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Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China

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ABSTRACT

Air pollution is one of the most harmful consequences of China's rapid economic development and urbanization. Particularly in the Beijing-Tianjin-Hebei (BTH) regions, particulate matter concentrations have consistently exceeded the national air quality standards. Over the last years, China implemented ambitious measures to reduce emissions from the power, industry and transportation sectors, with notable success during the 11th and 12th Five Year Plan (FYP) periods. However, such strategies appear to be insufficient to reduce the ambient $PM_{2.5}$ concentration below the National Air Quality Standard of 35 μg m^{-3} across the BTH region within the next 15 years. We find that a comprehensive mitigation strategy for the residential sector in the BTH region would deliver substantial air quality benefits. Beyond the already planned expansion of district heating and natural gas distribution in urban centers and the foreseen curtailment of coal use for households, such a strategy would redirect some natural gas from power generation units towards the residential sector. Rural households would replace biomass for cooking by liquid petroleum gas (LPG) and electricity, and substitute coal for heating by briquettes. Jointly, these measures could reduce the primary $PM_{2.5}$ and SO_2 emissions by 28% and 11%, respectively, and the population-weighted $PM_{2.5}$ concentrations by 13%, i.e., from 68 μg m^{-3} to 59 μg m^{-3}. We estimate that such a strategy would reduce premature deaths attributable to ambient and indoor air pollution by almost one third.

1. Introduction

Air pollution is one of the most harmful consequences of China's rapid economic development and urbanization. Over large areas, ambient concentrations of $PM_{2.5}$ (particulate matter with aerodynamic diameter equal to or smaller than 2.5 μm) exceed the Air Quality Guidelines of the World Health Organization (WHO) as well as National Air Quality Standards. Exposure of the population to such high pollution levels causes a significant burden to public health and economic development, although precise quantification remains uncertain. Published estimates range between 0.35 million (Chen et al., 2013) and more than 1.1 million cases (Cohen et al., 2017) of premature death annually that are attributable to outdoor air pollution in China, and indicate even larger impacts on morbidity. Associated welfare losses have been valued at between 3.8% of GDP (World Bank, 2007) and 9.9% of GDP (World Bank, 2016).

Due to heavy industrialization, high population density and meteorological conditions, the Beijing-Tianjin-Hebei (BTH in short) region in the Northern China Plain is one of the most polluted hotspots in China, next to the Yangtze River Delta and the Pearl River Delta. During 2013-2014, monitoring stations located in cities in the BTH region measured the highest annual average ambient $PM_{2.5}$ concentration in China - up to 144 μg m^{-3} in Shijiazhuang, followed by Tianjin with 92 μg m^{-3}, and Beijing with 87 μg m^{-3} (Wang et al., 2014a). Thereby, annual average ambient $PM_{2.5}$ concentrations in the BTH region were up to four times higher than China's Ambient Air Quality Standard level II of 35 μg m^{-3} (equivalent to the Interim Target Level 1 of the World Health Organization [WHO]).

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In response, the Chinese government has established ambitious policy targets to improve air quality and initiated comprehensive plans and programs to achieve these targets. In contrast to most other countries in the world, in China the largest share of pollution used to originate from power generation and industry, caused, inter alia, by the heavy reliance on coal (Wang et al., 2012; Zhang et al., 2012). Consequently, the emission reduction programs used to focus on these sectors. However, the contributions of other sources, including households and agricultural activities, are sizeable as well, even if they did not receive the same policy attention in the past (Liu et al., 2016; Zhao et al., 2017). Only recently, the authorities started to address mitigation in the residential sector, and are striving to switch fuel use in households (MEP, 2017).

In this study, we employ the Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model (Amann et al., 2011) to facilitate a systematic integrated exploration of effective policy intervention options. By tracking the pathways of air pollutants from energy consumption to emissions, the atmospheric chemistry and transport processes, and the human health impacts, we develop scenarios to seek opportunities in residential clean heating and cooking in the BTH region during 2010–2030. The study explores mitigation pathways for the residential sector, and shows that re-thinking of the energy supply strategy could deliver large benefits on air quality and development, and make an efficient contribution to China's endeavor to achieve cleaner air.

2. Methodology

2.1. GAINS model

The scenarios are built on IIASA's (International Institute for Applied Systems Analysis) Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model. As a scientific tool for integrated policy assessment, the GAINS model describes the air pollution pathways from atmospheric driving force to environmental impact, with information on economic, energy and agricultural development, emission control strategies and cost, atmospheric dispersion and source sensitivities (Amann et al., 2011). It quantifies the emissions and impacts of six air pollutants (SO_2, NO_x, CO, NH_3, VOCs, $PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_1, BC, OC) and six greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) on human health, crop losses, acid deposition, and long-term radiative forcing in a multi-pollutant perspective. This interdisciplinary model has already guided European governments in key negotiations on air pollution control agreements across the continent without compromising economic development (Amann et al., 2008; Amann et al., 2015). It has been applied for analysis of air pollutant emissions and air quality and health impacts in the IEA 2016 World Energy Outlook Special Report on Energy and Air Pollution (IEA, 2016), and has also been developed to evaluate co-benefits of emission reductions on the city scale (GAINS-City) (Amann et al., 2017; Liu et al., 2013).

The GAINS model estimates emissions with technology-based methodology following equation (Amann et al., 2011):

$$E_p = \sum_k \sum_m A_k ef_{k,m,p} \chi_{k,m,p} \tag{1}$$

where, *k, m, p* represents activity type, abatement measure, pollutant respectively; *Ep* stands for emission of pollutant *p*, *Ak* stands for activity data of type *k*, *efk,m,p* stands for emission factor of pollutant *p* for activity *k* after application of control measure m, $\chi_{k,m,p}$ stands for penetration of control measure *m* for pollutant *p* of activity *k*. The emission factors used in the GAINS model for Asia were originally collected within the GAINS-Asia project (Amann et al., 2008). The current version of the model incorporates updates, which use literature reported measurements of emissions from residential combustion sources in China (Cao et al., 2008; Chen et al., 2009; Li et al., 2009; Zhi et al., 2008, 2009) as well as local information on parameters to calculate emission factors from large stationary combustion sources including coal-fired power plants. For instance, updates were made for sulphur and ash content of fuels, as well as efficiency and penetration rates of control measures (Klimont et al., 2009, 2017; Zhao et al., 2013). These emission factors have been applied to estimate air pollutant emissions for the World Energy Outlook Special Report 2016: Energy and Air pollution (IEA, 2016). The $PM_{2.5}$, SO_2 and NO_x emission factors used in this study are summarized in Table S1.

