Applied Energy 87 (2010) 1247–1259

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China

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ARTICLE INFO

Article history:
Received 10 April 2009
Received in revised form 2 June 2009
Accepted 15 June 2009
Available online 10 July 2009

Keywords:
Combined cooling, heating and power (CCHP) system
Multi-criteria analysis
Climate zones
Energy demand
Operation mode
China

ABSTRACT

The design and operation of combined cooling, heating and power (CCHP) systems are greatly dependent upon the seasonal atmospheric conditions, which determine thermal and power demands of buildings. This paper presents a mathematical analysis of CCHP system in comparison to separate system. The corresponding primary energy consumption in thermal demand management (TDM) and electrical demand management (EDM) operation modes are deduced. Three relative criteria, primary energy saving (PES), CO_2 emission reduction (CO_2ER), and annual total cost saving (ATCS) are employed to evaluate the respective performances of CCHP systems for a hypothetical building in five different climate zones from the technical, environmental and economic aspects. The results indicate that CCHP system in TDM mode in the cold area, where the building requires more heating during the year, achieves more benefit over separate system while CCHP system in EDM mode suits the building having stable thermal demand in mild climate zone.

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1. Introduction

Combined cooling, heating and power (CCHP) system is broadly identified as an alternative for the world to meet and solve energy-related problems, such as increasing energy demands, increasing energy cost, energy supply security, and environmental concerns [1–6]. In recent years, CCHP systems have been introduced in China into various kinds of buildings such as hotels, offices and hospitals [7].

The design and operation of CCHP systems are obviously dependent on the seasonal atmospheric conditions, which determine thermal and power demands [8–10]. China has an area of about 9.6 million km^2. Approximately 98% of the land area stretches between a latitude of 20°N and 50°N, from subtropical zones in the south to temperate zones (including warm-temperate and cool-temperate) in the north. The maximum solar altitudes vary considerably and there is a large diversity in climates, especially the temperature distribution during winter. China also has a complex topography ranging from mountainous regions to flat plains. These diversities and complexities have led to many different climates with distinct climatic features [11]. The application analysis of CCHP systems in different climate zones is beneficial to save energy and reduce greenhouse gas (GHG) successfully in China.

The feasibility of CCHP system is firstly considered by governments, producers or users. The economic and/or thermoeconomic analysis are often used in a project. The financial analysis was applied to various CCHP projects, such as micro system with Stirling engine [12], sewage treatment plant [13], kraft pulp mill [14], hybrid CCHP and heat pump [15], village-scale CCHP [16], and organic rankine cycle and gasification for biomass CCHP system [17]. The thermoeconomic analysis is an additional supplement method. It was also already applied to micro system driven by engine and adsorption chiller [18], CCHP systems serving a 300-bed hospital in a Mediterranean area [19] and a 646 rooms hotel in Italy [20].

The technical analysis is related to the feasibility of CCHP system besides to economic performance. Many new CCHP systems having different configurations or characteristic such as silica gel–water adsorption chiller [21], landfill gas utilization [22] and integrated thermal management controller [23] were analyzed technically. Primary energy consumption [24], primary energy ratio (PER) [25,26], primary energy saving (PES) [22,27], fuel energy saving ratio [9], energy-efficiency [6,28,29] are often employed to evaluate the technical performance of CCHP system. More importantly, the environmental effect of CCHP system is an important factor, especially in the global environmental issues. Several researchers have evaluated and analyzed the benefits of CCHP systems in terms of environmental protection for different applications. Mago et al. [24] adopted CO_2 emission to evaluate CCHP systems in four different cities. Chicco and Mancarella [30–32] presented a novel approach to assess the emission reduction of CO_2

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doi:10.1016/j.apenergy.2009.06.027

Nomenclature

ATCS	annual total cost saving
CCHP	combined cooling heat and power
CO_2ER	CO_2 emission reduction
COP	coefficient of performance
EDM	electricity demand management
GHG	greenhouse gas
PGU	power generation unit
PER	primary energy ratio
PES	primary energy saving
TDM	thermal demand management

Symbols

C	cost
E	electricity
F	fuel
N	installation capacity
Q	heat
R	capital recovery factor
α	conversion factor
η	efficiency
μ	CO_2 emission conversion factor

Subscripts

b	boiler
c	cool
ch	absorption chiller
e	electricity
f	fuel
$grid$	electricity grid
h	heat
p	pump
pgu	power generation unit
r	recovery heat
rc	the part of recovery heat for cooling
rec	waste heat recovery system
rh	the part of recovery heat for heating

Superscript

SP	Separate production

and other GHGs from CCHP systems. Medrano et al. [6] studied the environmental impacts of the high temperature fuel cells, microturbine generators and photovoltaics into four types of commercial buildings. Hao et al. [22] evaluated the GHG emission reduction of a landfill gas CCHP system in Hong Kong. Jaber and Probert [33] predicted the air, land and water impacts for a proposed commercial-sized oil-shale integrated CCHP system. Fumo et al. [34] presented a CO_2 emission operational strategy of CCHP system compared with primary energy operational strategy.

Generally, multi-criteria evaluation for CCHP systems has been paid more and more attention from economic/thermoeconomic, technical, and environmental aspects. Wang et al. [4,5] employed grey relational method and fuzzy analytical hierarchy process method to compare five CCHP schemes for a building in Shanghai, China, from technical, economic, environmental and social aspects, respectively. Alanne et al. [35] utilized multi-criteria method to select the optimal CCHP system for a residential building according to financial and environmental performances. Cho et al. [36] used operational cost, primary energy consumption and CO_2 emission to evaluate the CCHP systems for different cities.

This paper aims to analyze the technical, environmental and economic performances of CCHP systems following the thermal demand management (TDM) and the electricity demand management (EDM) operation modes in different climate zones in China. This paper is organized as follows: Section 2 analyzes CCHP model and introduces the evaluation criteria. Section 3 presents the numerical application analysis of a commercial building located in five typical cities, China. Some concluding comments are concluded in the last section.

2. CCHP system and evaluation criteria

To carry out this analysis, an separate system in China, as a reference system, is compared to CCHP system. The energy flow diagrams of reference system and CCHP system are shown in Fig. 1. The left part is the separate system and the other side is the CCHP system. The energy demands of building include: (1) electric energy use (lights and equipments), E; (2) cool demand for space cooling, Q_c; and (3) heat demand for space heating and domestic hot water, Q_h.

2.1. Reference system

The cooling system in the separate system adopts the electric chiller, and the heat comes from gas boiler and is distributed to users through heating coils. The electricity needed by building and chiller is from the local electricity grid.

The total electrical energy from grid, E_{grid}^{SP}, is

$$E_{grid}^{SP} = E + E_c + E_p^{SP} \tag{1}$$

where E_c is the electricity supplied to the chiller and E_p^{SP} is the additional electrical energy use of distribution equipments such as pumps and fans.

The electricity needed by the chiller can be replaced to

$$E_c = \frac{Q_c}{COP_e} \tag{2}$$

where COP_e is the coefficient of performance (COP) of electric chiller.

Based on the energy consumption ratio of hotel in China and the equation in Ref. [37], the electricity consumption of pumps and fans is estimated to

$$E_p^{SP} = 0.26\left(E_c + \frac{Q_h}{3Q_c}\right) \tag{3}$$

Considered the energy loss of grid during the transmission, the total electric energy from grid is converted to the fuel energy consumption as follows:

$$F_e^{SP} = \frac{E_{grid}^{SP}}{\eta_e^{SP}\eta_{grid}} \tag{4}$$

where η_e^{SP} and η_{grid} are the power generation efficiency and grid distribution efficiency, respectively.

The fuel energy consumption for heating system is computed as

$$F_b^{SP} = \frac{Q_b}{\eta_b^{SP}} = \frac{Q_h}{\eta_b^{SP}\eta_h^{SP}} \tag{5}$$

where Q_b is the output heat of boiler, and η_b^{SP} and η_h^{SP} are the efficiencies of boiler and heating coil, respectively.

