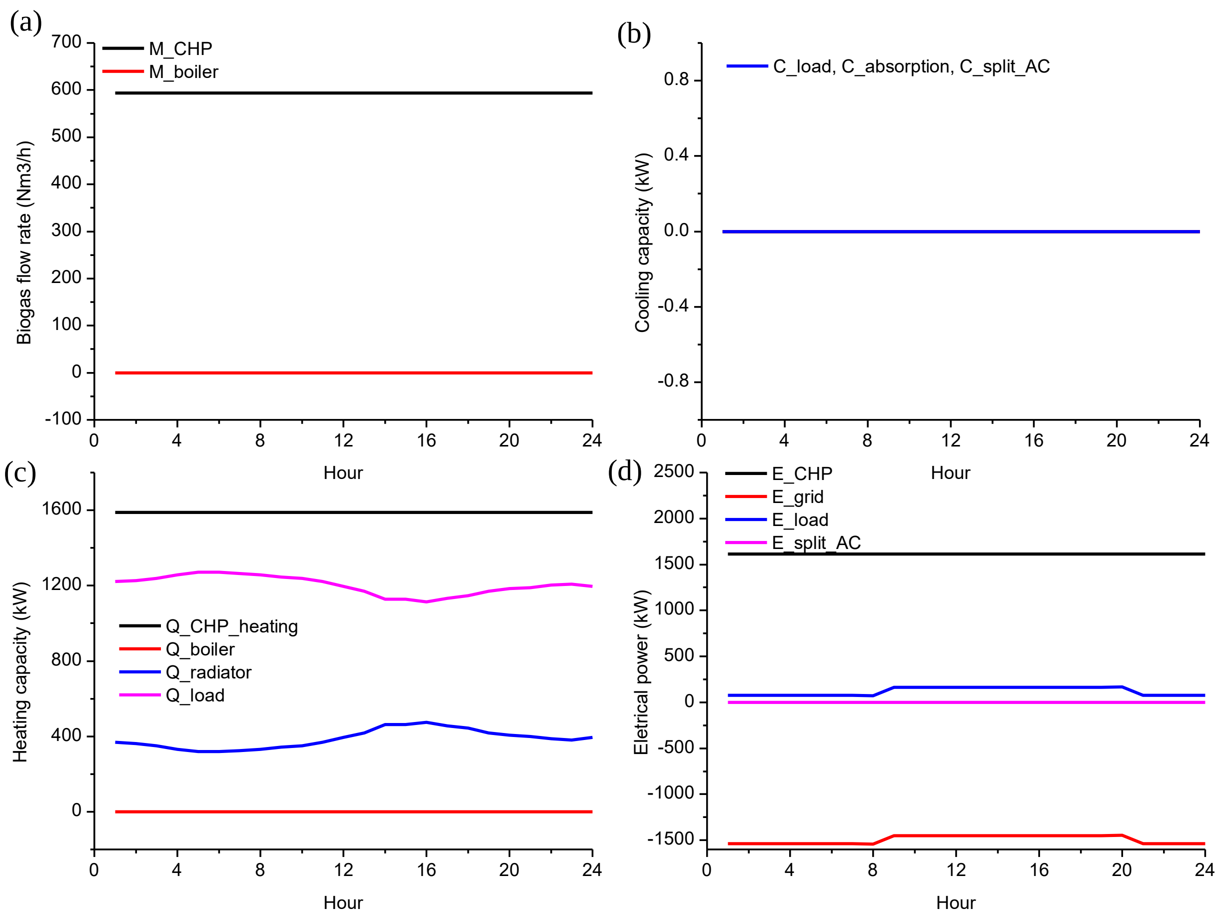

Fig.13 Performances of CCHP in winter under the sizing criteria of peak heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

In this case, the CCHP system is sized large enough to meet the peak thermal demand, so that it can be disconnected from any grid. Compared with the previous systems, this system can make the most profits but need huge investment. Fig.13 shows the winter performances of the CCHP system. The nominal power and thermal outputs of the CHP are 1590kW and 1615kW, respectively. Like the previous cases in which the CHP operates at full load all day long, the CHP also operates at full load for 24 hours a day in this case. It is because the biogas price is 0 in the sewage treatment case. So the biogas should be fully utilized to order to achieve maximum profit by selling the excess electricity to the grid. As there is no cooling load in winter, all the thermal energy is used for digester heating. However, the thermal output of the CHP is beyond the need so that excess energy has to be released to the ambient by radiators. This part of waste energy is sacrificed in order to make more profit by generating more electricity to the utility grid.

