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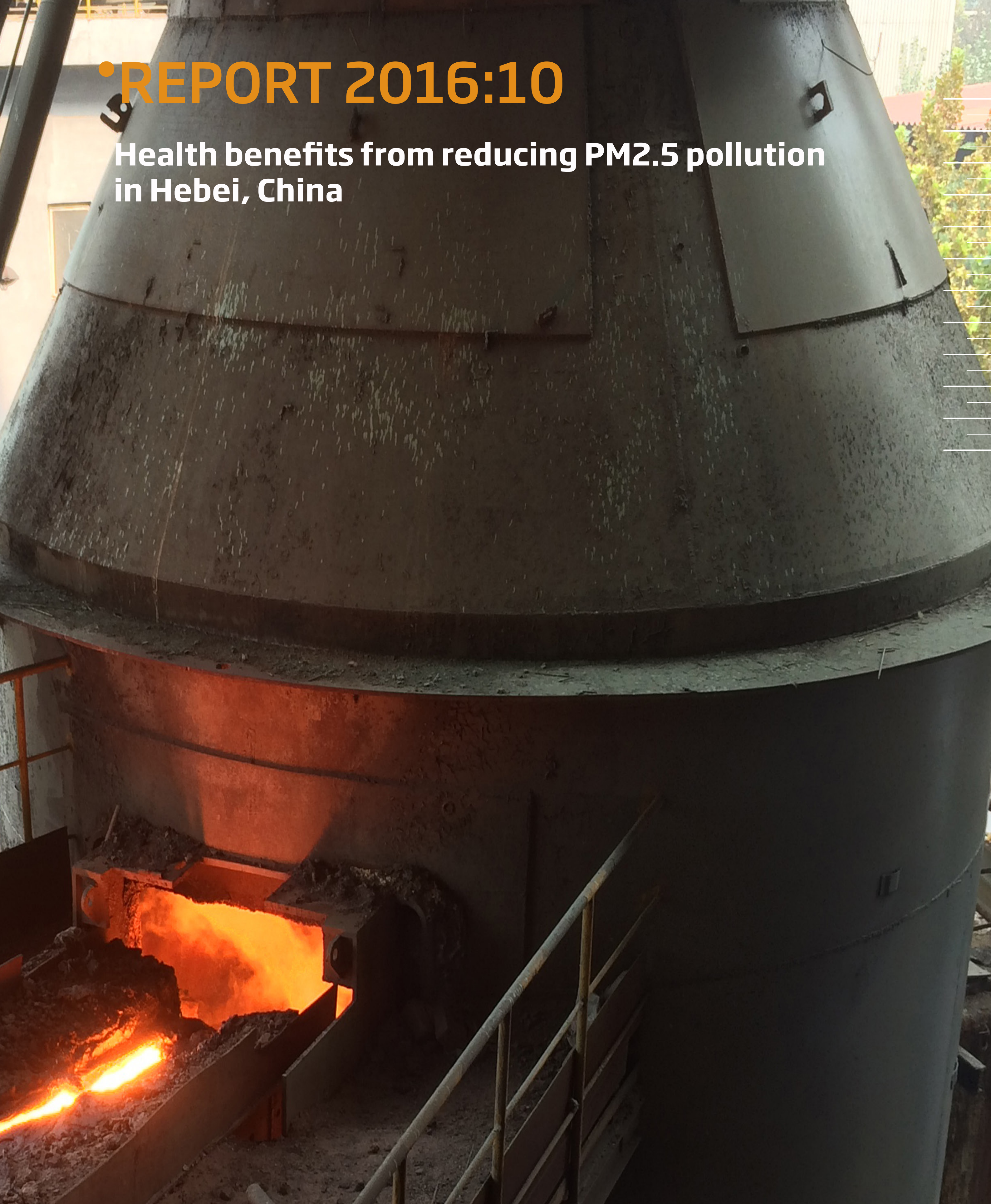

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Health benefits from reducing $PM_{2.5}$ pollution in Hebei, China

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Abstract: We estimate the impact on population exposure and associated health damage of reducing the PM2.5 concentration in ambient air in Hebei, China. We calculate the health benefit in 2017 and onwards of an overall 15% reduction in the PM2.5 level in the province compared to the level in 2012. This corresponds to the assumed reduction resulting from policies and measures included in the multi-sectoral Hebei Air Pollution Prevention and Control Action Plan for 2012-2017. Moreover, we estimate the impact of expanding the Action Plan so as to achieve a 25% reduction in pollution levels by 2017. This corresponds to the target set for the province, but which is unlikely to be met given the current policies and measures. We estimate the health benefit of alternative designs of an expanded Action Plan. These include scenarios that leads to a PM2.5 reduction in urban areas only, and scenarios which, in addition to improving ambient air quality, imply that households switch from traditional coal and biomass to clean fuels and thereby reduce the exposure for population groups depending on solid fuels. The report is part of the background documents for the preparation of a possible World Bank Program-for-Results (PforR) operation on PM2.5 pollution in Hebei, aiming at assisting the province in reducing air pollution. We find that the health benefit of expanding the current Action Plan (from a 15% to a 25% reduction in ambient PM2.5 concentration) likely exceeds the PforR investment, and conclude that – given that the investment contributes to reaching the 25% reduction target – the investment is profitable. In addition to health benefits, we provide a qualitative assessment of other benefits, including climate benefits.

Cover picture: From a steel plant in Handan, Hebei (foto: Kristin Aunan)

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Contents

Summary

As part of the preparation of a World Bank Program-for-Results (PforR) operation on $PM_{2.5}$ pollution in Hebei, the current report provides an economic evaluation of the health benefits that may be achieved from alternative scenarios for $PM_{2.5}$ reductions in Hebei in 2017 and onwards. We also include a qualitative evaluation of other benefits, e.g., how the program may contribute to abating emissions of CO_2 and short-lived climate forcers (SLCF).

We estimate a population weighted exposure to ambient $PM_{2.5}$ (PWE) of 95 $\mu g/m^3$ in the province for the base year 2012. The area weighted concentration is 51 $\mu g/m^3$. In nearly all parts of the province, the annual average $PM_{2.5}$ concentrations is exceeding China's Air Quality Standard of 35 $\mu g/m^3$ $PM_{2.5}$ (annual mean). The number of annual premature deaths due to $PM_{2.5}$ pollution in the base year is estimated at approximately 69,000, with a monetized value of 254 (127-381) bill RMB (corresponding to 10% of the province GDP). Taking into consideration the additional $PM_{2.5}$ exposure burden due to household air pollution from traditional cooking fuels in the province, we arrive at around 86,000 premature deaths.

According to the National Air Pollution Prevention and Control Action Plan, issued by the State Council in 2013, the concentration of $PM_{2.5}$ in the Beijing-Tianjin-Hebei region shall be reduced by 25% by 2017 compared with the level in 2012. A recent study estimated that the measures included in the province level multi-sectoral Hebei Air Pollution Prevention and Control Action Plan (AP) would lead to an approximate 15% reduction. In the current report, we find that a general 15% reduction in ambient $PM_{2.5}$ concentration in Hebei, would result in approximately 3,420 avoided deaths annually. An expanded AP, leading to a 25% reduction and thus meeting the target, would result in approximately 6,160 avoided deaths. Thus, expanding the AP with additional measures and policies may contribute to an additional 2,740 avoided deaths. The present value of the annual health benefit of an expanded AP over a 10 year lifetime (i.e. the benefit of expanding from a 15% to a 25% reduction) is estimated at 120 (49-210) bill RMB (19 (8-34) bill USD). The corresponding figure assuming a 5 year lifetime is 72 (31-121) bill RMB (12 (5-19) bill USD). We thus find that an investment of 0.5 bill USD is firmly justified, given that it assists the Government of Hebei in reaching the 25% reduction target.

In addition to the main scenarios, we include health benefit estimates for alternative scenarios that target ambient air pollution abatement in urban areas only and exposures to household air pollution from solid fuel use particularly.

Overall, we suggest there is only a modest co-control potential for CO_2 mitigation from the current and expanded AP plan, with important exceptions for policies targeting coal consumption in industry and power production and policies promoting industrial transformation. These policies may potentially bring large reductions in CO_2, but may also need more time to be fully implemented. We suggest there may be large co-benefits for short-lived climate forcers, but do not have data to conclude quantitatively on the sign and amount of the avoided forcing from the program. As some of the sub-programs target black carbon intensive sources, some reduction in forcing may be expected for limited parts of the program. Particularly, we suggest that abating domestic black carbon emissions is important for abating short-term climate forcing. Such action will also bring large health benefits from reduced exposure to household air pollution and contribute to reducing ambient $PM_{2.5}$ levels in Hebei.

Introduction

The number of days with severe haze in China has increased steadily over the last decades. This is closely linked to the rapid economic growth and concurring increase in the burning of fossil fuels for energy production and increased motorization. While urban levels of particulate pollution improved to some extent from around 2000 to 2012, particularly in the Northern China, it has since then been worsening. Meteorological conditions may have played a role. Low wind speeds and precipitation both contribute to increasing concentrations of air pollution. In Eastern China, both wind speeds and precipitation have shown an overall decline over the years [1, 2].