Therefore, the total fuel energy consumption is calculated by combining Eqs. (1)–(5) as follows:

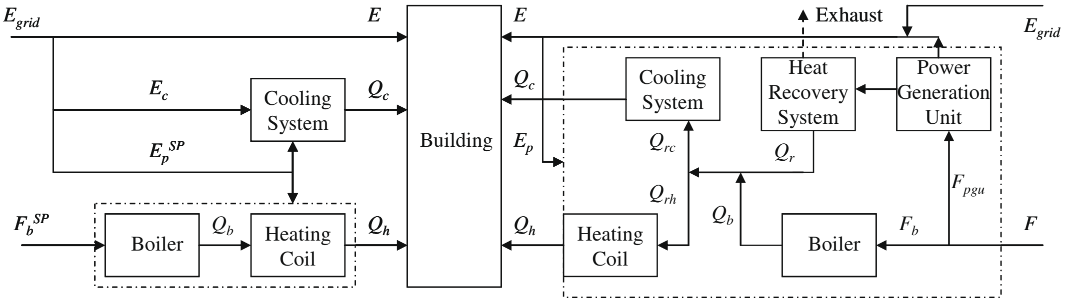


Fig. 1. General structures of reference separate system and CCHP system.

$$F^{SP} = \frac{E}{\eta_e^{SP}\eta_{grid}} + \frac{E_p^{SP}}{\eta_e^{SP}\eta_{grid}} + \frac{Q_c}{COP_e\eta_e^{SP}\eta_{grid}} + \frac{Q_h}{\eta_b^{SP}\eta_h^{SP}} \tag{6}$$

2.2. CCHP system

2.2.1. Energy flow of CCHP system

The schematics of CCHP system are shown in the right part of Fig. 1. Fuel, natural gas, is supplied to the power generation unit (PGU) to produce electricity. The waste heat is recovered and used to produce cool or heat for building. To simplify the structure of CCHP system, the cooling system adopts the absorption chiller to utilize the recovered heat from PGU and produce cool (to improve the performance of CCHP system, the cooling system can adopt the mix chillers according to the "redundant design" concept [38]. Herein, the performance of general CCHP system is analyzed, not to especially outstand the benefits achieved by CCHP system in comparison to separate system). The auxiliary boiler is used to provide the additional heat, and the supplemental electricity comes from grid when the electricity produced by PGU is not enough.

The balance of the electric energy is expressed as

$$E_{grid} + E_{pgu} = E + E_p \tag{7}$$

where E_{grid} is the electricity from grid, E_{pgu} is the generated power by PGU, and E_p is the parasitic electric energy consumption of CCHP system, such as the electricity consumption of pumps and fans, etc.

The additional electric energy in cooling demand is estimated as [39]

$$E_p = \alpha_c E_p^{SP} \tag{8}$$

and for heating demand, the parasitic electricity is estimated to

$$E_p = \alpha_h E_p^{SP} \tag{9}$$

where α_c and α_h are factors when cooling and heating are required, respectively. When a CCHP system operates, most of the original parasitic electricity demand remains as part of the distribution system. Additionally, some electric energy is required by new equipment to recover the waste heat from the PGU in the heating mode. For the cooling mode of CCHP systems, more electric energy is required compared with the heating condition because of the additional equipment associated with the absorption chiller. Therefore, in general, α_c is greater than α_h [39,40].

The PGU fuel energy consumption, F_{pgu}, can be estimated as

$$F_{pgu} = \frac{E_{pgu}}{\eta_e} \tag{10}$$

where η_e is the PGU generation efficiency.

The recovered waste heat from PGU, Q_r, can be calculated as

$$Q_r = F_{pgu}\eta_{rec}(1-\eta_e) \tag{11}$$

where η_{rec} is the efficiency of heat recovery system.

The heat supplied to the cooling system and heating coil is

$$Q_r + Q_b = Q_{rc} + Q_{rh} \tag{12}$$

where Q_b is the supplementary heat from the boiler, Q_{rc} and Q_{rh} are the heat supplied to cooling system and heating coil, respectively.

The heat required by the cooling system and heating coil are estimated, respectively, as

$$Q_{rc} = \frac{Q_c}{COP_{ch}} \tag{13}$$

and

$$Q_{rh} = \frac{Q_h}{\eta_h} \tag{14}$$

where COP_{ch} is the absorption chiller's COP, and η_h is the efficiency of heating coil.

The supplementary fuel energy consumption to the boiler, F_b, can be estimated as

$$F_b = \frac{Q_b}{\eta_b} = \frac{Q_{rc} + Q_{rh} - Q_r}{\eta_b} \tag{15}$$

where η_b is the auxiliary boiler efficiency.

Therefore, the on-site fuel energy consumption, $F_{on\text{-}site}$, is calculated as

$$F_{on\text{-}site} = F_{pgu} + F_b \tag{16}$$

During analysis and application of CCHP system, some important assumptions are followed:

(1) The CCHP equipments can operate anywhere between 0% and 100% of its rated capacity, and ramping rate for load adjustment is not included.
(2) The CCHP system is assumed to be 100% reliable.
(3) The efficiency drops of CCHP equipments at part load operation are neglected to simplify the analysis and calculation.
(4) One of operation strategies of CCHP system is the TDM mode [8,29]. When PGU runs in TDM operation mode, CCHP system may produce excess electricity that can usually be exported or stored for future use. However, the electricity generated by micro-CCHP system for building is not allowed to be sold back to grid in China. Consequently, it is assumed that the excess electricity is not sent to grid. The additional electricity can be sent to other nearby users or be stored. The energy saving or economical saving of the excess electricity is not considered into the independent CCHP system. However, it is important to understand this does not preclude the fact that electricity may still be sold back to the grid as the technical dissipation of the surplus electricity for this possibility.
(5) EDM operation mode is another simple operation mode of CCHP system. Indeed in the practical CCHP system, the

excess heat may be produced in EDM operation mode and can be distributed to other users. For an independent CCHP system, the energy saving or economical saving of the excess heat is not considered. Therefore, it is assumed that the surplus heat is dissipated directly.

From Eq. (15), it can be seen that F_b may be negative in the mathematical calculation, which is against reality. In addition, the excess electricity is not sold back to grid. Therefore, the general expression of the primary energy consumption in TDM and EDM modes is

$$F = F_{pgu} + \frac{Q_b}{\eta_b} \cdot V + \frac{E_{grid}}{\eta_e^{SP}\eta_{gird}} \cdot U \tag{17}$$

where

$$V = \begin{cases} 1, & Q_b \geqslant 0 \\ 0, & Q_b < 0 \end{cases}$$

and

$$U = \begin{cases} 1, & E_{grid} \geqslant 0 \\ 0, & E_{grid} < 0 \end{cases}$$

2.2.2. TDM operation mode

The capacities of equipments in CCHP system are determined according to the heat cumulative curves and the energy demands of building (the detailed explanation can be found in Section 3.1) in TDM mode. After the equipments are selected, the outputs of equipments are limited. The maximum input fuel energy of PGU is assumed to $F_{\max}$. When the recovery waste heat from PGU is not enough to provide the cooling system and heating coil, the supplemental boiler provides the additional heat. When the electricity needed by the building and the auxiliary equipments is more than the generated power from PGU, the additional electricity is bought from the grid. In this operation mode, there are not excess heat while the excess electricity may be produced. However, the surplus generated electricity from PGU is not allowed to be sold back grid.

The operating condition and the primary energy consumption are expressed in Eqs. (18)–(20) according to the energy flow of CCHP system as follows:

$$\text{Test condition}: \frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} \geqslant F_{\max}(1-\eta_e)\eta_{rec} \tag{18}$$

If Test condition = True then

$$F = F_{\max} + \frac{\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - F_{\max}(1-\eta_e)\eta_{rec}}{\eta_b} + \frac{E_{grid}}{\eta_e^{SP}\eta_{gird}} \cdot U \tag{19}$$

where $E_{grid} = E + E_p - F_{\max}\eta_e$.

