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Pre-feasibility of building cooling heating and power system with thermal energy storage considering energy supply–demand mismatch

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HIGHLIGHTS

- Define degree of mismatch (DM) to describe energy supply–demand disparity.
- When DM = 1, primary energy saving ratio reaches maximum.
- TES–BCHP system is more applicable when heating load is dominant.
- The exportability of co-generated power is favorable for energy saving.
- As the key impact factor, high gas turbine efficiency is desirable.

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ABSTRACT

Natural-gas-driven building cooling heating and power (BCHP) system shows high energy efficiency and low greenhouse gases emission, but is of dissatisfactory performance under part load working conditions due to the non-synchronized and fluctuating thermal and electrical demands. Integrating thermal energy storage (TES) device with BCHP system proves to be an effective way to improve the performance of the whole system. In this paper, the applicability of TES–BCHP system is investigated according to the relationship between user load demands and system energy supply. Based on the supply thermal power ratio of the prime mover and the required one of users, a new parameter, the degree of mismatch (DM), is defined. Moreover, the analytical relationship between primary energy saving ratio (PESR) of TES–BCHP system and DM is established, under following thermal load (FTL) and following electrical load (FEL) respectively for three typical working conditions. The results show that the more DM approaches to unity, the higher PESR of TES–BCHP will be, and that the exportability of the co-generated electricity is favorable for energy saving. It also indicates that TES–BCHP is more applicable for those where the heating demand is dominant. This work is of great significance in further understanding the energy saving mechanism between TES and BCHP and guiding the design of practical TES–BCHP systems.

1. Introduction

The increasing scarcity of energy resources, global warming and blackouts resulting from weather conditions have stimulated the search for more efficient methods of energy conservation, reducing greenhouse gases emissions and ensuring power supplies [1]. Meanwhile, increasing demands for cooling and heating power in buildings calls for resurveying traditional energy production. One method for sustainable development is to adopt the technology of tri-generation, which is also known as building cooling heating and power (BCHP) for application in a building [2,3]. Natural-gas-driven building cooling heating and power system is of high energy utilization efficiency, low pollutions emission, high energy supply safety and reliability and good economic benefit. In recent years, its application is getting more and more attentions [4]. Nevertheless, some practical BCHP systems do not work efficiently. On one hand, thermal and electrical demands of users are not synchronized. On the other hand, building loads are fluctuating during one day, which results in part load working condition and leads to low energy efficiency of the energy supply devices [5]. Integrating thermal energy storage (TES) device with BCHP system proves to be an effective way to improve the part load performance of the whole system and save the primary energy consumption (PEC) [6].

Many studies investigated on the thermodynamic or economic analysis of co-generation and tri-generation systems with TES devices [7,8]. For instance, Khan et al. [9] and Bogdan and Kopjar [10] studied the combined heating and power (CHP) systems with

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Nomenclature

C	cooling power (kW)
E	electrical power (kW)
H	heating power (kW)
Q	overall thermal capacity (kW)
r	accumulated heating load ratio
t	time (s)
T	energy storage cycle (s)
η	efficiency

Subscripts

d	demand
s	supply
cri	critical value
max	maximal value
boiler	gas boiler
grid	power grid

Abbreviations

AC	absorption chiller
BCHP	building cooling heating and power
COP	coefficient of performance
DM	degree of mismatch
EC	electrical chiller
FEL	following electrical load
FTL	following thermal load
GT	gas turbine
HE	heat exchanger
PEC	primary energy consumption
PESR	primary energy saving ratio
SG	separated generation
SR	simultaneous ratio
TPR	thermal power ratio

heat accumulators. The solution proved to offer a better economic benefit and more energy savings compared with that for only co-generation. Barbieri et al. [11] presented a model for profitability calculation of CHP system and found it could be profitable to store the heat during electricity peak hours in order to satisfy delayed demands. Rong and Lahdelma [12] used the linear programming and the Tri-Commodity Simplex algorithm for tri-generation optimization. Campos [13] proposed three approaches for heat storage modeling in co-generation system and found that the technology and its modeling had a great influence on the simulation results. Zaltash et al. [14] and Fu et al. [15] done experiments to investigate the operating parameters and the overall efficiency for practical BCHP system. Then Wang et al. [16] found that the operation strategy of practical co-generation systems is of high significance. Mongibello et al. [17] analyzed the operations of four different micro-CHP systems and performed the economic optimization of prime movers operations. Katulic et al. [18] proposed a novel method to find the optimal daily heat storage tank capacity for a co-generation power plant.

During recent years, BCHP systems with energy storage equipment had raised increasingly growing researches [19]. Zhang et al. [20] analyzed and compared different TES device locations in the system based on ideal model and Xiong et al. [21] obtained the optimal phase change temperature through optimization for a PCM-TES–BCHP system. Liu et al. [22] optimized the hourly operation strategy for TES–BCHP system and found that the installed capacity of devices could be decreased greatly. However, some practical TES–BCHP systems are not energy-saving compared to separated generation systems, or even worse than the traditional ones. It was found that the energy saving effect of TES–BCHP system highly depends on the user load characteristics [23]. To evaluate the asynchronism between heat and power demand, Li [24] proposed a new concept, simultaneous ratio (SR), and found that BCHP system was more feasible for those whose SR value was relatively low. The SR index only describes the supply thermal power ratio when the system works under following electrical load (FEL) mode, and it fails to alleviate the disparity of the energy amount between supply and demand [25].

Thus accurate feasibility evaluation and rational match between energy supply and demands are necessary for the realization of advantages of TES–BCHP systems [26]. Nonetheless, few researchers focused on the applicability of TES–BCHP system, especially the relation between its applicability and load characteristics. How to quantitatively describe the energy amount of supply–demand mismatch and how to analyze its influence on the energy saving effect of the TES–BCHP system are important but unsolved problems. In this paper, in order to pre-estimate the energy saving potential of the BCHP system with thermal energy storage, the ideal TES device assumption is made to theoretically obtain the optimal system thermal performance. Then a new parameter, degree of mismatch (DM), is defined to describe the energy amount disparity between supply and demand in one concerned cycle and the applicability of TES–BCHP system is investigated for three typical kinds of user loads under different operation strategies. Through the proposed method, the feasibility of TES–BCHP system from the perspective of energy saving can be evaluated initially before design and operation when the specific user load and device thermal performance are known. This work is of high significance in guiding the application of practical TES–BCHP systems.

2. Methods

2.1. Typical processes of separated generation and BCHP system

To directly compare the energy saving effect of traditional system and TES–BCHP system, it is assumed that both these systems utilize natural gas as the primary energy. As shown in Fig. 1(a), in a separated generation system, electricity is supplied by the power grid and the compression chiller is often used to meet cooling demand in summer. The efficiency of integrated gasification combined cycle at the power plant can reach about 55%. It is assumed that η_{grid} = 50%, considering the electrical loss for long distance delivery [25]. Moreover, the electrical chiller is used to produce cooling water (COP_{EC} = 5) in summer and the gas boiler is used to meet heating demand (η_{boiler} = 90%) in winter.

Fig. 1(b) shows the typical process of a BCHP system. The gas turbine is driven by the natural gas to generate power. Meanwhile, the absorption chiller utilizes the exhaust gas to produce cooling water in summer (COP_{AC} = 1.2). In winter, the heat exchanger utilizes those exhaust gas to produce hot water (η_{HE} = 100%) and the insufficient heat can be made up by the gas boiler. For the operation strategy, Teng et al. [27] found that following thermal load (FTL) was better than following electrical load (FEL) for energy saving. Hence, the BCHP system gives priority to meet cooling/heating