Multi-objective optimization design and operation strategy analysis of BCHP system based on life cycle assessment

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A R T I C L E   I N F O

Article history:
Received 26 June 2011
Received in revised form 7 November 2011
Accepted 9 November 2011
Available online 3 December 2011

Keywords:
Building cooling heating and power (BCHP) system
Optimization of capacity and operation mode
Life cycle assessment (LCA)
Energetic and environment benefits
Weights of evaluation criteria

A B S T R A C T

The promising energetic and environmental benefits of building cooling heating and power (BCHP) system are greatly dependent upon its design and operation strategy. In this paper, the energetic and environmental benefits of producing excess electricity for nearby users are not considered.

1. Introduction

Recently, energy saving and sustainable development have been the subjects of wide-ranging discussion due to energy consumptiondriven problems caused by energy consumption [1,2]. The building sector accounts for a large amount of energy consumption in industrialized countries [3,4]. The increase of building energy consumption has lead to a number of energy-related problems and degraded the environment and public health [5,6]. In China, some regulations have been established to improve energy utilization efficiency and mitigate environmental impact, such as Energy Conservation Law [7], Renewable Energy Law, National Building Codes for Residential and Commercial Buildings, and Energy Efficiency Appliance Standards [8].

One of mitigation methods is to utilize energy efficiently and recover the waste heat in buildings. Because of its energy-efficient technology and friendly environment benefits, combined cooling heating and power (CCHP) system is broadly identified as a friendly alternative for the world to meet and solve energy-related problems and environmental issues [9–16]. When CCHP system is used for a building, it is called building cooling heating and power (BCHP) system. BCHP systems have been applied into various kinds of buildings such as hotel, office and hospital [17]. Nowadays, BCHP system is not yet the dominant energy supply mode in China. However, it will be a promising sustainable technique in China’s energy field [18].

The promising performance of BCHP system is closely dependent upon its design and operation strategy. In order to achieve the maximum energetic and environment benefits, many efforts have been made to optimize the capacity scheme and operation strategy of BCHP systems. Wang et al. applied genetic algorithm to optimize the equipment size of BCHP system to obtain its optimal energy saving potential and ozone depletion potential impacts [19]. Mago et al. modeled a BCHP system for a large office building under different operation strategies and examined its primary energy consumption (PEC) with respect to a reference building using conventional technology [20]. Ruan et al. evaluated BCHP systems with different driving equipments and heat-to-power ratios for various commercial buildings regarding their energetic and environment benefits [21]. Carvalho et al. optimized the configuration of a BCHP system to minimize carbon dioxide emissions based on life cycle assessment (LCA) [22].

The purpose of this paper is to optimize the equipment capacity of BCHP system in different operation strategies to maximize its life cycle assessment (LCA) benefits.
cycle energy saving potential and pollutant emission reduction in comparison to separation production (SP) system. Section 2 presents the energy and emission flows of the SP system and BCHP system, and analyzes the classical operation strategies of BCHP system. Section 3 introduces the LCA methodology and lists the life cycle inventory of energy systems. Section 4 describes the details of a commercial building in Beijing, China for case study. Section 5 applies the optimization model to a BCHP system for the baseline building and analyzes the influence of different combinations of evaluation criteria weights on the optimal results. Section 6 summaries some conclusions.

2. System description

2.1. Separation production (SP) system

A classical SP system composed by gas boiler and electric chiller is selected as the reference system. The energy and pollutant emission flows of the SP system are shown in Fig. 1. The building energy demands include the electricity demand, $E$ (kW h), the cool demand for space cooling, $Q_c$ (kW h), and the heat demand for space heating and domestic hot water, $Q_h$ (kW h).

In the SP system, natural gas is supplied to the gas boiler to produce heat for the heating exchanger to satisfy the heat demand of the building. Electric chiller is employed to meet the cool demand of the building. The power demand comes from the power plants driven by fossil energy through the utility grid. The electricity consumption includes the building electrical load, $E$ (kW h), electricity demands of the electric chiller, $E^\text{sp}_\text{ec}$ (kW h), and parasitical electrical equipments (such as pumps and fans), $E^\text{sp}_\text{eq}$ (kW h), of the SP system. Consequently, the electrical energy balance of the SP system can be expressed as follows:

$$E^\text{sp}_\text{grid} = E + \frac{Q_c}{\text{COP}_{\text{ec}}} + E^\text{sp}_\text{eq}$$  \hspace{1cm} (1)

where $E^\text{sp}_\text{grid}$ (kW h) is the electricity from the utility grid and $E^\text{sp}_\text{eq}$ is the electricity consumed by the parasitical electrical equipments. COP_{ec} is the coefficient of performance (COP) of the electric chiller.

When the electricity from the utility grid is converted to the fossil energy consumption, the energy losses of generation and transmission should be considered. The natural gas consumption can be obtained based on the heat demand of the building. Thus the PEC of the SP system in the operation stage, $E^\text{sp}_\text{op}$ (kW h), can be calculated as:

$$E^\text{sp}_\text{op} = F^\text{sp}_f + F^\text{sp}_g \cdot \frac{E + E^\text{sp}_\text{ec} + E^\text{sp}_\text{eq}}{\eta_{\text{gen}} \eta_{\text{tra}}} + Q_h$$  \hspace{1cm} (2)

where $F^\text{sp}_f$ (kW h) and $F^\text{sp}_g$ (kW h) are the fossil energy consumption of power plants and the natural gas consumption of the SP system, respectively. $\eta_{\text{gen}}$ and $\eta_{\text{tra}}$ are the electricity generation efficiency of the power plant and the transmission efficiency of the utility grid, respectively. $\eta_{\text{he}}$ and $\eta_{\text{gb}}$ are the heating exchanger efficiency and gas boiler efficiency, respectively.