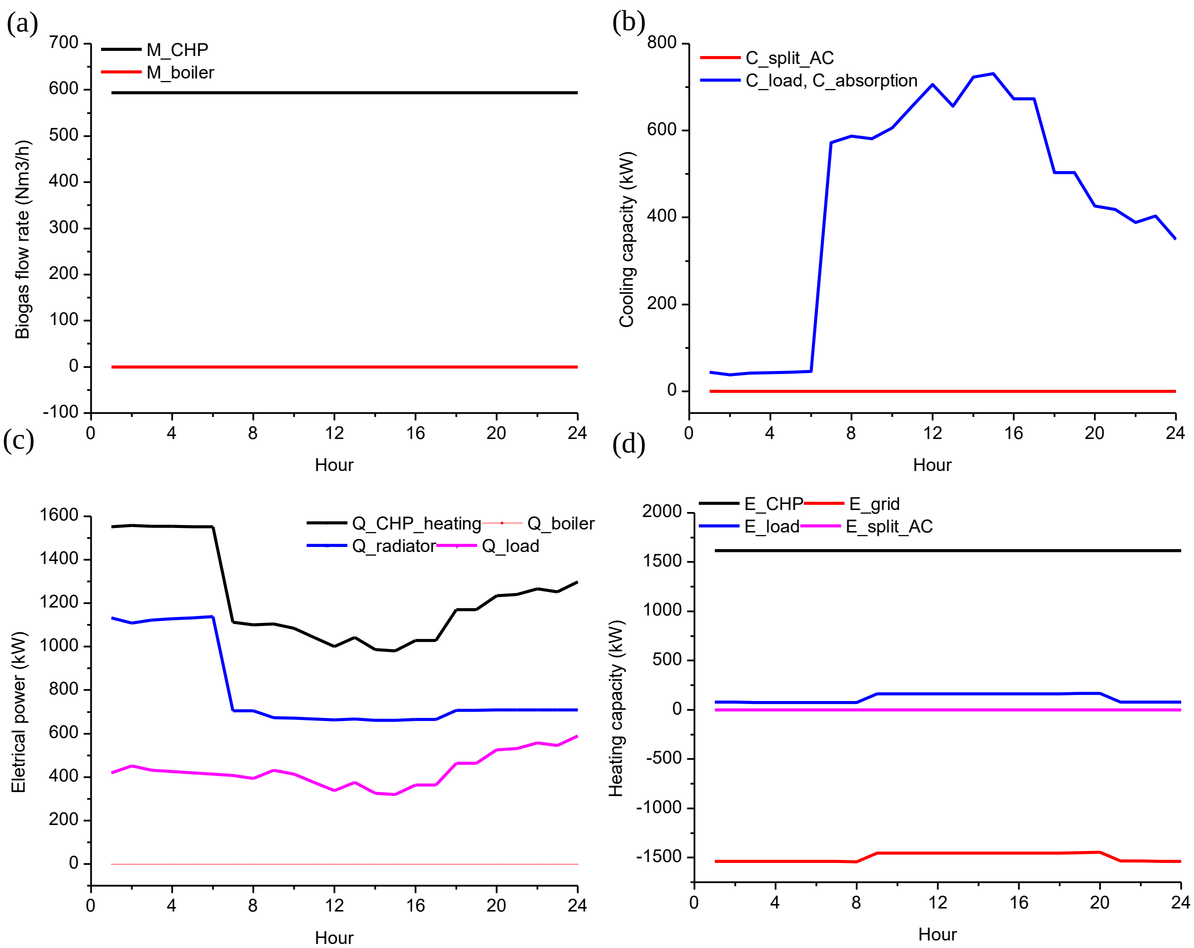

Fig.14 Performances of CCHP in summer under the sizing criteria of peak heating load: (a) biogas consumption (b) cooling performance (c) heating performance (d) electrical performance