When the heat needed by building is more than the maximum recovery heat from PGU, $\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} \geqslant F_{\max}(1-\eta_e)\eta_{rec}$, the back-up boiler runs to supplement the additional heat and the fuel energy consumption of CCHP system consists of three parts. The first is the input gas from PGU to get the maximum recovery heat, $F_{\max}(1-\eta_e)\eta_{rec}$, as the first item in Eq. (19). The second is the supplemental fuel from boiler aiming to supplement the additional heat, $\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - F_{\max}(1-\eta_e)\eta_{rec}$, as the second item in Eq. (19). The last is the fuel consumption of electricity from grid as the third item in Eq. (19). The third part is based on the difference between the generated electricity of PGU and the electrical demand.

If Test condition = False then

$$F = \frac{\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h}}{(1-\eta_e)\eta_{rec}} + \frac{E_{grid}}{\eta_e^{SP}\eta_{gird}} \cdot U \tag{20}$$

where

$$E_{grid} = E + E_p - \frac{\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h}}{(1-\eta_e)\eta_{rec}}\eta_e.$$

Contrarily, the back-up boiler is not needed, $F_b = 0$ in Eq. (17), and the fuel energy consumption consists of two parts when the heat needed by building is less than the maximum recovery heat from PGU. The first is the input gas from PGU to obtain the heat needed by building, $\frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h}$, as the first item in Eq. (20). The second is the fuel consumption of electricity from grid as the second item in Eq. (20). Similarly, the second part is based on the electrical difference.

2.2.3. EDM operation mode

Similarly, the capacities of CCHP system are decided according to the electricity cumulative curves and the energy demands of building in EDM mode. The maximum input of PGU is also assumed to $F_{\max}$. PGU operates according to the electricity load of building. When the electricity generated by PGU is not enough to satisfy the electricity demands of building and the pumps, etc. the additional electricity comes from grid. The recovered heat is used to produce cool or heat. When the recovered heat is not enough, the boiler begins to run to supplement the additional heat. CCHP system would not export excess electricity to grid in this operation mode while the surplus heat may be exhausted.

The operating condition and the total primary energy consumption are expressed in Eqs. (21)–(23) as follows:

$$\text{Test condition}: E + E_p \geqslant F_{\max}\eta_e \tag{21}$$

If Test condition = True then

$$F = F_{\max} + \frac{Q_b}{\eta_b} \cdot V + \frac{E + E_p - F_{\max}\eta_e}{\eta_e^{SP}\eta_{gird}} \tag{22}$$

where $Q_b = \frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - F_{\max}(1-\eta_e)\eta_{rec}$.

When the electrical demand is more than the produced electricity from PGU, $E + E_p \geqslant F_{\max}\eta_e$, the additional electricity from grid is needed and the energy consumption of CCHP system consists of three parts. The first is the input gas from PGU to obtain the maximum electricity, $F_{\max}\eta_e$, as the first item in Eq. (22). The second is the supplemental electricity from grid, $E + E_p - F_{\max}\eta_e$, as the third item in Eq. (22). The last is the fuel consumption of heat from boiler as the second item in Eq. (22). The last part is based on the difference between the recovered heat and the heat demand.

If Test condition = False then

$$F = \frac{E + E_p}{\eta_e} + \frac{Q_b}{\eta_b} \cdot V \tag{23}$$

where $Q_b = \frac{Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - \frac{E+E_p}{\eta_e}(1-\eta_e)\eta_{rec}$.

When the electrical demand is less than the maximum electricity from PGU, the generated electricity is enough, $E_{grid} = 0$ in Eq. (17), and the fuel energy consumption includes two items. The first is the input fuel from PGU to get the electrical demand, $E + E_p$, as the first item in Eq. (23). The second is the fuel consumption of heat from boiler as the second item in Eq. (23). Similarly, the second part is based on the thermal difference.

2.3. Evaluation criteria

To quantifying the benefits achieved by use of CCHP systems over the reference separate system, many evaluation criteria have been formulated [8,28,30,31,41].

(1) Primary energy rate (PER) is defined as the ratio of the required output to primary energy demand. It is a satisfac-

tory criterion to evaluate the combined system. It is expressed as

$$PER = \frac{E + Q_c + Q_h}{F} \tag{24}$$

(2) To measure the benefit of CCHP system over separate system, primary energy savings (PES) is defined as the ratio of the saving energy of CCHP system over separate system to the energy consumption of separate system. It can be written as

$$PES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{F^{SP}} \tag{25}$$

(3) The amount of CO_2 emission from CCHP system can be estimated using the emission conversion factor as follows [30]:

$$CO_2E = \mu_{CO_2,f} F_{on\text{-}site} + \mu_{CO_2,e} E_{grid} \tag{26}$$

where $\mu_{CO_2,f}$ and $\mu_{CO_2,e}$ are the emission conversion factors of natural gas and electricity from grid, respectively.

Referred to the definition of PES, the amount of the CO_2 emission reduction (CO_2ER) of CCHP system over separate system can be calculated as follows:

$$CO_2ER = \frac{CO_2E^{SP} - CO_2E}{CO_2E^{SP}} = 1 - \frac{CO_2E}{CO_2E^{SP}} \tag{27}$$

CO_2ER shows the environmental benefits achieved by use of CCHP systems over separate systems.

(4) The annual total cost, which includes the annual capital cost and the annual energy charge, is calculated as

$$ATC = C_e + C_m \tag{28}$$

The annual capital cost of equipment, C_e, is expressed by

$$C_e = R \times \sum_{k=1}^{l} N_k C_k \tag{29}$$

where N and C are the installation power of equipment and the unit capital cost of each kind of equipment, respectively (the units of N_k and C_k are kW and Yuan/kW in this paper), l is the number of equipments. The capital recovery factor, R, is defined to:

$$R = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{30}$$

where i is the interest rate and n is the service life of the equipment. Herein it is assumed that the values of i and n are equal to all kinds of equipment.

The annual operational hours in a year are discretized by setting 365 days and by dividing each day into 24 h. The annual energy charge, C_m, is calculated as:

$$C_m = \sum_{i=1}^{365} \sum_{k=1}^{24} (E_{ik,grid} C_{ik,e} + F_{ik} C_{ik,f}) \tag{31}$$

where $C_{ik,e}$ and $C_{ik,f}$ are the hourly energy charges of electricity and natural gas, respectively (the units of $C_{ik,e}$ and $C_{ik,f}$ are Yuan/kW h here), and $E_{ik,grid}$ and F_{ik} are the hourly demands of the electricity bought from grid and the natural gas (the units of $E_{ik,grid}$ and F_{ik} are kW h here).

Similarly, to measure the economic benefits of CCHP systems over separate system, annual total cost saving (ATCS) is defined to the ratio of the saving annual cost of CCHP system in comparison to separate system to the annual cost of separate system. It can be written as

$$ATCS = \frac{ATC^{SP} - ATC}{ATC^{SP}} = 1 - \frac{ATC}{ATC^{SP}} \tag{32}$$

3. Application analysis in five climate zones in China

To analyze the application performances of CCHP systems in China, different climate zones are selected to compare in numerical analysis. In China, a major climate classification defines five major climatic types: severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter [11]. Five cities, Harbin, Beijing, Shanghai, Kunming and Guangzhou, are selected to represent the five climate zones, respectively. The geographic information of the five cities is shown in Table 1.

3.1. Building description and energy demands

The baseline building under consideration is a hypothetical hotel building. The hotel has a floor area of 9400 m^2 and an average main ceiling height of 3.6 m. The total area of the windows and glazing comprises about 30% of the total wall area. The building includes guest rooms, office rooms, dinning halls, ballrooms and divans. The building operates during the entire year. The temperature setpoint of guest room is 22–24 °C. The hourly energy consumption of the building is estimated using the software DeST [42].