Haze events are particularly frequent in the regions of intense anthropogenic activities in China, especially in regions such as the Beijing-Tianjin-Hebei region (JingJinJi), the Yangtze River Delta, and the Pearl River Delta. Since 2013, a series of severe haze episodes occurred over Northern and Eastern China. The highest pollution levels were measured during winter in the JingJinJi region, one of the most densely populated regions in the world. During haze episodes, the concentration levels of nitrogen dioxide, sulfur dioxide and fine particulate matter ($PM_{2.5}$) increase significantly, along with a decrease in visibility and increase in relative humidity. The enhanced gas to particle conversion taking place in the atmosphere under humid conditions results in a large fraction of the ambient $PM_{2.5}$ being so-called secondary particles during these episodes (as opposed to primary particles, directly emitted from sources). Coal burning for space heating and traffic are found to be important sources during severe haze in the JingJinJi region [3]. Different from the typical air pollution in western countries, in China the air pollution, or haze (*wumai* 雾霾) is richer in sulfur dioxide, which so far has not been abated to the same extent as in, e.g., the US and Europe. While motor vehicles are the main source of nitrogen oxides (NOx) in western countries, industrial emissions is the major source in high pollution regions in China, contributing 71% in 2012. Even though traffic is a major source in cities like Beijing, a large fraction of NOx pollution comes from sources in the neighboring provinces. Thus, local abatement of traffic sources in the city will not necessarily be very effective in abating local pollution levels [4]. In addition to emissions from energy production, ammonia from livestock farming and N-fertilizer application (the largest sources of ammonia) is suggested to play an important role for particulate pollution in China, *inter alia* in the JingJinJi region [5].

Hebei's economy is dominated by heavy industry, particularly iron and steel manufacturing. Industry contributed 46% of the gross regional product in 2013[1]. In addition to being a strong manufacturing base, Hebei province is one of the major grain- and cotton-producing regions of China, and in the suburbs of large cities there has been considerable development of freshwater aquaculture and animal husbandry including dairy cows. The province thus plays an important role in the region, providing an industrial base as well as a food producer and a transportation hub. These factors have made the province a dominant contributor to emissions of air pollutants in the JingJinJi region. While also being affected by nearby provinces to some extent, $PM_{2.5}$ pollution in the most polluted parts of Hebei is dominated by sources within the province. For instance, Wang et al (2012)[6] found that during the period 2000-2010, 65% of $PM_{2.5}$ in Shijiazhuang and Xingtai originated from emissions in the southern Hebei area.

In order to tackle the challenge of reducing air pollution and obtain the target of a 25 percent reduction in $PM_{2.5}$ pollution within 2017[2], Hebei has developed the multi-sectoral Hebei Pollution Prevention and Control Implementation Action Plan (AP). Tsinghua University and the China Council for International Cooperation (CCICED) in 2014 evaluated in a series of studies the capacity of the Beijing, Tianjin and Hebei Action Plans to reach their respective 2017 targets. The findings of these studies indicate that while the full implementation of the action plans will deliver significant improvements in air quality in the region by 2017, the targets are unlikely to be attained. For Hebei, the Tsinghua University study showed that at the current pace annual average ambient $PM_{2.5}$ concentrations would decline from 113μg/m^3 to 96μg/m^3, a 15 percent decrease over the five-year period 2012-2017. This is far less than the 25 percent reduction target. The Tsinghua University study recommended additional measures for Hebei to achieve the 25 percent $PM_{2.5}$ reduction target (CAAC, 2014)[3].

The Word Bank proposed to support the AP through a Program-for Results (PforR) operation, constituting of a loan in the amount of 0.5 billion USD (see PforR Concept Note[4]). The operation will include support for additional policies as compared to the original AP, in order to assist the province reaching its 25% reduction target. As part of the preparation of the Project

1 NBS, 2014. China Statistical Yearbook 2014. http://www.stats.gov.cn/tjsj/ndsj/2014/indexeh.htm

2 Clean Air Alliance for China 2013. State Council Air Pollution Prevention and Control Plan. China Clean Air Updates. English translation, October 2013.

Available: www.cleanairchina.org/file/loadFile/27.html

3 Clean Air Alliance of China, 2014. Can Beijing, Tianjin and Hebei achieve their PM2.5 targets by 2017? Assessment of the potential for air quality improvements in the Beijing-Tianjin-Hebei region under China's new air pollution action plan. Available: www.cleanairchina.org/file/loadFile/73.html

4 See WB, 2015. Program-for-results Concept Note on the Hebei pollution prevention and control program.

Document of the PforR, the current report provides an economic evaluation of the health benefits that may be achieved from alternative realizations of $PM_{2.5}$ reductions in Hebei in 2017 and onwards.

1 Materials and methods

1.1 Scenarios

In the current report, we provide estimates of the health damage (in physical and monetary terms) of $PM_{2.5}$ pollution in the base year of the AP (2012), the impact of the current AP, and the impact of an extended AP. We assume the original AP will lead to a general 15% reduction in $PM_{2.5}$ concentrations over the entire province during the period 2012-2017, and that an extended program will contribute to reaching a 25% reduction within the same period. Obviously, the program will likely not provide a uniform reduction in all parts of the province, and the approach taken here is a preliminary rough approximation until detailed modelling results of individual abatement options are available. Whereas the PforR operation will support the original coverage of AP, which is the entire province, most of the abatement measures in the plan applies to emission sources in urban areas (industries, traffic). We carry out a sensitivity analysis where we assume concentration levels are primarily reduced for urban populations. We also carry out separate analyses of potential health benefits of targeting traditional household fuels (an important source of $PM_{2.5}$ exposure in China), and briefly discuss the potential climate co-benefits of targeting this source of $PM_{2.5}$.

1.2 Population of Hebei

In the following, we use population data from the China Census 2010 in GIS format provided by the China Data Center at the University of Michigan[5]. Hebei consists of 11 prefecture cities with a total of 172 counties. The total population in Hebei in 2010 was 71.9 million, of which 44% was urban (i.e. 44% lived in urban areas, without necessarily possessing an urban *hukou*).

[5] China Data Center, University of Michigan, Web: http://chinadataonline.org

The population density varies considerably throughout the province, see township level data in Figure A1.

In the calculations below, we take into account population growth, but not any intra-provincial migration that may change the geographical distribution of people over the scenario period. The average annual population growth from 2010-2014 was 0.68%[6], and we assume an approximate 5% growth over the period 2010-2017. Estimates of premature deaths in the base year are given for an estimated 2012 population (using the annual growth rate above), while corresponding estimates for the scenarios are given for an estimated 2017 population. Monetized estimates are given for the full life-time of the program beyond 2017, see details below.

1.3 Population exposure to ambient PM2.5

We estimate the annual average ambient $PM_{2.5}$ concentration per county for the baseline and the two reduction scenarios using estimates of geographically resolved $PM_{2.5}$ concentration in Hebei from the Oslo Chemical Tracer and Transport Model (Oslo-CTM), with 2010 meteorology [7, 8]. Emission data for primary PM and PM precursors in 2010 are from the European ECLIPSE project (ECLIPSE version 5 emission data) described in Stohl et al. (2015)[9]. County level $PM_{2.5}$ concentrations are derived from the gridded output of the Oslo-CTM by using IDW (Inverse Distance Weighting) interpolation in a GIS tool (ArcMap 10.3.1)[7]. As the resolution of the Oslo-CTM output is too coarse to model the enhanced pollution levels in cities (we used a 1° x 1° resolution), we use urban monitoring data for 2013 (when an extensive monitoring network had been established) from the 11 prefecture cities in Hebei to estimate the local urban increment in counties defined as urban. The urban increment factor is calculated as the ratio between the average monitored $PM_{2.5}$ in a prefecture city and the average $PM_{2.5}$ modelled in the CTM. Within each prefecture city the adjustment factor is applied to boost the PM concentration in counties where the population density is above 500 people/km^2, which we use as an indicator for urbanized counties (see Figure A2 in Appendix)[8]. The reason behind this procedure is that air pollution monitoring is carried out only in urban areas (to our knowledge the limited monitoring data from rural areas are not publicly available), and we assume rural areas are better represented by the CTM regional estimates. While there are a

[6] https://en.wikipedia.org/wiki/List_of_Chinese_administrative_divisions_by_GDP_per_capita

[7] We suggest estimates for administrative units are more useful for policy makers than gridded data, as policies typically are targeting and/or implemented in administrative units.

[8] Regarding the choice of 500 people/km^3 (county level population density): The area and the population of the counties where we apply the urban increment factor constitutes, respectively, 2.4% and 33% of China total. Using township level data from the China Data Center (the administrative level below the county level), we find that the administrative unit JieDao (city districts, i.e. core urban areas) represent 2.7 percent of China's area and 27% of the population, thus we suggest our approach with respect to the urban increment factor is reasonable.

limited number of monitoring stations in each city, we assume the data are representative of the average values the urban populations are exposed to. The average value of the booster factor is 1.39 in Hebei. We assume the resulting figures reasonably represent the baseline 2012 situation in the province.

The population weighted exposure (PWE) to ambient $PM_{2.5}$ in the baseline and the scenarios for a population group *P*, is calculated as:

$$PWE_P = \frac{1}{P}\sum_i (P_i \bullet C_i)$$

(Equation 1)

where *P* is the population, *C* is the $PM_{2.5}$ concentration and *i* refers to any given geographical unit.

Note that using the method described here, we arrive at a PWE for all China of 56 $\mu g/m^3$. For 2005 and 2010, respectively, Brauer et al (2012) [10] arrive at 55 $\mu g/m^3$, while Apte et al (2015) [11] arrive at 59 $\mu g/m^3$. A study by Zhang and Cao estimated a PWE of 61 $\mu g/m^3$ for 2014-2015 [12].

