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LETTER

To what extent can China's near-term air pollution control policy protect air quality and human health? A case study of the Pearl River Delta region

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Xujia Jiang^{1,2}, Chaopeng Hong^{1,2}, Yixuan Zheng¹, Bo Zheng^{1,2}, Dabo Guan^{1,3}, Andy Gouldson⁴, Qiang Zhang^{1,5} and Kebin He^{2,5}

¹ Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, People's Republic of China

² State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, People's Republic of China

³ School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

⁴ Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK

⁵ Collaborative Innovation Center for Regional Environmental Quality, Beijing 100084, People's Republic of China

E-mail: qiangzhang@tsinghua.edu.cn

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Abstract

Following a series of extreme air pollution events, the Chinese government released the *Air Pollution Prevention and Control Action Plan* in 2013 (China's State Council 2013). The Action Plan sets clear goals for key regions (i.e. cities above the prefecture level, Beijing-Tianjin-Hebei Province, the Yangtze River Delta and the Pearl River Delta) and establishes near-term control efforts for the next five years. However, the extent to which the Action Plan can direct local governments' activities on air pollution control remains unknown. Here we seek to evaluate the air quality improvement and associated health benefits achievable under the Action Plan in the Pearl River Delta (PRD) area from 2012 to 2017. Measure-by-measure quantification results show that the Action Plan would promise effective emissions reductions of 34% of SO₂, 28% of NO_x, 26% of PM_{2.5} (particulate matter less than 2.5 μm in diameter), and 10% of VOCs (volatile organic compounds). These emissions abatements would lower the PM_{2.5} concentration by 17%, surpassing the 15% target established in the Action Plan, thereby avoiding more than 2900 deaths and 4300 hospital admissions annually. We expect the implementation of the Action Plan in the PRD would be productive; the anticipated impacts, however, fall short of the goal of protecting the health of local residents, as there are still more than 33 million people living in places where the annual mean ambient PM_{2.5} concentrations are greater than 35 μg m⁻³, the interim target-3 of the World Health Organization (WHO). We therefore propose the next steps for air pollution control that are important not only for the PRD but also for all other regions of China as they develop and implement effective air pollution control policies.

Abbreviations

| Definition | Abbreviation | | |
|---|-------------------|--|------|
| Pearl River Delta | PRD | Cyclone dust collector | CYC |
| Particulate matter less than 2.5 μm in diameter | PM _{2.5} | Wet scrubber | WET |
| Volatile organic compound | VOC | Electrostatic precipitator | ESP |
| World Health Organization | WHO | High efficiency electrostatic precipitator | ESP2 |
| | | Fabric filters | FF |

| | |
|---|------|
| Flue gas desulfurization | FGD |
| Low NO _x combustion technology | LNB |
| Selective catalytic reduction | SCR |
| Selective noncatalytic reduction | SNCR |

1. Introduction

Faced with worsening air pollution, the Chinese government has been showing strong determination to combat the pollution. From the 11th Five Year Plan (FYP) for SO₂ control to the 12th FYP for NO_x control, dozens of policies have been released at an accelerated rate in an attempt to limit emissions increases and curb the worsening air quality. In 2013, China launched the most comprehensive and ambitious air pollution policy to date, the *Air Pollution Prevention and Control Action Plan* (Action Plan), to guide near-term air pollution control. This marks an unprecedented effort by the government to reduce air pollution levels (China's State Council 2013). Hundreds of billions of US dollars were invested to implement specific policies on emission abatement, energy structure adjustment and industrial structure optimization (Huo *et al* 2014). However, the actual performance of the Action Plan has not been well evaluated (He *et al* 2014).

Health impacts, as the most direct effect, are always estimated to reveal the subsequent social effects and economic losses that are attributable to air pollution. Several studies have evaluated the health effects of China's air pollution at the national level (e.g., World Bank 2007, He *et al* 2010, Lim *et al* 2012, Chen *et al* 2013). For instance, the latest research from Global Burden Diseases (GBD) reported that 1.2 million annual deaths in China are caused by exposure to outdoor PM_{2.5} air pollution (Lim *et al* 2012). Contributions from specific emissions sources such as households have also been evaluated (Zhang and Smith 2007). At the regional level, the health effects associated with pollution have been quantitatively estimated in Shanghai (Kan and Chen 2004), Beijing (Zhang *et al* 2007a), the PRD (Huang *et al* 2012), and other parts of China (e.g., Shandong (Wang and Mauzerall 2006)), all of which identified significant health impacts of air pollution on local residents. For example, according to Kan and Chen (2004), air pollution induced more than 4000 premature deaths in Shanghai in 2001, which is nearly 20% of the US total in the same period (Mokdad *et al* 2004). Given these considerable health impacts of air pollution in China, estimating the potential health benefits from air pollution control provides an effective means of evaluating the performance of control policies.