Fig. 2 displays the heat demand cumulative curves for the hotels in the five cities. The thermal demands in Guangzhou and Harbin are almost equivalent and located in the former second place because there is very hot in summer in Guangzhou while there is severe cold in winter in Harbin. The thermal demand in Kunming is the lowest. Fig. 3 displays the electricity demand cumulative curves for the hotels including the parasitic electricity. Because of the different cool load and heat load, the parasitic electricity in the five CCHP systems are different. Additionally, because the parasitic electricity in cooling mode is more than in heating mode, the electricity demand in Guangzhou is more than in Harbin. The trend and range of the electricity demands in the five cities are almost close while the thermal demands are very various. Fig. 4 displays the monthly ratio of heat to electricity in the five climate zones. It can be found that the trends of ratios are similar except to Guangzhou due to the less thermal demand in warm winter, and they change with the season. The thermal demands of cooling season in the four cities except to Harbin, severe cold zone, are the maximum.

The sizes of various plant components must be chosen in order to maximize the benefits produced by CCHP systems, in terms of PES, CO_2ER or investment profitability. Some researchers developed special methods to optimize the designs of CCHP systems [20,43–49], for example robust algorithm and genetic algorithm. A common practice, which the capacity of a CCHP is based on the maximum amount of energy annually supplied at full load, may be simply implemented in the duration curve. The method prevents dramatic undersize or oversize of the CCHP unit, providing a good compromise between the requirements for a good part of the annual energy demand from CCHP system and for a sufficient annual operation at high load levels. However, the simple method could be considered rough and the detailed limits of this method can be found in Ref. [49].

Herein, the simple method based on the cumulative curve is adopted, and in particular it is finalized to choose the prime mover size. Beijing is taken as an example and the detailed selection method is described. In TDM operation mode, the capacity is based on the thermal cumulative curve. The maximizing area of Beijing, *XY*, in Fig. 2 could be determined and *Y* is the maximum heat

Table 1
Geographic information of the five cities.

Cities	Location	North latitude	East longitude	Climate
Harbin	Heilongjiang province	45°	126°	Severe cold
Beijing	Beijing	40°	116°	Cold
Shanghai	Shanghai	35°	121°	Hot summer and cold winter
Kunming	Yunnan province	25°	102°	Mild
Guangzhou	Guangdong province	23°	113°	Hot summer and warm winter

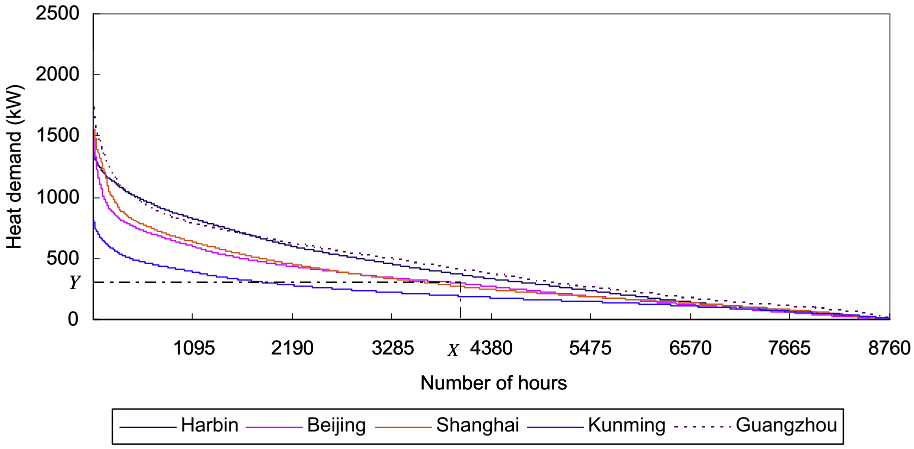


Fig. 2. The heat demands cumulative curves of the hotels in five cities.

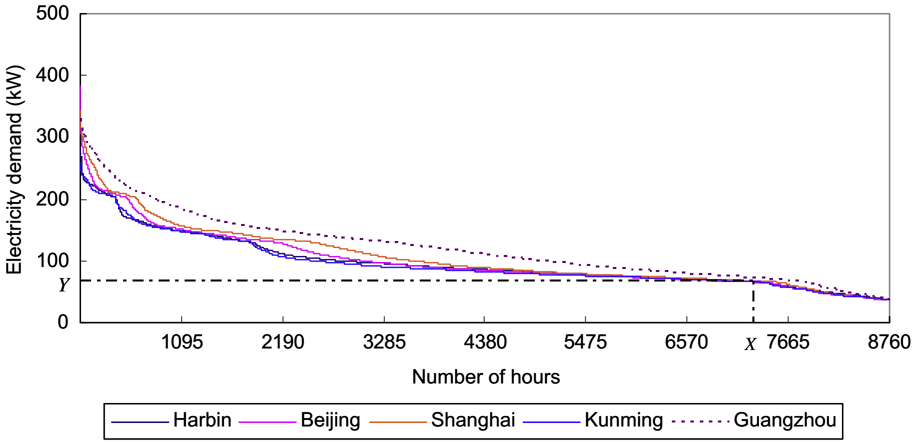


Fig. 3. The electricity demands cumulative curves of the hotels in five cities.

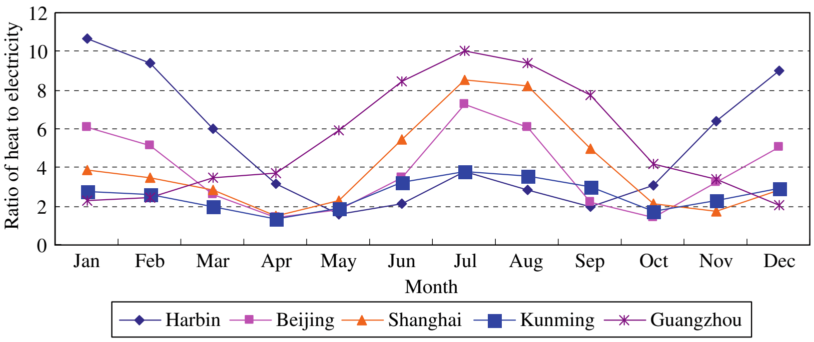


Fig. 4. Monthly ratio of thermal demand and electricity demand of the hotels in the five cities.

output from PGU. Such area represents, in fact, the heat amount annually supplied at full load of PGU. When this area is maximized, a good part of the annual heat consumption is provided by heat recoveries from PGU, while running at high load levels. The PGUs of CCHP systems for the five cities are selected according on this principle. Based on maximizing the area below heat cumulative curves, the maximum heat from PGUs, *Y*, and the duration time, *X*, are determined and summarized to the corresponding columns in the TDM mode of Table 2. Here it is assumed that the maximum recovery waste heat from PGU is just equal to the determined heat in Table 2. Similarly, the maximum electricity of PGU in EDM operation mode can be determined according to the electricity cumulative curves in Fig. 3 and is filled into the electricity column in the EDM mode of Table 2.

The values of the variables in CCHP system are presented in Table 3 [24,31,39,50]. To evaluate the impact of cooling system on performance of CCHP system, the single-stage absorption chiller is the base CCHP system and the double-stage absorption chiller is used to compare their performances with the base CCHP system. Used the determined values by cumulative curves and the input values of CCHP system, the generated electricity of PGU, the recovered heat from PGU, the maximum input fuel's capacity, $F_{\max}$, the maximum supplementary combustion fuel's capacity, the captivity of absorption chiller, and the maximum supplemental electricity from grid can be calculated and filled into Table 2. It is also assumed that the calculated values in Table 2 are the installation captivities of equipments.