2.2. Emission scenarios

Two scenarios are constructed and analyzed in this study: Baseline and Household scenario. In the Baseline, fuel consumption by sector and by province in base year 2010 is obtained from the China Energy Statistical Yearbook (National Bureau of Statistics, 2011), and is implemented in the GAINS model as the base year activity. The GAINS approach and, in particular, the methodology for the household and commercial sector is described in Klimont et al. (2017). Quantities of fuels were converted into energy equivalents using net calorific values (Table S2) in the GAINS model. The household energy consumption for cooking is obtained from recent Chinese household surveys (Table S3) (Liang et al., 2013; Zheng et al., 2014), and the residues from the total household energy consumption are distributed as fuel for heating. Table S4 presents the resulting residential energy consumption by fuel type and final application in the BTH region in the base year 2010.

For the future scenarios, an annual economic growth of 6% per year up to 2030 is assumed, following the projections of the IEA World Energy Outlook 2015 (IEA, 2015), which is in accordance with China's recent economic growth and the economic development target in the Thirteenth Five-year Plan. A continuing urbanization (2%/a) was assumed based on the government development plan of the three regions (Beijing Municipal Government, 2017; Tianjin Municipal Government, 2006; DHUDH, 2017), and the population growth trend was forecast by the IIASA world population projection model (Lutz et al., 2014), based on a moderate change of fertility, mortality, and inter-provincial migration up to 2030 in Beijing, Tianjin and Hebei. Energy use projections are based on the provincial energy use pattern in 2010 from the China Energy Statistical Yearbook and the national trends from the International Energy Agency (IEA) World Energy Outlook 2015 (IEA, 2015), with additional assumptions on the evolution of energy consumption for individual use in the residential sector to reflect current policies of limiting residential coal and biomass use in the BTH region. The development of other fuel consumption (LPG, heat, renewable energy, liquid fuel and electricity) is consistent with the trend from the IEA WEO (2015) projection, and the natural gas demand is determined by meeting the assumptions for energy consumption for individual needs and coal consumption decrease. Details on the policy incorporation and the establishment of the Baseline scenario are provided in the Supporting information (SI).

Starting from the Baseline, the Household scenario targeting emission reductions from cleaner fuel use in the household and commercial sectors employs measures on four aspects: 1) in the commercial sector, all the solid use is replaced by natural gas; 2) in the urban and suburban areas, all the solid fuel for heating is completely replaced by natural gas; similarly, all LPG for cooking is substituted with natural gas; 3) the substituted LPG for cooking in the urban and suburban areas is used to replace coal and biomass for cooking in rural areas, and to completely phase out solid fuels for cooking in rural areas, additional wind power is used to replace the remaining coal and biomass for cooking; 4) considering the potentially high distribution cost of natural gas due to low population density, the demand for solid fuel for heating in rural areas will not be replaced with natural gas, but will be supplied with coal briquettes and biomass briquettes instead. Details on the building of the Household scenarios and methods for fuel substitution are provided in the SI.

2.3. Modelling $PM_{2.5}$ concentration and health impact estimation

The air quality in each scenario is estimated with the GAINS model. The annual ambient $PM_{2.5}$ concentration in GAINS includes two components (Kiesewetter et al., 2015): 1) a regional background concentration related to emissions (including $PM_{2.5}$, SO_2, NO_x, NH_3 and VOCs) from Chinese provinces and other Asian countries calculated using linear source-receptor transfer coefficients derived from sensitivity simulations of the EMEP (European Monitoring and Evaluation Programme) chemical transport model (Simpson et al., 2012) at a resolution of 0.5° × 0.5°; 2) a sub-grid increment related to primary $PM_{2.5}$ emissions from local, low-level sources (including residential and transportation emissions), with grid-specific local, low-level $PM_{2.5}$ transfer coefficients derived from linear regression analysis of the low-level emission EMEP model perturbation runs. For the calculation of the sub-grid increment, to make the calculations manageable, the cities with over 100,000 inhabitants identified by Global Rural-Urban Mapping Project (GRUMP) v1 dataset are defined as large urban areas in the model, while the remaining smaller cities and other remaining regions are defined as suburban and rural areas, in order to distribute the urban and rural low-level primary $PM_{2.5}$ emissions separately. Therefore, the $PM_{2.5}$ concentrations in small cities may be underestimated if the low-level primary $PM_{2.5}$ emission intensity in small cities is higher than that in rural areas within the same grid cell. Then the combined results are used to estimate population exposure of ambient $PM_{2.5}$ concentrations. Details on the methodology for the air quality modelling are provided in the SI.

Since 2013 the Chinese national monitoring network has included direct measurements of $PM_{2.5}$, and the observed $PM_{2.5}$ annual average concentrations for major cities are obtained from the China Statistical Yearbook (National Bureau of Statistics, 2016). For the base year 2010, there are limited $PM_{2.5}$ observations available in China, so model validation is carried out with the observed $PM_{2.5}$ annual concentrations for 2015 (Fig. S1 and Table S5). The modelled annual $PM_{2.5}$ concentrations agree well with observations, with correlation coefficients at 0.8, and RMSE at 16.3 $\mu g\,m^{-3}$. 98% of the modelled concentrations are within a factor of two of the observations, although the model slightly overestimates observations (NMB 5%). Overall, the model evaluation results are comparable with other model studies over China (Geng et al., 2017; Ma et al., 2017).