The emission pollutants are calculated by an energy input-related emission factor model:

$$[X_i] = [F_i] \cdot [\mu_i]$$  \hspace{1cm} (3)

where $[X_i]$ (g) is the emission mass vector of pollutants, $[F_i]$ (kW h) is the input fuel of the ith combustion device, and $[\mu_i]$ (g/kW h) is the emission factor with respect to $[F_i]$.

The total pollutants of the SP system in the operation stage, $M^\text{sp}_{\text{op}}$ (g), can be obtained as follows:

$$M^\text{sp}_{\text{op}} = [X^\text{sp}_{\text{plant}}] + [X^\text{sp}_{\text{gb}}] = [F^\text{sp}] \cdot [\mu_f] + [F^\text{sp}] \cdot [\mu_g]$$  \hspace{1cm} (4)

where $[X^\text{sp}_{\text{plant}}]$ and $[X^\text{sp}_{\text{gb}}]$ are the emission mass vectors of the power plants and the gas boiler, respectively. $[\mu_f]$ and $[\mu_g]$ are the emission factors of fossil energy and natural gas, respectively.

2.2. BCHP system

Different BCHP systems have different driving units and the combinations of components are various. In this paper, a BCHP system driven by gas engine is evaluated and compared with the SP system.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Symbols</th>
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<tbody>
<tr>
<td>CCHP</td>
<td>$E$</td>
</tr>
<tr>
<td>BCHP</td>
<td>$Q_c$</td>
</tr>
<tr>
<td>SP</td>
<td>$F$</td>
</tr>
<tr>
<td>PEC</td>
<td>$\eta$</td>
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<td>LCA</td>
<td>$\mu$</td>
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<tr>
<td>PGU</td>
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<tr>
<td>FEL</td>
<td>$\xi$</td>
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<td>$\eta_{\text{he}}$</td>
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<tr>
<td>GWP</td>
<td>$\eta_{\text{gb}}$</td>
</tr>
<tr>
<td>AP</td>
<td>$\eta_{\text{gen}}$</td>
</tr>
<tr>
<td>REP</td>
<td>$\eta_{\text{tra}}$</td>
</tr>
<tr>
<td>PESR</td>
<td>$\mu_{\text{f}}$</td>
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<td>GWP-RR</td>
<td>$\mu_{\text{g}}$</td>
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<td>AP-RR</td>
<td>$\mu_{\text{ec}}$</td>
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<tr>
<td>REP-RR</td>
<td>$\mu_{\text{eq}}$</td>
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<tr>
<td>Subscripts</td>
<td>$\text{h}$</td>
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<tr>
<td>Symbols</td>
<td>$\eta_{\text{f}}$</td>
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</tbody>
</table>

X: emission mass vector
$\mu$: emission factor
$M$: emission mass
$f$: instantaneous fraction
$N$: capacity
$\omega$: weights
$U$: objective function
$c$: cool
$h$: heat
ec: electric chiller
eq: electrical equipment$f$: fossil energy
gen: electricity generation
tra: grid transmission$g$: natural gas
gb: gas boiler
he: heating exchanger
g: gas engine
hr: heating recover
ac: absorption chiller$A$: alternative
During the analysis and calculation in this study, some important assumptions of energy systems are shown as follows:

(1) The energy equipment can operate anywhere between 0% and 100% of its rated capacity and the efficiencies of the energy equipments, except the gas engine, are constant at any load operation.

(2) The system is assumed to be 100% reliable, so the influence of maintenance is not considered. In order to enhance the starting reliability of the system, the electricity consumptions of system parasitical electrical equipments such as pumps and fans are from the utility grid.

(3) The waste heat from the system including parasitical equipments is ventilated outside to the environment.

(4) The gas engine and the heating recover are seen as a packaged unit, power generation unit (PGU) to simplify the calculation and the heating recover efficiency accounts for the heat loss in the gas engine.

**Fig. 2** displays the energy and emission flows of the BCHP system. Gas engine is employed to generate electricity to satisfy the power demand of the building. The waste heat form the gas engine is recovered by the heating recover and supplied to the absorption chiller and heating exchanger to meet the cool or heat demands of the building. When the recovery heat is not enough to satisfy the thermal demand of the absorption chiller and heating exchanger, the auxiliary gas boiler begins to run to provide the additional heat. When the electricity from the gas engine is not enough, the supplemental electricity is from the utility grid. The application of gas boiler and the connection between the BCHP system and the utility grid can also decrease the accidental risk and enhance the operation reliability of the system.
The electricity balance of the BCHP system can be expressed as follows:

\[ E_{\text{grid}}^{\text{BCHP}} = (E - F_{\text{ge}}^{\text{BCHP}}) W + E_{\text{eq}}^{\text{BCHP}} \]  

(5)

where

\[ W = \begin{cases} 1, & E - F_{\text{ge}}^{\text{BCHP}} > 0 \\ 0, & E - F_{\text{ge}}^{\text{BCHP}} \leq 0 \end{cases} \]

\[ F_{\text{ge}}^{\text{BCHP}} \] (kW h) is the electricity produced by the gas engine. The natural gas consumption of the gas engine, \( F_{\text{ge}}^{\text{BCHP}} \) (kW h), is calculated to:

\[ F_{\text{ge}}^{\text{BCHP}} = \frac{F_{\text{BCHP}}^{\text{ge}}}{\eta_{\text{ge}}} \]

(6)

where \( \eta_{\text{ge}} \) is the power generation efficiency of the gas engine, which is corresponding to those of the load factors nonlinearly as [23]:

\[ \eta_{\text{ge}} = a + b_{\text{ge}} f_{\text{ge}} + c_{\text{ge}}^2 + d_{\text{ge}} f_{\text{ge}} \]

(7)

where \( f_{\text{ge}} \) is the instantaneous fraction of the gas engine, which can be expressed as follows:

\[ f_{\text{ge}} = \frac{F_{\text{BCHP}}^{\text{ge}}}{F_{\text{MAX}}^{\text{ge}}} \]

(8)

where \( F_{\text{MAX}}^{\text{ge}} \) (kW h) is the maximum power output of the gas engine, which can be obtained through its capacity (kW) multiplied the unit operating time, 1 h.