Fig.14 shows the summer performances of the CCHP system under the sizing criteria to meet peak heating demand. Similar with the winter case, the CHP operates at full load from all day long. The boiler is out of usage as the heating capacity of the CHP is large enough. Besides, as the capacity of the CHP as well as the absorption chiller is large, the cooling load can be fully covered by the absorption chiller so that no split-type air condition is necessary. However, the shortcoming of the system is high energy waste, especially in summer. The waste energy by the radiator in summer is almost twice than that of in winter because of lower heating demand. This system can be disconnected to any other grid but needs huge investment, operation and maintenance fee.

4.2.4 Influence of different sizing criteria

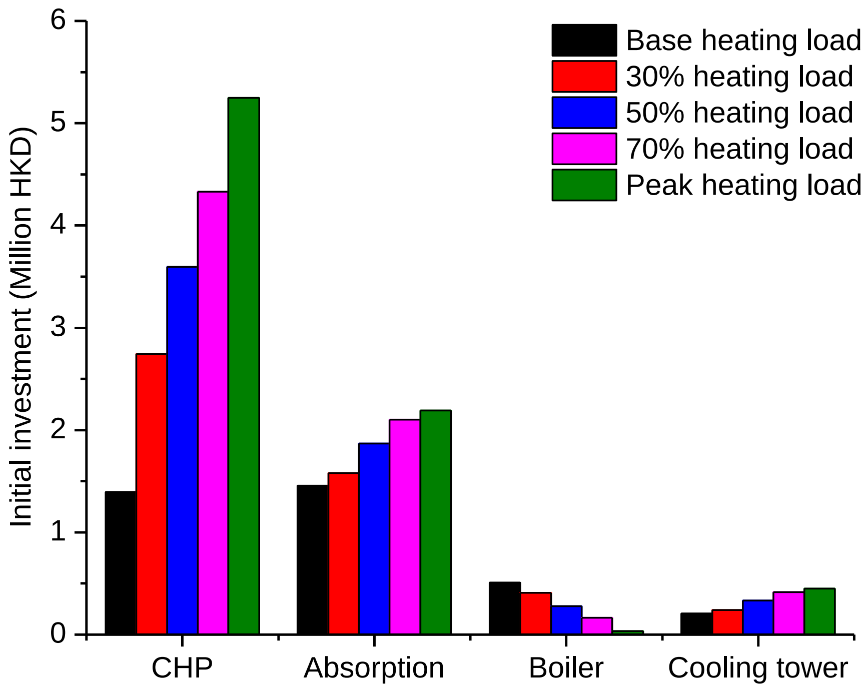

Fig.15 Initial investment of main components in CCHP system under different sizing criteria

As there is flexibility in choosing the sizing creteria of CCHP system, preliminary study should be conducted for selecting an optimal sizing scheme. The proposed program can be used for optimizing system sizing by taking profit, fuel cost, investment, operation and mantanence fee into consideration. The simulation were conducted under 5 different sizing schemes: base heating load, 30% peak heating load, 50% peak heating load, 70% heating load and peak heating load. Their investment on main equipment were shown in Fig.15. It can be seen that CHP unit and absorption chiller account for the majority of the total investment (80% ~90%). The annual optimal objective function values (*fval*) of different sizing schemes under three biogas prices were plotted in Fig.16. The smaller the value, the more economically attractive it is. It can be seen that the optimal sizing (as circled in red) was different under different biogas price. It would be better to size the CCHP system on the peak heating load when the biogas price is 0, such as in the sewage treatment plant where the biogas is self-generated. But it is more economically attractive to size the system on the base heat load when the biogas price increases to 4 HKD/Nm^3. So the cheaper the fuel price, the larger the system should be.

