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Life cycle assessment of a solar combined cooling heating and power system in different operation strategies

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ABSTRACT

A novel solar building cooling heating and power (BCHP) system driven by solar energy and natural gas is proposed in this paper. The performance of the presented system is greatly dependent upon the operation strategy. The primary energy consumption (PEC) and pollutant emissions of the solar BCHP system in following the electricity loads (FEL) and following the thermal loads (FTL) operation strategies are estimated based on life cycle assessment (LCA). Furthermore, three most important energy-related environment problems and human health issues, global warming, acid precipitation and respiratory effects, are considered to assess the environmental impacts of the system. In order to evaluate the comprehensive benefits achieved by the solar BCHP system in different operation modes, grey relation theory is employed to integrate the energetic benefits with environmental performances. Finally, a numerical case of the solar BCHP system for a commercial office building in Beijing, China is applied to compare the integrated performance in the FEL operation strategy with that of the FTL operation strategy. The results indicate that the energy saving and pollutant emissions reduction potentials of the FTL operation mode are the better than that of the FEL mode.

1. Introduction

In many countries, building energy consumption accounts for nearly 40% of the total energy use, and about 40% of greenhouse gas and other air pollutant emissions [1,2]. In China, building energy consumption has been increasing at more than 10% a year during the past 20 years [3]. The increasing building energy consumption has lead to more and more building-related problems and environmental impacts. One of mitigation methods is to recover the waste heat in buildings so as to improve the energy efficiency. Because of its energy-efficient technology and friendly environment benefits, combined cooling heating and power system is broadly identified as a friendly alternative for the world to meet and solve energy-related problems and environmental issues [4–12]. When combined cooling heating and power system is used for a building, it is called building cooling heating and power (BCHP) system.

As a kind of renewable energy, solar energy has been applied to BCHP systems to decrease the utilization of non-renewable energy and reduce pollutant emissions. Meng et al. showed that the BCHP system integrated with solar collectors is superior to the traditional BCHP systems concerning the fuel energy saving ratio, equivalent thermodynamic coefficient and exergy efficiency [13]. Medrano et al. calculated the energy cost savings and CO_2 emission reductions of a BCHP system with solar support in comparison to conventional energy systems [14]. Wang et al. analyzed the system exergy efficiency variations of a BCHP system driven by solar energy with different slope angle and hour angle [15]. Eman et al. studied the percentage external energy supplied by the solar collectors of a solar-assisted trigeneration system under different levels of carbon credits [16].

The performance of BCHP systems is obviously dependent upon the operation strategy which determines the power and thermal outputs. In general, two simple operation strategies are following the electric load (FEL) and following the thermal load (FTL) [17]. Currently some researchers have studied and compared the energetic and environmental performances of BCHP systems in the different operation modes [18–20]. The energy and environment analysis are very important to the feasibility of BCHP system. Several researchers have evaluated and analyzed the benefits of BCHP systems in terms of energy saving potential and environment impacts with different evaluation methods. Fumo et al. compared the primary energy consumption (PEC) saving and CO_2 emission reduction of a BCHP system based on emission strategy with that of the primary energy strategy [21]. Li et al. established a mix-integer nonlinear programming model to analyze energy demands of BCHP systems for hotel and hospital [22]. Wang et al. studied the energetic and environmental benefits achieved by BCHP systems in comparison to separate production system based on a particle swarm optimization algorithm [23].

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Nomenclature

BCHP	building cooling heating and power
PEC	primary energy consumption
LCA	life cycle assessment
FEL	following the electricity load
FTL	following the thermal load

Symbols

E	electricity
Q	heat
COP	coefficient of performance
F	fuel consumption
η	efficiency
f	instantaneous fraction
X	emission mass vector
μ	emission factor
M	emission mass
P	evaluation value
ω	weights
A	area
θ	solar ratio

Subscripts

c	cool
h	heat
f	fossil energy
g	natural gas
gb	gas boiler
$grid$	utility grid
$plant$	power plant
eq	equipment
he	heat exchanger
ge	gas engine
$gpgu$	gas power generation unit
hr	heating recover
ac	absorption chiller
spv	solar photovoltaic
sc	solar collector
GWP	global warming potential
AP	acidification potential
REP	respiratory effects potential

However, in order to estimate the pollutant emissions and PEC comprehensively, it is not sufficient to consider only on-site impacts, because off-site impacts are also need to be accounted for, if not internalized [24]. Life cycle assessment (LCA) methodology, which is also called the assessment from cradle to grave, is useful for analyzing both on-site and off-site environment-related problems and energy consumption occasioned by any type of product or process [25–32]. In this paper, LCA is employed to evaluate the environment and energetic benefits of a novel solar BCHP system in different operation strategies during its life span. Section 2 constructs the energy consumption and pollutant emission flows of the solar BCHP system and analyzes the FEL and FTL operation strategies. Section 3 establishes the LCA model of the solar BCHP system and presents a comprehensive evaluation method based on grey relation theory. Section 4 applies the evaluation model to a BCHP system for a commercial office building in Beijing, China and compares the whole life energy and environmental performances of the system in the FEL operation strategy with that of the FTL operation strategy. Section 5 summaries some conclusions.

2. Solar BCHP system

2.1. System model

The emission and energy flows of the solar BCHP system are shown in Fig. 1. The energy demands of building include electricity demand, E (kW h), cool demand, Q_c (kW h) and heat demand for space heating and domestic hot water, Q_h (kW h).

Natural gas and solar energy are supplied to the gas engine and the solar photovoltaic unit, respectively, to provide electricity for the building. The waste heat from the gas engine is recovered by the heating recover and used to satisfy cool or heat demands of the building in the absorption chiller and the heat exchanger respectively. When the recovered heat is not enough, the solar collectors and auxiliary gas boiler are employed to provide the insufficient heat. When the electricity generated by the gas engine and solar photovoltaic unit is not enough, the supplementary electricity is from the power plant through the utility grid. On the other hand, the application of auxiliary boiler and the

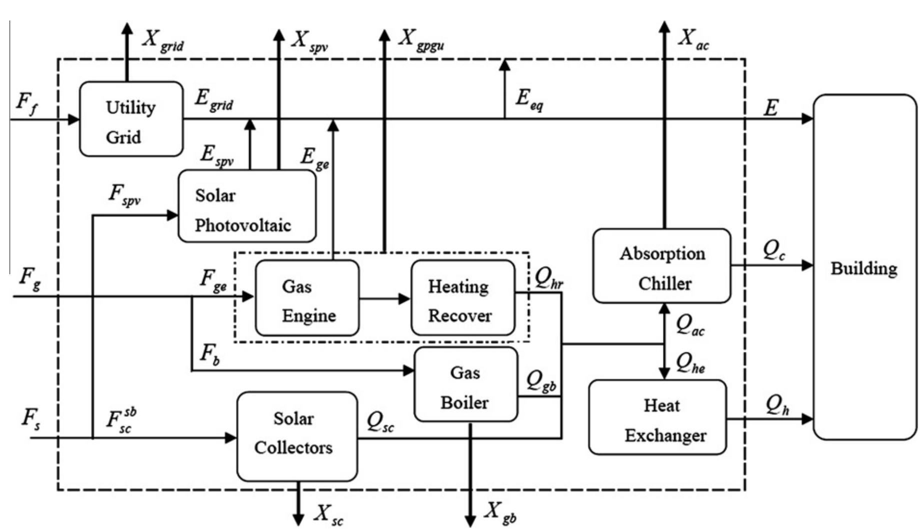

Fig. 1. The energy and emission flow chart of the solar BCHP system. The thin solid line and thick solid line represent the energy flow and emission flow respectively, and the equipments inside the dotted line are a package unit.

connection between the BCHP system and the local grid can also decrease accidental risk and enhance reliability.