1.4 Household air pollution exposure

It is well established that indoor and neighborhood pollution from incomplete combustion of solid fuels in household stoves (coal and biomass) contributes disproportionately to population exposure to $PM_{2.5}$ (compared to its total emissions) [13]. Whereas household stoves may be an important source of outdoor ambient air pollution, the largest exposures and thus health effects of household cooking and heating with solid fuels, however, are usually related to its contribution to indoor and neighborhood pollution (denoted household air pollution by the World Health Organization). This is due to the fact that people spend many hours indoors in their home and that cooking and heating with solid fuels in traditional stoves leads to high PM concentrations close to the breathing zone. We use county level data on household cooking fuel use from China Census 2010 to estimate the additional $PM_{2.5}$ exposure in Hebei that can be attributed to use of solid fuels in parts of the population, and the potential health benefits of targeting this source. We rely on Aunan and Wang (2014)[14] regarding exposure levels associated with the different household fuels (differentiated for urban and rural areas). Below, the total exposure from ambient air pollution and household air pollution in combination is denoted integrated population weighted exposure (IPWE). Note that according to the World

Health Organization (2010), there is "no convincing evidence of a difference in the hazardous nature of particulate matter from indoor sources as compared with the outdoors"[9].

According to province level China Census data for 2010 [15], 45% of the population in Hebei had gas or electricity as their main cooking fuel, while 31% still used firewood and 24% used coal. Among the urban population 71% had clean fuels (gas and electricity), 18% used coal, and 11% used firewood. Among the rural population, the corresponding figures were 25%, 29%, and 46% (Figure 1). Fuel use data are not given specifically for urban and rural populations in the county levels Census data, and the urban-rural allocation used below is an estimate.[10] The highest percentage of solid fuel users (coal and biomass) were in Xingtai (70%), Handan and Cangzhou (both 66%), and Chengde (65%). Handan had by far the highest share of households using coal (61%). Detailed fuel use is shown in the Appendix (Table A1 and Figure A3 and A4). In the following, we do not take into consideration how rural-urban migration may affect fuel use over the scenario period. As described in Aunan and Wang (2014) [14] there is a rapid fuel transition happening in China, partly related to urbanization processes that entail increased access to clean household energy. Note that somewhat different figures for household fuel use in Hebei (for 2011) is given in the survey by Duan et al. (2014) [16], in which 4400 households were recruited from the province (64% clean, 21% coal, and 15% biomass fuels).

We include a scenario where we assume all household coal use is banned throughout the province in addition to the 15% reduction of ambient air pollution (a minor reduction in the use of residential coal and biomass was assumed by the Tsinghua University in their report on the AP). A coal ban would be in accordance with the recommendation in WHO 2014[11], at least for use of unprocessed coal. Importantly, we assume there is no fuel stacking in the scenario, i.e. we assume a 100% fuel switch is taking place in the homes.

Finally, we include a scenario where we assume that all urban firewood users (3.5 mill according to NBS 2012 [15]) and one sixth of the rural biomass users switch to gas and/or electricity in addition to the 15% reduction of ambient air pollution. As both gas and electricity should be available in urban areas in Hebei and most likely also in many parts of the rural areas, we deem this a realistic scenario.

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[9] WHO (World Health Organisation), 2010. WHO guidelines for indoor air quality: selected pollutants. Copenhagen: WHO Regional Office for Europe; Available: http://www.euro.who.int/en/what-we-publish/abstracts/who-guidelines-for-indoor-air-quality-selected-pollutants

[10] We denote fuel users in a county as "urban" if the urban population in the county exceeds 38%, and as "rural" if it is lower. This results in the correct total urban and rural population in Hebei.

[11] "Unprocessed coal should not be used as a household fuel", recommendation #3 in WHO (2014): Air Quality Guidelines for Household Fuel Combustion. WHO, Geneva. 152 pp.

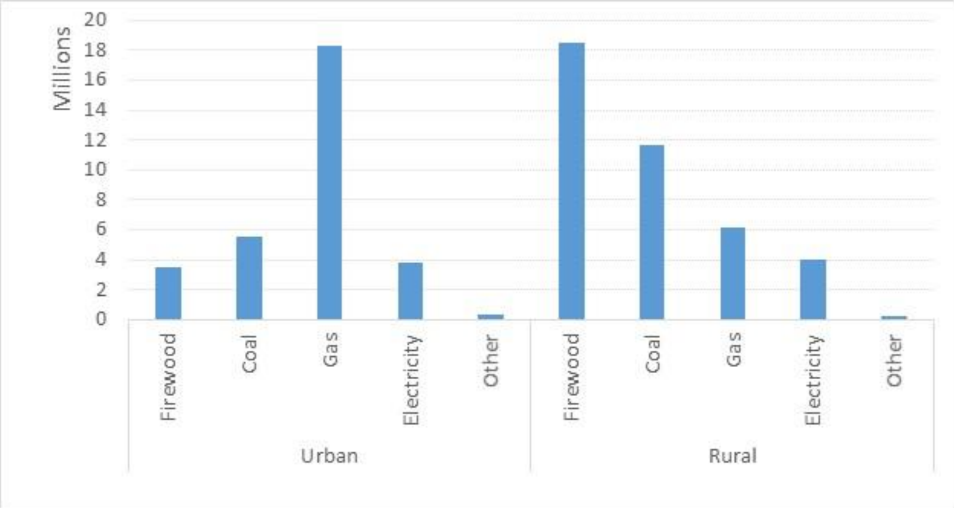

Figure 1. Main household cooking fuel in urban and rural Hebei, number of people (million), 2010. Source: NBS (2012)[15].

1.5 Calculating premature mortality

Particulate air pollution, $PM_{2.5}$, is associated with premature death for a number of diseases. To calculate the health benefit from ambient air pollution reductions in Hebei we use the methodology applied by the Global Burden of Disease Study 2013 [13]. We calculate the number of premature deaths due to ambient $PM_{2.5}$ pollution in the baseline situation (before implementation of the PM Action Plan) and in scenarios where the $PM_{2.5}$ concentration has been reduced by 15% and 25%, respectively.

The annual excess cases of deaths that are attributable to $PM_{2.5}$ exposure in Hebei under alternative scenarios, i.e. the attributable cases (AC), are calculated as:

$$AC_{i,j,k}=[(RR_{i,j}-1)/RR_{i,j}] \cdot p_{i,j,k} \cdot P_{i,k} \qquad \text{(Equation 2)}$$

where *RR* is the relative risk of premature deaths associated with a given level of PM pollution, *p* is the baseline mortality rate, and P is the population in a given geographical unit, while *i* refers to age group and *j* refers to the specific cause of death, and *k* refers to gender.

The five health end-points included here are chronic obstructive pulmonary disease (COPD), lower respiratory infections (LRI), tracheal, bronchus and lung cancer (LC), ischemic heart disease (IHD), and ischemic stroke (IS). Regarding the RR estimates for the five deaths causes, we use the lookup table provided by Apte et al. (2015) [11], which are derived from exposure-response functions for the relationship between exposure to $PM_{2.5}$ and the five health end-points from Burnett et al (2013) [17] (Figure A5).

Regarding disease specific baseline mortality rates (*p* in Eq 2), we use data for Hebei for 2013 from Institute of health Metrics and Evaluation (IHME)[12], see also Zhou et al (2015) [18]. Table 1 shows the age-standardized mortality rates for the five end-points in the three JingJinJi provinces and all of China. While the mortality rates for COPD, LRI, and LC in Hebei are lower than, or on par with, the all-China rates, the mortality rate for IHD and IS are substantially higher. Table A2 (Appendix) shows the baseline mortality rates for men and women, respectively, applied in the current analysis. For COPD, LRI, an LC we apply the age-standardized mortality rate and calculate health effects for the total population in the counties. The RR estimates for IHD and IS in Apte et al. (2015) are age-specific, thus we apply the age specific mortality rates (*p* in Eq 2) from IHME for these two diseases. We did not have separate mortality rates for urban and rural populations and assume they are similar.

Table 1. Age-standardized, disease specific death rate per 100,000, for the JingJinJi provinces and all-China, for the five mortality causes included in the health benefit calculation. Data source: IHME, 2015[12].

	COPD	LRI	LC	IHD	IS
Beijing	30,3	16,0	36,8	126,4	77,0
Hebei	38,0	13,2	39,8	152,1	94,7
Tianjin	30,1	21,9	41,2	136,6	65,1
China	78,6	18,9	40,1	114,7	62,2

1.6 Calculating monetized health benefits

To monetize the avoided premature deaths, AC, in the period 2012–2017 and beyond, we use the present value (PV) formula:

$$\text{Benefit} = \sum_{t=0}^{N} \frac{AC\ VSL\ (1+g^t)}{(1+r)^t}$$

(Equation 3)

VSL is value of statistical life, a metric of the willingness to pay for lower mortality risk. g is the growth in VSL over time. r is the discount rate. N is the life-time of the measures, here assumed to be 10 years.

