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Environmental co-benefits of energy efficiency improvement in coal-fired power sector: A case study of Henan Province, China

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HIGHLIGHTS

- Pollutant surcharge is considered in Energy Conservation Supply Curve.
- Intake Fraction method is incorporated into Energy Conservation Supply Curve.
- Health benefits contribute 97% of co-benefits of energy efficiency improvement.

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ABSTRACT

The coal-fired power sector is one of the major contributors to environmental problems and has great potential of air pollution abatement. This study employs Energy Conservation Supply Curves (ECSCs) combined with pollutant surcharge and health benefits to evaluate the environmental co-benefits of energy efficiency improvement in the coal-fired power sector. Health benefits and the pollution surcharge are considered as the environmental co-benefits that reduce costs of conserved energy (CCEs) in ECSCs. The health benefits of energy efficiency improvement are quantified using Intake Fraction method, while the pollutant surcharge is calculated based on the regulation. Three scenarios including a Business As Usual (BAU) scenario, an Energy Efficiency Improvement (EEI) scenario, and an Upgrading Standards and Incentive (USI) scenario is considered in a case study for Henan Province of China. Our results show that costs of conserved energy (CCEs) are reduced by 0.56 and 0.29 USD/GJ under the EEI and USI scenarios due to health benefits and pollutant surcharge reductions related to energy efficient technologies, respectively. In particular, health benefits account for 97% of the reductions in CCEs, while the pollutant surcharge only contributes 3%. Under the EEI and USI scenarios, in 2020, energy efficiency improvement reduces energy consumption in Henan's coal-fired power sector by 3.3% and 3.5% compared with the BAU scenario, respectively. The EEI and USI scenarios indicates that health benefits of 1.5×10^9 and 2.4×10^9 USD are gained and the reductions of pollutant surcharges of 197 and 226 million USD are realized in 2020, respectively.

1. Introduction

According to the International Energy Agency [1], coal-fired power generation, the main source of electricity in many countries [2,3], is a major contributor to the increase in the global primary energy demand. Air pollutant emissions from coal-fired power plants are regarded as one of the major contributors to environmental problems [4–6] that affect residents' health. Consequently, energy efficiency of the coal-fired power sector should be improved to reduce pollutant emissions as well as mitigate their related economic losses.

A number of studies have explored this topic in various countries. Wang et al. [7] evaluated measures for improving the energy efficiency of China's thermal power sector, dominated by the coal-fired power plants, using the Malmquist index, taking into account the cost of coal. Wei et al. [8] assessed the extent of improvement for energy efficiency in China's coal-fired power plants using Weighted Russell Directional Distance Function. Li et al. [9] used a hybrid model, combining a regression model and a generalised autoregressive conditional heteroskedasticity model to evaluate energy efficiency of China's coal-fired power plants. Wang et al. [10] analyzed the impact of multi-objective optimization on energy efficiency improvement in coal-fired plants. Dai et al. [11] estimated the energy saving potential of equipments in China's thermal power sector, taking into account capital costs. Lin and

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Nomenclature

Abbreviations

BAU	business as usual
ECSC	Energy Conservation Supply Curve
EEI	energy efficiency improvement
USI	upgrading standards and incentive
CCE	cost of conserved energy

Symbols

AEEI	additional energy efficiency improvement
B_{ps}	annual health benefit
B_{ps}	annual benefit from the decrease of pollutant surcharge
BR	breathing rate
CC	capital cost
CCE_{ps}	cost of conserved energy coupled with pollutant surcharge
CCE_{ps+h}	cost of conserved energy coupled with pollutant surcharge and health benefits
CE	cost of energy
$CR_{p,h}$	concentration-response coefficient of the health outcome *h* and the air pollutant *p*
CRF	capital recovery factor
d	discount rate
E_p	emission of pollutant *p* (SO_2, NO_x, TSP, PM_{10}, $PM_{2.5}$ and mercury)
EC	energy consumption
ef_p	emission factor for pollutant *p*
EL_p	emission standard for pollutant *p*
ESP	annual energy saving potential
fr	fraction of mercury released to atmosphere
I	energy intensity for power generation
IF_p	intake fraction of pollutant *p*
n	lifetime of energy efficient technology
O&M	annual change in operation and maintenance costs
PG	power generation
PSU	pollutant surcharge per unit of emission equivalent
Q	low heating value
RR	removal efficiency for air pollutant
T	temperature of the flue gas
$UR_{Hg,k}$	degree of utilization for mercury emission removal technology *k*
UV_h	unit value of health outcome *h*
V	volume of generated flue gas per unit of energy consumption
Vn	volume of generated flue gas per unit of energy consumption under normal condition
β_{PM}	proportion of PM_{10} or $PM_{2.5}$ to TSP in the treated flue gas
$\delta_{p,h}$	baseline of mortality and morbidity incidence rate for the health outcome *h* of pollutant *p*
λ_p	equivalent constant for air pollutant *p*