During the analysis and calculation in this study, some important assumptions are shown as follows:

(1) The energy equipments can operate anywhere between 0% and 100% of its rated capacity, and the solar BCHP system is assumed to be 100% reliable.
(2) The electricity consumptions of parasitic electrical equipments such as pumps and fans in the solar BCHP system are from the utility grid to enhance the operation reliability of the system.
(3) In order to simplify the calculation, the gas engine and the heating recover are seen as a packaged unit, gas power generation unit, and the heating recover efficiency accounts for the heat losses in the gas engine. The pollutant emissions from the heat exchanger are neglected.
(4) The solar photovoltaic unit and solar collectors can operate day and night due to the application of their own energy storage devices.

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

$$E_{grid} = (E - E_{ge} - E_{spv})U + E_{eq} \tag{1}$$

where

$$U = \begin{cases} 1, & E - E_{ge} - E_{spv} > 0 \\ 0, & E - E_{ge} - E_{spv} \leqslant 0 \end{cases}$$

E_{grid} (kW, kW h, the sample is 1 h) is the electricity from the utility grid and E_{eq} (kW h) is the electricity consumption of parasitic distribution equipments such as pumps and fans in the system. E_{spv} (kW h) and E_{ge} (kW h) are the electricity produced by the solar photovoltaic unit and the gas engine respectively.

Considered the energy losses of power generation and transmission, the electrical energy from the utility grid can be converted to fossil energy consumption as follows:

$$F_f = \frac{E_{grid}}{\eta_{gen}\eta_{tra}} \tag{2}$$

where F_f (kW h) is the fossil energy consumption of the power plants, η_{gen} and η_{tra} are the electricity generation efficiency of the power plants and the transmission efficiency of the utility grid, respectively.

The fuel energy consumption of the gas engine, F_{ge} (kW h), can be estimated as

$$F_{ge} = \frac{E_{ge}}{\eta_{ge}} \tag{3}$$

where η_{ge} is the power generation efficiency of the gas engine, which is corresponding to those of the load factor nonlinearly as [21]:

$$\eta_{ge} = a + bf_{ge} + cf_{ge}^2 + df_{ge}^3 \tag{4}$$

where f_{ge} is the instantaneous fraction of the gas engine capacity, which can be expressed to:

$$f_{ge} = \frac{E_{ge}}{E_{ge}^{\max}} \tag{5}$$

where $E_{ge}^{\max}$ (kW h) is the maximum power output of the gas engine and this value is equal to the gas engine capacity.

The thermal energy balance of the solar BCHP system is expressed as follows:

$$Q_{hr} + Q_{gb} + Q_{sc} = Q_{ac} + Q_{he} = \frac{Q_c}{COP_{ac}} + \frac{Q_h}{\eta_{he}} \tag{6}$$

where Q_{ac} (kW h) and Q_{he} (kW h) are the heat supplied to the absorption chiller and the heat exchanger, respectively. COP_{ac} is the coefficient of performance (COP) of the absorption chiller. η_{he} is the heat exchanger efficiency. Q_{sc} (kW h) and Q_{gb} (kW h) are the heat produced by the solar collectors and the gas boiler, respectively.

Q_{hr} (kW h) is the recovery heat of the gas power generation unit, which can be replaced to:

$$Q_{hr} = F_{ge}(1 - \eta_{ge})\eta_{hr} \tag{7}$$

where η_{hr} is the heating recover efficiency. When the gas engine is operating at full load, the recovery heat reaches its maximum value $Q_{hr}^{\max}$.

Based on Eq. (6), the fuel energy consumption of the gas boiler, F_{gb} (kW h), can be computed from:

$$F_{gb} = \frac{Q_{ac} + Q_{he} - Q_{ge} - Q_{sc}}{\eta_{gb}} V \tag{8}$$

where

$$V = \begin{cases} 1, & Q_{ac} + Q_{he} - Q_{ge} - Q_{sc} > 0 \\ 0, & Q_{ac} + Q_{he} - Q_{ge} - Q_{sc} \leqslant 0 \end{cases}$$

η_{gb} is the gas boiler efficiency.

Therefore, the general expression of the operation PEC of the solar BCHP system, F_{op} (kW h), is:

$$\begin{aligned} F_{op} &= F_f + F_g \\ &= \frac{(E - E_{ge} - E_{spv})U + E_{eq}}{\eta_{gen}\eta_{tra}} + \frac{E_{ge}}{\eta_{ge}} + \frac{(Q_{ac} + Q_{he} - Q_{ge} - Q_{sc})V}{\eta_{gb}} \end{aligned} \tag{9}$$

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

$$[X_i] = [F_i] \cdot [\mu_i] \tag{10}$$

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 in the operation stage can be obtained as follows:

$$[M_{op}] = \sum_{i=1}^{n} [X_i] \tag{11}$$

where M_{op} (g) is the corresponding emission mass during the operation stage and n is the number of combustion devices.

According to the solar BCHP system in Fig. 1, the total pollutants in Eq. (11) can be rewritten by substituting the detailed items to:

$$[M_{op}] = [X_{plant}] + [X_{gpgu}] + [X_{gb}] = [F_f] \cdot [\mu_f] + [F_g] \cdot [\mu_g] \tag{12}$$

where$[X_{plant}]$, $[X_{gpgu}]$ and $[X_{gb}]$ are the emission vectors of the power plants, the gas power generation unit and the gas boiler respectively, $[\mu_f]$ and $[\mu_g]$ are the emission factors of the fossil energy and natural gas respectively.

2.2. Operation strategy

The pollutants emissions and energy consumption of BCHP systems are closely related to their operation strategy. Following electricity load (FEL) and following thermal load (FTL) are the two most distinctive operation strategies for BCHP systems. In the FEL operation strategy, there may be excess heat produced by the gas engine, which can be distributed to other users. However, for an independent BCHP system, the energy saving and emission reduction potentials of the excess heat are not considered. Therefore, it is assumed that the surplus heat is dissipated directly. When the gas engine runs in the FTL operation mode, the solar BCHP system may

Table 1
The operation cases and PEC of the solar BCHP system in the FEL operation mode.