3.2. Evaluation

3.2.1. Technical performance

Firstly, the technical performances of CCHP systems in TDM operation mode are analyzed. The excess hourly electricity generated by PGU is calculated and then it is normalized by the hourly electricity demand in TDM operation mode. Fig. 5a indicates the normalized monthly electricity variation. The positive value represents the excess electricity. Conversely, the part electricity needed by building comes from grid. The electrical output of CCHP system has to increase in order to provide the necessary thermal demand. There are not excess electricity generated by CCHP system in Kunming because of the lowest thermal load. Excess electricity are produced by CCHP systems in Harbin, Beijing and Shanghai in winter while the electricity is not enough in other seasons. There are surplus electricity for about 9 months from March to November in Guangzhou. Because the excess electricity cannot be allowed to be sold back to grid, it leads to the waste of energy. Therefore, the electricity export to grid should be paid more attention, especially in Guangzhou.

The top figure in Fig. 6a shows the monthly PES variation of CCHP systems in the five cities. Compared to Fig. 4, the trends of

Table 2
The capacities of equipments in CCHP systems.

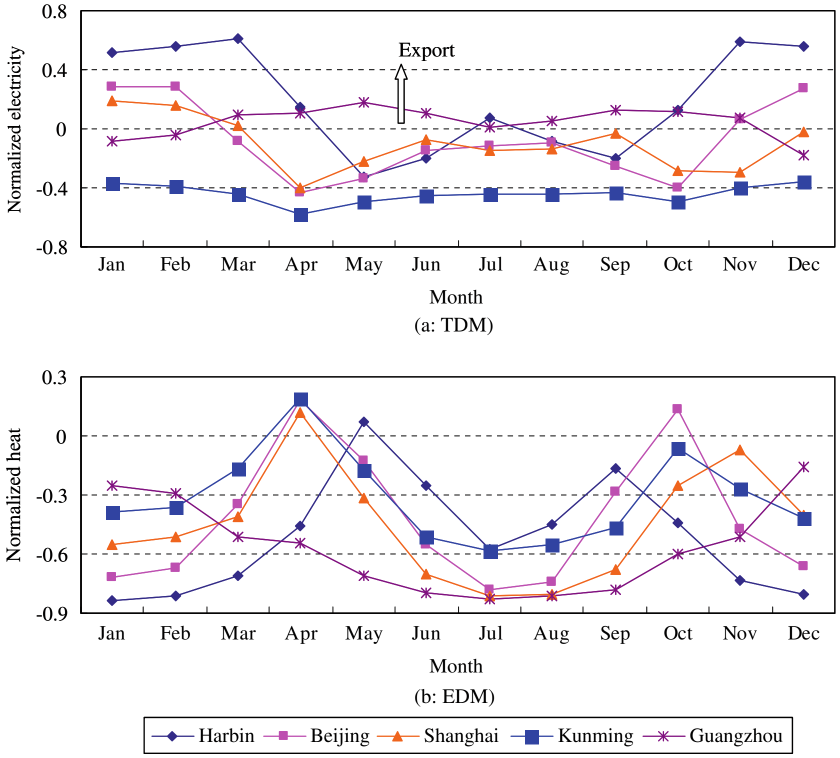
Operation modes	Cities	Prime mover				Auxiliary boiler (kW)	Absorption chiller (kW)	Max(E_{grid}) (kW)
		Heat (kW)	Electricity (kW)	F_{max} (kW)	Duration time (h)			
TDM	Harbin	391.20	163.00	652.00	3838	1469.90	1242.47	122.77
	Beijing	298.14	124.23	496.90	4042	2924.38	2343.63	258.74
	Shanghai	303.37	126.40	505.62	3673	2148.68	1785.44	215.81
	Kunming	146.20	60.92	243.67	5496	1125.78	823.28	198.23
	Guangzhou	395.44	164.77	659.07	4189	2111.80	1927.40	165.36
EDM	Harbin	159.17	66.32	265.28	7251	1759.95	1242.47	219.45
	Beijing	158.30	65.96	263.84	7301	3099.17	2343.63	317.00
	Shanghai	158.52	66.05	264.20	7531	2329.74	1785.44	276.16
	Kunming	158.57	66.07	264.28	7369	1110.32	823.28	193.08
	Guangzhou	168.91	70.38	281.52	7472	2394.96	1927.40	259.75

Table 3
Input values employed for the energy used calculations for separation system and CCHP system.

System	Variable	Symbol	Value
CCHP system	PGU efficiency	η_e	0.25
	Waste heat recovery system efficiency	η_{rec}	0.8
	Cooling system COP (single-stage)[a]	COP_{ch}	0.7
	Cooling system COP (double-stage)[a]	COP_{ch}	1.1
	Heating coil efficiency	η_h	0.8
	Boiler efficiency	η_b	0.8
	Factor in cooling mode	α_c	1.4
	Factor in heating mode	α_h	1.2
Separate system	PGU efficiency	η_e^{sp}	0.35
	Cooling system COP	COP_e	3
	Heating coil efficiency	η_h^{sp}	0.8
	Boiler efficiency	η_b^{sp}	0.8
	Grid transmission efficiency	η_{grid}	0.92
CO_2 emission conversion factor	Electricity from gird (g/kW h)	$\mu_{CO_2,f}$	220
	Natural gas (g/kW h)		
	Harbin[b]	$\mu_{CO_2,e}$	877
	Beijing		968
	Shanghai		911
	Kunming[b]		877
	Guangzhou		877

[a] The single-stage absorption chiller is the base CCHP system and the double-stage absorption chiller is used to compare their performances with the base CCHP system.

[b] The CO_2 emission conversion factors in Harbin and Kunming are selected based on Guangzhou's.



(a: TDM)

(b: EDM)

Fig. 5. Monthly electricity from grid or heat from supplemental boiler of CCHP systems for the hotels in the five cities.

the PES curves are reverse with the seasonal variation of the monthly thermal demands of the hotels. PES of CCHP system over the reference system deceases with the increase of the heat/electricity ratio. PES in summer is the lowest and even negative because of the higher ratio of heat to electricity, and PES in transitional seasons is relatively high because of the lower heat/electricity ratio except to Guangzhou.

Secondly, the technical performances in EDM operation mode are analyzed. Similarly, the excess hourly heat from CCHP system is calculated and then it is normalized by the hourly heat demand of building. Fig. 5b displays the normalized monthly heat variation. The positive value means that the surplus heat is produced by CCHP system while the negative value shows that the supplemental heat from back-up boiler is needed. The trends of heat are reverse with the seasonal variation of the monthly thermal demands. There are excess heat in only several month, and the months when there are excess products in EDM operation mode are less than in TDM mode. There are less supplemental heat from boiler in Kunming because of the lowest thermal load.

The top figure in Fig. 6b shows the monthly PES variation of CCHP systems in EDM mode. Compared to Fig. 6a, it can be seen that the trends of PES variation in EDM mode is similar to the trends in TDM mode. The only difference between TDM and EDM modes is the fluctuant range. CCHP system in EDM mode cannot save primary energy in more months.

