Co-benefits of energy efficiency for air quality and health effects in China's cement industry

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1. Introduction

The environmental burdens from air pollution due to massive fossil fuels combustion have drawn considerable attention in recent years worldwide [1–3]. The World Health Organization (WHO) estimates that about one million premature deaths are caused by outdoor air pollution in the world each year, with PM2.5 as one of the prominent contributors [4,5]. In China, the population-weighted average exposure to PM2.5 was 52 μg/m^3, which led to about 1.6 million people dying per year (0.7-2.2 million death per year at 95% confidence rate) from heart, lung and stroke problems, account for 17% of total number of deaths in China [6]. In 2013 an estimated 257 thousand premature death in 31 Chinese capital cities could be linked to PM2.5 air pollution, which result in the excess mortality rate increased to 0.9‰. The study also found that If the annual PM2.5 concentration meets the Air Quality Guidelines set by Chinese government standards, the mortality rate could be decreased by 0.41‰, compared to 2013 [7]. There is growing recognition that actions to reduce the combustion of fossil fuels often decrease GHG emissions as well as air pollutants, bring multiple benefits for improvement of energy efficiency, climate change, and air quality and related human health benefits [8–12]. While the understanding on many aspects of energy efficiency, climate change, air quality and associated health effects has drastically increased in recent years, especially in China, limited attention has been paid to industrial contributions of ambient air pollution levels and their health effects through implementing energy efficiency measures and assessment of the interactions between energy consumption, GHG emissions as well as air pollution and associated health effects. Therefore, synergies between policies (e.g., energy policy and air quality policy) have been neglected by industrial policy makers to some extent [13,14]. The purpose of this paper is to overcome this gap by quantifying the co-benefits between energy saving and emission mitigation of air pollutants, as well as the environmental and health impacts of pollution arising from China's cement industry at the provincial level during the period 2011-2030.

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The structure of this paper is as follows. The material and methodology is given in section 2, which include data sources, approach and scenario design. The results; air pollution abatement, changes of ambient concentrations of PM2.5 with varying emissions, and the health effects from air pollution are discussed in section 3. Finally, the conclusion is given in section 4.

2. Material and method

2.1 Data source

Data on potential and costs of advanced energy efficiency measures in the cement industry are obtained from our previous study [14], as well as other institutes [15–17]. The historical and future ambient air pollutant emissions inventory of China's cement industry at the provincial level are obtained from our recent study [18]. The original population data are from National Scientific Data Sharing Platform For Population and Health [19], Tabulation on the 2010 population census of the people's republic of China by County [20], and the Almanac of China's population [21]. The population with above

30 ages in 2020 and 2030 are calculated by the follow functions:

$$P_{2020} = P_{2010,>30\ ages} * \alpha_{2010,>30\ ages} + P_{2010,20-30\ ages} * \alpha_{2010,20-30\ ages}$$

$$P_{2030} = P_{2020,>30\ ages} * \alpha_{2010,>30\ ages} + P_{2010,10-20\ ages} * \alpha_{2010,10-20\ ages}$$

Where P is Population; α is the mortality rate in 2010 for different cohorts

The baseline(2010) mortality rate are calculated based on National Scientific Data Sharing Platform For Population and Health [19]. The baseline rates of various morbidity endpoints, hazard rates of premature mortality and morbidity are from current epidemiological studies (see Table 1).

Table 1 Relative risk factor used for the calculations for a change 10 µg/m3 of PM2,5

Cause of death	Adjusted Relative Risk (95% CI)	Baseline rates (‰)	Reference
All cause mortality	1.07 (1.05-1.09)	5.12	[7,22]
Cardiovascular disease (CVD)	1.06 (1.12-1,11)	2.55	[23]
Cardiopulmonary Disease	1.09 (1.03-1.16)	0.11	[24,25]
Ischemic heart disease (IHD)	1.06 (0.99-1.14)	1.09	[7,26]
Lung cancer disease	1.10 (0.99-1.22)	0.42	[7,26]

2.2 Co-benefit approach

Several studies have been conducted to estimate the co-benefits between energy saving, emission mitigation of GHGs and air pollution as well as the health effects from implementation advanced technologies, with varying methods under different scopes [3,27–29]. In this paper, the following steps are summarized to construct the integrated model in order to estimate the co-benefits between energy saving, emission mitigation of CO_2 and air pollutants as well as health effects from air pollution through implementation of current commercially available energy efficiency measures in China's cement industry up to 2030.

1. Calculate the emission inventory. First, the historical and future ambient air pollutant emissions inventory of China's cement industry at the county level are estimated using downscaling method, based on our recent study [18] and China's cement map [30]. Next, the ArcGIS was used to convert the emission data from county level to 1*1 grid format.