PEC	Case 1	Case 2	Case 3
	$E \leqslant E_{spv}^{max}$	$E > E_{spv}^{max}\ \&;\ E \leqslant E_{ge}^{max} + E_{spv}^{max}$	$E > E_{ge}^{max} + E_{spv}^{max}$
Power plant	$\frac{E_{eq}}{\eta_{gen}\eta_{tra}}$	$\frac{E_{eq}}{\eta_{gen}\eta_{tra}}$	$\frac{E_{eq}+E-E_{ge}^{max}-E_{spv}^{max}}{\eta_{gen}\eta_{tra}}$
Gas engine	–	$\frac{E-E_{spv}^{max}}{\eta_{ge}}$	$\frac{E_{ge}^{max}}{\eta_{ge}}$
Gas boiler	$\frac{Q_{ac}+Q_{he}-Q_{sc}}{\eta_{gb}}V$	$\frac{Q_{ac}+Q_{he}-Q_{sc}-Q_{hr}}{\eta_{gb}}V$	$\frac{Q_{ac}+Q_{he}-Q_{sc}-Q_{hr}^{max}}{\eta_{gb}}V$

Table 2
The operation cases and PEC of the solar BCHP system in the FEL operation mode.

PEC	Case 1	Case 2	Case 3
	$Q_{ac} + Q_{he} \leqslant Q_{sc}^{max}$	$Q_{ac} + Q_{he} > Q_{sc}^{max}\ \&;\ Q_{ac} + Q_{he} \leqslant Q_{hr}^{max} + Q_{sc}^{max}$	$Q_{ac} + Q_{he} > Q_{hr}^{max} + Q_{sc}^{max}$
Power plant	$\frac{E_{eq}+(E-E_{spv})U}{\eta_{gen}\eta_{tra}}$	$\frac{E_{eq}+(E-E_{ge}-E_{spv})U}{\eta_{gen}\eta_{tra}}$	$\frac{E_{eq}+(E-E_{ge}^{max}-E_{spv})U}{\eta_{gen}\eta_{tra}}$
Gas engine	–	$\frac{Q_{ac}+Q_{he}-Q_{sc}^{max}}{(1-\eta_{ge})\eta_{hr}}$	$\frac{E_{ge}^{max}}{\eta_{ge}}$
Gas boiler	–	–	$\frac{Q_{ac}+Q_{he}-Q_{sc}^{max}-Q_{hr}^{max}}{\eta_{gb}}$

produce excess electricity that can usually be exported or stored for future use. When the excess electricity produced in the FTL operation strategy is sold back to the utility grid, the economic benefits of the excess electricity can be obtained based on the unit online power price and the whole life excess electricity produced in the FTL operation strategy. However, from the view points of the consumers in the building, the energy saving and pollutant emission reduction of the solar BCHP system cannot be achieved by the excess electricity. Therefore, the energetic and environment benefits of the excess electricity are neither considered in this study.

In the FEL operation strategy, the capacities of energy equipments of the solar BCHP system are determined according to the electricity cumulative curves and the energy demands of building. After the equipments are selected, the outputs of equipments are determined. The operating condition and the system PEC are expressed in Table 1. Similarly, in the FTL operation strategy, the system size is decided based on the heat or cool cumulative curves and the energy demands of building. The operating condition and the system PEC are listed in Table 2.

3. Methodology

3.1. Life cycle assessment

Within LCA, there are four stages existed: Goal and Scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation and improvements [33].

3.1.1. Goal and Scope

The objective of this study is to calculate the pollutant emissions and PEC of the solar BCHP system within a life span of 10 years (the detailed system description can be found in Section 4.2). Specially, the goal of this work is to make evaluation and comparison between the FEL operation mode and the FTL operation mode in terms of the life cycle environmental and energy performance.

The system boundary of the scope is shown in Fig. 2. The diagram shows ‘‘Materials’’, which is a general term describing the energy consumption and pollutant emissions associated with the exploitation and transportation of raw materials such as steel and aluminum. Generally, the life cycle inventory of the ‘‘Manufacture’’ stage should be obtained by performing an LCA analysis on each equipment unit. At this point, it might be convenient to use rough estimates in the LCA calculations when there is little information available on the details of manufacture process [34]. Thus, the life cycle inventory of this phase will be approximated to the energy consumption and pollutant emissions caused by the electricity consumption. The major inputs of the ‘‘Transportation’’ stage are the fuel energy, such as coal, diesel oil and gasoline and the outputs are the life cycle pollutant emissions associated with railways and road transportation. The stage ‘‘Fuel’’ is mainly consisted of the extraction and transportation of the fossil energy consumption of the power plant and the natural gas consumption of the solar BCHP system. In the ‘‘Operation’’ stage, the energy inputs and emissions outputs are caused by the combustion of fuels, including fossil energy and natural gas. As there is no clearly policy about the disposal of BCHP systems, so the decommissioning stage is not considered in this study.

3.1.2. Life cycle inventory

The life cycle inventory analysis phase aims to determine the life cycle inventory of energy going into and pollutants emission coming out of the entire process of the solar BCHP system. The whole life pollutant emissions and PEC, M and F, can be computed form

$$[M] = [M_{rm}] + [M_{ma}] + [M_{tr}] + [M_{op}] + [M_{fu}] \tag{13}$$

$$F = F_{rm} + F_{ma} + F_{tr} + F_{op} + F_{fu} \tag{14}$$

where 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 in the ‘‘Material’’, ‘‘Manufacture’’, ‘‘Transportation’’, ‘‘Operation’’ and ‘‘Fuel’’ stages, respectively.

The environmental problems caused by the exploitation of raw materials are various, and the main pollutant emissions and PEC of unit raw material are shown in Table 3 [35,36]. The transportation impacts of unit distance in this phase are the same as the transportation stage, while the transport distance of materials is shorter than that of equipments [37]. The details of the materials required for energy equipments are listed in Section 4.2. The fuel consumed in the transportation phase is coal and diesel oil for railway and road respectively. The choices of g/(10^3 kg km) and kW h/(10^3 kg km) as the emission unit and PEC unit in the transportation stage respectively are decided by the transport distance and the transport loads of energy equipments [38]. The unit pollutant emissions and PEC in the transportation stage are listed in Table 4 [39–41]. According to the baseline data, it can be seen that road transportation can cause more serious environmental impacts and