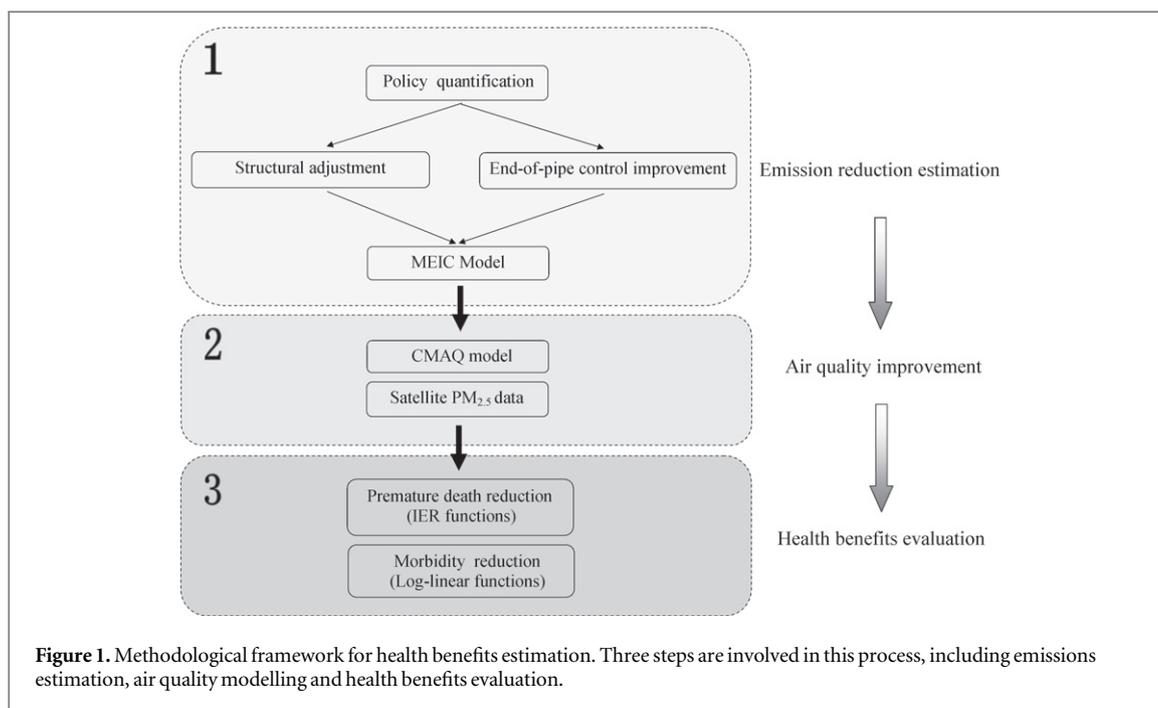
Several studies have quantified the health benefits of air pollution control in different regions (e.g., Streets *et al* 1999, Kan *et al* 2004, Li *et al* 2004, He *et al* 2010, Zhou *et al* 2010). For example, Li *et al* (2004)

estimated that more than 4000 deaths in 2020 could be avoided in Shanghai by adopting advanced power generation technology and effectively controlling industrial coal consumption. Recently, the health benefits from air quality improvements in Taiyuan from 2001 to 2010 were evaluated by Tang *et al* (2014). Through several initiatives and mandated factory shutdowns, they found that the annual average PM₁₀ concentration in Taiyuan decreased from 196 $\mu\text{g m}^{-3}$ to 89 $\mu\text{g m}^{-3}$ during the period 2001–2010, preventing more than 2000 deaths annually relative to 2001 levels (Tang *et al* 2014). Although numerous studies have investigated the health benefits of air pollution control, to the best of our knowledge, until now, no study has estimated the potential health benefits related to the implementation of the Action Plan, one of the most important policies in the history of Chinese air pollution control.

Our study will fill this gap by evaluating the air quality improvements and health benefits of curbing air pollution in the PRD area as a result of the Action Plan. The PRD region is one of the most economically vibrant regions in China and is well-known for export manufacturing. The prosperity of the manufacturing industry has attracted millions of laborers, making this region one of the most densely populated regions, with more than 56 million people residing within an area of 56 000 km² (>1000 residents/km²). Accompanying the rapid economic development, the region has experienced air quality deterioration in recent years. According to 52-year records between 1954 and 2006, the annual number of haze days in Guangzhou, the central city in the PRD, has increased rapidly (Deng *et al* 2008, Wang *et al* 2012). PM_{2.5} has been identified as the major pollutant in the PRD (Andreae *et al* 2008, Xu *et al* 2008, Peng *et al* 2011, Wang *et al* 2012). Over 12 000 premature deaths attributable to particulate air pollution were estimated in the PRD area in 2006 (Huang *et al* 2012).