2. Estimate the changes annual mean concentration of PM2.5 with varying emissions. The annual mean concentration of PM2.5 with changes in emissions were calculated based on the rollback model, which represents the relationship between air pollutants emissions and annual PM2.5 concentration that can be extrapolated into the future [31]. The rollback coefficients were estimated based on GAINS database and calibrated based on Shih et al. [31], Ma et al. [32] and Wang and Richard et al [33,34].

$$\Delta C_{PM_{2.5}} = \beta * \Delta E_{PM_{2.5}}$$

Where $\Delta C_{PM_{2.5}}$ is the changes of concentration; β is the rollback coefficient- µg/m3 increase of PM2.5 concentration per ton of emissions

3. Convert the PM2.5 concentrations from county level to provincial level using ArcGIS.

4. Assess the health impacts from air pollution. Exposure-response functions have been widely used in epidemiological studies to examine the relationship between air pollution and adverse health effects [23,24,35–37]. In this study, the changes of mortality/morbidity rates under different scenarios are estimated using the following function [38]:

$$\Delta Y = \alpha_{2010,>30\ ages} * \left(1 - \frac{1}{HR^{\Delta C}}\right) P$$

Where ΔY is the change of mortality/morbidity rate; $\alpha_{2010,>30\,ages}$ is the mortality/morbidity rate of over 30 years of age cohort at the base year (2010); HR is the Hazard ratio for an increase in PM2.5 concentration of 10 μg/m^3; ΔC is the changes of PM2.5 concentration under different scenarios; P is the affected population.

In this step, we not only quantify the mortality outcomes related to long-term exposure to PM2.5, also estimates the morbidity outcomes to short-term exposure to PM2.5. Note that the estimates from short-term exposure to PM2.5 should not be added to analyze the co-benefits due to avoided double counting. However, the short-term exposure to PM2.5 can capture a useful information that provide a part of the total burden of air pollution [4]. The limitation of this study is that we only consider the health impacts to adults over 30 years of age although there is mountain evidence of health impacts for the youth below the ages of 18 years and the children below the ages of 5 years [1].

2.3 scenarios design

In this study, we mainly focus on selected energy efficiency measures as discussed in our previous studies to estimate the impacts of such scenarios on changes of PM2.5 concentrations and related health effects in China's cement industry at the provincial level, we also attempt to quantify how co-benefits would affect the advanced technologies. Hence, we developed three scenarios of China's cement industry, described in detail in [14,18], as a basis to estimate the potential co-benefits of energy saving, emission mitigation of CO2 and air pollutants, as well as health effects. The scenarios are named Baseline scenario (BL), Energy Efficiency Policy with cost effective energy saving potential (EEPCP) scenario, and Energy Efficiency Policy with technical energy saving potential (EEPTP) scenario, respectively. These scenarios combine assumptions about future output of cement, application of advanced technologies with projected implementation rates, leading to long-term energy saving of 4.2 EJ, and long-term emission reduction of 455 Mt of CO2 and 864 kt of air pollutants [14]. Specially, the baseline scenario assumed the annual autonomous energy efficiency improvement (AEEI) is 0.2%, which represent the future trajectories for the China's cement industry in the absence of advance technologies. Alternatively, two energy efficiency policy scenarios in which varying energy efficiency measures and their related implementation rates are projected by 2030 with a five year step. A more in-depth description of energy efficiency measures contribution to emission mitigation of air pollutants is provided in our previous studies [14,18]. Note that the affected population, rates of mortality and morbidity and related hazard rates are assumed the same in all scenarios.

3. Results and discussion

3.1 Changes of PM2.5 emissions

Fig. 1 shows the changes of PM2.5 concentrations from China's cement industry at the provincial level, the year 2020 and 2030 under Baseline, EEPCP and EEPTP scenarios, compared to 2010. In the baseline scenario, the average annual PM2.5 concentrations across the countries would increase by 0.057 μg/m3 (min =0.001 μg/m3 in Tibet province and Tianjin, max =0.225 μg/m3 in Hunan province) by 2020, inversely, the annual PM2.5 concentration would decrease by 0.216 μg/m3 (min =0.003 μg/m3 in Tibet province and Tianjin, max =0.902 μg/m3 in Hunan province) by 2030, when compared to 2010. In EEPCP and EEPTP scenarios this level would increase by 0.049 and 0.046 μg/m3 by 2020, and then decrease by 0.225 and 0.229 μg/m3 by 2030, respectively.