For health impacts, we estimate the premature mortality attributable to $PM_{2.5}$ exposure from both ambient air pollution and indoor air pollution for each scenario. The exposure to ambient air pollution is calculated by the overlay of modelled annual average $PM_{2.5}$ concentrations and population distribution. The household air pollution is calculated for residents using solid fuel cooking. A typical exposure of 300 $\mu g\,m^{-3}$ is assumed for traditional stoves and 70 $\mu g\,m^{-3}$ for clean stoves, based on the wide range of observed concentrations (Balakrishnan et al., 2013). The human health impact in terms of premature mortalities of each scenario is estimated for all relevant diseases, including ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) in five-year age classes. Baseline mortalities are taken from the GBD-2013 database. The integrated exposure–response (IER) function (Burnett et al., 2014) developed for the GBD-2013 study (Forouzanfar et al., 2015) and used in the WHO 2016 assessment of ambient air pollution (WHO, 2016) is used to estimate the relative risk associated with a certain level of $PM_{2.5}$ exposure. Details on the methodology for the air quality modelling and health impact estimation are provided in the SI.

3. Results

3.1. Air pollution in the BTH region

For this study, we employ the East-Asia implementation of the GAINS model, which distinguishes 31 regions and provinces in China, including the BTH region. Relying on provincial energy statistics, fuel characteristics and emission inventories, we estimate with the GAINS model that in 2010 power plants and industry were the largest sources of SO_2, NO_x and primary $PM_{2.5}$ emissions in BTH, responsible for 85%, 66% and 52% of total emissions, respectively (Table S6). Transportation caused 30% of NO_x and 5% of $PM_{2.5}$ emissions. In comparison, the residential sector (defined as households and commercial sector in this study) was a smaller source, with 35% of total $PM_{2.5}$, 15% of SO_2 and 5% of NO_x emissions. Agricultural activities (manure management and mineral nitrogen fertilizer application, primarily urea) made the predominant contributions (more than 90%) to NH_3 emissions in the region.

However, stack heights and proximities between emissions and population differ across these sectors. Based on emission inventories and the EMEP atmospheric chemistry and transport model, GAINS quantifies the contributions of the various source categories to ambient concentrations of $PM_{2.5}$ across the BTH region with a resolution of 0.5° × 0.5° (roughly 40 × 50 km), on top of which concentrations are calculated explicitly at higher resolution for each individual city with more than 100,000 inhabitants. Combined with population density data, the total population exposure to $PM_{2.5}$ across the BTH region can then be computed.

Using such a methodology, we estimate for the BTH area a population-weighted $PM_{2.5}$ concentration of 85 $\mu g\,m^{-3}$ in 2010. For 96% of the population, exposure of $PM_{2.5}$ exceeded the China Ambient Air Quality level II of 35 $\mu g\,m^{-3}$. 79% of the people faced $PM_{2.5}$ levels of more than twice this level, 15% more than three times, and about 3% more than four times (Fig. 1).

Source attributions suggest that, averaged for the entire population within the BTH region, about 60% of the exposure to $PM_{2.5}$ in outdoor air originates from emissions in the BTH region, and another 34% from other Chinese provinces outside BTH. The contribution from natural sources (soil dust, sea salt) is estimated at 6% (Fig. 2A). Similar findings are proposed in previous studies (Li et al., 2015; An et al., 2007). Considering the BTH contributions, about one-third is the local concentration increment contributed by low-level residential and transportation primary $PM_{2.5}$ emissions (Fig. 2A), estimated with the downscaling methodology. The share of local primary concentration is even higher for Hebei conurbations, where the residential emissions are higher (Fig. 2B). From the population exposure that is caused by emission sources within the BTH area (60% of total exposure), the largest contribution comes from the power and industrial sectors (25%), 18% from residential sources (i.e., burning of coal and biomass for heating and cooking), 11% from agricultural emissions, 4% from transportation, and 2% from waste burning sources in the BTH region (Fig. 2A).

3.2. Outlook to 2030

The rapid economic development and urbanization, together with the re-orientation of industrial and energy policies and the ambitious sharpening of pollution control legislation and enforcement, will impact future pollution levels in China. We use the GAINS model to assess the likely interplay of these factors on future air quality in the BTH region, identify the most important pollution sources that will remain after implementation of current policies, and explore policy intervention options from small combustion sources in the residential and commercial sector.

3.2.1. Economic development, energy policy and pollution controls

Following the central projections of fertility, mortality and interprovincial migration of the integrated development plan of Beijing, Tianjin and Hebei in the next 15 years, we project population in BTH to increase by 21% compared to 2010. Urbanization will reach 78%, with a 68% increase of urban and a 40% decline of rural population (Table

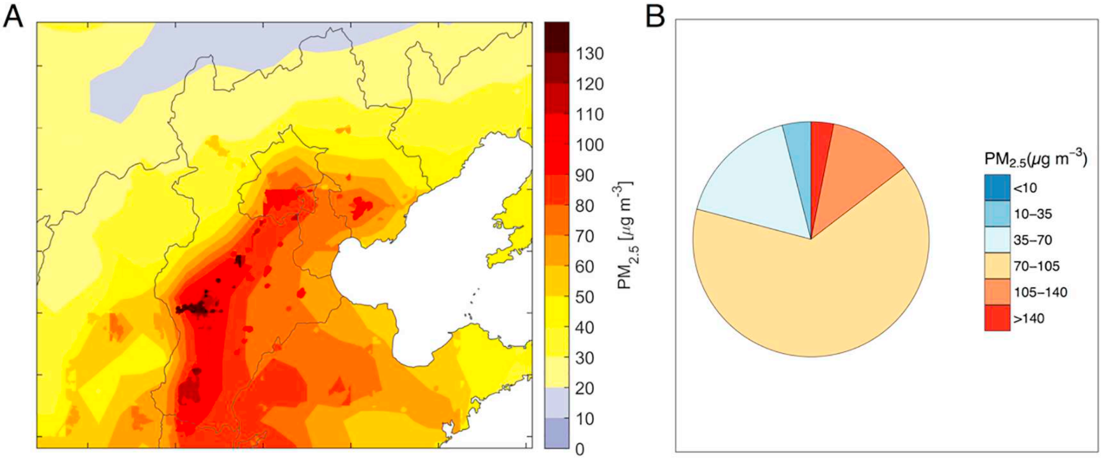

Fig. 1. Ambient $PM_{2.5}$ concentrations (A) and proportion of population exposed to different levels of $PM_{2.5}$ (B) in the BTH region in 2010, computed with GAINS model.