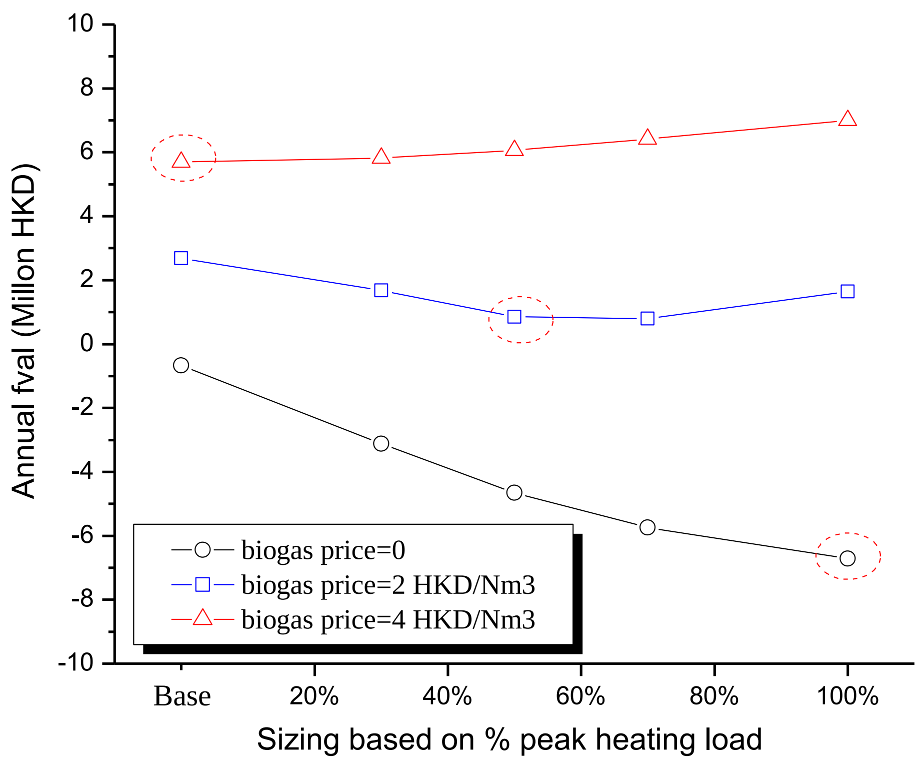

Fig.16 Annual *fval* of CCHP system under different sizing criteria

4.3 Simulation results under different biogas prices

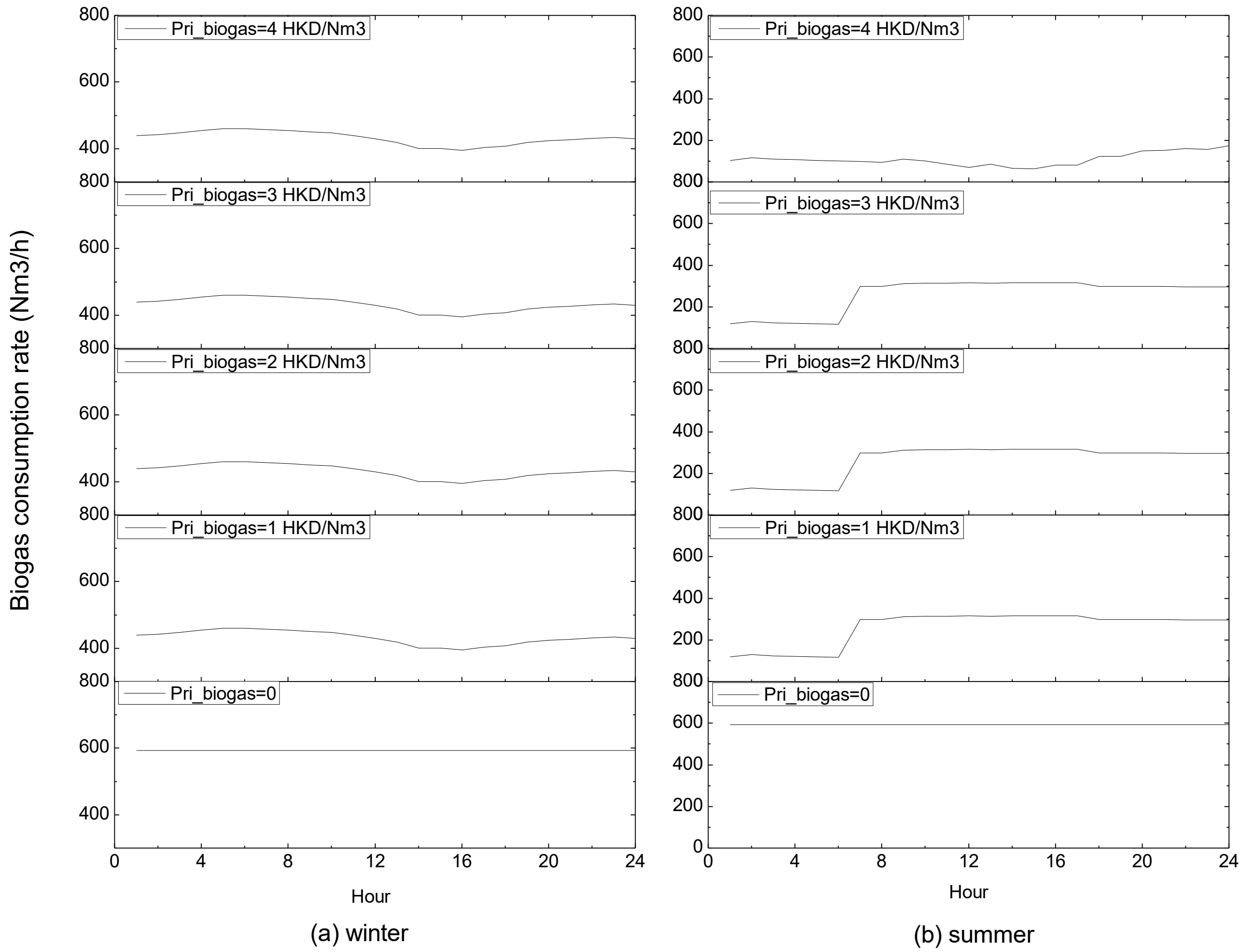

Fig.17 Biogas consumption under different biogas price: (a) winter (b)summer

The above results in Section 4.2 are based on the assumption that biogas price is 0. However, if the cost of biogas treatment and supply are considered, the simulation results can be different. Fig.17 presents the hourly biogas consumption by CHP under 5 different biogas price, ranging from 0 to 5.0 HKD/Nm^3.

It can be seen from Fig.17 that the higher the biogas's price, the less the CHP operates at full load. In winter, the CHP unit keeps operates at full load for 24 hours/day when the biogas's price is 0. However, as the biogas's price increases to 1.0 HKD/Nm^3, the CHP only operates at part load for the whole day. The biogas consumption drops a little at noon when the heating load of the digester is less. However, when the biogas's price keeps improving from 1.0 to 4.0 HKD/Nm^3, the hourly biogas consumption trend no longer changes in winter. It means that the CHP will always operate at part load only to satisfy the heating load when the biogas price is high. In this way, the cost of fuel can be saved but the electricity generation can be reduced. So there is a trade-off between saving biogas and producing more electricity, which is determined by the biogas price and electricity price. If the profit made by selling the excess electricity is less than the cost by consuming more biogas, it is more economy for CHP operates at lower load only to satisfy the heating load.

In summer, the similar conclusion can be drawn that the higher the biogas's price, the less the CHP operates at full load. There is trade-off between using the absorption chiller for cooling and using the electricity-driven split-type air-conditions. If the biogas's price is cheap enough compared with the electricity, CHP would operates more at full load in order to produce enough thermal energy to drive the absorption chiller. However, if the biogas is expensive, it is more economically attractive to use electricity for cooling directly. In Fig.17(b), we can see that the CHP operates at full load for 24 hours/day when the biogas price is 0. However, it only operates at high part load in the daytime as the biogas price increases to 1.0 HKD/Nm^3 and always operates at very low part load when the biogas price keeps increasing to 4.0 HKD/Nm^3. Under this condition, it is more economy for CHP operates only to meet the heating load. The cooling load will be satisfied by the split-type air-conditioning.