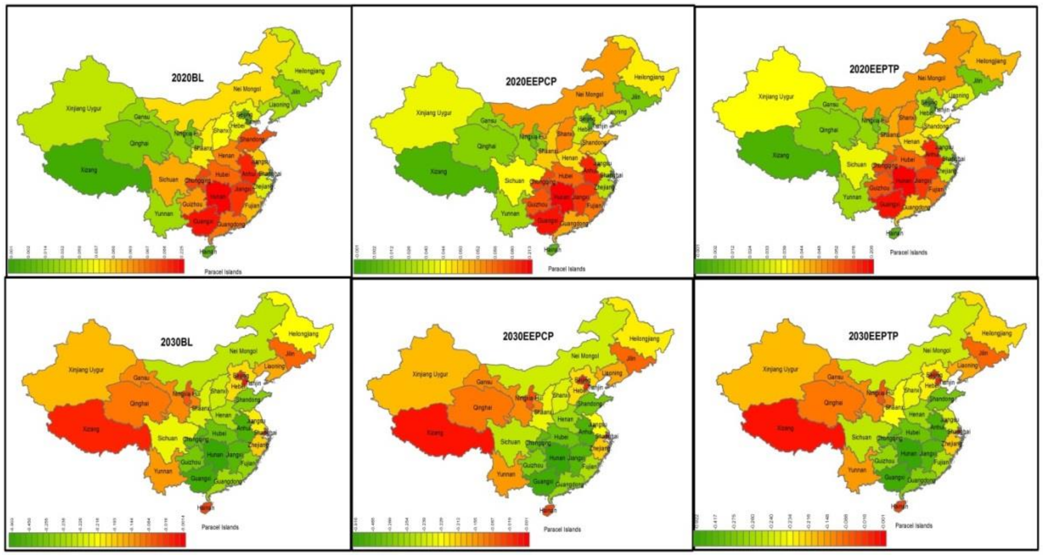

Figure 1 Changes of PM2.5 concentrations for the year 2020 and 2030, compared to 2010

3.2 Health impacts from PM2.5

We estimate the avoided premature death caused by PM2.5 for the year 2020 and 2030 under Baseline, EEPCP and EEPTP scenarios (in comparison to 2010 level). On the whole, the PM2.5-related mortality increase in 2020 and then decrease in 2030 under all scenarios. Specially, 24451 premature deaths could be increased each year in 2020 and then 109431 premature deaths could be delayed each year in 2030 when compared to 2010 under baseline scenario (see Figure 2-left). 3738 (nearly 15%) in 2020 and 5687 premature deaths (nearly 5%) in 2030 under EEPCP scenario would be avoided, compared to baseline scenario (see Figure 2-right). If all energy efficiency measures were implemented with projected application rates this level would further decrease by 7% by 2020 and 2% by 2030, respectively.

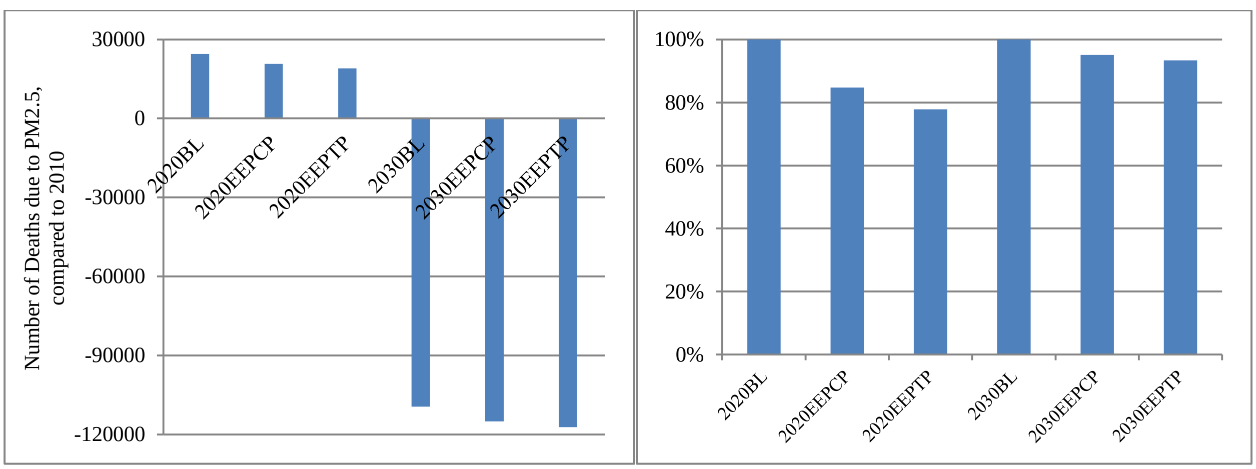

Figure 2 Comparison of computed (avoid) premature death caused by PM2.5 for the year 2020 and 2030, compared to 2010