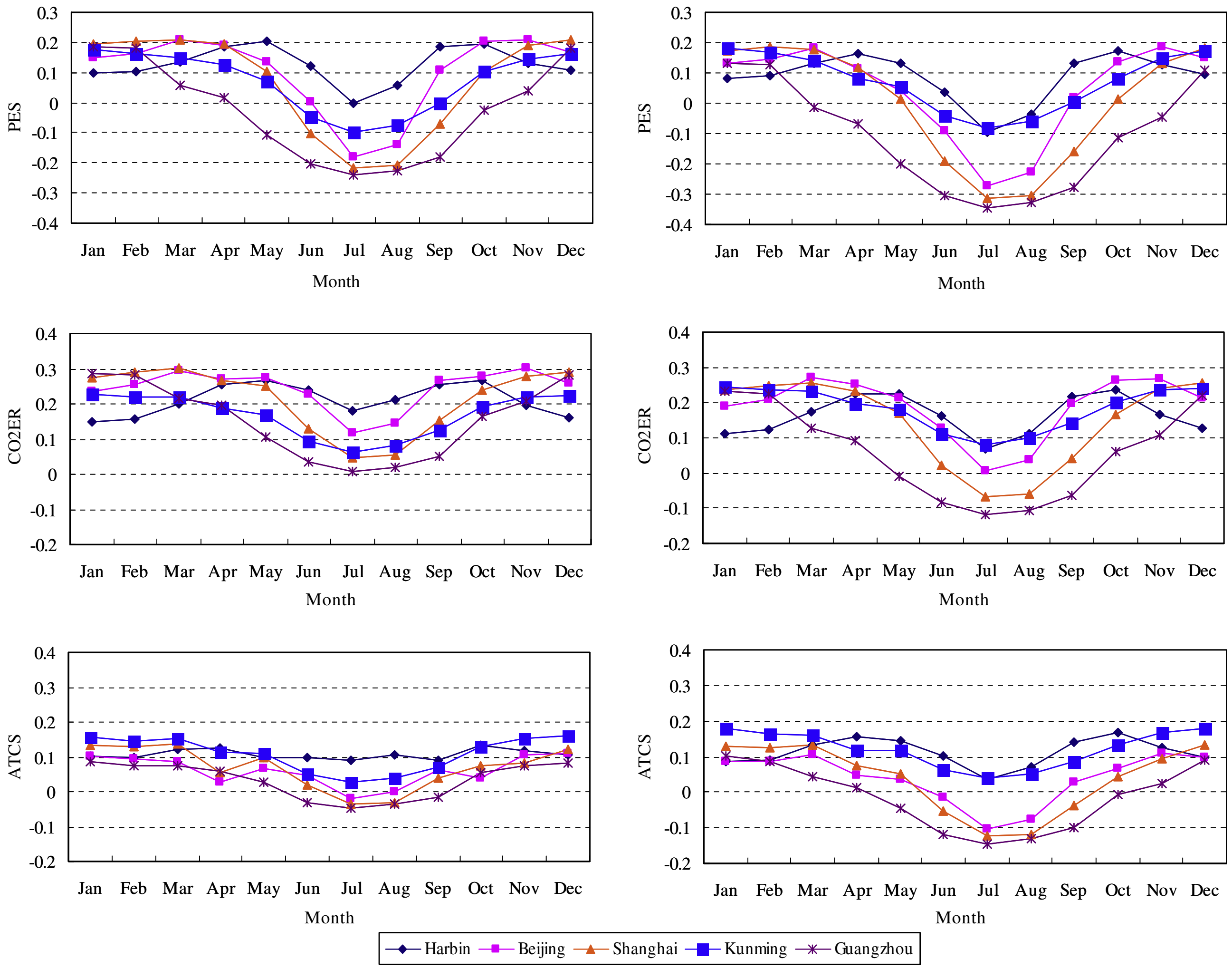
3.2.2. Environmental performance

Firstly, the monthly CO_2ER variations of CCHP systems in TDM operation for the five cities are shown as the middle figure in Fig. 6a. The trends of the CO_2ER curves are reverse with the ratio of heat to electricity in Fig. 3 except to Kunming's in winter. The whole trends of CO_2ER are similar to PES. All CO_2ER values are positive and the application of CCHP system in China is helpful to reduce GHG emission. The annual range of CO_2ER in Guangzhou is [0, 0.3] and its fluctuation is the maximum. Similarly, CO_2ER of CCHP system over separate system deceases with the increase of the heat/electricity ratio. The potential of CO_2ER is higher when the lower ratio of heat to electricity. Additionally, the CO_2 emission conversion factors of electricity from grid in Harbin and Beijing are 877 g/kW h and 968 g/kW h, respectively, while the corresponding annual fluctuant ranges are [0.15, 0.27] and [0.12, 0.30]. It can be found that the fluctuant range of CO_2ER in Beijing is higher than Harbin's and the maximum of CO_2ER in Beijing is better than Harbin's.

Secondly, the environmental performance in EDM operation mode are analyzed. The middle figure in Fig. 6b displays the monthly CO_2ER variation of CCHP systems in EDM mode. Compared to Fig. 6a, the trends of CO_2ER variation in EDM mode is similar to the trends in TDM mode. There are some negative values in summer in Guangzhou and Shanghai, and the application of CCHP system in summer does not always reduce GHG emission, especially the area where separate system has low emission. The annual range of CO_2ER in Guangzhou is [−0.12, 0.23] and the fluctuation is also the maximum. Additionally, the annual fluctuant ranges of CO_2 emission in Harbin and Beijing become to [0.07, 0.23] and [0.01, 0.27], respectively.

3.2.3. Economic performance

Use Eqs. (28)–(32), and the economic performances of CCHP systems are analyzed. The unit price of equipments are given in Table 4 (1 dollar ≅ 6.83 Yuan) [51]. The fee of power capacity increasing tariff (PCIT) in China is a specific fee, which is based on the size of installation power and used to construct grid and necessary system. The purpose of setting PCIT in China is to restrain the rising of high energy consumption and solve Chinese energy and environmental issues effectively. Although it is of an important regulation and controlling manner, it is a disputed fee to users and may be held or canceled in the following years. The base cost analysis includes the PCIT fee, and the Section 3.3 will discuss the cost performance when PCIT is canceled. The prices of electricity and natural gas are shown in Table 5 [51]. Here it is assumed that the prices of electricity and natural gas are all equal in the five cities, and the time



(a: TDM) (b: EDM)

Fig. 6. Monthly performance variation of CCHP systems for the hotels in the five cities.

Table 4
Unit price of the facilities in 2008 [51].

Facility	Prime mover	Heating coil	Boiler	Absorption chiller	Electric chiller	Power capacity increasing tariff
Unit price (Yuan/kW)	6800	200	300	1200	970	150

dependent electricity price is adopted. The interest rate is assumed to 0.1, and the service life is 20 year.

Firstly, the monthly ATCS variation of CCHP systems in TDM operation for the five cities are displayed as the bottom figure in Fig. 6a. The whole trends of ATCS are similar to the trends of PES and CO$_2$ER. In summer, the ATCS performance of CCHP system is not still ideal, especially in Guangzhou and Shanghai. Secondly, the monthly ATCS variation in EDM mode are shown as the bottom figure in Fig. 6b. The trends are same as in TDM mode and the fluctuant ranges are amplified. The time that CCHP system in EDM mode is worse than separate system are more than in TDM mode.

Table 5
Unit price of electricity and natural gas [51].

	Natural gas	Electricity (6:00–21:00)	Electricity (22:00–5:00)
Unit price (Yuan/kW h)	0.194	0.964	0.435

Then the detailed economic indexes of CCHP systems running in different strategies for the five cities are shown in Table 6, which includes the annual total cost per unit area and the annual total cost per unit primary energy. It can be seen that the annual total cost per unit area of the hotel in Kunming is the lowest, Shanghai's is in the second place and Guangzhou's is the maximal. The annual total cost per unit area of CCHP system in Kunming is lower 77.36 Yuan/m^2 year in TDM and 90.97 Yuan/m^2 year in EDM than Guangzhou's. The ranking order of the annual total cost per unit primary energy mode is Harbin $\succ$ Kunming $\succ$ Guangzhou $\succ$ Shanghai $\succ$ Beijing in EDM mode.

3.2.4. Overall evaluation

The annual total PES, CO$_2$ER and ATCS of CCHP systems including baseline case and double-stage cooling system in TDM and

Table 6
Economic index of CCHP systems for the hotels in the five cities.