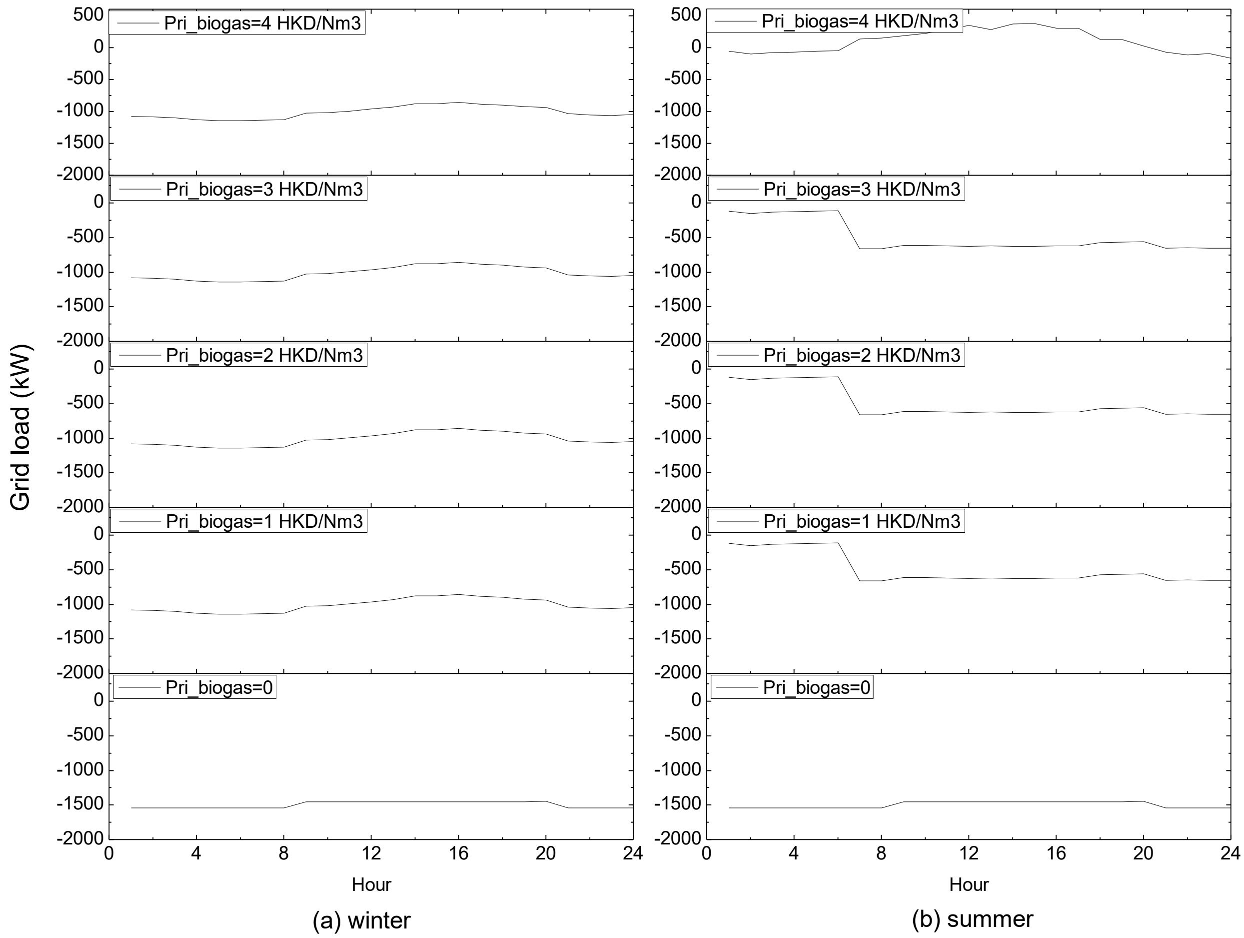

Fig.18 Utility grid load under different biogas price: (a) winter (b)summer

Fig.18 shows the utility grid load under different biogas price in winter and summer. The positive value means electricity is needed from the grid, so payment should be made for purchasing the power. The negative value means there is excess electricity supplied to the utilitiy grid, so extra income can be made by selling the power. Relvent with Fig.17, the CHP operates longer at full load when the biogas is cheaper, so more extra electricity can be obtained. In Fig.18, the excess electricity obtained under the biogas price is 0 is much more than that of biogas price is 4 HKD/Nm^3. There is always electricity needed from the grid in the summer daylight when the biogas price reaches 4 HKD/Nm^3.