We take as the starting point 1) the number of attributable cases avoided from reducing the $PM_{2.5}$ concentration by 15% or 25% within 2017 as compared to the 2012 baseline, and 2) the

[12] Institute of Health Metrics and Evaluation 2015. Province level mortality rates (per disease and for age groups and gender) are available at: http://vizhub.healthdata.org/gbd-compare/ (accessed 2 November, 2015).

difference between the two scenarios, i.e. the additional number of deaths avoided from the extended program. As explained above, we account for population growth by adjusting the figures with an annual growth rate of 0.68 percent. We follow Aunan and Wang (2014) [17] and assume that the Value of Statistical Life (VSL) in China is 100 [50-150] times the GDP/cap. Using the 2012 GDP/cap in China, 36,584 RMB/cap[13], we arrive at a VSL of approximately 3.66 [1.83-5.49] million RMB (using an exchange rate of 6.25, this corresponds to 585,000 [293,000-878,000] USD). In line with WB (2011) [19] we suggests using an elasticity of the Value of Statistical Life higher than 1.0. In the following calculations, an elasticity of 1.2 is used, with a lower estimate of 0.8 (based on Lindhjem et al. (2011) [20] and an upper estimate of 1.5, based on WB (2011) [19] and Aunan et al (2013)[21]. Assuming an average economic growth rate of 6 percent over the program period (IMF, 2015[14]), this means the benefit estimates are inflated with an annual growth factor of 7.2 percent. We use a discount rate of 8%. An overview of the input parameters for the economic evaluation is given in Table 3 below. The uncertainty intervals given for the results is based on calculations using the upper and lower input parameters.

[13] NBS 2014. China Statistical Yearbook 2014.

Available: http://www.stats.gov.cn/tjsj/ndsj/2014/indexeh.htm (accessed December 17, 2015).

[14] IMF, 2015. World Economic Outlook (WEO). Adjusting to Lower Commodity Prices. October 2015. Available: http://www.imf.org/external/pubs/ft/weo/2015/02/

2 Results

2.1 Exposure levels

The estimated county level annual average $PM_{2.5}$ pollution in the base year is shown in Figure 2. Figure 3 shows the exposure profile, i.e. the number of people living in counties with different levels of $PM_{2.5}$. Figure 4 shows the aggregated PWE for Hebei's prefecture cities for the baseline and for the two scenarios.

As evident from the figures, the current exposure levels in Hebei are high. According to our estimates, the population weighted annual average exposure to ambient $PM_{2.5}$ pollution in the province (PWE) is 95 $\mu g/m^3$ in the base year. The area weighted concentration in the province is 51 $\mu g/m^3$. The highest annual average PWE value for ambient $PM_{2.5}$ is estimated for the urban population in Shijiazhuang (139 $\mu g/m^3$). We find that 98% of the population in Hebei live in counties where the annual average $PM_{2.5}$ concentrations is exceeding China's Air Quality Standard of *35 $\mu g/m^3$ $PM_{2.5}$* (GB3095-2012; the value equals World Health Organization's Interim Target 1). Corresponding figures for the two scenarios, a 15% and 25% reduction in the county level annual mean $PM_{2.5}$ concentrations, are 95% and 91%. Even at a 50% reduction, 76% of the population would still live in areas where the annual AQS is exceeded. An approximate 80% reduction would be needed to ensure no one in the province would be living in areas where the annual standard is exceeded.

Taking into consideration the additional exposure from household air pollution, we estimate an IPWE of 241 $\mu g/m^3$ in Hebei, i.e. the widespread use of dirty household fuels adds on average 146 $\mu g/m^3$ to the 95 $\mu g/m^3$ estimated for exposure to ambient air pollution. Due to different fuel use and ambient $PM_{2.5}$ concentrations across the province, prefecture level estimates varies substantially, see Figure A6 in the Appendix.

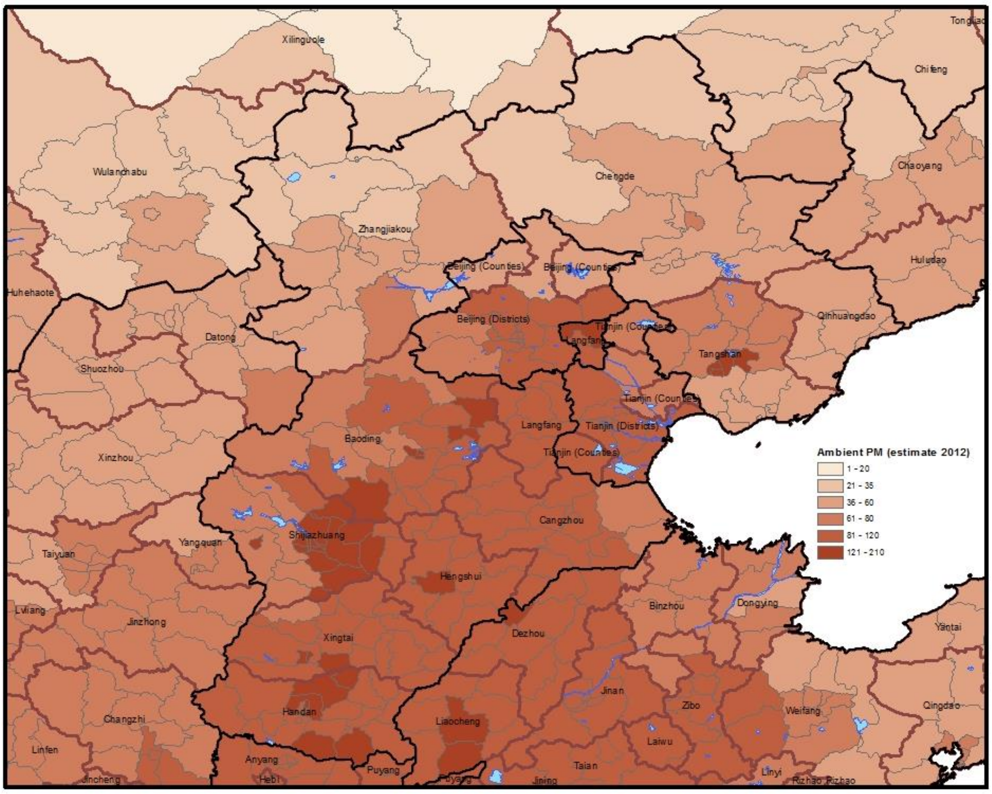

Figure 2. Modelled county level annual mean $PM_{2.5}$ in the base year ($\mu g/m^3$) (from CTM modelling, adjusted in urban areas based on monitoring data, see text).

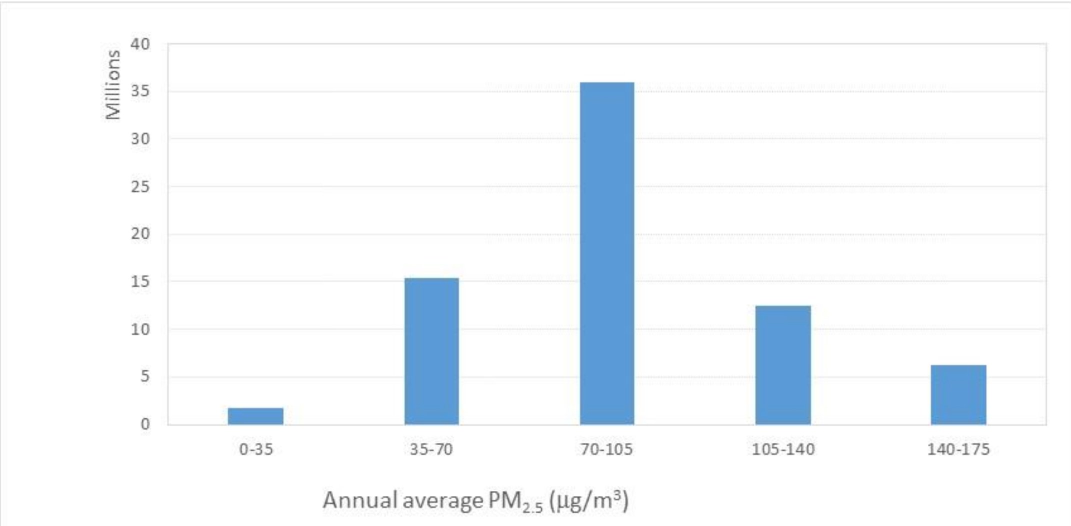

Figure 3. Estimated exposure profile to ambient annual average $PM_{2.5}$ concentration in Hebei in the base year (2012). Million people.

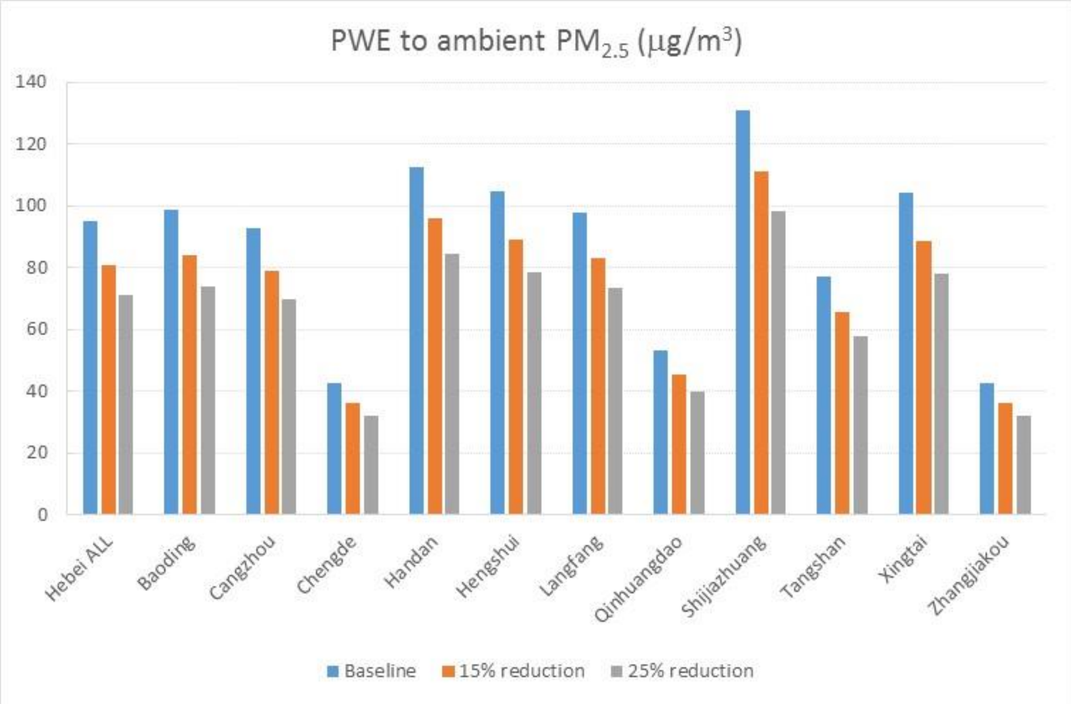

Figure 4. Population weighted exposure (PWE) to annual average $PM_{2.5}$ in prefecture cities in Hebei. Baseline: Base year situation (2012); 15% reduction: Current PM action plan for Hebei; 25% reduction: Extended PM action plan for Hebei.