The recovery heat from the heating recover, \( Q_{\text{hr}}^{\text{BCHP}} \) (kW h), can be estimated as

\[ Q_{\text{hr}}^{\text{BCHP}} = Q_{\text{o}}^{\text{BCHP}} (1 - \eta_{\text{hr}}) \eta_{\text{hr}} \]

(9)

where \( \eta_{\text{hr}} \) is the heating recover efficiency. When the gas engine operates at full load, the recovery heat reaches its peak, \( Q_{\text{hr}}^{\text{MAX}} \).

The thermal energy balance of the BCHP system can be expressed as follows:

\[ Q_{\text{hr}}^{\text{BCHP}} + Q_{\text{gb}}^{\text{BCHP}} = Q_{\text{hr}}^{\text{BCHP}} + Q_{\text{he}}^{\text{BCHP}} = \frac{Q_{\text{n}}}{\text{COP}_{\text{ac}}} + \frac{Q_{\text{n}}}{\eta_{\text{hr}}} \]

(10)

where \( Q_{\text{gb}}^{\text{BCHP}} \) (kW h) is the heat generated by the gas boiler, \( Q_{\text{ac}}^{\text{BCHP}} \) (kW h) and \( Q_{\text{he}}^{\text{BCHP}} \) (kW h) are the heat supplied to the absorption chiller and the heating exchanger, respectively. \( \text{COP}_{\text{ac}} \) is the COP of the absorption chiller.

The energy consumption of the BCHP system in the operation stage, \( F_{\text{op}}^{\text{BCHP}} \) (kW h), is expressed as:

\[ F_{\text{op}}^{\text{BCHP}} = f^{\text{BCHP}} f^{\text{BCHP}} = \frac{F_{\text{BCHP}}^{\text{grid}}}{\eta_{\text{gen}}\eta_{\text{tra}}} + \frac{F_{\text{BCHP}}^{\text{ge}}}{\eta_{\text{ge}}} + \frac{Q_{\text{BCHP}}^{\text{gb}}}{\eta_{\text{gb}}} - V \]

(11)

where

\[ V = \begin{cases} 1, & Q_{\text{BCHP}}^{\text{ac}} + Q_{\text{BCHP}}^{\text{he}} - Q_{\text{BCHP}}^{\text{hr}} > 0 \\ 0, & Q_{\text{BCHP}}^{\text{ac}} + Q_{\text{BCHP}}^{\text{he}} - Q_{\text{BCHP}}^{\text{hr}} \leq 0 \end{cases} \]

Based on the emission flows in Fig. 2, the total pollutant emissions of the BCHP system in the operation stage, \( M_{\text{op}}^{\text{BCHP}} \) (g), can be computed from:

\[ M_{\text{op}}^{\text{BCHP}} = \left[ M_{\text{BCHP}}^{\text{plant}} + M_{\text{BCHP}}^{\text{pgu}} \right] + \left[ M_{\text{BCHP}}^{\text{gb}} \right] \]

(12)

where \( M_{\text{BCHP}}^{\text{plant}} \), \( M_{\text{BCHP}}^{\text{pgu}} \) and \( M_{\text{BCHP}}^{\text{gb}} \) are the emission mass vectors of the power plants, the PGU and the gas boiler in the BCHP system, respectively.

2.3. Operation strategy

The environment and energetic performances of BCHP systems are closely related to their operation strategies. Following electricity load (FEL) and following thermal load (FTL) are the two most distinctive operation strategies for BCHP systems [24]. In FEL operation strategy, the PGU runs following the electricity demand of the building. In this case, there may be excess heat produced which can be distributed to other users. However, for an independent BCHP system, the surplus heat is assumed to dissipate to the outside directly [25]. Thus, the energy saving potentials and emission reductions achieved by the excess heat are not considered. When the PGU runs following the thermal demand of the building, BCHP system may produce excess electricity. However, the electricity generated by micro-BCHP system is not allowed to be sent back to the utility grid for further use in China. Therefore, the surplus electricity is assumed to be consumed indirectly via nearby users. In this study, the energetic and environment benefits of the excess electricity are neither considered.

2.3.1. FEL operation strategy

In FEL operation strategy, the capacities of energy equipments in the BCHP system are determined according to the electricity cumulative curves and the energy demands of building [26]. After the equipments are selected, the maximum outputs of equipments are fixed.

The PGU operates according to the electricity load of building. When the power demand of building is more than the maximum output of gas engine, the additional electricity is supplied by the utility grid. The recovery heat from the heating recover is used to produce cool and heat in absorption chiller and heating exchanger, respectively. When the recovery heat is not enough, gas boiler begins to run to supply the supplementary heating. BCHP system would not produce excess electricity in this operation mode while the surplus heat may be exhausted. The operating conditions and energy consumptions are expressed in Eqs. (13)–(16): If

\[ E \leq F_{\text{MAX}}^{\text{ge}} \]

then

\[ F_{\text{op}} = F_{\text{BCHP}}^{\text{grid}} + F_{\text{BCHP}}^{\text{ge}} + F_{\text{BCHP}}^{\text{gb}} = \frac{F_{\text{BCHP}}^{\text{grid}}}{\eta_{\text{gen}}} + \frac{E}{\eta_{\text{ge}}} + \frac{Q_{\text{BCHP}}^{\text{gb}}}{\eta_{\text{gb}}} - V \]

(14)

In this case, the electricity demand of the building can be satisfied by the gas engine and the power demand of the system electrical equipments is from the utility grid. The natural gas consumption of the gas engine is determined by the electricity demand of the building. While the natural gas consumption of the gas boiler, if any, is based on the difference between the heat supplied by the heating recover and the thermal demands of absorption chiller and heating exchanger. Otherwise, if
When the electricity produced by the gas engine can not meet the power demand of the building, the electricity from the utility grid is based on the difference between the maximum output of gas engine and the electricity demands of the building and system parasitical equipments. In this case, the gas engine operates at full load and the natural gas consumption of the PGU is determined by its capacity. Additionally, the natural gas consumed by the gas boiler is based on the difference between the maximum recovery heat of the PGU and the cool or heat demands of the building.