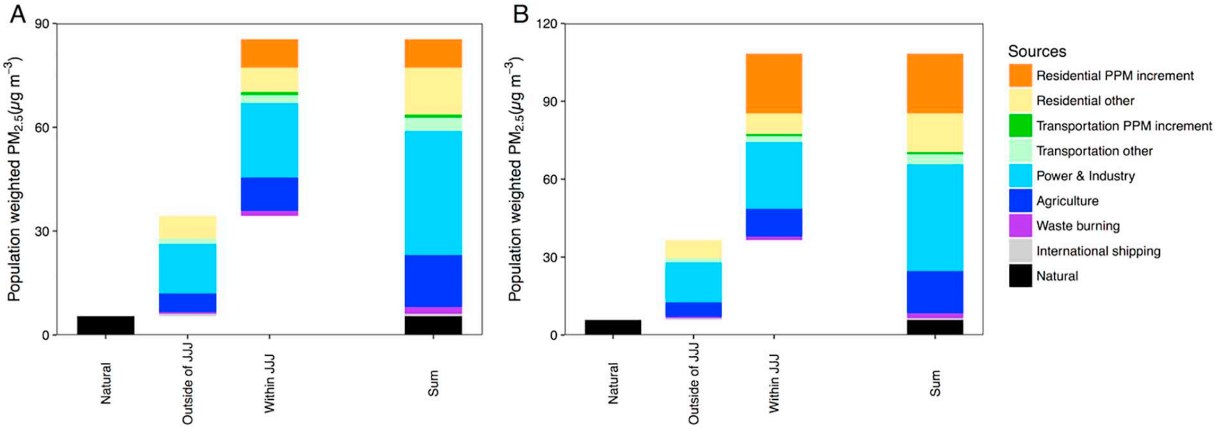

Fig. 2. Source apportionment for population-weighted $PM_{2.5}$ concentration in the BTH region (A) and Hebei conurbations (B) in 2010. The source regions are distinguished by regions outside of BTH and regions within BTH; five types of sources are identified, including natural, power plus industry, residential, transportation, agriculture, waste burning, and international shipping. The contribution of primary $PM_{2.5}$ increment from local low-level residential and transportation sources are estimated individually with the down-scaling method.

S7). For economic development and energy consumption we adopt the scenario of the IEA as presented in its World Energy Outlook 2016 Special Report on 'Energy and Air Pollution' (IEA, 2016), which assumes a continued economic growth of 6%/year. This will triple per capita GDP in 2030.

The projection assumes continuation of the ongoing trend towards consumption and services, and further transformation towards less energy-intensive production. Together with the latest policy measures, this will reduce the energy intensity of GDP by 54%, although total primary energy use will still increase by 54%. Overall, the share of coal in the primary energy mix of the BTH region will decline from about two-thirds in 2010 to 50% in 2030, although the absolute volume will still increase by 25%. Natural gas will double its share, and consumption will grow by almost a factor of two. 26% of the natural gas volume will be consumed in the commercial sector and households, while the amount of natural gas distributed in the power and industrial sectors is larger, accounting for 34% and 37% of the total supply, respectively.

Growing population and economic wealth will increase energy consumption in the households and commercial sector by 50%. At the same time, we assume that the latest policies on limiting residential coal and biomass use in the BTH region will decrease solid fuel consumption for heating in urban areas by 26%, and by 44% in the rural area following the decline in rural population. For cooking, we assume that by 2030 all solid fuel use will disappear in all urban centers with population densities of more than 20 people/ha, and remain only in the urban fringes, suburban areas, small towns and rural areas (Table S8).

Although past experience with respect to compliance with legislation has not always been positive, we assume full implementation and effective enforcement of the measures and policies that have been decided by 2015. These include the measures outlined in the 12th Five-year Plan of the Chinese Government and more specifically in the Air Pollution Prevention and Control in Key Areas (MEP, 2012), as well as the measures specified in the 2013 Air Pollution Prevention and Control Action Plan of the State Council (hereafter referred to as the "Action Plan") (MEP, 2013), and the Implementation Plan specially for BTH and its surrounding regions. However, we consider only the specific pollution control measures outlined in these documents, but do not speculate about additional measures that might be required to fully achieve China's targets on ambient air quality. Furthermore, as at the time of writing there is no available translation of the 13th Five Year Plan into specific measures, we do not consider additional measures that might emerge from this document.

3.2.2. Emissions and population exposure

The policy measures outlined above will achieve a distinct decoupling between economic growth, energy use and pollution levels in the BTH region. Despite the doubling of GDP and a 50% higher energy consumption in 2030, SO_2, NO_x and $PM_{2.5}$ emissions would drop by

Table 1
BTH air pollutant and greenhouse gas emissions, population-weighted $PM_{2.5}$ concentration, and human health impacts in 2010 and 2030 for each scenario.