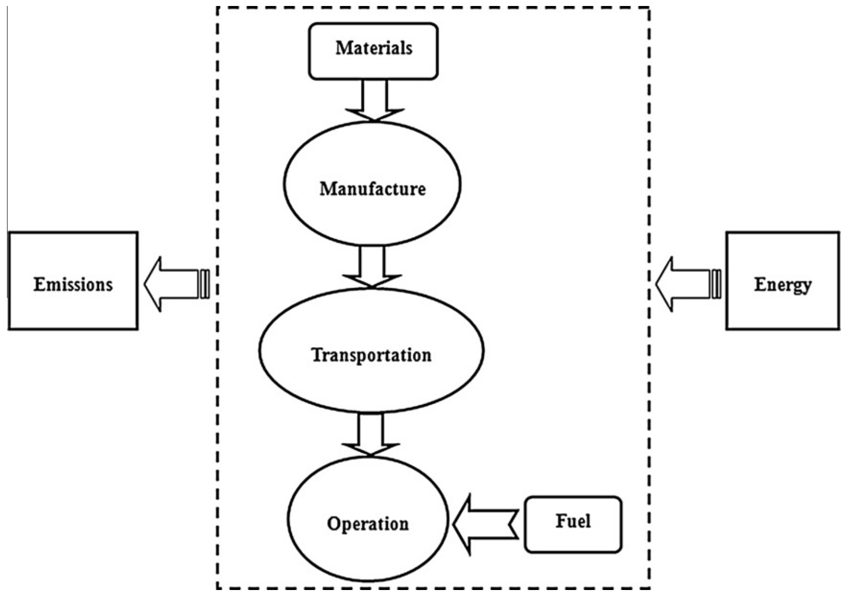

Fig. 2. System boundary of the LCA analysis for the solar BCHP system.

Table 3
The exploitation pollutant emissions and PEC of unit raw materials.

	SO_2 (g)	CO_2 (g)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	CH_4 (g)	Energy (kW h)
Steel (kg^{-1})	9.7	2000	4.000	15	25	53	1.7
Aluminum (kg^{-1})	205.5	25,800	94.70	1290	14	24	36.1
Glass (kg^{-1})	1.1	132.3	3.700	7	–	–	0.6
PVC (kg^{-1})	1.2	390	2.800	1.2	–	–	21.9

Table 4
Life cycle unit pollutant emissions and PEC of different transportation methods.

	SO_2 (g)	CO_2 (g)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	CH_4 (g)	N_2O (g)	Energy (kW h)
Railway $(10^3\ kg)^{-1}\ km^{-1}$	0.065	6.772	0.033	0.004	0.039	0.046	0.002	0.063
Road $(10^3\ kg)^{-1}\ km^{-1}$	9.421	209	3.159	0.942	8.944	0.143	6.409	0.9

Table 5
Unit pollutant emissions and PEC of the fuel stage.

	SO_2 (g)	CO_2 (g)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	CH_4 (g)	N_2O (g)	Energy (kW h)
Coal (kW h^{-1})	0.42	43.75	0.69	0.18	0.106	2.52	0.102	0.183
Natural gas (m^{-3})	0.42	232.6	0.247	0.011	0.018	0.301	0.0004	1.708

Table 6
Unit pollutant emissions and PEC of the operation stage.

	SO_2 (g)	CO_2 (g)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	CH_4 (g)	N_2O (g)	Energy (kW h)
Electricity (kW h^{-1})	3.14	326.37	1.134	0.061	2	0.003	0.01	3.28
Natural gas (m^{-3})	10.3	670	0.068	0.012	0.184	0.005	0.0004	9.76

energy-related problems than railway transportation. However, the transport distance of the road is shorter than that of the railway. Moreover, the pollutant emissions and PEC in this phase is determined by the weights of equipments in the system. In China, the utility grid is mainly composed of coal-fired power plants, thus fossil energy consumed by the power plants is coal. Tables 5 and 6 show the inventory data of the fuel and operation stages, respectively [42–45]. In order to facilitate the calculation, the units of coal and electricity are chosen as g/kW h and kW h/kW h for PEC and emissions respectively, while the units of natural gas in the two phases are selected as g/m^3 and kW h/m^3 for PEC and emissions respectively. It should be noticed that the PEC of the electricity in Table 6 is the energy consumption of the coal-power plants and the transmission efficiency and generation efficiency have been considered. However, the PEC of natural gas in the table is just the energy inputs of the solar BCHP system and the impacts of the combustion devices efficiency are analyzed based on Section 2.1.

Consequently, in this paper, the life cycle emission pollutants mainly include SO_2, CO_2, NO_x, $PM_{2.5}$, CO, CH_4 and N_2O, so the emission mass vector $[X]$ can be expressed by substituting the detailed items as:

$$[X]_{7\times1} = [SO_2, CO_2, NO_x, PM_{2.5}, CO, CH_4, N_2O]^T \quad (15)$$

Generally, the emission pollutants and energy consumption of the solar BCHP system lead to the following impacts, including air pollution, acid precipitation, ozone depletion, global warming, forest destruction, radiation effect, respiratory effects and energy resource depletion, which can be aggregated into three types of influence: environment damages, human health and energy depletion [46]. The energy depletion effects can be evaluated by the life cycle PEC of the system. As for emissions impacts, three most important pollutants-related environmental and health issues in Table 7, global warming, acid precipitation and respiratory effects, are considered to evaluate the environment benefits of the solar BCHP system [47–49]. These impacts are assessed in global warming potential, acidification potential and respiratory effects potential respectively.

The global warming potential describes the contribution made by an emission gas to the greenhouse effect in relation to carbon dioxide (CO_2), which is the most important of substances contributing to the vital and natural greenhouse effect [50]. In short, this means that quantities of any emission are converted into equivalent quantities of CO_2, CO_2-equivalent emission. The acidification potential is given in sulfur dioxide (SO_2) equivalents 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 [50]. Similarly, the respiratory effects potential can be defined as a measure representing potential of organic or inorganic substance to damage the respiratory of human beings. The respiratory effects potential is calculated 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 [51].

Through the emission pollutants multiplied the corresponding global warming potential, acidification potential and respiratory effects potential conversion factors, the total global warming potential, acidification potential and respiratory effects potential can be obtained to:

$$CO_2\text{-equiv.} = [GWP] \times [M]_{7\times1} \quad (16)$$

$$SO_2\text{-equiv.} = [AP] \times [M]_{7\times1} \quad (17)$$

$$PM_{2.5}\text{-equiv.} = [REP] \times [M]_{7\times1} \quad (18)$$

where CO_2-equiv., SO_2-equiv. and $PM_{2.5}$-equiv. are CO_2, SO_2 and $PM_{2.5}$ equivalent emissions respectively (g), [*GWP*], [*AP*] and [*REP*] are global warming potential, acidification potential and respiratory effects potential vectors of pollutants, $[M]_{7\times1}$ is the life cycle pollutant emissions.

Table 7
Conversion factors between various pollutant emissions for *GWP*, *AP* and *REP*.