2.3.2. FTL operation strategy

Similarly, in FTL operation strategy, the outputs and capacities of energy equipments in the BCHP systems are decided based on the heat or cool cumulative curves and the energy demands of building.

Contrarily to FEL mode, the PGU operates according to the cool or heat demands of the building. When the maximum recovery heat from the heating recover is less than the thermal demand of the building, the supplementary heat is supplied by the gas boiler. When the maximum recovery heat from the PGU is equal to the thermal demand of the building, the gas boiler is out of operation. The natural gas consumption of the gas boiler is based on the difference between the maximum power output of gas engine and the electricity consumption of the building and the parasitical electrical equipments.

3. Life cycle assessment (LCA) methodology

In order to evaluate the integrated energetic and environmental performances of energy systems, it is improper to consider only on-site impacts, because off-site impacts are also need to be accounted for, if not internalized [27]. Life Cycle Assessment (LCA), which is also called the assessment from cradle to grave, is suitable for investigating both on-site and off-site energy-related problems and environmental issues occasioned by any type of product or process [28–35]. In this study, LCA is employed to assess the whole life energetic and environment benefits of energy systems. LCA methodology mainly includes four phases: Goal & Scope, Life Cycle Inventory, Life Cycle Impact Assessment, and interpretation and improvements [36].

3.1. Goal & scope

The goal of this paper is to estimate and compare the PEC and pollutant emissions of the BCHP system in FEL and FTL operation strategies with the SP system during a life span of 10 years. The system boundary of the scope of the energy system is displayed in Fig. 3. The rectangles outside the dotted line indicate the energy inputs or pollutant outputs of energy systems. The rounded rectangles inside the dotted line show the contents covered in the LCA, which include the exploitation of raw materials, the manufacture of equipments, the transportation of materials and equipments, the acquisition and transportation of fuels and the operation of system.

The “Materials” designation shown in Fig. 3 mainly includes the energy consumptions and pollutant emissions associated with the
mining and metallurgy of raw materials such as steel, copper et al., while the operation, construction and access roads of the mine are outside of the LCA analysis scope. In the “Manufacture” stage, the life cycle inventory data should be calculated by performing an LCA analysis on each equipment unit of energy systems. However, when there is little information available on the details of manufacture process it might be convenient to use rough estimates in the LCA analysis [37]. Thus, in this study, the energy consumption in this stage will be approximated by only the electricity consumption caused by equipments manufacturing. The energy used to build the manufacturing machines and manufacturing factory is not included in this inventory. The major inputs and outputs of the “Transportation” stage are associated with the combustion of fuels such as diesel oil, gasoline or coal consumed by trucks and trains for road transportation and railway, respectively. The impacts caused by building or maintaining the roads or railroads are not considered in this study. The “Fuel” phase consists of extraction, pretreatment and transportation of the fossil energy consumed by power plants and the natural gas consumed by the energy systems. In the “Operation” stage, the energy inputs and pollutant outputs are associated with the consumption of electricity and natural gas. The impacts caused by building the equipments room and system maintaining are not considered. As there is no clearly policy about the disposal of BCHP system, the decommissioning stage is not considered in this study.

### 3.2. Life cycle inventory

The life cycle inventory analysis phase aims to determine the life cycle inventory of energy going into and the pollutant emissions coming out of the entire process of energy systems, which are shown in Eq. (21) and Eq. (22)

\[
[M_{lc}] = [M_{rm}] + [M_{ma}] + [M_{tr}] + [M_{op}] + [M_{fu}] \quad (21)
\]

\[
F_k = F_{rm} + F_{ma} + F_{tr} + F_{op} + F_{fu} \quad (22)
\]

where \(M_{lc}, F_k, M_{rm}, F_{rm}, M_{ma}, F_{ma}, M_{tr}, F_{tr}, M_{op}, F_{op}, M_{fu} \) and \(F_{fu} \) are the pollutant emissions and PEC during the stages of the life cycle, materials, manufacture, transportation, operation and fuel, respectively.

The life cycle inventory data are shown in Table 1 [38–45]. As the energy and environment impacts in the “Materials” stage are the functions of weights, g/kg and kW h/kg are selected as the units of pollutant emissions and PEC, respectively. The fuels consumed in the “Transportation” stage are mainly coal and diesel oil for railway and road respectively, and the fuel consumption amounts are based on the transport distance and transport load [46,47]. As the electricity consumptions in the “Manufacture” and “Operation” phases are both from the utility grid, their inventory data are included in the same line. In China, the utility grid is mainly composed by coal-fired power plants, thus the electricity from the grid is assumed to be totally produced by coal-fired power plants [48]. In order to facilitate the calculation, the units of natural gas consumed by energy systems are selected as m\(^3\) and the unit of coal consumed by the power plants is selected as kg\(^{-1}\). It should be noticed that the inventory data of electricity consumption in the “Operation” stage are the data when 1 kW h electricity is obtained by the building consumers, which account for the transmission efficiency of utility grid and generation efficiency of power plants. However, the inventory data of natural gas consumption in this stage are the data associated with combustion of 1 m\(^3\) natural gas. The energy consumptions and pollutant emissions of the gas engine and gas boiler are related to their natural gas consumption amounts which are dependent upon not only their energy outputs but also their efficiencies.