	2010	2030 Baseline scenario	2030 Household scenario
$PM_{2.5}$ (kt)	1160	728	524
SO_2 (kt)	2483	1393	1235
NOx (kt)	2441	1673	1634
NH_3 (kt)	1059	1196	1192
CO_2 (Mt)	944	1265	1261
CH_4 (Mt CO_2eq)	60.8	78.0	77.8
$PM_{2.5}$ population-weighted exposure (μg m^{-3})	85	68	59
Households (population) using solid fuels for cooking	14.0 (42.6) million	7.3 (24.2) million	0
Premature deaths			
From ambient pollution	89,788	118,742	113,250
From household air pollution caused by solid fuel use for cooking	73,865	50,880	0

44%, 31% and 37%, respectively, as a result of the new policies (Table 1). However, in the absence of any emission regulation for the agricultural sector, NH_3 emissions, an important precursor of $PM_{2.5}$, will grow by 13% following closely the production trend.

Assuming that similar policies will be implemented in the provinces surrounding BTH, population-weighted $PM_{2.5}$ concentrations in the BTH region would decline from 85 μg m^{-3} in 2010 to 68 μg m^{-3} in 2030, i.e., by 20% (Table 1). As a consequence, fewer people will be exposed to extreme levels; e.g., while in 2010 almost 80% of the population faced more than 70 μg m^{-3} of $PM_{2.5}$ (i.e., more than double the Chinese Ambient Air Quality standard II and the WHO Interim Target Level 1), this share will drop to 45% in 2030 (Fig. S2). In addition, 24.2 million people who were using solid fuels for cooking and heating will switch to clean fuels, and will be thereby relieved from the health burden of indoor pollution caused by solid fuel use for cooking.

However, these reductions will not be sufficient to significantly enlarge the share of population facing concentrations that comply with the current Chinese air quality standards. We estimate major contributions from natural sources and emitters outside the BTH region (about 25 μg m^{-3} on a population–weighted basis). Residual emissions from the industrial and power sectors in BTH will still contribute about 16 μg m^{-3}, the household and commercial sector 11 μg m^{-3}, agricultural activities 11 μg m^{-3}, and other sources including transportation about 5 μg m^{-3} (Fig. S2). It should be noted that further efforts from the Acton Plan and 13th FYP are underway, which will significantly reduce industrial emissions, especially SO_2, and the 16 μg m^{-3} contribution of industrial and power sectors can be further reduced by these latest efforts (Zheng et al., 2018).

3.3. *An alternative strategy for household energy use*

3.3.1. *The household scenario*

While, for good reasons, significant attention has been paid to pollution controls in power plants and industry in China, the residential sector, despite making the second-largest contribution to population exposure in 2010, has received less consideration. Per unit of energy use, solid fuel combustion in small, low-level sources in the household and commercial sector has a significantly stronger impact on ambient air quality and population exposure than large point sources, and its strong seasonality makes it a key source in pollution episodes during the heating season, as confirmed by source apportionment (Yang et al., 2016; Li et al., 2015) and remote sensing (Xiao et al., 2015) studies. According to the estimates presented in Section 3.2.2, in 2030 solid fuel use in the residential sector of the BTH region will still account for 16% of the population exposure (including sources outside the BTH region), despite the measures taken in the baseline scenario.

It is noteworthy that in spite of the policies for household energy use, (i.e., expansion of district heating, phase-out of coal for heating and cooking in urban centers, etc.), in 2030 a substantial amount of solid biomass and coal remains for cooking and heating in suburban and rural areas. At the same time, natural gas use will be expanded by 170%; however, only less than one-third of the additional gas volume is directed to the residential sector, while more than two-thirds will be used to substitute coal in large industrial installations and power plants.

As there are only limited possibilities to reduce emissions from solid fuel use in the residential sector without fuel switches, while there are ample opportunities for controlling emissions at large installations through end-of-pipe technologies, we explore in an alternative scenario the practical scope for air quality improvements in the BTH region from an enhanced penetration of clean fuels to the residential sector.

In 2015, total heated floor space in the cities of Hebei amounted to 1.07 billion m^2, 80% connected to central heating systems (HPDHURC, 2017). However, despite major investments into grid-based energy supply in the cities, there remains a persistent fraction of coal use, mainly among low-skilled rural-to-urban migrants due to housing conditions, easy access, and low costs of coal (Ru et al., 2015). In the entire BTH region, estimated with GAINS, district heating supplied 56% of the demand in cities and sub-urban areas, other forms of clean energy (natural gas, electricity and renewable energy) about 13%, and about 29% of the population is still using coal for heating.

For the future, we assume for the urban areas in the BTH region that all coal and biomass for heating, as well as coal for the commercial sector, will be completely replaced by natural gas. Similarly, all LPG used for cooking in urban areas will be shifted to rural areas to substitute solid fuels for cooking. Furthermore, rural households that are currently using solid fuels for cooking will switch to electric stoves, with the electricity generated by additional wind power. This will increase wind power generation by 13% above the baseline projection, a small margin compared to the seven-fold growth that is assumed there (China Electric Power Yearbook Editorial Committee, 2011, 2015; IEA, 2015). Furthermore, as a conservative assumption, we do not consider replacement of solid fuels for heating in rural areas by natural gas due to potentially high distribution costs in low-density areas. Instead, the residual demand for solid fuels for heating in rural areas will be supplied by coal briquettes and biomass briquettes.

Such a strategy would increase the projected demand for natural gas in the residential sector by 21% (or 5% of total gas demand in the BTH region) compared to the baseline (Table S9). Most likely, this additional quantity could be obtained on the market (e.g., additional imports from Russia, shale gas, LNG). However, as a conservative assumption, we divert this gas volume from the power sector and replace it there by coal, which will increase coal consumption in the power sector by 6%.

Compared to the baseline scenario, such a strategy would replace in urban areas (mainly suburban) 11.3 million tons of coal and 0.9 million tons of biomass used for heating by 4.6 bcm of natural gas. In 4.2 million (sub-)urban households, 0.69 million tons of LPG used for cooking will be substituted by 0.84 bcm of natural gas. This will allow 3.4 million households in rural areas to replace biomass and coal for cooking by LPG, while 3.9 million rural households will switch to electricity for cooking. For heating, 6.1 million rural households will replace conventional coal and biomass with briquettes. In total, this would reduce biomass combustion in the BTH area by 29% and coal consumption by 2% compared to the baseline; natural gas use will remain the same, and wind power increase by 13%.

