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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

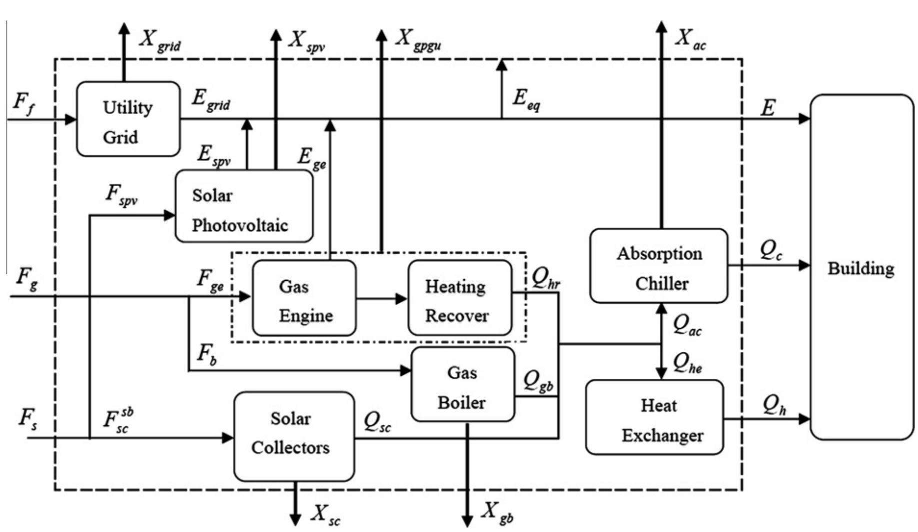

Fig. 1. The energy and emission flow chart of the solar BCHP system. The thin solid line and thick solid line represent the energy flow and emission flow respectively, and the equipments inside the dotted line are a package unit.