From Table 1, it can be seen that the pollutant emissions mainly include SO\(_2\), CO\(_2\), NO\(_x\), PM\(_{2.5}\), CO, CH\(_4\) and N\(_2\)O, thus the emission mass vector \(X\) can be expressed as:

\[
[X]_{7 \times 1} = [SO_2, CO_2, NO_x, PM_{2.5}, CO, CH_4, N_2O]^T
\]

Generally, the emission pollutants and energy consumptions of energy systems lead to the following impacts, including air pollution, acid precipitation, ozone depletion, global warming, forest destruction, radiation effect, respiratory effects and energy resource depletion [49]. The impacts on energy consumption can be evaluated from the whole life PEC of energy systems. For environment issues, three most important pollutants-related problems, global warming, acid precipitation and respiratory effects, are considered to evaluate the pollutant impacts of energy systems [50,51]. These three impacts are assessed in global warming potential (GWP), acidification potential (AP) and respiratory effects potential (REP), respectively.

The GWP describes the contribution made by an emission gas to the greenhouse effect in relation to carbon dioxide (CO\(_2\)), which means that quantities of any emission are converted into equivalent quantities of CO\(_2\), CO\(_2\)-equivalent emission [52]. The AP is given in sulfur dioxide (SO\(_2\)) equivalent emission. It is described as the ability of certain substances to build and release H\(^+\) protons, which is expressed in terms of the H\(^+\) potential of the reference substance SO\(_2\) [52]. Similarly, the REP is described as the respiratory effects caused by a unit of the emission gas and small particulate (the diameter is less than 2.5 µm), converted into respiratory effect values produced by the reference PM\(_{2.5}\), PM\(_{2.5}\)-equivalent emission [53].

The conversion factors between various pollutant emissions for GWP, AP and REP are shown in Table 2. Through the emission pollutants multiplied the corresponding GWP, AP and REP conversion factors, the total GWP, AP and REP can be obtained to:

### Table 1

<table>
<thead>
<tr>
<th>Stage</th>
<th>SO(_2) (g)</th>
<th>CO(_2) (g)</th>
<th>NO(_x) (g)</th>
<th>PM(_{2.5}) (g)</th>
<th>CO (g)</th>
<th>CH(_4) (g)</th>
<th>N(_2)O (g)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
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<tr>
<td><strong>Materials (kg(^{-1}))</strong></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Steel</td>
<td>9.7</td>
<td>2900</td>
<td>4000</td>
<td>15</td>
<td>25</td>
<td>53</td>
<td>–</td>
<td>1.7</td>
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<td>Aluminum</td>
<td>205.5</td>
<td>25800</td>
<td>94.70</td>
<td>–</td>
<td>1290</td>
<td>14</td>
<td>–</td>
<td>36.1</td>
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<tr>
<td>Copper</td>
<td>17.7</td>
<td>1900</td>
<td>11.48</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.8</td>
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<td>PVC</td>
<td>3.37</td>
<td>247</td>
<td>2.80</td>
<td>2.2</td>
<td>1.1</td>
<td>–</td>
<td>–</td>
<td>21.9</td>
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<td><strong>Transportation (10(^3) kg(^{-1}) km(^{-1}))</strong></td>
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<tr>
<td>Railway</td>
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<td>Road</td>
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<td>3.159</td>
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<td>8.944</td>
<td>0.143</td>
<td>6.409</td>
<td>0.9</td>
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<td><strong>Operation &amp; manufacture</strong></td>
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<td></td>
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<tr>
<td>E (kWh(^{-1}))</td>
<td>3.14</td>
<td>326.37</td>
<td>1.134</td>
<td>0.061</td>
<td>2</td>
<td>0.003</td>
<td>0.01</td>
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<td>Gas (m(^3))</td>
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<td>0.184</td>
<td>0.005</td>
<td>0.0004</td>
<td>9.76</td>
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</tr>
<tr>
<td>Coal (kg(^{-1}))</td>
<td>0.74</td>
<td>73.71</td>
<td>1.219</td>
<td>0.318</td>
<td>0.187</td>
<td>4.452</td>
<td>0.1802</td>
<td>0.323</td>
</tr>
<tr>
<td>Gas (m(^3))</td>
<td>0.42</td>
<td>232.6</td>
<td>0.247</td>
<td>0.011</td>
<td>0.018</td>
<td>0.301</td>
<td>0.0004</td>
<td>1.708</td>
</tr>
</tbody>
</table>
Table 2
Conversion factors between various pollutant emissions for GWP, AP and REP [6,50,51].

<table>
<thead>
<tr>
<th>Pollutant emissions</th>
<th>GWP (g CO₂-equiv./g)</th>
<th>AP (g SO₂-equiv./g)</th>
<th>REP (g PM₂.₅-equiv./g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>–</td>
<td>1</td>
<td>1.9</td>
</tr>
<tr>
<td>CO₂</td>
<td>1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>NOₓ</td>
<td>–</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>CO</td>
<td>3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CH₄</td>
<td>21</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>N₂O</td>
<td>310</td>
<td>0.7</td>
<td>–</td>
</tr>
</tbody>
</table>

CO₂ – equiv. = \([\text{GWP}] \times [M/J]_{7 \times 1}\) \quad (24)

SO₂ – equiv. = \([\text{AP}] \times [M/J]_{7 \times 1}\) \quad (25)

PM₂.₅ – equiv. = \([\text{REP}] \times [M/J]_{7 \times 1}\) \quad (26)

where CO₂–equiv. (g), SO₂–equiv. (g) and PM₂.₅–equiv. (g) are CO₂, SO₂ and PM₂.₅ equivalent emissions, respectively. [GWP], [AP] and [REP] are GWP, AP and REP vectors of various pollutants, \([M/J]_{7 \times 1}\) are the pollutant emissions in the jth stage.