3.3.2. *Emissions, air quality and health impacts*

Such a re-arrangement of fuel use will have major beneficial impacts on air pollutant emissions: in 2030, primary $PM_{2.5}$ emissions will be 28% lower than in the baseline projection, and SO_2 emissions decline by 11%. At the same time, greenhouse gas emissions will also be slightly lower (CO_2 by 0.3%, CH_4 by 0.3%) (Table 1).

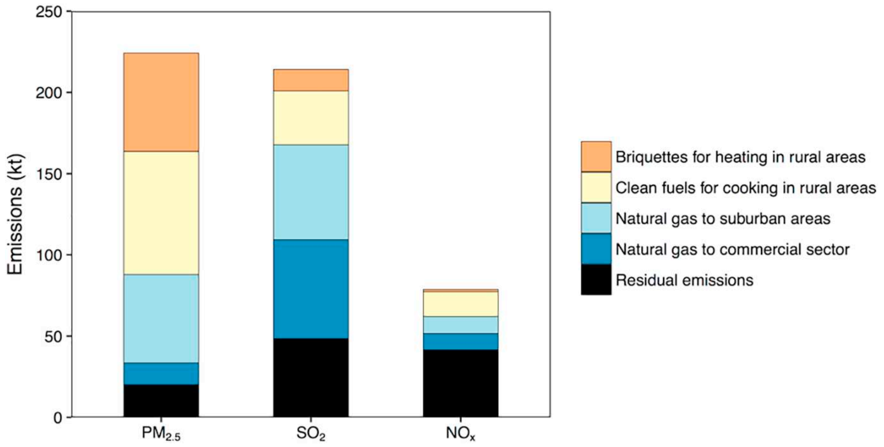

Fig. 3. $PM_{2.5}$, SO_2 and NO_x emission reductions in the residential sector in the Household scenario compared with Baseline.

For $PM_{2.5}$, three groups of measures deliver similar emission reductions: extended natural gas supply in sub-urban areas, clean fuels for cooking in rural areas, and replacement of coal and biomass by briquettes for heating in rural areas. SO_2 reductions also emerge from an increased supply of natural gas to suburban areas, while the introduction of briquettes makes a smaller difference (Fig. 3). All together, these measures will reduce the residential $PM_{2.5}$, SO_2 and NO_x emissions by 91%, 77% and 47%, respectively, compared with Baseline.

These emission reductions, although they affect only a small share of sources that contribute to ambient $PM_{2.5}$ in the BTH region, will have large benefits for air quality, as they cut low-level emission sources which have a more direct impact on ground-level concentrations and population exposure than emissions from high stacks. Despite being limited to the BTH region, they will reduce mean population exposure by 13% compared to the baseline, i.e., from 68 $\mu g\,m^{-3}$ to 59 $\mu g\,m^{-3}$. Most importantly, they will allow 81% of people to be exposed to less than 70 $\mu g\,m^{-3}$ (i.e., twice the Chinese Ambient Air Quality Standard II and WHO Target Level 1), compared to only 54% of the population in the baseline case (Fig. 4). In addition, they will enable 7.3 million people to switch to clean cooking fuels, so that they will not be exposed to indoor household pollution caused by solid fuel use for cooking any more.

While these measures alone will not be sufficient to meet the air quality standards, they could form an important and effective element of a comprehensive strategy and bring down the contributions from local residential sources to population exposure to about 1 $\mu g\,m^{-3}$, from 15 $\mu g\,m^{-3}$ in 2010. Four times as much exposure will then originate from household sources in the provinces surrounding BTH, where similar strategies could deliver comparable benefits. It is noteworthy that there is a strong seasonal component in the emissions from heating, and these sources make a much larger relative contribution during the heating season and especially during high pollution episodes in winter (Liu et al., 2016).

The additional coal use in the power sector resulting from the conservative assumption of maintaining the total demand for natural gas in BTH would increase population exposure by only 0.03 $\mu g\,m^{-3}$. Further emission reductions for industry and power plants as well as from agricultural sources in BTH and surrounding areas, are essential to bring exposure levels in compliance with the National Ambient Air Quality standard II.

Beyond the improved compliance with the air quality standards, these emission and exposure reductions will also benefit human health. However, the quantification of health impacts (e.g., number of premature deaths, hospital admissions, absence from work, child mortality) remains uncertain, as most of the available epidemiological evidence is derived from studies in developed countries. To elaborate more robust messages about potential health benefits from policy interventions, we focus on the relative changes in health impacts.

From this, we estimate for the baseline projection that the premature deaths that can be associated with air pollution would decline by 4% between 2010 and 2030. This overall change is a consequence of various factors: (i) total population will increase by 21% in the BTH region; (ii) improved access to clean cooking fuels will reduce mortality

