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Techno-economic analysis of a coal-fired CHP based combined heating system with gas-fired boilers for peak load compensation

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ABSTRACT

Combined heat and power (CHP) plants dominate the heating market in China. With the ongoing energy structure reformation and increasing environmental concerns, we propose gas-fired boilers to be deployed in underperforming heating substations of heating networks for peak load compensation, in order to improve both energy efficiency and environmental sustainability. However, due to the relatively high price of gas, techno-economic analysis is required for evaluating different combined heating scenarios, characterized by basic heat load ratio (β). Therefore, we employ the dynamic economics and annual cost method to develop a techno-economic model for computing the *net heating cost* of the system, considering the current state of the art of cogeneration systems in China. The net heating cost is defined as the investment costs and operations costs of the system subtracted by revenues from power generation. We demonstrate the model in a real-life combined heating system of Daqing, China. The results show that the minimum net heating cost can be realized at β=0.75 with a cost reduction of 16.8% compared to coal heating alone. Since fuel cost is the dominating factor, sensitivity analyses on coal and gas prices are discussed subsequently.

1. Introduction

Energy savings and environmental concerns of district heating (DH) systems have remarkable influence on the development of society and national economies. China is now undergoing a stage of extensive urbanization and industrialization. The annual rate of new construction for residential buildings is approximately 2000 million square meters, which accounts for about 40% of worldwide residential construction (Zhang, 2005). As a consequence, heating areas in China have boomed dramatically in recent years, particularly in the urban areas within the national Eleventh Five-Year Plan period (2006–2010). An objective of 15% primary energy savings on the basis of unit floor area in the district heating sector has been set during this Five-Year period. Meanwhile, China has always confronted the problems of low efficiency heating systems characterized by huge primary energy consumption and poor operation and regulation, particularly in some heating systems worn down by the years in large cities. This also causes aggravated environmental pollution, especially during heating seasons. Since the ultimate way to improve the atmospheric environment is to change the energy structure (Marbe et al., 2006; Tromborg et al., 2007) and with the background of energy structure reformation in China, we propose gas-fired boilers to be deployed in underperforming heating substations for peak shaving. Gas-fired boilers can provide effective adaptation to the regulation demands of heat load fluctuations, improve the energy efficiency, and thus mitigate the environmental impacts caused by DH systems.

In fact, gas-fired boilers are becoming more and more common in the heating markets. Papadopoulos et al. (2008) pointed out that with the introduction of natural gas in the Greek energy market, the DH options were broadened. In Finland, gas accounts for more than a third of the fuel market for district heating and combined heat and power generation (Finish Energy Industries, 2010). Barelli et al. (2006) modulated the heat load with auxiliary boilers fueled by natural gas, which resulted in savings in primary energy. Brkić and Tanasković (2008) carried out a systematic study of natural gas usage for domestic heating in urban areas including direct use with individual gas-fired boilers and indirect combustion through DH systems. Park and Kim (2008) tried to verify the high energy efficiencies of DH using combined-cycle gas power plants (CCs) including CHPs and gas-condensing boilers. Nevertheless, due to the projection percentage of coal more than 50% in energy structure even by the year of 2050 (Lin, 2002), and with the premise of coal being the basic energy source of Chinese heating systems in the near future (Zhang et al., 2009), combined heating systems with CHP plants as basic heat

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Nomenclature

A_c	annual cost, ¥/a
a	thermalization coefficient
B	coal consumption or gas consumption, t/a or N m^3/a
b	coal consumption rate, gce/Kwh$_e$
CNY	Chinese Yuan, labeled as ¥, 1 US dollar ≈7 CNY (2008)
C	various cost of a combined heating system, ¥/a
d	nominal diameter of a heating pipeline, m
E	electricity consumption, kWh/a
G	flow rate, t/h
G'_2	design flow rate of secondary heating network, t/h
g	supplementary water consumption, t/a
H	water head of a pump, m
h	operation time of a coal-fired boiler in a CHP plant, h
I	internal rate of return (IRR), %
J	electricity or water price, ¥/kWh or ¥/t
K_z	the integrated investment index of CHP plants, ¥/kW
l	length of a heating pipeline, m
n	service life, a
n_0	the number of operation hours during a year of a water pump, h
P	rated power capacity or steam production capacity, kW or t/h
p	fuel price, ¥/t or ¥/N m^3
Q	heat provisions, GJ/a
Q'_{load}	design heat load of a combined heating system, MW
$\overline{Q}$	relative heat load factor
S_g	estimated local salary level in district heating sectors, ¥/(person · a)
t_w	outdoor temperature, °C
t_n	design indoor temperature, °C
t'_g	design supply water temperature, °C
t'_h	design return water temperature of heat users, °C
$t'_{w,tf}$	critical peak heating temperature, °C
W	estimation of electric energy production from a combined heating system, kWh/a
X	thermalized power generation percentage of extraction condensing steam turbine units, %
Z	net heating cost, ¥/a