4. Case study

In order to evaluate and compare the integrated energetic and environmental performances of the BCHP system with traditional SP system, a hypothetical nine-floor commercial office building in Beijing, China is selected as the baseline building. The study building has a floor area of 19,986 m² and the total area of the windows and glazing comprises about 50% of the total wall area. The first and second floors of the building are shopping malls and the ceiling heights are both 6.0 m. The third floor is a gym with the ceiling height 5.1 m and the forth-eighth floors are office rooms with the ceiling height 3.5 m. The ninth floor is a meeting room and the ceiling height is 4.5 m. Summer is from June 1 to August 30 and winter is from November 15 to March 15. The average temperature setting ranges of the building in summer, winter and transient seasons are 24–26 °C, 20–26 °C and 20–22 °C, respectively.

The annual hourly cooling, heating and electricity loads of the building can be obtained based on DeST software [54], which are shown in Fig. 4. It should be noticed that the hourly load in Fig. 4 is instantaneous value, which means the energy demand of the building in per hour. According to the hourly curves, the hourly power load is stable relatively, while the hourly heat or cool demands fluctuate more than the electricity demand. Moreover, the electricity load is generally lower than the thermal load in summer and winter, while, in transient seasons, the thermal demands of the building are low. Additionally, the peak value of the cool load in summer is greater than the maximum heat load in winter because of the hot climate of Beijing.

5. Optimization

5.1. Objective function

The selection of objective function associated with the optimization problem will determine how good the solution is. In order to evaluate the integrated performance of the BCHP system, the objective function should measure not only the energetic benefit and but also the environmental benefit achieved by the BCHP system in comparison to the SP system. According to the life cycle inventory analysis, the following evaluation criteria are employed to assess their corresponding performances.

Primary energy saving ratio (PESR) is defined as the ratio of the saving energy of the BCHP system with respect to the SP system to the energy consumption of the SP system, which can be expressed as follows:

\[
PESR = \frac{F_{SC}^{SP} - F_{SC}^{BCHP}}{F_{SC}^{SP}} \quad (27)
\]

where \(F_{SC}^{SP}\) and \(F_{SC}^{BCHP}\) are the life cycle energy consumptions of the SP system and the BCHP system, respectively. When PESR is positive, it means that BCHP system is more energy-efficient than SP system. Contrarily, when PESR is negative, BCHP system can’t save energy in comparison to SP system.

Similarly, the reduction ratio of pollutant-related impact is defined to the ratio of the emission reduction of BCHP system compared with SP system to the pollutant emission of the SP system. Thus, based on the CO₂-equivalent emissions of the two systems, the GWP reduction ratio (GWP-RR) is written to:

\[
GWP – RR = \frac{CO₂ – equiv.^{SP} – CO₂ – equiv.^{BCHP}}{CO₂ – equiv.^{SP}} \quad (28)
\]

when GWP-RR is positive, the global warming impacts caused by BCHP systems are less serious than the SP system. Contrarily, when
GWP-RR is negative, BCHP system can’t reduce CO2-equivalent emissions in comparison to the SP system.

Likewise, according to the SO2-equivalent emissions and PM2.5-equivalent emissions of the two energy systems, the AP reduction ratio (AP-RR) and REP reduction ratio (REP-RR) can be defined based on Eq. (28).

Consequently, the comprehensive objective function, $U$, is defined to:

$$\max U = \omega_1 \cdot \text{PESR} + \omega_2 (\omega_{21} \cdot \text{GWP-RR} + \omega_{22} \cdot \text{AP-RR} + \omega_{23} \cdot \text{REP-RR})$$

where $\omega_1$ and $\omega_2$ are the weights of energetic and environment benefits, respectively. $\omega_{21}$, $\omega_{22}$ and $\omega_{23}$ are weights of GWP-RR, AP-RR and REP-RR, respectively. $0 \leq \omega_1, \omega_2, \omega_{21}, \omega_{22}, \omega_{23} \leq 1$, $\omega_1 + \omega_2 = 1$ and $\omega_{21} + \omega_{22} + \omega_{23} = 1$.

5.2. Decision variables

In BCHP systems, the energy consumption and pollutant emissions are greatly dependent upon the sizes of energy equipments. According to the energy flow and operation strategy analysis, it can be found that gas engine is the key equipment that determines the capacities of other equipments and the operation mode of the system. The optimal capacity of gas engine provides a good compromise between the requirements for a reasonable energy demand from BCHP system and for a high operating efficiency. After the gas engine capacity is selected, the capacity of the heating recover is obtained according to the maximum waste heat carried by the exhaust flue gas from the gas engine. For the SP system, the gas boiler is sized on the heat load peak to enhance the operation safety. While, in the BCHP system, once the operation strategy is determined, the size of the auxiliary boiler depends on the difference between the maximum recovery heat of the PGU and the thermal peak load of the building. Therefore, the capacity of gas engine, $N_{ge}$, is selected as a decision variable to be optimized.

Additionally, the weights in Eq. (29) are assigned to the evaluation criteria to indicate their relative importance. Different weights in the integrated objective function directly influence the optimal results. However, the importance of criteria is uncertain, which may be greatly affected by the national policy, government preferences and even the interest of the investors. Thus the weights of the evaluation criteria, $\omega_1$, $\omega_2$, $\omega_{21}$, $\omega_{22}$, $\omega_{23}$, are also defined to be decision variables to show the influence of different combinations of weights on the optimum results.

5.3. Optimization calculation

In this sector, the weights of the evaluation criteria are based on the following assumptions, $\omega_1 = \omega_2$ and $\omega_{21} = \omega_{22} = \omega_{23}$.

The technical parameters, main material compositions and manufacture electricity consumptions of energy equipments in energy systems are listed in Table 3. In order to facilitate the optimization problem, based on the hourly loads and energy demands of the building in Fig. 4, the type of gas engine selected in this paper is Caterpillar. Additionally, the amounts of material composition and the manufacturing electricity consumption are the functions of equipment capacity. As the case study is for a building in Beijing,
the coal or natural gas consumed in the operation phase is from the same coal mine or the same natural gas field nearby. Thus the contents of coal and natural gas are assumed to be constant. According to the operation strategy, hourly power, cool and heat loads of the building and technical parameters of energy equipments, the optimization results can be obtained as follows.

