Applied Energy 88 (2011) 5143–5152

Contents lists available at ScienceDirect

Applied Energy

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

Sensitivity analysis of optimal model on building cooling heating and power system

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ARTICLE INFO

Article history:
Received 20 January 2010
Received in revised form 11 July 2011
Accepted 11 July 2011
Available online 3 August 2011

Keywords:
Building cooling heating and power (BCHP) system
Optimization
Genetic algorithm (GA)
Sensitivity analysis

ABSTRACT

The optimization of building cooling heating and power (BCHP) system is helpful to improve its comprehensive performance including energetic, economic and environmental aspects. However, the optimal results are closely dependent on the initial setting parameters. This paper deduces the energy consumption of BCHP system following the electrical load and presents the optimization problem of BCHP system that includes the decision variables, the objective function, the constraint conditions and the solution method. The influences of the initial parameters, which include the technical, economic and environmental parameters, the building loads and the optimization setting parameters, on the optimal decision variables and the performances of BCHP system are analyzed and compared. The contour curves of the performances of BCHP system in comparison to the conventional separation production (SP) system, and the sensitivity of the optimal decision variables to the initial parameters are obtained.

1. Introduction

In many counties, buildings account for nearly 40% of energy use, and about 40% of carbon dioxide (CO_2) emissions along with other greenhouse gas and air pollutant emissions [1,2]. The increasing of energy consumption leads to more problems such as energy security, environmental pollution and climate change. As an energy-efficient and environmental-friendly technology, cogeneration system (combined heating and power (CHP) or combined cooling heating and power (CCHP) system) is broadly identified as a highly efficient way to use both fossil and renewable fuels and to make a significant contribution to the sustainable energy development [3–8]. When CCHP system is applied to a building, it is called building cooling heating and power (BCHP) system. BCHP systems have been introduced into various kinds of commercial buildings such as hotels, offices, hospitals and schools [8,9].

The performance of cogeneration system is closely dependent on its design and operation strategy. Many researchers have concerned the design [10,11], the operation [12,13], the modeling [14], the energetic and the environmental aspects [15–21] to improve the performances of cogeneration systems. Moreover, aimed to obtain the most benefits achieved by the cogeneration system in comparison to the conventional separation production (SP) system, many optimization models are proposed to optimize the structure, the capacity and/or the operation strategy of cogeneration system [22–31]. During the optimization, the initial parameters including technical, economic and environmental parameters are important to obtain the rational optimal results. Different parameters lead to the various optimal results directly. To show the influence on the performances of cogeneration system, some researchers have studied and reported some sensitivity analysis of cogeneration systems. The influence analysis mainly includes the energy demands of building [28,32–34] and the key economic parameters [30,35–40].

The optimal results and the performances of congregation system are closely related to the building energy demands. Li et al. [28] studied the influence of energy demands on the optimal facility scheme and the feasibility of BCHP system for a hotel in terms of different heat-electricity ratio and cooling-electricity ratio. Li et al. [32] analyzed the economic influences of BCHP systems into a hotel and a hospital by the energy demands. Gamou et al. [33] carried out a numerical study on a fuel cell BCHP system installed in an office building and clarified the influence of uncertainties in energy demands on a system's economics and optimal equipment capacities. Mavrotas et al. [34] employed the uncertain degree of demand satisfaction and used fuzzy set theory to optimize and study the economic performance of BCHP system into a hospital.

The sensitivity analysis on the economic parameters mainly includes electricity price [30,35–38] and fuel price [30,35–40]. Fragaki et al. [35] studied a gas engine CHP system with thermal store and analyzed the most economic plant size net present value (NPV) in terms of sensitivity to electricity sale prices and gas price including the climate change levy when applicable. Ren et al. [36] optimized a residential CHP system and presented the sensitivity analysis to show how the optimal solutions would vary due to

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doi:10.1016/j.apenergy.2011.07.015

changes of natural gas price, electricity price, electricity buy-back price and carbon tax, etc. Rentizelas et al. [37] optimized a multi-biomass CCHP system and presented the sensitivity analysis performed for the parameters: interest rate, inflation, investment cost, electricity price, cooling price, biomass cost, oil price and operation and maintenance cost. Streckiene et al. [38] presented the feasibility of a CHP system with thermal store in a spot market and showed which extent the optimal solution would vary by changing investment cost, electricity and natural gas price. Wang et al. [30] analyzed the optimal operation strategy changed with electricity price and gas price and presented the fitting functions. Lozano et al. [39] developed an optimization model for BCHP system into a hospital and carried out the sensitivity analysis by varying the amortization and maintenance factor as well as the natural gas price. Sayyaadi [40] proposed a multi-objective optimization model for a benchmark CHP system and performed the sensitivity analysis on the fuel specific cost and the interest rate.

Most literatures about the sensitivity analysis of BCHP system analyzed the influences of load and/or economic parameters, there are few literatures to present the sensitivity analysis of the optimal model and/or the technical parameters. This paper is the extension of Ref. [30] and to pay attention to the sensitivity analysis on the optimal results and the performances of BCHP system in terms of the technical, economic and environmental parameters. Section 2 presents the different points with Ref. [30], analyzes the energy consumption of BCHP system in consideration of the operation strategy, and constructs the optimization model. Section 3 analyzes the influences of criteria weight, building loads, technical parameters, economic parameters and emission factors, etc. Section 4 gives summaries and conclusions.