Superscripts:

0	base year
T	target year

Subscripts:

h	health outcome
i	energy efficient technology
k	mercury emission removal technology
p	air pollutant

Yang [12] estimated the cumulative energy saving potential of China's thermal power sector, using the stochastic frontier method, with the conclusion that incentives were the key to energy conservation. Ghosh and Kathuria [13] also used the stochastic frontier method to evaluate efficiency improvement in power generation for coal thermal power plants in India, and indicated that the state-level policies/planning aided energy efficiency improvement. Meanwhile, the environmental influence of energy efficiency improvement was concerned by some studies. For instance, Yu et al. [14] analyzed energy efficiency improvement for innovative coal-fired power generation technologies considering the constraints of coal price, pollutant emissions. Bi et al. [15] analyzed the relationship between energy efficiency improvement and environmental regulations in China's thermal power sector. Although there has been abundance of literature regarding the potential of energy efficiency improvement in coal-fired power sector, information related to the environmental benefits of energy efficiency improvement is limited. In particular, the benefit related to the reduction of environmental pollutants due to energy efficiency improvement needs to be further quantified.

Energy Conservation Supply Curve (ECSC), developed by Rosenfeld and his colleagues, is a bottom-up model for evaluating energy efficiency improvement and environmental benefits from both engineering and economic perspectives [16,17]. Because of its flexibility, ECSCs were used to quantify the potential of energy savings and CO_2 abatements around the world. For instance, Hasanbeigi et al. [18,19], Li and Zhu [20], Morrow et al. [21], and Tesema and Worrell [22] estimated the cost-effective potentials of energy saving and CO_2 abatement for iron and steel and cement industries in China, India and Ethiopia. Morrow et al. [23] also quantified the cost and potential of energy saving and CO_2 emission reduction for the petroleum refining industry in the US. Meanwhile, cost curves of air pollution abatements were given much recent attention. For example, Zhang et al. [24–26] implemented ECSCs under the Greenhouse Gas and Air Pollution Interactions and Synergies model to estimate air pollution abatements of China's iron and steel and cement industries. Ma et al. [27] analyzed the potential of air pollutant emission reductions in China's ammonia industry. To extend the original ECSCs, health benefits were considered as the environmental benefit of energy efficiency improvement by many researchers. Yang et al. [28,29] quantified the health benefits of energy efficient technologies in China's cement industry, with reference to the environmental damage impacts of the European Union. Hasanbeigi et al. used an air quality model to estimate the health benefits of energy efficiency improvement for cement plants in Shandong Province, China [30]. Among such benefit studies, health benefits identified in regional studies are not likely transferable to other regions. Thus, it is difficult to model air quality and estimate health benefits when meteorology and population distribution information is not available. Besides health benefits, other environmental benefits need to be addressed.

The Intake Fraction, defined as the fraction of pollutant inhaled by population, was adopted to estimate health benefits for cost curves. The Intake Fraction method is demonstrated to be more accurate than the reference method and more viable than one based on air quality model in the absence of relevant information [31]. Hence, this method was used to quantify the health benefits of air pollution control strategies for China's coal-fired power sector [31]. Similar studies using the Intake Fraction approach in combination with ECSCs for the coal-fired power sector are quite few. Furthermore, the pollutant surcharge or environmental tax is typically levied on pollutant emissions in many countries [32] and has

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