The optimization processes of the BCHP system in FEL and FTL operation strategies are shown in Fig. 5. It can be seen that the optimization curves of FTL mode are stable relatively, while the energetic and environment benefits of the FEL mode change dramatically with different gas engine capacities. Moreover, the environment criteria of the two operation modes fluctuate more than the energetic criteria. The optimization curves increase with the increasing capacity of gas engine at small capacity, when the gas engine capacities are greater than the corresponding optimal values for different evaluation criteria, the objective functions begin to decrease with the increasing gas engine size because of the poor efficiency of gas engine at low load ratio. It also can be found that when the BCHP system runs in FEL mode, the GWP-RR, AP-RR and REP-RR can reach their corresponding optimal values, while the optimum PESR is obtained when the system operates in FTL mode. Therefore, the environment benefits of the FEL mode are more powerful, while the energy saving potential of the FTL strategy is better than that of the FEL strategy. The evaluation ranking order of the optimal criteria is GWP-RR > AP-RR > REP-RR > PESR. Additionally, the optimal gas engine capacities for different criteria are different. Different emission conversion factors among various pollutant impacts lead to this inconsistent optimum system size. It should be noticed that when the gas engine capacity is too large or too small, the energy saving ratio or the pollutant emission reduction ratio is negative which means the energetic or environment benefits of the BCHP system are worse than those of the SP system. Finally, when concerning the optimal comprehensive benefits of BCHP system, the integrated objective function of the FEL mode, 33.9%, is better than that of the FTL mode, 29.5%.

Based on the optimal gas engine capacities of the two operation strategies, the energy consumption structures of the annual operation PEC in SP system and BCHP system in FEL and FTL operation modes are displayed in Fig. 6. It can be known that the natural gas consumption of the SP system is the lowest, BCHP system in FTL mode follows, while the FEL mode consumes the largest amount of natural gas. However, the ranking order of the coal consumption of the three alternatives is just the opposite of that of the natural gas consumption. Moreover, the electricity from the power plants in FEL mode is much less than other two options. Additionally, the operation energy consumptions of BCHP system in the two operation modes are almost the same and the energetic benefits of the BCHP system are better than those of the SP system.

5.4. Life cycle impact assessment

Once the optimal gas engine capacities for the tow operation strategies are determined, the Life Cycle Impact Assessment can be obtained. The LCA results of various pollutant emissions and PEC of SP system and BCHP system in FEL and FTL operation strategies are listed in Table 4. In terms of various pollutant-related impacts, the life cycle environment benefits of the BCHP system in FEL mode are the best, FTL mode follows, while SP system is the worst alternative. Moreover, the CO₂ emissions are significantly larger than any other pollutant emissions, while the N₂O emissions are the lowest among various pollutant emissions. In the energetic benefits, although the energy consumption of BCHP system in the fuel stage is larger than

<table>
<thead>
<tr>
<th>Table 4</th>
<th>The LCA results of pollutant emissions and PEC for SP system and BCHP system in FEL and FTL operation strategies.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Materials</td>
</tr>
<tr>
<td>SO₂ (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>4.10E + 05</td>
</tr>
<tr>
<td>FEL</td>
<td>9.24E + 05</td>
</tr>
<tr>
<td>FTL</td>
<td>9.24E + 05</td>
</tr>
<tr>
<td>CO₂ (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>6.92E + 07</td>
</tr>
<tr>
<td>FEL</td>
<td>1.86E + 08</td>
</tr>
<tr>
<td>FTL</td>
<td>1.86E + 08</td>
</tr>
<tr>
<td>NOₓ (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>2.00E + 05</td>
</tr>
<tr>
<td>FEL</td>
<td>3.83E + 05</td>
</tr>
<tr>
<td>FTL</td>
<td>3.83E + 05</td>
</tr>
<tr>
<td>PM₂.₅ (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>7.81E + 05</td>
</tr>
<tr>
<td>FEL</td>
<td>1.60E + 06</td>
</tr>
<tr>
<td>FTL</td>
<td>1.60E + 06</td>
</tr>
<tr>
<td>CO (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>6.66E + 05</td>
</tr>
<tr>
<td>FEL</td>
<td>2.29E + 06</td>
</tr>
<tr>
<td>FTL</td>
<td>2.29E + 06</td>
</tr>
<tr>
<td>CH₄ (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>1.39E + 06</td>
</tr>
<tr>
<td>FEL</td>
<td>4.85E + 06</td>
</tr>
<tr>
<td>FTL</td>
<td>4.85E + 06</td>
</tr>
<tr>
<td>N₂O (g)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>—</td>
</tr>
<tr>
<td>FEL</td>
<td>—</td>
</tr>
<tr>
<td>FTL</td>
<td>—</td>
</tr>
<tr>
<td>PEC (kWh)</td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>2.37E + 05</td>
</tr>
<tr>
<td>FEL</td>
<td>1.62E + 05</td>
</tr>
<tr>
<td>FTL</td>
<td>1.62E + 05</td>
</tr>
</tbody>
</table>
the SP system, the whole life PEC of BCHP system is lower than that of the SP system because of its promising energy saving potentials in the operation phase.

The life cycle structures of the CO2-equiv., SO2-equiv., PM2.5-equiv. emissions and PEC are shown in Fig. 7. It can be found that the influences of the operation and fuel stages on the LCA results are more significant than other three stages. Compared GWP with AP and REP, the orders of magnitude of SO2-equivalent emission and PM2.5-equivalent emission are one hundredth of the CO2-equivalent emission. Compared with FTL mode, because of its lower SO2-equivalent emission and PM2.5-equivalent emission in the fuel stage, the whole life AP and REP impacts of FEL mode are less serious. The friendly energetic benefits of FTL mode in the fuel stage make it be the best alternative among the three options when concerning the energy performance. Additionally, among the five LCA stages, the contribution of the transportation phase is the minimum, thus the rough estimation in the life cycle inventory phase is feasible.