2.2 Premature deaths

We estimate that there were 69,448 premature deaths attributable to ambient $PM_{2.5}$ pollution in the base year of 2012. In the baseline scenario, with no changes in $PM_{2.5}$ concentrations, this corresponds to 71,758 in 2017 given the assumed population growth. Because baseline mortality rates for IHD and IS are higher for men than for women and that these diseases are particularly prominent in Hebei (Table 1 and Table A2), there is a large gender bias, with 65% of premature death occurring in men and 35% in women.

Taking into consideration the additional exposure from household air pollution, the number of premature deaths is 86,406 in the base year. Note that the relatively modest increase in excess deaths estimated for IPWE compared to AAP exposure in isolation is due to the curvilinear exposure-response functions (Figure A5).

A general 15% reduction in $PM_{2.5}$ concentration in Hebei result in an estimated 3,424 avoided deaths annually according to our model. A 25% reduction would result in an estimated 6,159 avoided deaths. The impact of strengthening the Action plan may thus contribute to an additional 2,735 avoided deaths. As seen in Table 2 and Figure 5, the largest number of avoided deaths are found for IHD deaths, the top cause of death associated with air pollution exposure. As the exposure-response function is more linear for ALRI, lung cancer, and COPD as compared to IHD and IS (see Figure A3), the benefit of enhanced pollution reduction increases more rapidly for the three first end-points compared to the latter two. In the sensitivity calculations where we assume that PM reductions are mainly obtained in urban areas, we arrive at an estimated 932 avoided deaths in the 15% scenario and 1677 in the 25% scenario. Thus, if policies affect urban areas only, the impact of increasing the reduction rate from 15% to 25% is an estimated 744 extra avoided deaths.

In the scenario where we assume that household coal use in banned throughout the province (in addition to the 15% reduction in ambient air pollution), we apply the IPWE approach in order to include the impact of household air pollution from the coal stoves. We arrive at an annual 4,487 avoided deaths by 2017. Again, note that when calculating health effects from IPWE we are on the flatter part of the exposure-response functions, thus the calculated impact of a reduction is smaller.

Table 2. Annual avoided premature deaths in 2017 for the two main $PM_{2.5}$ reduction scenarios.

Scenario	COPD	Lung cancer	ALRI	Ischemic heart disease (Age >25y)	Ischemic stroke (Age >25y)	SUM
15% reduction	647	850	389	925	613	3 424
25% reduction	1 126	1 485	703	1 681	1 163	6 159
Difference	479	635	314	756	550	2 735

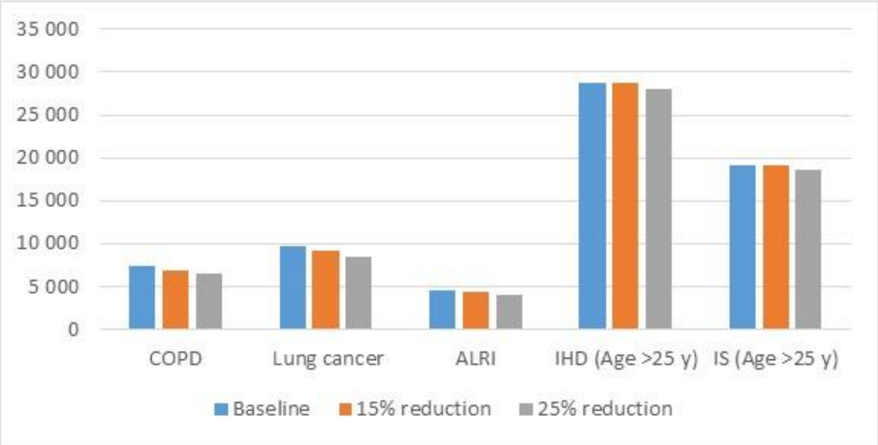

Figure 5. Annual number of premature deaths attributable to $PM_{2.5}$ pollution in 2017 given the baseline scenario (without the Hebei Action Plan (AP)) and the two scenarios of, respectively, 15% and 25% reduction.

2.3 Monetized health benefits of PM reductions

Main parameters for the economic evaluation and summary results are shown in Table 3, together with the benefit estimates. We find that the cost of premature deaths attributable to $PM_{2.5}$ exposure in Hebei in the base year 2012 is 254 (127-381) bill RMB, which corresponds to

9.6% (4.8%-14.3%) of the province GDP[15]. The present value (PV) in the base year of the 15% reduction program is estimated at 150 (61-263) bill RMB, whereas the PV of a 25% reduction program is estimated at 271 (110-474) bill RMB. The PV of the benefit of expanding the current program to a program that reduces the PM pollution with 25% within 2017 is thus estimated at 120 (49-210) bill RMB, corresponding to 19 (8-34) bill USD. If we assume a 5-year life time of the program (instead of 10 years) we arrive at a PV of 72 (31-121) RMB. As seen in Figure 6, the central parameters applied in the evaluation imply that the discounted annual health benefits is nearly constant over the life-time of the alternative programs.

Assuming the impact of PM reductions mainly applies to urban counties (defined by a population density >500 per km^2), the health benefit of the expanded program is reduced to 43 (18-74) bill RMB, i.e. 7 (3-12) bill USD.

As evident from Table 3 there are large health benefits to be gained from targeting the use of solid fuels in household, as the exposure levels are reduced substantively from this type of measures. These estimates do not single out how targeting this source influences the *ambient* air pollution concentrations, however. Solid fuels is a major source of primary $PM_{2.5}$ emissions in China[22] and in regions where solid fuel use is widespread, these emissions may contribute substantially to ambient air pollution concentrations. For East Asia as a whole, Chafe et al (2014) [23] estimate a 10% contribution from cook stove emissions to average ambient $PM_{2.5}$ pollution. For China, Butt et al. (2016) [24] estimate that residential emissions account for 13% of the annual mean $PM_{2.5}$ concentration, with larger contributions of 20–30% in the eastern China. For Hebei, using the Oslo CTM (see above), we here estimate a contribution to surface level $PM_{2.5}$ concentrations from household cooking and other domestic and small-scale commercial emission sources of 40% (varying from 27% to 45% across the province). This is comparable with a recent study which estimated that eliminating residential emissions in the JingJinJi-region (for the winter months January and February 2010) would have reduced the daily average surface $PM_{2.5}$ concentration with 27%-43% in Hebei[16] [26].

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[15] GDP in Hebei in 2012 was 2,657 million RMB in 2012.
https://en.wikipedia.org/wiki/List_of_Chinese_administrative_divisions_by_GDP_per_capita

[16] Karagulian et al (2015) estimate a 15% contribution from domestic fuel burning to population-weighted $PM_{2.5}$ exposure in urban North China.[25. Karagulian, F., et al., *Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level.* Atmospheric Environment, 2015. **120**: p. 475-483.]

Table 3. Economic input parameters, monetized health damage in base year, and benefits of the two main PM reduction scenarios, and additional sensitivity scenarios. (AAP: Ambient air pollution in terms of $PM_{2.5}$).

	Central	Low	High
Program start year	2012		
Program reaches full effect	2017		
Life-time of program after full effect reached (years)	10		
Annual pop growth (%)	0,68		
Unit cost premature death (VSL estimate) 2012 (mill RMB)	3,66	1,83	5,49
Economic growth rate	0,06		
Discount rate	0,08		
Income elasticity of VSL	1,2	0,8	1,5
VSL growth rate	0,072	0,048	0,09
Baseline annual health cost from AAP (2012) (bill USD)	254	127	381
PV (2012) of 15% reduction in AAP (bill RMB)	150	61	263
PV (2012) of 25% reduction in AAP (bill RMB)	271	110	474
PV (2012) of benefit of program expansion[1] (bill RMB)	120	49	210
PV (2012) of benefit of PM program expansion assuming 5 y life-time (bill RMB)	72	31	121
Urban only[2]: PV (2012) of 15% reduction in AAP (bill RMB)	54	23	93
Urban only[2]: PV (2012) of 25% reduction in AAP (bill RMB)	97	41	166
Urban only[2]: PV (2012) benefit of program expansion (bill RMB)	43	18	74
PV (2012) of 15% reduction in AAP and coal ban for homes (bill RMB)	192	78	336
PV (2012) of 15% red. in AAP and switch from biomass to gas/el. for 6.6 mill people (bill RMB)	210	85	370

[1]i.e. benefit of increasing from 15% to 25% reduction.
[2]Areas defined as urban are shown in Fig A2 (Appendix).