We also estimate the morbidity effects attributed to PM2.5 as seen in Figure 3. In 2020, the number of morbidity cases increased by 10493 of cardiovascular disease, 693 of cardiopulmonary disease, 2822 of lung cancer disease, and 4485 of Ischemic heart disease under baseline scenario, compared to 2010. However, the estimates decreased by 46850 of Cardiovascular disease, 3115 of cardiopulmonary disease, 12716 of lung cancer disease, and 20026 of Ischemic heart disease. The avoided morbidity cases from the EEPCP and EEPTP scenarios as compared to 2010 are also shown in Figure 3. It is clear that implementing energy efficiency measures significantly improves health issue related to $PM_{2.5}$

emissions. Especially, in EEPCP scenario, 1604 and 2433 of Cardiovascular disease, 106 and 162 of cardiopulmonary disease, 431 and 663 of lung cancer disease, and 686 and 1040 of Ischemic heart disease can be avoided in 2020 and 2030 respectively, compared to the Baseline. If all energy efficiency measures were implemented (EEPTP scenario), this level would further decrease by 7% in 2020 and 2% in 2030, respectively.

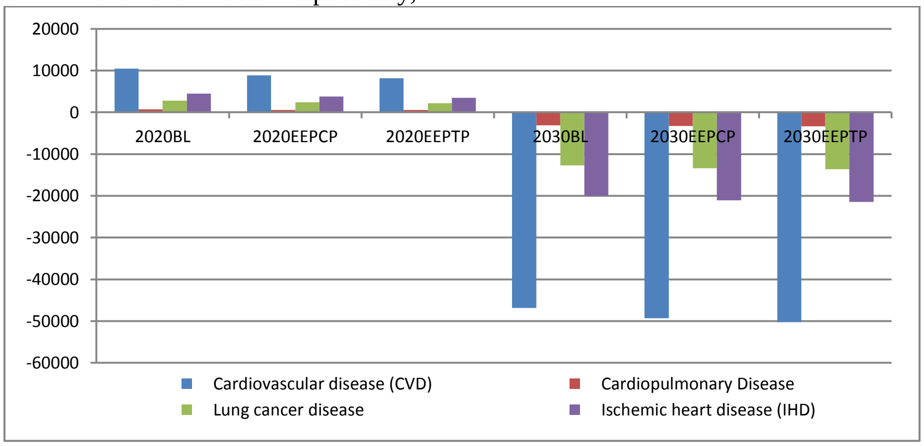

Figure 3 Comparison of computed health endpoints caused by PM2.5 for the year 2020 and 2030

4. Conclusion

Actions to reduce the combustion of fossil fuels often decrease GHG emissions as well as air pollutants and hereby bring multiple benefits for improvement of energy efficiency, climate change, and air quality associated with human health benefits. Therefore, air quality and health co-benefits can provide strong additional motivation for improving energy efficiency. In China, the cement industry is the second largest energy consumer and key emitter of CO_2 and air pollutants. It accounts for 7% of total energy consumption in China and 15% of CO_2, 21% of PM, 4% SO2 and 10% of NOx of total emissions, respectively. In this study, An integrated approach that comprises a number of different methods and tools within the same platform (i.e. provincial energy conservation supply curves (ECSC), Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, geographical information system (GIS), Roallback model, and Health Impact Assessment (HIA)) is developed and used to assess the potential of energy savings and emission mitigation of air pollutants, as well as the environmental and health impacts of pollution arising from China's cement industry at the provincial level during the period 2011-2030. The results show significant heterogeneity across provinces in terms of potential energy saving as well as emission mitigation of CO_2 and air pollutants (i.e. PM, SO_2, and NOx) in the next two decades. In addition, the current commercially available energy efficiency measures would decrease 25% of SO_2, 20% of NOx, and 5% of $PM_{2.5}$ reducing 0.017 ‰ (5425 case in 2020 and 7811 case in 2030) of premature deaths (adults ≥ 30 ages). Therefore, It is more cost effective for policy makers to consider both air quality and health impacts together when planning and implementing energy policy than to pay attention to each issue separately.

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Acknowledgments

The work was supported by the China Scholarship Council under Grant Number: 201207040022. The authors gratefully acknowledge Janusz Cofala and Fabian Wagner from The International Institute for Applied Systems Analysis (IIASA) for their valuable guidance to this study. We extend our gratitude to the valuable comments of the anonymous reviewers. All remaining errors remain the sole responsibility of the authors.