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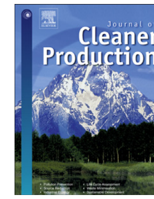

Thermodynamic and environmental evaluation of an improved heating system using electric-driven heat pumps: A case study for Jing-Jin-Ji region in China

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A B S T R A C T

The current heating pattern using household coal (HC) or coal-fired heating boiler (HB) with small scale and scattered distribution normally features low energy efficiency and high pollutant emissions. In this study, an improved heating approach using electric-driven heat pumps to replace HC and HB was proposed and its thermodynamic superiority, environmental benefit and economic viability were quantitatively determined based on the scenario of a large metropolitan area including Beijing, Tianjin, and Hebei area in North China (abbr. with Jing-Jin-Ji region). The results showed that using the proposed heating pattern, the primary energy efficiency of the overall energy system (OES) could be improved by 8.2 percentage points with a reduction of 20.31 Mt coal as compared to the original OES using the HB and HC. The emissions of main pollutants and CO_2 per kg coal and per MJ heating output could be significantly reduced, leading to a 74.85, 329.7, 87.7 kt and 37.4 Mt reduction in particulate matter (PM), SO_2, NO_x, and CO_2 emissions of the OES, respectively. Moreover, the annualized investment and O&M costs of the proposed heating system would increase by \$1.36/m^2 and \$0.31/m^2, respectively, while the energy costs would decrease by \$0.23/m^2 as compared to the traditional heating system. Finally, the general analyses from the perspectives of strength, weakness, opportunity and threat (SWOT) were performed and the results revealled that the inherent advantages toghther with some preferential policies will play a positive role in promoting the proposed heating system application in China.

1. Introduction

China has experienced the fastest economic growth in the world and its industry development and rapid urbanization resulted in elevated concentrations of air pollutants, which not only degrade regional air quality, but also exert significant impacts on Chinese public health, especially in winter as energy are highly demanded for power generation and heating (Zhang et al., 2015a). Coals, which dominate ~70% of the national energy mix to meet China's energy demand, are considered as the largest source of air pollutants and greenhouse gas emissions (Long et al., 2015; Xue et al., 2016a). In particular, Jing-Jin-Ji (an abbreviation of Chinese names of Beijing, Tianjin, and Hebei) region in North China, covering 216,000 square kilometers and home to more than 100 million people, consumed ~9% of total coal consumptions in China (DES, 2017) and experienced an annual average fine particulate matter ($PM_{2.5}$) concentration of 77 μg/m^3 in 2015 (MEP, 2016), far exceeding the World Health Organization $PM_{2.5}$ standards of 10 μg/m^3.

Chinese government has placed a great priority on pollutant control from coal-based industries, especially for coal-fired power plants. The stringent environmental regulations have been implemented for all-types of coal-fired power plants, and the emissions control technologies also progress aggressively. The state-of-the-art emissions control technologies could reduce the emission concentration of NO_x, SO_2 and particulate matter (PM) to be less than 100 mg/Nm^3, 50mg/Nm^3, and 20 mg/Nm^3, respectively (MEP, 2011; Ma et al., 2016; Hao et al., 2017). After employing the advanced pollutant control system, the emission level of the thermal coal (TC) in the modern power plants are nearly close to the natural gas (Li et al., 2016). Therefore, the marginal benefit of pollutants mitigation from coal-fired power plants would significantly diminish.

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Nomenclature

A	Total heating areas [billion m^2]
c	Pollutant emission limits Value [mg/Nm^3]
$\overline{C}_{ar}$	Average carbon content [wt%]
E	Pollutant emission factor [g/kg]
f	Scaling factor in the present scale
I	Costs/Expenditures
k	Life span of equipment [year]
M	Coal consumptions [billion kg]
m'	Coal mass [kg]
m	Pollutant emissions mass [g]
Mr	Relative molecular mass
M_q	Coal consumption per unit heating output [kg/MJ]
O_j	Carbon oxidation rate [%]
Q	Heating; Energy [billion MJ]
r	Discounted rate[%]
S	Scale parameter
S'_{ar}	Sulfur content in HC [wt%]
V	Actual flue gas volume[Nm^3/kg]
V_g^0	Theoretical volume of the flue gas [Nm^3/kg-coal]
V^0	Theoretical volume of the air [Nm^3/kg-coal]
W	Electric power [billion kWh]