Operation modes	Cities	Annual total cost per unit area (Yuan/m^2 year)	Annual total cost per unit primary energy (Yuan/kW fuel)
TDM	Harbin	168.95	0.250
	Beijing	161.22	0.285
	Shanghai	157.80	0.264
	Kunming	114.43	0.250
	Guangzhou	191.79	0.253
EDM	Harbin	168.77	0.241
	Beijing	165.64	0.276
	Shanghai	164.67	0.258
	Kunming	112.77	0.246
	Guangzhou	203.74	0.248

EDM operation modes for the five cities are displayed in Fig. 7. For PES criteria, the ranking orders in two operation modes are both Harbin $\succ$ Kunming $\succ$ Beijing $\succ$ Shanghai $\succ$ Guangzhou when the single-stage absorption chiller is adopted. The CCHP system in the city having more cool load saves less primary energy than separate system, and even does not save energy at all. When the cooling system adopts double-stage chiller, the CCHP systems could save more primary energy than the single-stage absorption chiller. However, the ranking orders in two operation modes are different, and it is Shanghai $\succ$ Beijing $\succ$ Guangzhou $\succ$ Kunming $\succ$ Harbin in TDM mode while Kunming $\succ$ Beijing $\succ$ Harbin $\succ$ Shanghai $\succ$ Guangzhou in EDM mode. The improvement of CCHP system for the building having more cool load is more when the double-stage absorption chiller is adopted. Compared between TDM mode and EDM mode, it can be seen that the CCHP system for the hotel in TDM mode can save more primary energy than in EDM mode.

For CO$_2$ER performance of CCHP system over separate system, all annual CO$_2$ER values in the five cities in two operation strategies are positive. CCHP system can really reduce CO$_2$ emission in China. The potential order to reduce CO$_2$ emissions of CCHP systems in the five climate zones is Beijing $\succ$ Harbin $\succ$ Shanghai $\succ$ Kunming $\succ$ Guangzhou in TDM mode when adopting the single-stage chiller. When running in EDM mode, the potential to reduce CO$_2$ emissions of CCHP systems deceases except to Kunming and the ranking order becomes to Kunming $\succ$ Beijing $\succ$ Harbin $\succ$ Shanghai $\succ$ Guangzhou. When adopting double-stage chiller, CCHP systems would reduce more CO$_2$ emission than the single-stage absorption chiller. The CO$_2$ER of CCHP system in Guangzhou and Shanghai are sensitive with the COP of cooling system. Compared TDM mode to EDM mode, it can be seen that the CCHP system for the hotel in TDM mode can reduce more CO$_2$ emission than in EDM mode except to in Kunming.

For the economical performance of CCHP system over separate system, all CCHP system is better than the separate system's except to Guangzhou's CCHP system that adopts single-stage absorption chiller in EDM. The ATCS ranking order of CCHP systems in the five

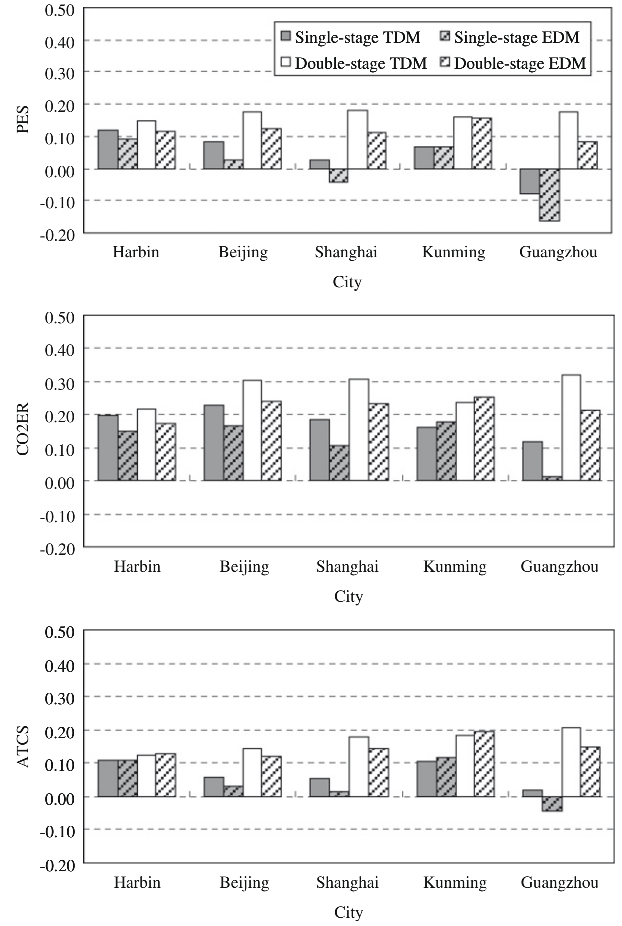


Fig. 7. The annual performance of CCHP systems for the hotels in the five cities.

Table 7
Ranking orders of CCHP systems in the five cities.

Operation modes	Cities	Technology	Environment	Economy	Overall
TDM	Harbin	1	2	1	**1**
	Beijing	2	1	3	**2**
	Shanghai	4	3	4	**4**
	Kunming	3	4	2	**3**
	Guangzhou	5	5	5	**5**
EDM	Harbin	1	3	2	**2**
	Beijing	3	2	3	**3**
	Shanghai	4	4	4	**4**
	Kunming	2	1	1	**1**
	Guangzhou	5	5	5	**5**

climate zones is Harbin ≻ Kunming ≻ Beijing ≻ Shanghai ≻ Guangzhou in TDM mode when adopting the single-stage chiller. When running in EDM mode, the potential of saving cost deceases except to Kunming and the ranking order becomes to Kunming ≻ Harbin ≻ Beijing ≻ Shanghai ≻ Guangzhou. When utilizing double-stage chiller, CCHP systems could save more cost than the single-stage absorption chiller. The improvement in Guangzhou is the most outstanding because of the more cool load.

Additionally, it can be found that the CO_2ER performance of CCHP system is the most in the three criteria. The environmental-friendly characteristic of CCHP system is the most outstanding in China. The ranking orders of baseline CCHP system in two modes are summarized to Table 7. The ranking orders in the three aspects are different. It is necessary to aggregate the sequencing results and present a final result.

Adopted entropy weighting method [4], the weights of criteria are calculated to [0.309, 0.309, 0.382] in TDM mode and [0.321, 0.317, 0.362] in EDM mode, respectively. After calculating the weighted performances of CCHP systems in the five cities, the scores of CCHP systems in two modes for the five cities are shown in Fig. 8, and the overall ranking order is summarized to Table 7. It is seen that the ranking order of the benefits achieved by CCHP system in the five cities is Harbin ≻ Beijing ≻ Kunming ≻ Shanghai ≻ Guangzhou in TDM operation mode while Kunming ≻ Harbin ≻ Beijing ≻ Shanghai ≻ Guangzhou in EDM operation mode. As a whole, the application of CCHP in cold climate in China is ideal when CCHP system runs in TDM mode. When CCHP system runs in EDM mode, the CCHP system for the building having stable thermal demands during the entire year achieves more benefits over the local separate systems.

3.3. Discussion

This section discusses the cost performance of CCHP system when canceling PCIT and the impact of the reference separate system on the relative performance of CCHP system.

Firstly, the fee of PCIT is not included into the capital cost, and the economic performances of CCHP systems are recalculated and compared the corresponding baseline CCHP systems including PCIT as shown in Fig. 9. It can be seen that the economic performances of CCHP systems decreases with the elimination of PCIT in TDM operation mode. The decrease in Beijing is the maximum because the supplemental electricity from grid is the maximum as shown in Table 2. The economic benefit achieved by CCHP system over separate system will be lessen when PCIT is canceled. When CCHP system runs EDM mode, ATCS of CCHP systems over separate systems increase except to in Beijing. The increase in Guangzhou is the maximum.

Additionally, in order to highlight the impact of the reference separate systems, the reference efficiency scenarios reported in Table 8 are selected to recalculate PES of CCHP systems in the five climate zones. The low-efficiency reference (S1) values could be used for a typical comparison with equipment used in non-centralized systems for residential or tertiary applications. The average reference (S2) values could be applied for dealing with the equipment used in centralized systems for residential or tertiary or some industrial applications. The intermediate reference (S3) values could be used for dealing with industrial equipment. Finally, the state-of-the-art reference (S4) values point to the best technologies that can normally be encountered today (ruling out specific higher-efficiency equipment and prototypes available but not yet commercialized) [27].