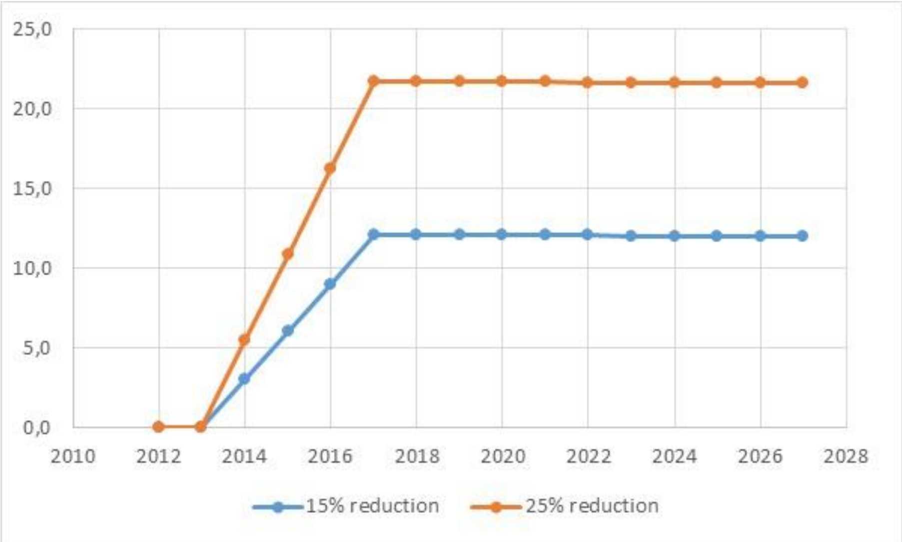

Figure 6. Annual discounted health benefit of the two scenarios (bill RMB).

3 Appropriateness of the PforR investment

Our results demonstrate that an investment of 0.5 bill USD in the PforR, given that it contributes to reaching the 25% reduction target in Hebei, is likely to be a highly profitable operation. The results also demonstrate that the current AP, given that it leads to a 15% reduction within 2017, brings large health benefits. We do not have data for the investments in the AP and thus cannot estimate the cost/benefit-ratio (C/B).

As a matter of fact, our analysis implies that even if the operation renders only a fraction of the $PM_{2.5}$ reduction assumed in this report (i.e. a further reduction in ambient $PM_{2.5}$ from 15% to 25%), the investment is justified. Using our model tool and the VSL and other parameters as presented in Table 3, while assuming a modest 5-year life-time, an investment of 0.5 bill USD is profitable (benefit/cost ratio above 1) if at least 118 (70-276) statistical deaths are avoided (estimate not shown in Table 3).

Another way of demonstrating the profitability of a PforR investment of 0.5 bill USD is to look at the break-even value of the VSL, i.e. the lowest value of a statistical life that will render a C/B>1. In our case this is 0.10 (0.08-0.12) mill RMB, i.e. 0.015 (0.013-0.019) mill USD[17].

As discussed below, there are other benefits of the suggested PforR operation apart from the monetized health effects that are relevant for the World Bank.

[17] As a comparison the US-EPA uses a VSL of 7.4 mill USD (2006 USD) in all benefits analyses that seek to quantify mortality risk reduction benefits, see http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/MortalityRiskValuation.html#whatvalue

4 Climate impacts

To a large extent the sources of particulate air pollution are the same as the sources of CO_2, the main greenhouse gas. The health co-benefits from CO_2 mitigation related to co-control of air pollutants are well documented. While using different methods, including for monetization of mortality risks, IPCC Assessment Report 4 in 2007 concluded that "all studies agree that the health benefits may offset a substantial fraction of the (CO_2) mitigation costs (high agreement, much evidence)"[18]. Due to a relatively limited application of end-of-pipe technologies in China as compared to, e.g., the EU, the co-benefits of CO_2 mitigation in China are estimated to be high [27, 28]. Rive and Aunan (2010) [29] estimated co-abatement rates for China with respect to main air pollutants for a range of typical CO_2 abatement measures. As seen in Table A7 (Appendix) the largest co-abatement rates for $PM_{2.5}$ and SO_2 (an important $PM_{2.5}$ precursor) are found for fossil fuel switch (typically from coal to gas) and for energy efficiency measure in supply-side and industry.

The existing multi-sectoral Hebei Pollution Prevention and Control Implementation Action Plan (AP) includes several abatement options that are likely to entail co-control of $PM_{2.5}$ (and its precursors) and CO_2. Particularly promising are the sub-plans targeting the energy structure in itself (e.g. by implementing a coal consumption cap and increase the supply of natural gas and renewable energy) and promoting industrial transformation and upgrade.

Overall, however, the existing AP plan as well as the additional measures suggested by the Tsinghua University study (potential areas to be considered by the PforR operation[4]) is biased towards end-of-pipe solutions, which typically do not bring substantive co-control of CO_2 (sometimes even an increase), but may be very effective in cutting air pollutants. As some air pollutants are short-lived climate forcers (SLCF), the AP may, on the other hand, substantively

[18] IPCC, 2007. Climate Change 2007: Working Group III: Mitigation of Climate Change https://www.ipcc.ch/publications_and_data/ar4/wg3/en/tssts-ts-11-5-co-benefits-of.html

reduce the climate disturbance that arise from these components[19]. Whether the net impact on global warming of the individual $PM_{2.5}$ reduction options (measured as top-of-the atmosphere radiative forcing) is positive or negative depends on the composition of the emissions from the source abated. We do not have data for the composition of emissions targeted by the AP and thus can only make general comments regarding the likely sign of the forcing. For instance, most industrial sources, including power plants, typically have a net cooling impact (there are larger emissions of cooling components than of warming). As a consequence, abating them will most likely lead to warming.

An assessment of opportunities for air pollution and climate benefits from reducing short-lived climate forcers carried out by UNEP in 2011 [30] [31] identified control measures that are particularly promising for air pollution and climate benefits. These are measures that target sources with a high share of BC compared to other particulates. For East Asia, the measures estimated to give the highest benefits for climate (in terms of global temperature in 2050) were 1) a switch from traditional biomass cookstoves to stoves fueled by LPG or biogas or to fan-assisted biomass stoves; 2) replace lump coal with coal briquettes in cooking and heating stoves; and 3) elimination of high-emitting vehicles. The first measure was also the dominant contributor to avoided mortality in the region, while abating emissions from vehicles and coal stoves was also found to be important.

Building on the UNEP report, one may conclude that the sub-plans in AP targeting high-emitting vehicles in particular and mobile source pollution in general will provide substantive co-control of BC (i.e. without high amounts of scattering (cooling) co-pollutants) and thus come with a climate benefit. The same applies to the additional measures suggested by Tsinghua University targeting diesel vehicles. Efforts to reduce VOCs and NOx may also reduce ozone, another SLCP, but the climate impact is probably small. Likely more important as a climate measure is the initiative suggested in the PforR Concept Note on abating black carbon from burning of solid fuels in the household sector. Residential coal and biomass burning is by far the dominant source of BC in China, contributing 51% of the total BC emissions in 2007 (28% from residential coal and 23% from residential biomass [32]). For Hebei we find that, on average, about 17% of the surface level $PM_{2.5}$ concentration is BC. Moreover, nearly a quarter of the surface level BC in Hebei comes from the domestic sector, thus abating domestic BC is

[19] Different from the greenhouse gases, aerosols like carbonaceous aerosols, sulfates and nitrates interfere with solar short-wave radiation. Most aerosols in the atmosphere scatter sunlight (which means they are cooling the atmosphere), but some are absorbing (which means they are warming the atmosphere). Organic carbon (OC), sulfates, and nitrates are scattering aerosols, while black carbon (BC) is the main absorbing aerosol. As all aerosols interfere with sunlight, high concentrations of aerosols in the atmosphere leads to less sunlight reaching the surface, and a surface cooling may result regardless of whether the atmosphere above is heated or cooled. Changes in the vertical temperature profile may lead to changes in the larger scale hydrological cycles and regional precipitation patterns, thereby the term 'climate disturbance'.

important not only for abating climate forcing and health damage (see calculations above in this report), but also for reducing ambient $PM_{2.5}$ levels.

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5 Conclusions and caveats

Particulate air pollution in Hebei poses a heavy burden on human health in the province. We estimate that without the existing AP, by 2017 nearly 72,000 people would die annually due to air pollution. This figure is reduced by about 3,400 by the AP and may be further reduced by about 2,700 by expanding the AP. Using standard methods for monetization of a statistical life, we find that an investment cost of 0.5 bill USD is firmly justified. We have assumed a 10 year life-time of the investment, which is highly uncertain. However, even with a 5 year life time we find that the investment is justified. As we did not have detailed information about the concrete abatement options and their costs we were at this stage not able to carry out a cost-effectiveness analysis for individual measures. Improving the Air Quality Monitoring and Planning capacity of Hebei is suggested as part of the PforP operation, and will hopefully enable more detailed analyses in the future, promoting cost-effectiveness in policies to abate $PM_{2.5}$ pollution in the region.

Whereas the main benefit of the proposed PforR is the avoided human suffering due to disease and premature death from $PM_{2.5}$ exposure, there are other benefits not quantified here that represent additional value added for the World Bank. These include benefits related to climate change mitigation, capacity building, and rural development. We find that some parts of the program likely will contribute to CO_2 abatement, while other parts of the program will likely contribute to avoided climate warming from SLCF components. By focusing on collection of emission data from rural areas, the up till now mainly urban focus of air quality management systems in China expands to rural areas which may render more effective and comprehensive policies. By supporting improved methods and coverage of monitoring systems, not only is installation and utilization of end-of-pipe technologies likely to increase, but the capacity and vigilance of staff in industries and governmental agencies overseeing the industries is likely to increase. Supporting capacity building with respect to air quality management may have long-term benefits beyond the current effort within the AP.