Pollutant emissions	Environment damage		Human health
	GWP (g CO_2-equiv./g)	*AP* (g SO_2-equiv./g)	*REP* (g $PM_{2.5}$-equiv./g)
SO_2	–	1	1.9
CO_2	1	–	–
NO_x	–	0.7	0.3
$PM_{2.5}$	–	–	1
CO	3	–	–
CH_4	21	–	–
N_2O	310	0.7	–

3.2. Grey relation analysis

Grey relation analysis or grey system theory is applicable to facilitate the comprehensive comparison of different evaluate criteria with different magnitude orders values. When the assessment of BCHP systems is regarded as a grey system problem, the different performance in single criteria between ideal operation strategy and anti-ideal operation strategy can be quantified as geometric distance. Therefore, the integrated benefits of the solar BCHP system can be evaluated by the cumulative geometric values.

The energy and environmental benefits of the system can be evaluated by three types of criteria: environment damages (including global warming potential and acidification potential), human health (respiratory effects potential) and energy depletion (PEC). Therefore, the objective function P_{in}, the integrated performance, is defined to:

$$P_{in} = \omega_1 \cdot P_{GWP} + \omega_2 \cdot P_{AP} + \omega_3 \cdot P_{REP} + \omega_4 \cdot P_{PEC} \quad (19)$$

where P_{GWP}, P_{AP}, P_{REP} and P_{PEC} are the evaluation value of global warming potential, acidification potential, respiratory effects potential and PEC respectively, ω_1, ω_2, ω_3 and ω_4 are the weights of global warming potential, acidification potential, respiratory effects potential and PEC, $0 \leqslant \omega_1, \omega_2, \omega_3, \omega_4 \leqslant 1$ and $\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1$. Weight is assigned to criteria to indicate its relative importance. In this paper, it is assumed that the influences of the three criteria and two sub-criteria are equally important, so $\omega_1 = \omega_2$ and $\omega_1 + \omega_2 = \omega_3 = \omega_4$.

According to the grey relation theory, P_{GWP}, P_{AP}, P_{REP} and P_{PEC} can be obtained based on the geometric values comparison between the FEL operation strategy and the FTL mode. As all the evaluation criteria of the system are negative criteria, so the operation strategy which has the smaller pollutant emissions or PEC is the ideal choice. Take the CO_2-equiv. as example, the evaluation value of global warming potential is calculated as follows,

If $CO_2\text{-equiv.}^{FEL} \leqslant CO_2\text{-equiv.}^{FTL}$,

$$P_{GWP}^{FEL} = 1 \quad (20)$$

$$P_{GWP}^{FTL} = \frac{CO_2\text{-equiv.}^{FEL}}{CO_2\text{-equiv.}^{FTL}} \quad (21)$$

Otherwise, when $CO_2\text{-equiv.}^{FEL} > CO_2\text{-equiv.}^{FTL}$,

$$P_{GWP}^{FTL} = 1 \quad (22)$$

$$P_{GWP}^{FTL} = \frac{CO_2 - equiv.^{FTL}}{CO_2 - equiv.^{FEL}} \quad (23)$$

Similarly, P_{AP}, P_{REP} and P_{PEC} of FEL and FTL operation strategies can be also obtained.

4. Case study

4.1. Building description

To apply the LCA methodology to estimate the pollutant emissions and energy consumption of the solar BCHP system in FEL and FTL operation strategies, the baseline building under consideration in this study is a hypothetical nine-floor commercial office building in Beijing, China. The average daily sunshine hours and the daily average solar radiation of Beijing are 5 h and 18 MJ/m^2, respectively. The study building has a floor area of 19,986 m^2 and the total area of the windows and glazing comprises about 50% of the total wall area. The maximum surface area for harvesting solar energy, including ceiling and curtain wall, is 1920 m^2. The first and second floors of the building are shopping mall and the ceiling heights are 6.0 m. The third floor is a gym with the ceiling height 5.1 m. The forth to eighth floors are office room and the ceiling heights are 3.5 m. The ninth floor is a meeting room with the ceiling height 4.5 m. The average temperature set points 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 power loads of the building are estimated using DeST software [52], which are shown in Fig. 3. From the hourly curves, it can be seen that the hourly electricity demand is stable relatively, while the hourly heat load and cool load both fluctuate more than the electricity demand. The cool load peak is greater than the heat load peak because of the hot climate of Beijing. The electricity load is generally less than the heat and cool loads in summer and winter, while, in spring and autumn, the energy demands for cooling and heating are low.

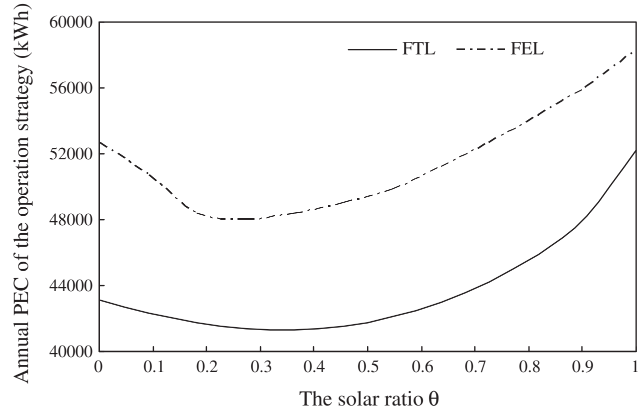

Fig. 4. Variation of annual operation PEC with the solar ratio θ in the typical day for FEL and FTL operation strategies.

4.2. System description

According to the building loads and the operation strategy, the capacities and technical parameters of energy equipments in the solar BCHP system can be initially determined. However, the harvested solar energy is entirely consumed by the solar collectors and solar photovoltaic unit, and the solar ratio is necessary to be defined to identify the ratio of the area used to harvest solar energy for the solar photovoltaic unit to the total harvest area of the building. Therefore, the solar ratio, $0 \leqslant \theta \leqslant 1$, is defined to:

$$\theta = \frac{A_{spv}}{A_{total}} \tag{24}$$

where A_{spv} and A_{total} are the harvest area of the solar photovoltaic and the total harvest area of the building, respectively, and the harvest area of the solar collectors is $A_{total} - A_{spv}$.

The solar ratio θ is important to optimize the PEC of the solar BCHP system in the operation phase. Once the ratio is determined, the operation strategy and calculation complexity can be simplified. Fig. 4 shows the optimization processes of the annual operation PEC in FEL and FTL operation modes based on different solar ratio in a typical day. It can be found that the operation PEC of the solar BCHP system decreases with the increasing solar ratio at small solar photovoltaic capacity, while when the ratio is greater than the optimal ratio, the PEC begins to increase with the increasing solar ratio. From the variation trends of the PEC, the annual operation PEC of the FEL operation strategy is generally more than that of the FTL operation strategy. Additionally, the optimal capacity of solar photovoltaic unit in the FTL operation strategy is larger than that of the FEL operation strategy, while the ranking order of solar collectors capacity is just the opposite.