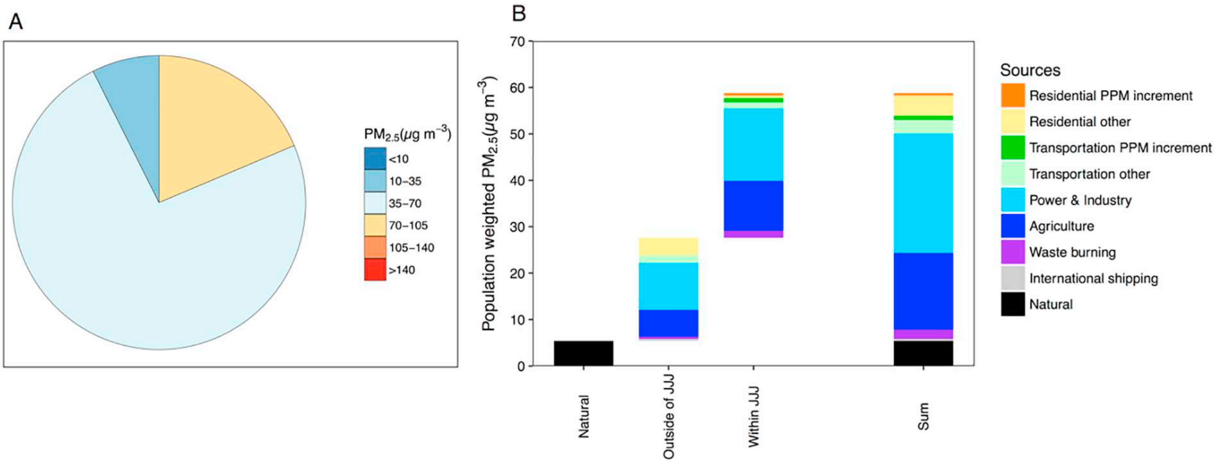

Fig. 4. Proportion of population exposed to different levels of $PM_{2.5}$ concentrations in Household scenario in 2030 (A); source apportionment for population-weighted $PM_{2.5}$ concentrations in the BTH region in the Household scenario in 2030 (B).

from indoor air pollution by 31%; (iii) the mean population exposure to ambient $PM_{2.5}$ will decrease by 20%; (iv) the non-linear shape of the IER curve of the GBD study, which hypothesizes less health improvements from the same absolute reduction of exposure at high concentrations compared to cleaner environments; and (v) the strong aging of the society will make people more susceptible to air pollution, so that premature deaths from ambient pollution are estimated to grow by 32%. In contrast to the rather limited improvement in overall health impacts that can be expected for the baseline scenario, the household scenario would reduce health impacts by almost one-third, with the majority delivered by the elimination of solid fuel use for cooking. In the Household scenario, where the solid fuels used for cooking are completely replaced with LPG and wind power, the premature mortality attributable to household air pollution caused by solid fuel use for cooking is eliminated. This would mostly benefit poorer segments in the society, and especially women and children. Due to the dispersion of $PM_{2.5}$ in the atmosphere, ambient air quality and public health will also improve beyond the BTH area, and we estimate that health benefits outside in the neighboring regions add another 31% to the numbers computed for BTH.

4. Discussion

Faced with the challenge of high air pollution in the densely populated areas, the Chinese government has undertaken significant efforts to reduce emissions from important pollution sources. Early efforts, such as the 11th and 12th Five-Year Plans, focused on SO_2 and NO_x emissions, mainly addressing large point sources in the power and industry sectors, as they are responsible for major shares of total emissions in China. These were complemented by regulations for mobile sources, which are growing rapidly, and small-scale industrial boilers, which relied to a large extent on coal without efficient pollution control equipment. Despite these efforts, episodes of high pollution continued to occur, so that in 2013 the State Council and other authorities issued the *Action Plan* and other regulations, which also included measures for some other sectors.

With a smaller share in energy consumption, pollution from the household and commercial sector received less attention in the past (Liu et al., 2016). However, per unit of energy use, solid fuel combustion in small, low-level sources in the household and commercial sector has significantly stronger impact on ambient air quality and population exposure than large point sources, and its strong seasonality makes it a key source in pollution episodes during the heating season, as confirmed by source apportionment (Yang et al., 2016; Li et al., 2015) and remote sensing (Xiao et al., 2015) studies. Recently, the authorities have begun to address residential emissions from coal use by substituting coal with natural gas and other clean fuels, controlling coal quality and promoting coal briquettes in rural areas. According to the *Action Plan for Comprehensive Management of Air Pollution during Autumn and Winter Season of 2017–2018*, substitution of coal with natural gas and electricity should be implemented in more than 3 million households in the BTH and surrounding regions by 2017 (MEP, 2017).

Previously, we have estimated with the GAINS model that household cooking with solid fuels accounted for 12% of ambient $PM_{2.5}$ concentration globally (Chafe et al., 2014). In this study, focusing on the regional mitigations in Northern China, we build the residential energy use by individual needs in the BTH region, and provide estimates for the potential air quality and human health benefits from implementation of mitigation policies on clean cooking and heating in the residential sector.

A wide range of alternatives is technically available to eliminate the use of solid fuels for cooking and heating in the household and commercial sector, including district heating, grid-based supplies of natural gas for space heating and cooking, LPG for cooking, electricity, biogas, and solar for space heating and cooking. Further expansion of these alternatives depends on policy decisions to prioritize investments in them. We developed a comprehensive strategy by replacing all the urban solid fuel use with grid-based natural gas, replacing all the rural solid fuel use for cooking with LPG and electricity, and replacing all the rural solid fuel use for space heating with briquettes. Such a re-arrangement of fuel use would substantially reduce the residential $PM_{2.5}$, SO_2 and NO_x emissions compared with the Baseline (Fig. 3). Although, strictly speaking, coal and biomass briquettes are not clean fuels, they can provide significant reduction of emissions of particulate matter [e.g., Zhi et al., 2008, 2009] and we consider them as short-term to interim alternatives. To meet the space-heating demand in the vast rural areas, the Government suggested regions which do not have proper conditions to use natural gas and electric-power heating devices use coal briquettes and other types of clean fuels as substitutes (MEP, 2017). But further reductions can be achieved when moving to the long-term solutions, such as natural gas, electricity (preferably from renewable sources like wind), and biogas.

Recently, electric-driven heat pumps were proposed as substitutes for household coal-fired heating devices, with preferential policies, such as electricity tariff, purchase subsidy to support the applications (NDRC, 2016), which foresees further reductions beyond our estimation. Xu et al. (2017) estimated that the coal-fired electricity generation and electric-driven heating system can significantly reduce the PM, SO_2 and NO_x emissions by 93%, 97% and 76% respectively, but increase the annualized investment, operation and maintenance cost by $\$1.44/m^2$, compared with the direct coal-fired heating system. Therefore, with the implementation of preferential policies and the improvement of technologies, there are large potentials to mitigate air pollution through clean heating and cooking strategies in China.