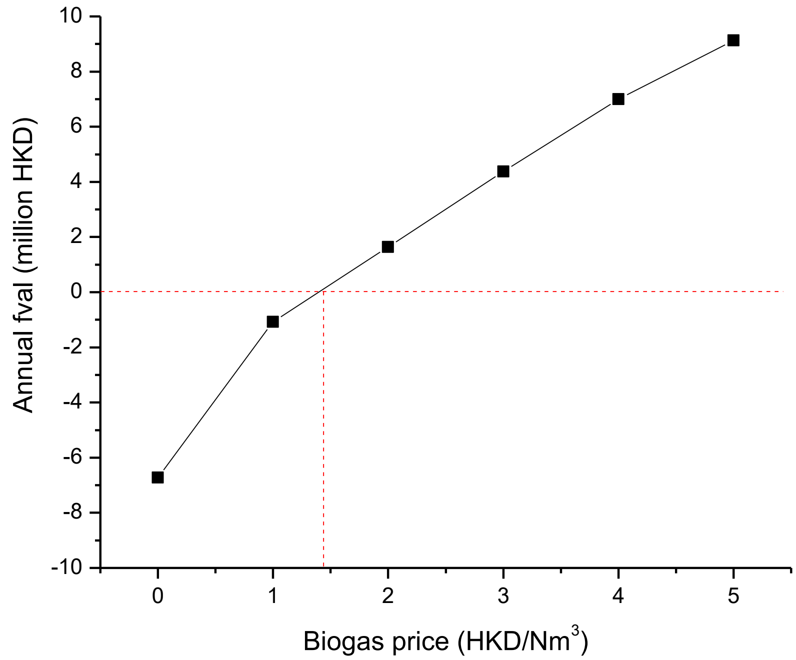

Fig.19 Annual *fval* of CCHP system under different biogas price

Fig.19 shows the annual optimal objective function value (*fval*) of peak-sized CCHP system under different biogas price. The smaller the annual *fval*, the less costly and more profitable of the system is. It can be seen that the annual *fval* decreases with the biogas's price decreases. As the annual *fval* represents the annual net expense of the CCHP operation when the heating, cooling and electricity load are satisfied, so extra profit can be obtained when the *fval* is negative. In the case study, it is definitely economically attractive to implement the CCHP system when the biogas's price is less than 1.4 HKD/|Nm^3.

5. Conclusions

This paper proposed an optimization method for design and operation of the Combined Cooling, Heating and Power (CCHP) system towards a smart grid. Two objectives can be achieved by the proposed program: (1) optimize the sizing of main components; (2) optimize the distribution of biogas and thermal energy and to predict the electricity demand from utility grid. The proposed program serve the smart grid from the aspect of demand side response. A sewage treatment plant in Hong Kong was selected as a typical study case because it needs simultaneous heating, cooling and electricity with self-generated fuel gas. Main conclusions can be summarized as follows.

(1) A simulation model of a CCHP system connected with smart grid was established considering electricity price, biogas price, system investment, maintenance and operation cost. It can be used for optimization of the system's design and operation.

(2) Different sizing criteria of a CCHP system can affect its optimized operation strategy. The CHP unit can avoid part load operation by under-sizing strategy, but the system has to rely on outside utility grid. The CCHP system can get rid of the dependency on outside utility grid if peak load sizing is adopted, but part load operation at night is inevitable. For the sewage treatment plant, it is more economic attractive to adopt a larger system. The CHP is optimized for always working at full load for fully satisfy the cooling and heating load and generate the most electricity for profit.

(3) The biogas price can affect the optimized CCHP operation strategy. The CHP unit operates longer at full load when the biogas price is cheaper. It operates at part load only to satisfy the heating load when the price increases to a certain value. The overall economic benefits will decrease with the increase of biogas price.

(4) The program can optimize the sizing of CCHP system at design stage. The higher the biogas price, the smaller the system should be sized. The optimal sizing is achieved when the the annual optimal objective function value is minimum.

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