Thus, the optimal capacities of solar photovoltaic unit and solar collectors for FEL and FTL operation strategies can be obtained. The capacity and technical parameters of energy equipments for the solar BCHP system are shown in Table 8. It can be seen that, in order to simplify the calculation, the efficiencies of energy equipments, except the gas engine, are assumed to be constant at any load operation, some explanations are shown as follows. The efficiency variations of the heating recover and heat exchanger are very small with different load operation. Because of the application of their own storage facilities, the efficiencies of the solar photovoltaic unit and solar collectors can be stable for a wide variation of load operation. When the rated capacity of the gas boiler is changed from 0% to 100%, its efficiency is between 0.76 and 0.95 [53]. However, gas boiler is used as auxiliary equipment in this system and its heat outputs are relative small compared with the gas power generation unit and the solar collectors. Thus, an experience value, 0.92, is selected as the efficiency of the gas boiler. As for absorption chiller, when the rated capacity is more than 30%, the efficiency is changed from 0.67 to 0.73. In Fig. 3, it can be seen that, most of the time, the cool load of the building is larger than 35% of the absorption chiller capacity in Table 8 [54]. Therefore, an average efficiency, 0.69, is selected as the efficiency of the absorption chiller. The required raw materials can be determined based on the capacities of energy equipments, which are listed in Table 9 [42,55–57].

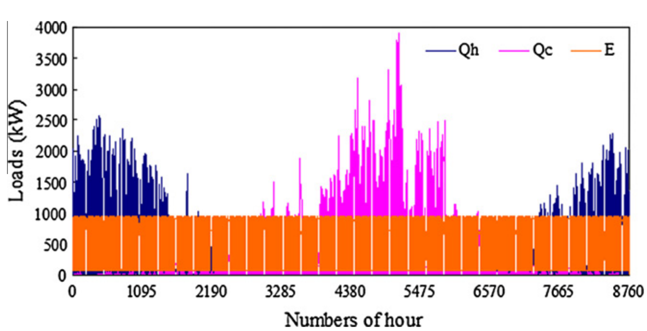

Fig. 3. The annual hourly cooling, heating and power loads of the commercial office building.

4.3. Analysis and result

4.3.1. Operation strategy analysis

According to technical parameters in Table 8, the monthly supplementary heat variations of the solar collectors and the gas boiler in FEL and FTL operation strategies can be obtained, which are shown in Fig. 5. Because of the higher thermal demands of the building in summer and winter, the supplementary heat in these two seasons is more than in transient seasons. The heat supplied by the solar collectors in the FTL operation strategy is much more than that of the FEL operation strategy. Additionally, the solar collectors operate almost in the whole year in both FEL and FTL operation strategies, while the gas boiler operates only 3 or 4 months in a year. Moreover, because of the application of solar collectors, the heat from the gas boiler is very few and the natural gas consumption of the gas boiler in the FTL operation strategy is a little more than that of the FEL operation strategy in some months.

Then the constitutions of fuels consumed in the operation phase of the two operation strategies are discussed. Fig. 6 shows the annual energy consumptions, including coal, natural gas and solar energy, and the energy structures of the solar BCHP system in FEL and FTL operation strategies. It can be found that the natural gas

Table 8
Technical parameters of the solar BCHP system in FTL and FEL operation strategies.

Equipment	Unit power (MW)	Power required (MW)	Nominal power (MW)	Efficiency
Gas engine	0.11	–	1.20	0.33[c] (at full load)
Absorption chiller	0.49	3.9	3.92	0.69
Heating recover	0.1	2.53	2.6	0.91
Heat exchanger	0.1	2.56	2.6	0.91
Gas boiler[a]	0.2	2.42	2.6	0.92
Solar collector[a]	0.2	1.05	1.2	0.6
Solar photovoltaic[a]	0.01	0.09	0.09	0.14
Gas boiler[b]	0.2	2.62	2.8	0.92
Solar collector[b]	0.2	0.92	1.0	0.6
Solar photovoltaic[b]	0.01	0.12	0.12	0.14
Utility grid	–	–	–	0.92[d]

[a] The equipments based on the FEL operation strategy.
[b] The equipments based on the FTL operation strategy.
[c] The values of the coefficients, $a = 8.935$, $b = 33.157$, $c = -27.081$, $d = 17.989$.
[d] The transmission efficiency of utility grid.

Table 9
Main material composition of the equipments for the solar BCHP system in FEL and FTL operation strategies.

Equipment	Material composition (kg)
Gas engine + heating recover	11,400 kg steel
Heat exchanger	5320 kg steel
Absorption chiller	72,000 kg steel
Gas boiler[a]	4250 kg steel, 125 kg aluminum
Solar collector[a]	3000 kg steel, 1350 kg aluminum, 5670 kg glass, 960 kg PVC
Solar photovoltaic[a]	2490 kg steel, 940 kg aluminum, 7200 kg glass, 820 kg PVC
Gas boiler[b]	4250 kg steel, 125 kg aluminum
Solar collector[b]	2500 kg steel, 1125 kg aluminum, 4725 kg glass, 800 kg PVC
Solar photovoltaic[b]	3320 kg steel, 1250 kg aluminum, 9600 kg glass, 1100 kg PVC

[a] The equipments based on the FEL operation strategy.
[b] The equipments based on the FTL operation strategy.

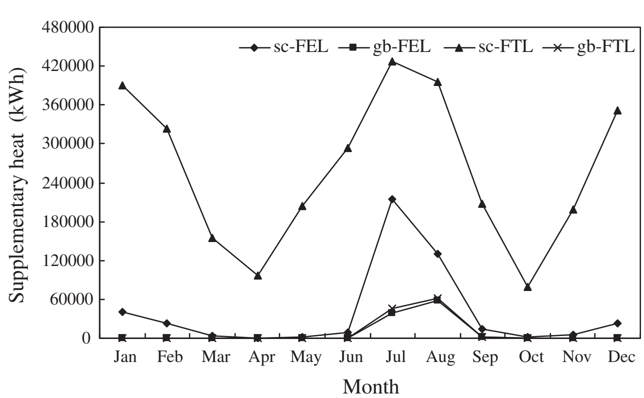

Fig. 5. Variation of the monthly supplementary heat share for the solar BCHP system in FEL and FTL operation strategies.

consumption of the FEL operation strategy is more than that of the FTL mode, while the coal consumption of the FEL operation mode is hardly any. For FTL operation strategy, the coal consumption is more than the natural gas consumption because of the considerable electricity consumption of the coal-power plants. Thus the environmental impacts caused by the FTL operation mode are more serious than the FEL operation mode. Moreover, the utilization of the solar energy in the FTL operation strategy is better than that of the FEL operation strategy. Therefore, the energy performance of the FTL operation strategy is better than FEL operation strategy in terms of the annual PEC, while when solar energy is took into consideration, the total energy consumption of the FEL operation strategy is a little lower than that of the FTL operation strategy.