2. BCHP system

2.1. Energy consumption of BCHP system

The BCHP system analyzed in this paper has the same structure and equipments as the BCHP system in Ref. [30]. The energy flows of the BCHP system driven by gas turbine are shown in Fig. 1. Natural gas is fed to the power generation unit (PGU) to produce electricity. The electricity is supplied to the building, the electric chiller, and the distribution pumps and fans. The shortage can be compensated by the outside grid when the electricity produced by the PGU is not enough. The exhaust heat from the PGU is recovered by the waste heat recovery system. The recovered heat is used to produce cool using an absorption chiller or heat using a heating exchanger. When the recovered heat is less than the heat demand, the shortage is supplemented by the gas-fired auxiliary boiler. In addition, the auxiliary boiler and the connection between the BCHP system and the outside grid can decrease the accidental blackout and enhance the reliability.

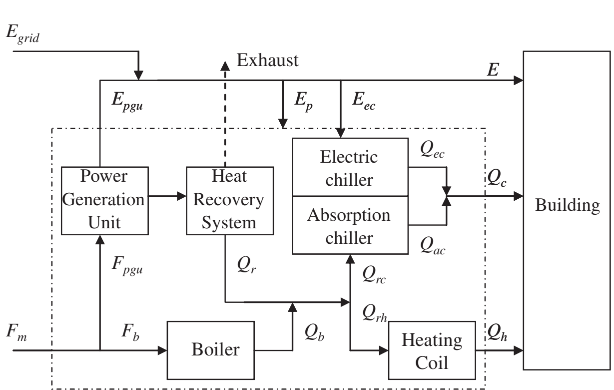

Fig. 1. The energy flow diagram of the BCHP system.

Compared to Ref. [30], there are two different points to reflect the real operation situation as follows.

2.1.1. The operation strategy

In Ref. [30], the BCHP system operates following the thermal demand, and moreover, the excess electricity is not allowed to be sold back to the grid. Because the excess electricity is not technically dissipated directly, it is assumed that the additional electricity can be stored or sent to other nearby users while the energy saving of the excess electricity is not considered. Herein, the BCHP system operates following the electricity demand. Thus, the excess heat can be exhausted directly, which is easily achieved in technology. However, it is emphasized that this operation strategy introduces the risk to affect the primary energy saving due to the surplus heat wasted to the environment. This operation mode is only suitable to the situation that the surplus electricity is not allowed to be sold back to the grid.

2.1.2. The generation efficiency and operation mode of the PGU

In Ref. [30], it is assumed that the efficiency drops of CCHP equipments at part load operation are neglected to simplify the analysis. Because the efficiencies of the PGU at part loads have large difference, the following conditions are considered:

(1) The generation efficiency of the PGU has the nonlinear characteristic with the load factor and it is expressed to:

$$\eta_e = a + bf_{pgu} + cf_{pgu}^2 + df_{pgu}^3 \quad (1)$$

where η_e is the PGU generation efficiency, and f_{pgu} is the instantaneous fraction of the PGU capacity and

$$f_{pgu} = \frac{E + E_p + E_{ec}}{E_{\max}} \times 100\% \quad (2)$$

where E is the electricity demand of building (kW h), E_p is the parasitical electricity consumption (kW h), $E_{\max}$ the maximum generation electricity of the PGU when the PGU runs at full load and numerically $E_{\max}$ corresponds to $E_{\max} = N_{\max} \cdot 1$ h (kW h), $N_{\max}$ is the PGU capacity (kW), and E_{ec} is the electricity consumption of the electric chiller (kW h) and

$$E_{ec} = \frac{Q_{ec}}{COP_e} \quad (3)$$

where Q_{ec} is the cool produced by the electric chiller (kW h) and COP_e is the electric chiller's coefficient of performance (COP).

(2) Because of the lower generation efficiency at the lower load, the BCHP system could not save energy and/or cost. To keep the PGU to run at the higher output, the following conditions determine the on–off status of the BCHP system [41]:

$$\begin{cases} E_{pgu} = 0, & 0\% \leqslant f_{pgu} < 25\% \\ E_{pgu} = E + E_p + E_{ec}, & 25\% \leqslant f_{pgu} \leqslant 100\% \\ E_{pgu} = N_{\max} & 100\% < f_{pgu} \end{cases} \quad (4)$$

where E_{pgu} is the output electricity from the PGU (kW h).

According to these points, the operating conditions and the total energy consumption of the BCHP system are expressed in Eqs. (5)–(7) as follows:

If $0\% \leqslant f_{pgu} < 25\%$

$$F = \frac{E + E_p + E_{ec}}{\eta_e^{SP}\eta_{grid}} + \frac{\frac{Q_{ac}}{COP_{ac}} + \frac{Q_h}{\eta_h}}{\eta_b} \quad (5)$$

If $25\% \leqslant f_{pgu} \leqslant 100\%$