Subscripts

R	heat production facilities
jb	basic heat production facilities
tf	peak shaving gas-fired boilers
by	back-pressure steam turbine units
c	extraction condensing steam turbine units
cn	pure condensing steam turbine units
d	power generation
r	heating
N	heating network
inv	initial investment
ope	operating cost
fj	accessories of a heating system
p	water pumps
gl	boilers in CHP plants

Greek letters

α	depreciation and maintenance rate, %
β	basic heat load ratio
η	efficiency, %
τ'_g	design supply water temperature of primary heating network, °C
τ'_h	design return water temperature of primary heating network, °C
ω	flow ratio of peak heating in a heating substation, %

production facilities and gas-fired boilers for peak load compensation are starting to appear (Wang et al., 2010). Further, Rezessy et al. (2006) reported that greater decentralization is the key determinant to local authorities' involvement in the market for energy services and energy efficiency equipment. Also, the decentralized energy supply solutions are more and more favored in China, but 'decentralized' does not mean low efficiency; on the contrary, it should require high efficiency energy supply systems, such as the proposed combined heating systems. They may alleviate the huge economic differences between coal and gas as well as reduce primary energy consumption and pollutant emissions. However, fuel price of gas heating is in general much higher than that of coal in China. Therefore, it is of great importance from the national energy policy perspective to seek economic harmony for successful penetration of gas into the heating market. For this reason, a rational techno-economic analysis of the combined heating system needs to be performed to identify the optimal basic heat load ratio (β) that leads to acceptable economic performance, on the premise of reliable heating provisions. Such an analysis has not been reported before for Chinese combined heating systems.

Many researchers have implemented various economy-oriented analyses on heating systems. Bowitz and Trong (2001) developed criteria using DH projects as a case study for cost-benefit analyses, emphasizing both economic and environmental costs. Dzenajavičienė et al. (2007) presented an economic analysis of heat power generation costs for various technological solutions and capacities suitable for consumers in small towns. Badescu (2007) studied economic feasibility of different active space heating systems based on ground thermal energy utilization. Ouyang et al. (2009) aimed to determine whether energy-saving renovations are applicable in an urban residential building for heating and cooling purposes using a life cycle cost (LCC) method. Some researchers have also concerned the economic aspects of heat production facilities themselves. Saidur et al. (2010) analyzed economic performances of energy saving measures for increasing energy and exergy efficiencies of industrial boilers. Lahdelma and Hakonen (2003) and Rong and Lahdelma (2007) planned the cost-efficient operation of a CHP system using an optimization model based on hourly load forecasts. They modeled the hourly CHP operation as a linear programming (LP) problem. Rong and Lahdelma (2005) also extended this analysis tool to the optimization of trigeneration planning. In addition, some multi-criteria decision making (MCDM) methods are also introduced to optimize different alternatives in energy sectors in the recent years (Lipošćak et al., 2006; Lahdelma et al., 2009; Wang et al., 2008; Xu et al., 2011). In particular, Wei et al. (2010) evaluated seven DH systems in China using fuzzy comprehensive evaluation method, in which the economics, environment and energy technology factors were taken into account synthetically. They concluded that CHP is the best choice from all systems; gas-fired boiler system is the best fossil-fed solution among coal- and oil-fired ones for heating purposes. The conclusion is well consistent with the idea of combined heating systems proposed in this study.