The PES of CCHP systems running different modes in the five climate zones over the different reference systems are shown in Fig. 10. The PES performances of CCHP system in two operation strategies are similar. It can be seen that the PES of CCHP system deceases with the improvement of separate system. Increasing separate system efficiencies leads to smaller energy saving for CCHP system, which becomes in negative for the state-of-the-art scenario. The application of CCHP systems in Harbin still save the primary energy when the local separate system adopts the intermediate reference system in Table 8. Additionally, the PES of CCHP

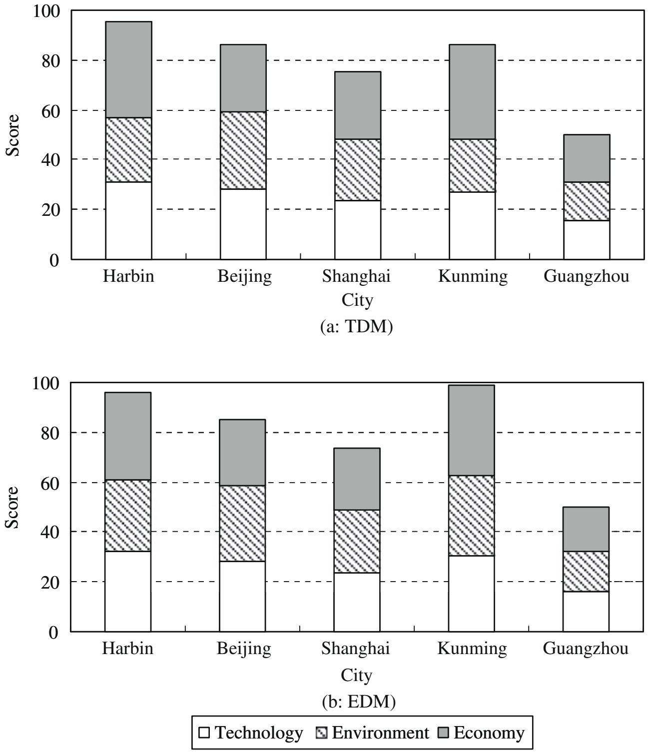


Fig. 8. The overall evaluation results of CCHP systems in the five cities.

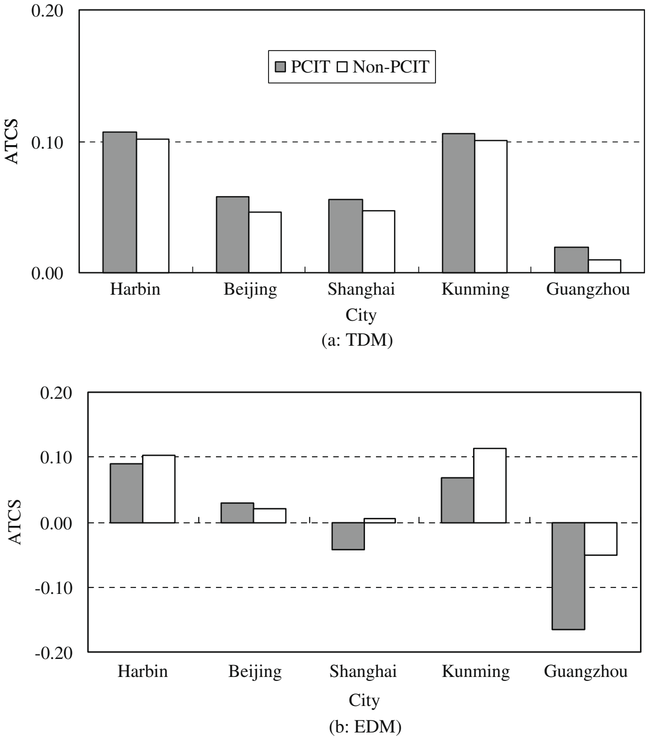
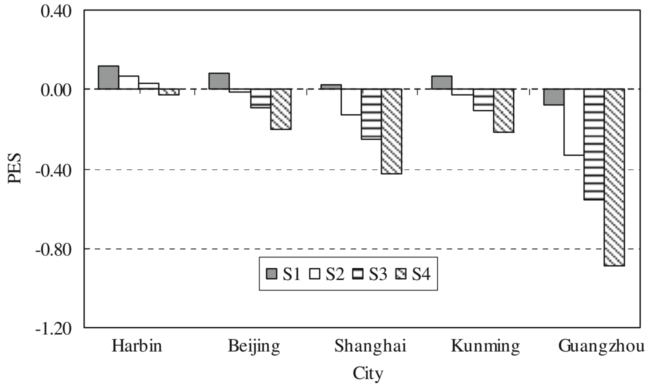


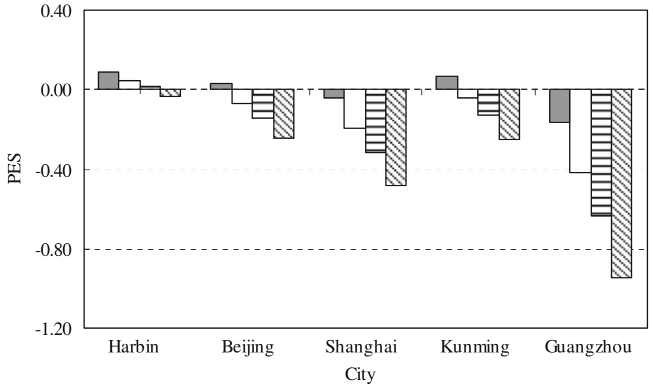
Fig. 9. The ATCS of CCHP systems for the hotels in the five cities.

Table 8
Reference efficiency scenarios of separate systems.

Efficiency scenario	η_e^{SP}	η_b^{SP}	COP_e
Low efficiency, S1	0.35	0.8	3
Average, S2	0.4	0.9	4
Intermediate, S3	0.45	0.95	5
State-of-the-art, S4	0.55	0.98	6



(a: TDM)



(b: EDM)

Fig. 10. The annual PES of CCHP systems in comparison to different reference separate system for the hotels in the five cities.

system in Guangzhou is the most sensitive to the reference separate system. The analysis of CCHP systems in the different climate zones in this paper is based on the same fixed separate system. From a practical standpoint, the selection of the most suitable CCHP system should be based on the local separate system. Increasing separate system reference efficiencies leads to smaller energy savings for CCHP system.

4. Conclusions

This paper presented a mathematical analysis of CCHP system in comparison to separate system and deduced the corresponding energy consumption in TDM and EDM operation modes. PES, CO_2ER, and ATCS were employed to synthetically assess the performances of CCHP systems for the hotel buildings in five different climate zones. The analysis leads to the following conclusions:

From the viewpoint of integrated performance of CCHP system, the achieved benefit in TDM operation mode is better than in EDM mode. When CCHP system operates in TDM mode, the highest benefit is obtained for Harbin while the lowest is obtained for Guangzhou. When CCHP system operates in EDM mode, the highest benefit is obtained for Kunming while the lowest is still for Guangzhou. Therefore, the results suggest that more benefit is achieved by the CCHP system for the building in the cold climate zone, which requires more heating during the year. The integrated performance of CCHP system is dissatisfactory for the building that requires more cooling. The CCHP system in the mild climate in China is also ideal, where the buildings have stable thermal demands during the entire year.

From the viewpoint of single performance, the potential of reducing CO_2 emission of CCHP system is more outstanding in China. The primary energy can be saved in the most regions except to the hot climate zones in China. ATCS of CCHP system in Guangzhou is the minimum because more primary energy is consumed. From the viewpoint of investors, the annual total cost per unit area in Kunming is the best.

Although the analysis does not include all climate zones in the world, the proposed evaluation method and the conclusions for CCHP system can be extended to the buildings in other climate zones.

Acknowledgement

This research has been supported by the Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, China.

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