The pollutant emission structures of CO2-equiv., SO2-equiv. and PM2.5-equiv. emissions of the SP system and the BCHP system in FEL and FTL operation strategies are displayed in Fig. 8. It can be seen that CO2 emission is the main factor to contribute the greenhouse effect, CH4 and N2O emissions follow, while the contribution of CO is the least significant. Although the corresponding GWP conversion factors of N2O, CO and CH4 are larger than CO2, they contribute less to the total GWP because of their lower emissions. Moreover, the contribution difference of CO emission among the three alternatives is merely. Additionally, the GWP of the three less important

![Fig. 7. The life cycle structure of the CO2-equiv., SO2-equiv., PM2.5-equiv. emissions and PEC for SP system and BCHP system in FEL and FTL modes.](image)

![Fig. 8. The emission structure of CO2-equiv., SO2-equiv. and PM2.5-equiv. emissions of SP system and BCHP system in FEL and FTL modes.](image)
pollutant emissions of SP system is nearly twice of those of BCHP system in FTL mode and five times more than those of FEL mode. From the AP evaluation criteria, SO\textsubscript{2} emission mainly contributes to acidification, but the impacts of NO\textsubscript{x} emission cannot be ignored. It can be found that the contribution of SO\textsubscript{2} emission on AP in FEL mode is larger than that of the FTL mode, while the life cycle acidification impacts of FEL mode are less serious than FTL mode due to its lower coal energy consumption. Besides, the influence of N\textsubscript{2}O emission on AP is hardly any. The SO\textsubscript{2} emission is also the main factor to affect human respiratory health because of its numerous impacts of different combinations of criteria weights on the optimal result and their details can be evaluated by its corresponding objective function value. The objective function can be simplified as follows:

\[ U = \omega_1 \cdot \text{PESR} + (1 - \omega_1) \left( \omega_{21} \cdot \text{GWP-RR} + \omega_{22} \cdot \text{AP-RR} + (1 - \omega_{21} - \omega_{22}) \cdot \text{REP-RR} \right) \]  

(30)

Based on Eq. (30), the integrated benefit of each alternative can be evaluated by its corresponding objective function value. The impacts of different combinations of criteria weights on the optimal alternative are displayed in Fig. 10. In the figure, surface 1 is based on the objective function difference between FTL-770 (FTL operation strategy with the gas capacity 770 kW) and FEL-660, FTL-770−FEL-660. The interval above surface 1 represents \( U_{\text{FTL-770}} - U_{\text{FEL-660}} > 0 \), while the interval below surface 1 shows \( U_{\text{FTL-770}} - U_{\text{FEL-660}} < 0 \). Similarly, surface 2 is based on \( U_{\text{FEL-660}} - U_{\text{FEL-770}} \), surface 3 is based on \( U_{\text{FEL-770}} - U_{\text{FEL-880}} \), surface 4 is based on \( U_{\text{FEL-880}} - U_{\text{FEL-990}} \) and surface 5 is the constrain condition. The optimal region of \( \omega_{1} , \omega_{21} \) and \( \omega_{22} \) for each alternative can be found from Fig. 10. The ranking order of the interval volumes is FEL-770 > FTL-770 > FEL-660 > FEL-880 > FEL-990.  

6. Conclusion

Based on the energy and emission flows and LCA methodology, BCHP system in different operation strategies is evaluated and compared with the SP system from energy consumption and pollutant emission related impacts. The gas engine capacity and evaluation criteria weights are selected as decision variables to maximize the energetic and environment benefits achieved by BCHP system in comparison to SP system. Through a numerical example of BCHP system for a commercial office building in Beijing, China, the optimal equipment size and operation mode can be obtained in consideration of evaluation criteria weights. The optimization calculation and life cycle analysis lead to the following conclusions:

The comprehensive energetic and environment performance of BCHP system increases firstly, then the increasing slope becomes slow gradually and reaches the peak, and finally decreases with the increasing of gas engine capacity. The integrated optimization result of FEL mode is better than that of FTL mode because of its friendly environmental benefits. Based on the optimum gas engine capacity, the CO\textsubscript{2}-equivalent, SO\textsubscript{2}-equivalent and PM\textsubscript{2.5}-equivalent emissions of FEL mode are lower than those of the FTL mode, while the energy consumption of FTL mode is lower than that of the FEL mode. Compared with the SP system, the reduction ratios of SO\textsubscript{2}-equivalent emission and PM\textsubscript{2.5}-equivalent emission in BCHP system are lower than the CO\textsubscript{2}-equivalent emission reduction ratio.

The life cycle impact assessment of BCHP system operating for ten years shows that contributions of the operation and fuel phases are more important for the evaluation results than the materials, manufacture and transportation stages. From the viewpoint of pollutant emission-related impacts, the environment benefits of FEL mode are better than those of FTL mode because of its lower coal energy consumption. However, when concerning energetic benefits, the energy saving potential of FTL mode is better than that of the FEL mode due to its reasonable energy consumption structure.
When the weights of evaluation criteria are uncertain and various, the optimal gas engine size and operation strategy of BCHP system are different. If energy benefits are paid more attention, FTL mode is the first choice, while if environment performance is more valuable, FEL mode is the good operation strategy. The integrated performance of BCHP system in FEL operation strategy with gas engine capacity 770 kW is the best alternative among the five candidate BCHP system models and can be stable for a wide interval of different combinations of criteria weights.

Acknowledgement

This research has been supported by the Fundamental Research Funds for the Central Universities (10MG12) and the Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, China.

References