In addition to the clear benefits of such a strategy for the compliance with ambient air quality standards and the improvement of public health, a rapid adoption of clean heating and cooking fuels will have particular benefits on air quality during the heating season and can significantly reduce the likelihood of extreme pollution episodes during the winter. This is of special relevance for the planning of the 2022 Winter Olympic Games in the BTH area.

Unlike in the earlier events, e.g., the 2008 Olympic Games (Wang et al., 2009), and the 2014 APEC Forum (Tan et al., 2016), heating demand will peak during this time. With large amounts of coal for heating (Zhu et al., 2013) and unfavorable meteorological conditions (Zheng et al., 2015), residential sources contributed about 50% to $PM_{2.5}$ in the urban areas of the BTH region during the January 2013 pollution episode (Li et al., 2015). Our baseline analysis does not foresee much change (a 21% contribution to annual mean exposure in 2030, which approximately doubles during winter episodes). Temporarily restricting emissions from industrial and transport emission sources as successfully mandated for industrial sources and transport in earlier events might not be sufficient to secure acceptable air quality during cold winter periods. Moreover, a temporary shut-down of space heating at the large scale – or of the most polluting space heating sources, i.e., small household devices burning solid fuels, does not seem practical nor socially acceptable. Any solution that does not cause hardship for the population during wintertime must strive for a rapid introduction of clean heating and cooking fuels in a socially acceptable manner. This would also make an important contribution to a long-term strategy towards the $PM_{2.5}$ Interim Targets and Guidelines of the World Health Organization.

Regional collaboration is needed to maximize benefits across the BTH region. Local governments shall evaluate existing plans of gas and electricity supply to residential consumers prioritizing densely populated, highly polluted regions with high reliance on coal. For regions where switching to natural gas and electricity is feasible, supporting funds should be arranged for the construction and upgrading of natural gas and power transmission and distribution networks. Preferential policies such as tax incentives, purchase subsidies can help to decrease the overall costs for the residents. For regions that do not have proper conditions for switching to gas or electricity, coal briquettes and other types of clean fuels can serve as substitutes. Production and supply of clean coal should be strengthened, and the sales of low quality coal should be prohibited to ensure that coal used in the households meets quality standards. The provincial governments should collaborate with prefectures to evaluate regularly the implementation progress and consider financial support to the less-developed Hebei province.

5. Uncertainties

We applied an integrated approach to highlight the potential opportunities of clean cooking and heating strategies, ranging from energy consumption, future projection, and emission estimation to air quality and human health impacts. Necessarily, the simplifications and assumptions that we had to introduce in order to characterize a complex reality add some uncertainty to quantitative results. Uncertainties emerge from many aspects, including constructing the baseline scenario, the adoption of emission factors, the process of $PM_{2.5}$ concentration modelling, health impact estimation, and the compliance of policies.

We did not perform a quantitative uncertainty analysis, because a comprehensive model to quantify the overall uncertainty of integrated assessment models is not available. Instead, we provided a qualitative analysis of the main sources of uncertainty in the SI. Since we are focused mostly on a scenario comparison, several components of uncertainty can cancel out by the differential analysis. Besides, we use similar emission factors and methodologies with other studies, the magnitude of uncertainty for emissions in GAINS is similar with previous bottom-up emission inventories (Streets et al., 2003; Zhang et al., 2009; Zhao et al., 2013; Li et al., 2017; Wang et al., 2014b). For example, Wang et al. (2014a, 2014b) estimated coefficients of variation for residential sector emissions of SO_2, NO_x, and $PM_{2.5}$ at $\pm$ 51%, $\pm$ 55%, and $\pm$ 68%, respectively, and average 90% confidence interval at about -29% to $+45\%$ for SO_2, -31% to $+44\%$ for NO_x, and -39% to $+49\%$ for $PM_{2.5}$. So far, the integrated assessment model GAINS has been widely applied in previous studies, including the topics of ammonia mitigation (Zhao et al., 2017) and synthetic natural gas development (Qin et al., 2017) in China.

6. Conclusions

Air pollution is causing a significant health burden in China. Over the last years, policy responses focused on measures to reduce emissions from the power, industry and transportation sectors, with notable success during the 11th and 12th FYP periods. However, we estimate that such strategies will be insufficient to fully reduce ambient $PM_{2.5}$ concentrations below the National Air Quality Standard II of $35\,\mu g\,m^{-3}$ throughout the BTH region by 2030, as other emission sources, notably solid fuel combustion for cooking and heating in the household sector, will remain. Furthermore, these sources make large contributions to extreme pollution episodes in winter, which are of great public concern, especially in view of the forthcoming Winter Olympic Games in the BTH area in 2022.

We find that a comprehensive strategy for the residential sector in the BTH region would deliver substantial air quality benefits. Beyond the already planned expansion of district heating and natural gas distribution in urban centers and the foreseen curtailment of coal use for households, such a strategy would

(i) redirect some of the natural gas that is currently allocated to large industrial facilities towards the residential sector, especially in suburbs with reasonable demand density, thereby eliminating the use of solid fuels and LPG in all households in urban and sub-urban areas (industrial sources might compensate the diverted natural gas by coal),
(ii) use this LPG, together with additional electricity, to replace biomass cooking in all rural households, and
(iii) substitute all remaining coal and biomass used for space heating in rural areas by briquettes.

Such a re-arrangement would reduce the residential $PM_{2.5}$, SO_2 and NO_x emissions by 91%, 77% and 47%, respectively, compared with the Baseline. Although these measures alone will not be sufficient to meet the air quality standards, they could form an important and effective element of a comprehensive mitigation strategy. Similar improvements could be achieved by addressing household sources in the provinces surrounding BTH.

Replacing coal and biomass use for space heating in rural areas with briquettes is a short-term to interim alternative to reduce the present severe air pollution. Further mitigation can be achieved when moving to long-term solutions, such as switching to natural gas, electricity and biogas. Supporting policies and facilities should be well prepared to meet the proper rural heating demand during winter.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.09.059.

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