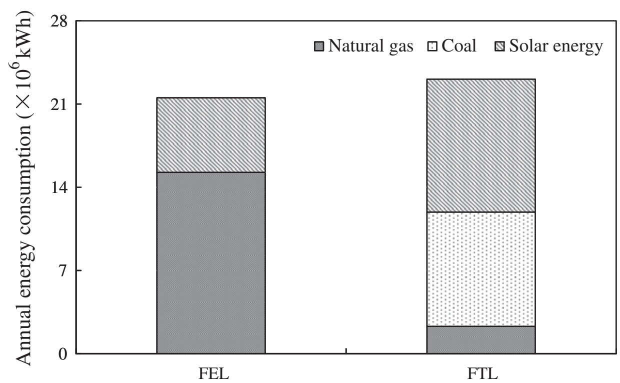

Fig. 6. The annual operation energy consumption of the solar BCHP system in FEL and FTL operation strategies.

4.3.2. LCA results

The whole life pollutant emissions and PEC of the solar BCHP system in FEL and FTL operation strategies are listed in Table 10 and the normalized comparison results are shown in Fig. 7. It can be seen that the SO_2 emission of the FEL operation strategy is higher than that of the FTL operation strategy due to its numerous natural gas consumption in the operation stage. Because of the contribution of natural gas in the fuel phase, the CO_2 emission of the FEL operation strategy is a little larger than that of the FTL operation strategy. Additionally, the NO_x, $PM_{2.5}$ and CO emissions of the FTL operation strategy are much more than those of the FEL mode, which is mainly caused by the considerable coal consumption in the operation mode. Moreover, because of the exploitation of coal in the fuel phase, the CH_4 and N_2O emissions of the FTL operation strategy are nearly 20 and 43 times more than those of the FEL operation strategy, respectively. However, the energy waste caused by the excess electricity produced in the FTL operation strategy is less than that caused by the excess heat generated in the FTL operation strategy, so the life cycle PEC of the FTL operation strategy is less than that of the FEL operation strategy. Therefore, the environmental impacts caused by the FEL operation strategy are less serious in comparison to the FTL mode, while the energetic benefits of the FTL operation strategy are better than

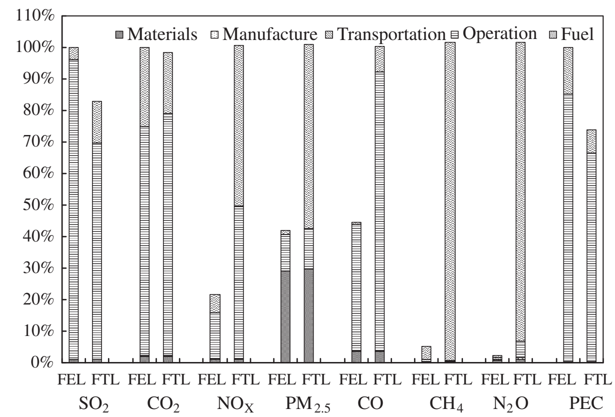

Fig. 7. The normalized life cycle pollutant emissions and PEC results and the LCI structures for the solar BCHP system in FEL and FTL operation strategies.

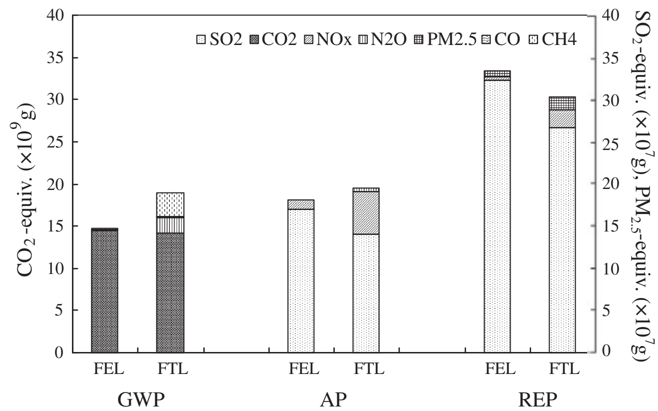

Fig. 8. The life cycle CO_2-equiv., SO_2-equiv. and $PM_{2.5}$-equiv. emissions and *GWP*, *AP* and *REP* structures of the solar BCHP system in FEL and FTL operation strategies.

the FEL mode. According to the LCI structure analysis, the pollutant emissions and PEC are mainly happened in the operation and fuel stages, the materials phase also makes some contributions to the CO_2, $PM_{2.5}$ and CO emissions, while other two stages of the LCA have less significant influence on the final results.

The life cycle global warming potential, acidification potential and respiratory effects potential of the solar BCHP system in FEL and FTL operation strategies are displayed in Figs. 8–11. From Fig. 8, it can be found that the CO_2 emission is the main factor to contribute the greenhouse effect. The corresponding conversion factors of N_2O, CO and CH_4 are larger than CO_2, but they contribute less to total global warming potential because of their lower emission. Although the CO_2 emission of the FTL operation strategy is lower than that of the FEL mode, the greenhouse effects caused by the FTL operation strategy are more serious than the FEL operation strategy due to the contribution of other greenhouse gases. Compared the three less greenhouse gases in Fig. 9, N_2O and CH_4 are the main contributors of global warming potentials in the FTL operation strategy and the CO_2-equivalent emission of these three gases in the FTL operation mode is 17 times more than that of the FEL operation strategy. Compared global warming potentials with acidification potentials and respiratory effects potentials, the orders of magnitude of SO_2-equivalent emission and $PM_{2.5}$-equivalent emission are one hundredth of the CO_2-equivalent emission. The SO_2 and NO_x emissions mainly contribute to acidification, while the impacts of N_2O emission are so few. Although the SO_2 emission of the FTL operation strategy is lower than that of the FEL operation strategy, the acidification-related environmental

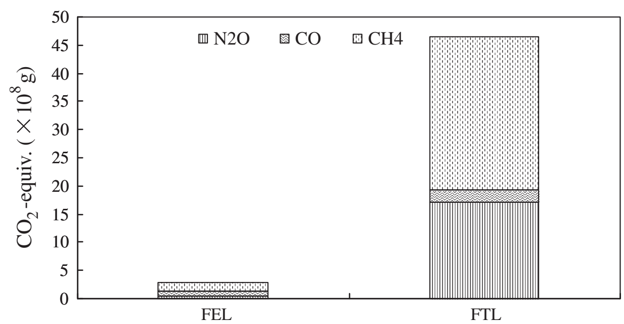

Fig. 9. Life cycle CO_2-equiv. emissions of the solar BCHP system in FEL and FTL operation strategy.

problems caused by the FTL operation strategy are more serious than the FEL operation mode due to the contribution of NO_x and N_2O emissions. The SO_2 emission is also the main pollutant to effect human respiratory health due to its large conversion factor, while the influence of NO_x and $PM_{2.5}$ emissions are less significant. The life cycle $PM_{2.5}$-equivalent emission in the FTL operation strategy is lower than that of the FEL operation mode because of its lower SO_2 emission.

From Fig. 11, it can be seen that the environment impacts and human health damages of the two operation modes in raw materials, manufacture and transportation stages are almost the same, and the contributions of these three phases are less important

Table 10
The LCA results of pollutant emissions and PEC for the solar BCHP system in FEL and FTL operation strategies.