With respect to activities that target black carbon emissions from rural areas, there are a range of benefits associated with switching from dirty to clean fuels in addition to the substantive health effects. In short, modern fuels enables a modern life style, with less time spent on fuel providing and cumbersome cooking, and without the soot, dirtiness and annoyance associated with solid fuels (WHO, 2014) [33].

There are several uncertainties in our benefit calculations. For instance, as we did not have access to detailed modelling results for individual abatement measures we used a simplified approach where we assume a flat percentage reduction in the county level ambient air pollution. The model resolution does not capture hot spots that may be important for health impacts in densely populated places. By combining modelled regional levels in 2010 (using 2010 emissions and 2010 meteorology) and urban monitoring data for 2013 we suggest, however, that the resulting concentrations may represent the 2012 situation in a reasonably good way. While being somewhat lower, the PWE results compare quite well with the estimates in the Tsinghua University report.

Our main focus has been on benefits from reducing ambient air pollution and we applied the exposure-response relationship from the IHME/Global Burden of Disease team to calculate risk reductions for the various disease end-points. For many of these end-points, the exposure-response curves are flattening at high pollution levels. The fact that a large share of the population in Hebei still use solid household fuels and thus in reality has a higher exposure burden than that arising from ambient air pollution alone, implies that the health impact of reducing ambient air pollution in this report may have been overestimated. The large margins in the profitability assessment implies, however, that the main conclusions are not affected by this uncertainty.

Finally, a major caveat is that there is not a one-to-one relationship between the measures suggested by the Tsinghua University to obtain a 25% reduction and the suggested PforR activities. As the PforR will need to support the attainment of only a fraction of the full 25% target to be profitable, we suggest, however, that our main conclusion about profitability is robust.

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7 Appendix

Table A1. Main cooking fuel in Hebei households (million people and percentage). Source: China Census 2010.

	Firewood	**Coal**	**Clean**
Million people:			
Hebei	21,3	18,2	32,4
Baoding	2,2	2,4	6,6
Cangzhou	4,6	0,1	2,4
Chengde	2,2	0,1	1,2
Handan	0,4	5,6	3,1
Hengshui	2,4	0,4	1,6
Langfang	1,7	0,2	2,4
Qinhuangdao	1,5	0,2	1,3
Shijiazhuang	0,7	3,7	5,8
Tangshan	3,1	0,3	4,2
Xingtai	1,1	3,9	2,1
Zhangjiakou	1,4	1,2	1,7
Percentage:			
Hebei	30 %	25 %	45 %
Baoding	20 %	21 %	59 %
Cangzhou	64 %	2 %	34 %
Chengde	63 %	3 %	35 %
Handan	4 %	61 %	34 %
Hengshui	55 %	9 %	36 %
Langfang	40 %	5 %	55 %
Qinhuangdao	51 %	8 %	42 %
Shijiazhuang	7 %	37 %	57 %
Tangshan	41 %	4 %	55 %
Xingtai	16 %	54 %	30 %
Zhangjiakou	31 %	29 %	40 %

Table A2. Baseline disease specific mortality rates for male and female (per 100,000 population) in Hebei (2013) used in health benefit calculation. Data source IHME, 2015.

		COPD	LRI	LC	IHD	IS
Male	**Age-standardized**	49,10	16,57	60,70		
	25-29 y				7,8	0,7
	30-34 y				14,7	1,4
	35-39 y				26,6	2,6
	40-44 y				46,7	7,1
	45-49 y				80,9	15,3
	50-54 y				122,3	38,7
	55-59 y				204,6	75,4
	60-64 y				328,8	167,0
	65-69 y				544,8	324,7
	70-74 y				845,5	670,5
	75-79 y				1430,8	1123,9
	80+ y				3491,7	2387,8
Female	**Age-standardized**	28,61	10,23	20,30		
	25-29 y				3,4	0,5
	30-34 y				4,8	0,7
	35-39 y				8,1	1,3
	40-44 y				13,9	3,1
	45-49 y				24,6	7,1
	50-54 y				42,9	13,7
	55-59 y				74,5	32,0
	60-64 y				137,8	73,3
	65-69 y				253,9	150,5
	70-74 y				488,8	346,5
	75-79 y				882,9	656,8
	80+ y				3035,6	1932,5

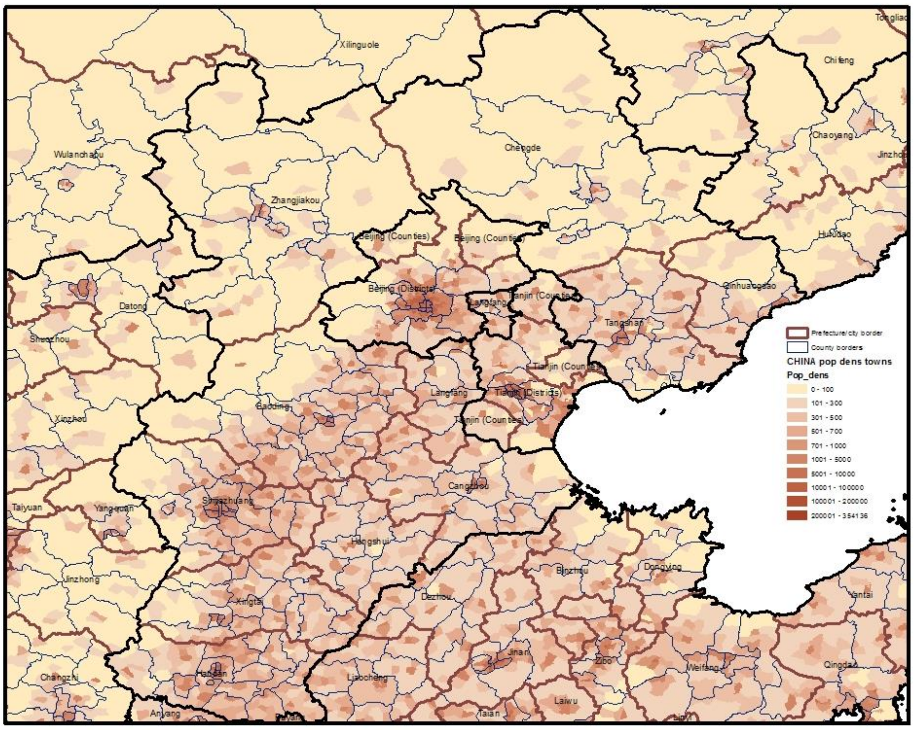

Figure A1. Population density in JingJinJi (pop/km^2). Township level data from China Census data for 2010. Names showed in map are prefectures.

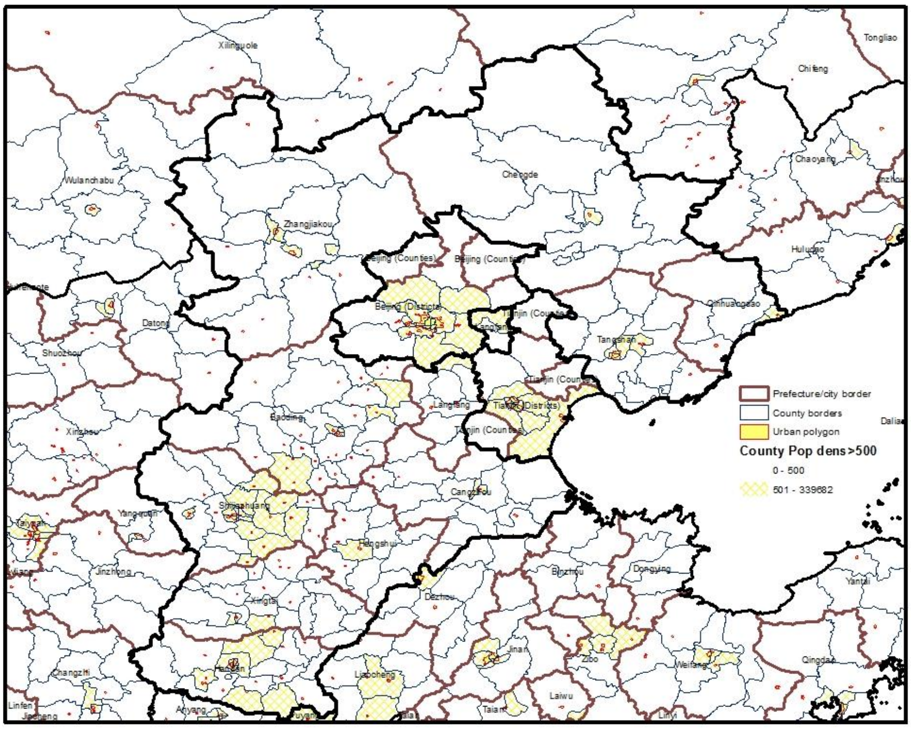

Figure A2. Counties characterized as urbanized in the PM estimation (see text).