Greek

α	Excess air ratio
β	Sulfur combustion efficiency
γ	Incomplete combustion ratio of carbon
η	Energy efficiency
η_{net}	Net power generation efficiency
η_d	Power transmission efficiency

Subscript

ar	As received
e	Electric
re	Reference
p	Pollutant types

Abbreviation

ASHP	Air source heat pumps
BC	Boiler coal
COP	Coefficient of performance
CRF	Capital recovery factor
HB	Coal-fired heating boiler
HC	Household coal
OES	Overall energy system
O&M	Operation and maintenance
PCE	Pollutant control equipment
PM	Particulate matter
SWOT	Strength, Weakness, Opportunity and Threat
TC	Thermal coal
UB	Utility boiler

It is worth noting that, in contrast to the bulk of coal used for power generation, large amounts of coals are used for decentralized boilers or residential sectors for heating (Shan et al., 2015). Taking Jing-Jin-Ji region as an example, the consumptions of household coal (HC) and boiler coal (BC) reached as high as 48.7 Mt in 2015, accounting for ~13% of the total coal consumptions in this region (DES, 2017). The small scale and decentralized distribution make them difficult and costly to control air pollutants using end-of-pipe solutions, especially for HC with no pollutant control device and low stack height (Liu et al., 2017). Some researchers have investigated the pollutant emissions from these decentralized used coals. Xue et al. (2016b) developed an emission inventory for multiple hazardous air pollutants associated with household coal combustion in Beijing in the period of 2000–2012 and the results showed that the contribution of HC combustion to the total air pollutants concentrations of PM_{10}, SO_2, NO_x, and CO are approximately 11.6%, 27.5%, 2.8% and 7.3%, respectively. Liu et al. (2016) investigated the contribution of residential emissions to the air pollution in Jing-Jin-Ji region during the heating season and concluded that the primary $PM_{2.5}$ from residential sources accounted for 32% of the total primary $PM_{2.5}$ emissions in 2010. All the relevant studies revealed that reducing the BC and HC consumptions may significantly contribute to the pollutant mitigation and the air quality improvement.

Recently, employing the clean energy, such as the natural gas, to replace the decentralized coal for heating has been considered as an effective way to improve the air quality. Pang et al. (2015) calculated the pollutant emission reductions for the replacement of coal-based district heating with natural gas in 15 representative cities in different areas in China in 2011 and revealed that using natural gas could decrease the CO_2, SO_2 and NO_x emissions by ~21.9, ~0.4 and ~0.23 Mt, accounting for 0.23%, 1.8%, 0.96% of the total pollutant emissions in China, respectively. However, replacing huge amount of HC and BC utilization by natural gas will bring about a soaring natural gas consumptions. Likewise, take Jing-Jin-Ji region as an example, an additional ~17 billion m^3 nature gas would be required per annum on the basis of the energy consumption scenario in the year of 2015, which may not be implemented in the short term considering the gas producing capacity and shortage of the facilities for natural gas transportation and storage. As an alternative, using electric heaters have also been advocated by Chinese government (NDRC, 2016), and some provincial governments have enacted series of preferential policies for electric heating. The electricity tariff could even decrease to 0.1 Chinese yuan at night in heating season for users and 85% of the costs for purchasing heating equipment would be supported by government in Hebei province (SXEH, 2017). However, from the viewpoint of the second law of thermodynamics, directly using the high-grade electricity for heat producing may bring about a large exergy destruction and thus is not thermodynamically desirable.

Against this backdrop, this study proposed an improved heating system using the electric-driven heat pumps, which could recover low-grade heat from the ambient, to replace the HC and HB. The primary energy efficiency improvement of the overall energy system (OES) using the proposed heating pattern was computed and the heat flow taken place in the proposed heating system were illustrated using the Sankey diagrams taken Jing-Jin-Ji region as an empirical context. In addition, the models for quantitative calculations and comparisons of the pollutant emissions per kg-coal for different types of coals were developed according to coals' chemical components, combustion environment and involved pollutant emissions technologies. The total pollutant emission reductions of the OES have also been quantitatively assessed. Finally, the economic viability and the strength, weakness, opportunity and threat (SWOT) aspects of the proposed heating system were comprehensively evaluated.