		Materials ($\times10^4$)	Manufacture ($\times10^2$)	Transport ($\times10^3$)	Operation ($\times10^3$)	Fuel ($\times10^4$)	Total ($\times10^5$)
SO_2 (g)	FEL	154.1	2349.5	71.3	161130.4	666.3	1696.4
	FTL	156.4	2389.9	72.6	116164.1	2246.1	1405.1
CO_2 (g)	FEL	28856.1	244208.9	2388.5	104,99,825	363,970	144,549
	FTL	29166.8	248402.7	2429.5	111,16,179	280,958	142,447
NO_x (g)	FEL	70.1	848.5	26.5	10528.8	403.8	153.7
	FTL	71.5	863.1	27.1	34645.2	3615.5	716.3
$PM_{2.5}$ (g)	FEL	4693.4	45.6	7.1	1881.1	22.1	68.1
	FTL	481.7	46.4	7.3	2065.2	947.1	163.6
CO (g)	FEL	256.1	1496.5	67.3	28378.9	31.2	314.7
	FTL	257.1	1522.2	68.5	62606.5	552.4	709.2
CH_4 (g)	FEL	55.4	2.2	7.3	764.7	536.4	66.9
	FTL	55.8	2.3	7.5	204.6	13,044	1312.1
N_2O (g)	FEL	4.4	7.5	44.7	7.8	3.4	1.3
	FTL	4.5	7.6	45.5	292.5	524.8	56.3
PEC (kW h)	FEL	31.2	2454.3	15.1	152729.1	2669.4	1799.9
	FTL	31.9	2496.4	15.3	118954.1	1350.1	1330.4

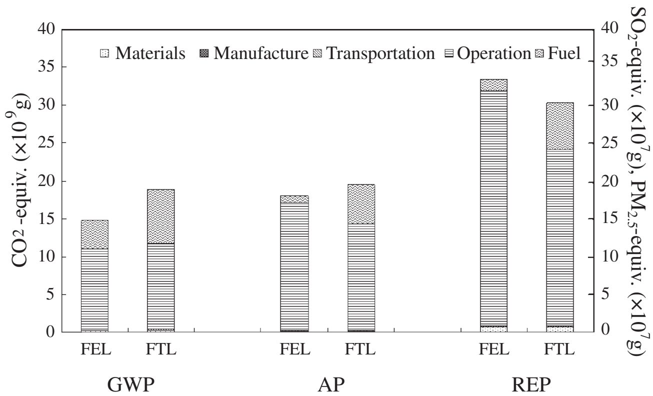

Fig. 10. The life cycle CO_2-equiv., SO_2-equiv. and $PM_{2.5}$-equiv. emissions and LCI structures of the solar BCHP system in FEL and FTL operation strategies.

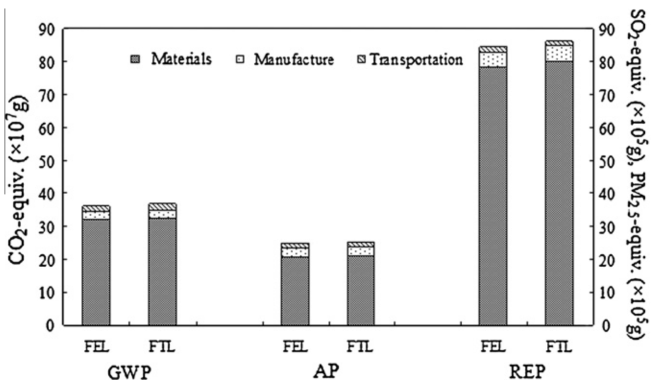

Fig. 11. The life cycle CO_2-equiv., SO_2-equiv. and $PM_{2.5}$-equiv. emissions in the materials, manufacture and transportation stages of the solar BCHP system in FEL and FTL operation strategies.

compared with the operation and fuel stages as shown in Fig. 10. From Fig. 10, the CO_2-equivalent emission in both operation and fuel stages in the FTL operation strategy is higher than that of the FEL operation strategy because of its considerable coal consumption. Although the SO_2-equivalent emission of the FEL operation strategy in the operation phase is a little higher than that of the FTL operation strategy, the life cycle acidification impacts caused by the FEL operation strategy are less serious than the FTL operation strategy because of its lower SO_2-equivalent emission in the fuel phase. Oppositely, the respiratory effects of the FEL operation strategy are more serious than that of the FTL mode due to its numerous $PM_{2.5}$-equivalent emissions in the operation phase.

Finally, the comprehensive evaluation results are shown in Table 11 based on the environment impacts, human health damage and energy depletion of two operation strategies. From the environment criteria, FEL operation strategy is better than the FTL mode because of its less serious greenhouse effects and acidification effects. In only human health criteria, according to respiratory effects, the FTL operation strategy has less negative impacts on human health than the FEL mode. Additionally, the energetic benefits of the FTL operation strategy are better than that of the FEL mode in terms of the life cycle PEC. Moreover, for the case building, the whole life energy saving and pollutant emission reduction potentials of the FTL operation strategy are better than that of the FEL operation mode.

Table 11
The comprehensive evaluation result of the two operation strategies.

	Environment impacts		Human health damage	Energy depletion	Integrated
	GWP	*AP*	*REP*	PEC	
FEL	0.167	0.167	0.301	0.244	0.879
FTL	0.128	0.153	0.333	0.333	0.947

5. Conclusion

LCA integrated with the grey relation theory is employed to estimate the pollutant emissions and PEC of a novel solar BCHP system in FEL and FTL operation strategies. Global warming potential, acidification potential, respiratory effects potential and primary energy consumption are employed as evaluation criteria to assess the energetic and environment performances of the system for a commercial office building in Beijing, China. The evaluation analysis leads to the following conclusions:

The optimal solar ratio θ is helpful to maximize the energy saving potential of the system. The optimum solar photovoltaic capacity of the FTL operation mode is larger than that of the FEL mode. According to the energy consumption structure in the operation phase, the PEC of the FTL operation mode is less than that of the FEL mode. While, the fossil energy consumption of the FEL operation mode is lower than that of the FTL mode, thus the environmental issues caused by the FEL operation strategy are less serious than the FTL mode.

LCA results indicate that the contributions of materials, operation and fuel stages are more important than the manufacture and transportation stages. From the viewpoint of the integrated performance, the comprehensive benefit of the FTL operation mode is better than that of the FEL mode. However, when concerning global warming potential and acidification potential, the environment benefits of FEL operation mode are friendly.

Although this energy and environmental evaluation model is still need to be improved, it is believed that if this assessment methodology is applied under suitable conditions and in combination with the reasonable weights method, disposal data of BCHP systems and the impacts of variable equipment efficiency under different load operation, it can become a powerful tool for manufacturers and users to evaluate the life cycle performance of BCHP systems.

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