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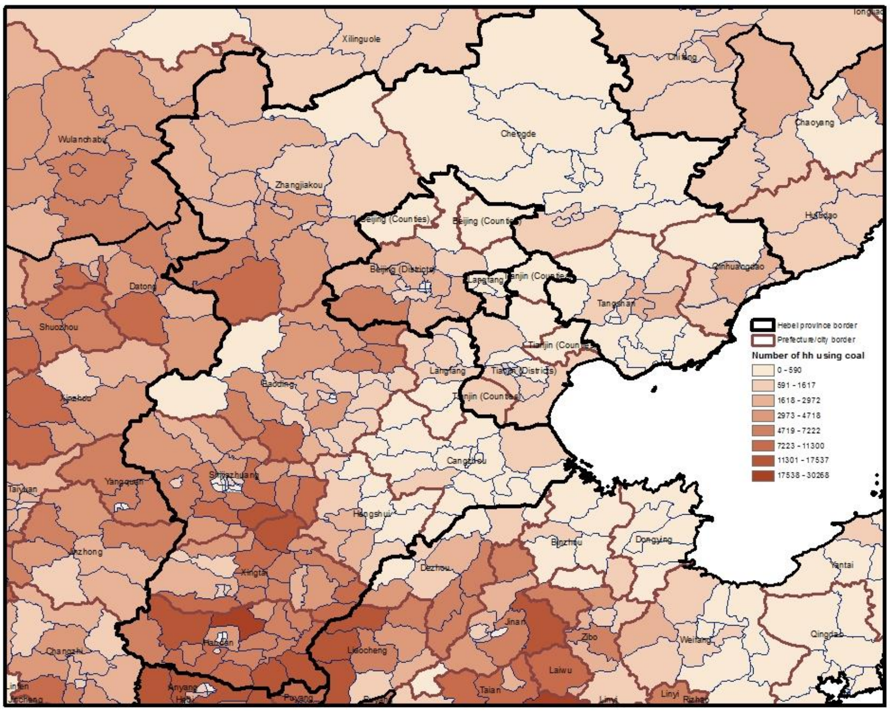

Figure A3. County level number of household with coal as main cooking fuel. Source: China Census 2010.

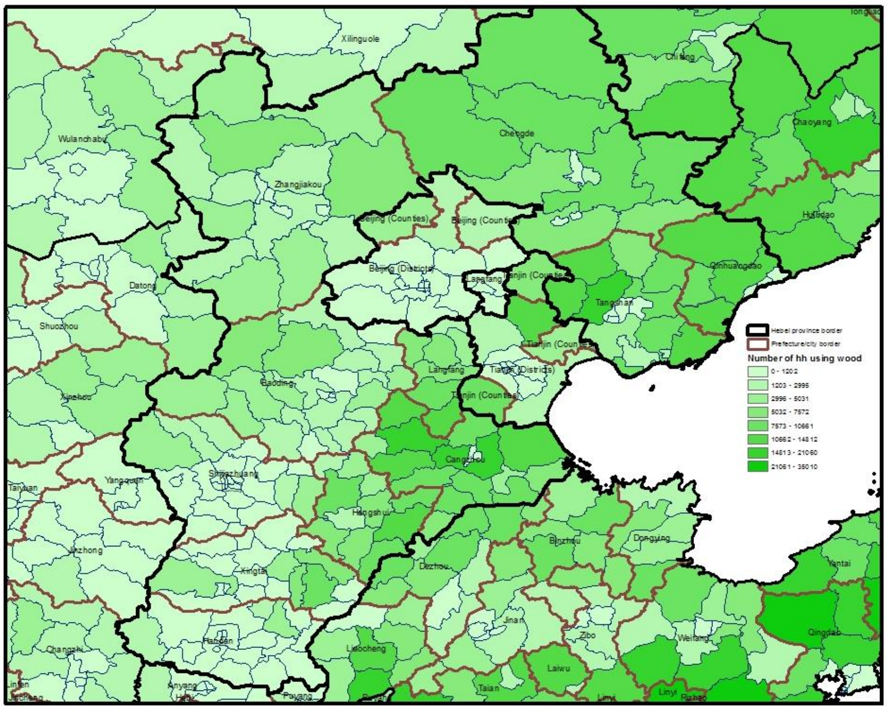

Figure A4. County level number of household with wood as main cooking fuel. Source: China Census 2010.

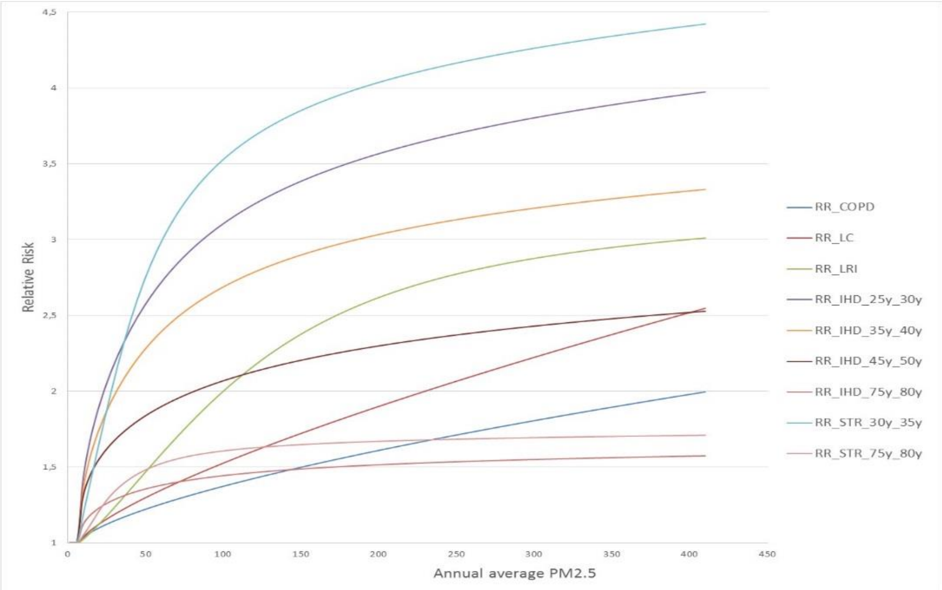

Figure A5. Exposure-response functions applied in current analysis, for COPD, LC, ALRI, and a selection of the age-specific functions for IHD and IS. Source Apte et al. 2015.

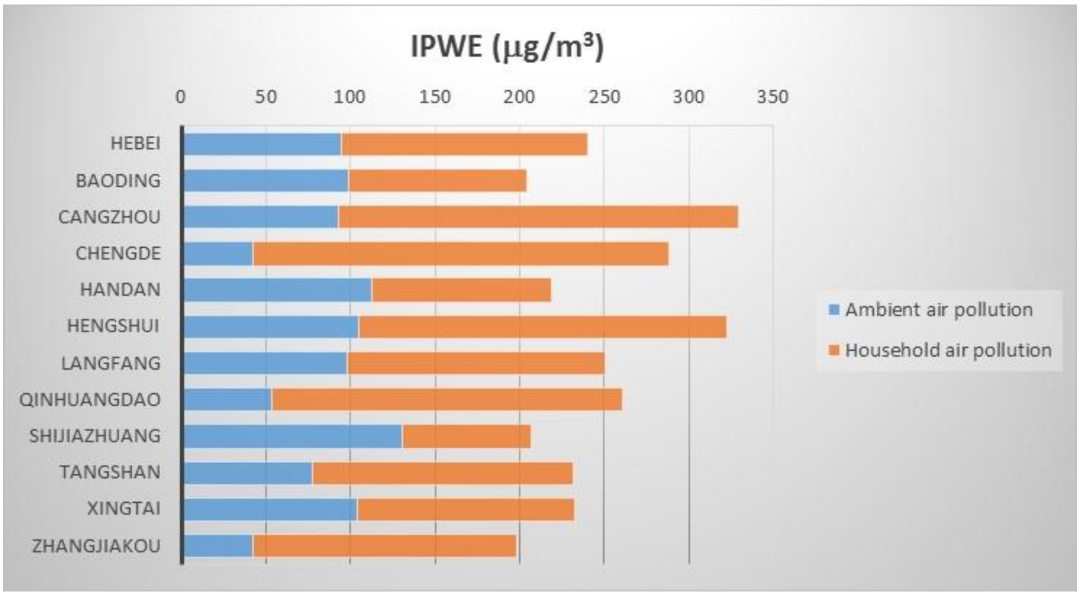

Figure A6. Integrated population weighted exposure (IPWE) in Hebei (urban and rural populations combined), estimated as the total exposure from ambient air pollution (AAP) and household air pollution (AP). In $\mu g/m^3$ $PM_{2.5}$.

All-China Weighted Averages	Co-Abatement Rates			Avoided Deaths from PM (RMB/tCO2)	Avoided Crop Loss from NOx (RMB/tCO2)
	$tSO_2/ktCO_2$	$tPM_{2.5}/ktCO_2$	$tNO_x/ktCO_2$		
Zero Emission Renewables	4.5	0.31	1.5	20	38
Biomass	5.6	0.74	1.5	50	38
Waste	0.79	0.042	0.082	2	2
FF Switch	12	0.79	0.12	55	3
Fugitive	1	0.06	0.22	4	6
F-Gas					
Cement	0.062	-0.0019	-0.022	0	0
N2O	0.0019	0.00013	0.0019	0	0
EE Own Generation	4.9	0.35	1.5	23	38
EE Supply-side and Industry	6.9	0.39	3.3	53	72
Forestry					
Energy-Related Weighted Average	4.9	0.35	1.2	24	30
All-Project Weighted Average	3.7	0.26	0.88	18	22

Figure A7. All-China Weighted Average Co-Abatement Rates and Monetized Benefits from CDM Activities. RMB in 2005 terms. (Source: Rive and Aunan (2010)[29]

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