Realizing the significant adverse health impacts caused by air pollution, the central government designated the PRD as one of the key control regions in the Action Plan and required this region to lower its PM_{2.5} concentration by 15% from 2012–2017. In response to the national Action Plan, the Guangdong government released the *Guangdong Air Pollution Prevention and Control Action Plan (2014–2017)* in 2014 (People's Government of Guangdong Province 2014), in which specific goals and more detailed control measures were introduced to achieve the goal set in the national Action Plan (People's Government of Guangdong Province 2014).

This study makes a first attempt to investigate the air quality improvements and health benefits resulting from implementation of the Action Plan in the PRD. The proposed measures are quantified individually to estimate emissions reductions from 2012 to 2017. By employing a state-of-the-art method, including an air quality model, concentration-response health



functions and satellite-based $PM_{2.5}$ concentrations, air quality improvements and associated health benefits are fully revealed. The analysis also evaluates the performance of the Action Plan from a health perspective and identifies the key next steps for air pollution control.

2. Methodology and data

Three models were integrated in this study to evaluate the health impacts of the Action Plan (figure 1). First, we used the Multi-resolution Emission Inventory for China (MEIC) to estimate the emissions reductions associated with the Action Plan in the PRD. $PM_{2.5}$ concentrations before and after emission abatement were estimated using the community multi-scale air quality modeling system (CMAQ) combined with satellite based $PM_{2.5}$ values. Finally, two types of health models were used to evaluate mortality and morbidity reductions as a result of $PM_{2.5}$ concentration change. These three procedures are discussed in detail in the following sections.

2.1. Emissions reduction estimation

The base year air pollutants emission inventory was directly obtained from the MEIC model (www.meicmodel.org). The MEIC is a technology-based bottom-up air pollutant inventory developed by Tsinghua University which covers 10 pollutants and greenhouse gases. The methodologies and data on which the MEIC is based have been described in our previous studies (Zhang *et al* 2009, Lei *et al* 2011, Zheng *et al* 2014).

Following a previous assessment (He *et al* 2014), emissions in the PRD for 2017 were estimated by

adjusting certain parameters for emissions estimates according to specific control measures. The emission reductions as a result of these measures can then be estimated from the emission difference between before and after policy implementation. Table 1 lists all of the quantifiable control measures proposed in the Action Plan. It is worth noting that some other policies (e.g., *Guangdong Energy Saving and the Low-Carbon Development Action Plan 2014–2015*) will be concurrently implemented during the Action Plan and might also affect air quality in the PRD. In this work, the impacts of those policies have also been considered. The main parameters used for emissions calculations in 2012 and 2017 are presented in table S1 (energy use and product outputs, activity level), table S2 (end-of-pipe control technologies and their penetration rate), and table S3 (emissions factors).

2.2. $PM_{2.5}$ air quality improvement

Several epidemiological studies have shown that air pollutants such as SO_2 , PM , O_3 , and CO are closely correlated with various adverse health effects (Pope *et al* 2002, Venners *et al* 2003, Wong *et al* 2008). However, it is impossible to separately quantify their individual health impacts as these pollutants are closely correlated (Tang *et al* 2014). Summing the health effects from each air pollutant would cause a double counting problem. We therefore chose $PM_{2.5}$, the most robust indicator of long-term mortality, to conduct the health benefit evaluation (World Health Organization 2003, Kappos *et al* 2004). Following the approach used in GBD 2010 (Lim *et al* 2012), we used satellite-based $PM_{2.5}$ concentrations in 2013 (figure S1) as the current exposure level. The $PM_{2.5}$ related air quality improvements from the Action Plan were

Table 1. Quantifiable control measures proposed in the Guangdong Action Plan.

| Measure No. | Types | Sectors | Target pollutants | Measures | Sources |
|-------------|--|---------------------|---|---|--------------|
| E-1 | Energy structure adjustment | Power | All | By 2017, the installed capacity of operational nuclear power plants will reach >9.6 million kW, and the proportion of non-fossil fuel consumption will increase to >20% in Guangdong Province. | Policy 1 |
| E-2 | | | All | Further increased electricity transfer from other provinces. | Policy 1 |
| E-3 | | | All | By the end of 2017, nearly all captive coal-power plants of <100 000 kW capacity will be replaced with clean energy such as natural gas in the PRD. | Policy 1 |
| E-4 | | Industry | All | Small industrial coal-burning boilers (<4t/h capacity and >8 year lifetime at 4-10 t/h) will be replaced with clean energy or converted into central heating. | Policy 2 |
| E-5 | | Residential | All | By the end of 2017, all urban districts in Guangdong Province are forbidden to burn raw coal, washed coal, coal slurry, briquettes, coke, charcoal, coal, coal tar, fuel oil, residual oil, and combustible waste; direct burning of biomass and other high-polluting fuels is forbidden; burning of diesel, kerosene, artificial gas and other gases beyond established limits is forbidden. | Policy 1 |
| I-1 | Industrial structure adjustment | Industry | PM _{2.5} , SO ₂ | A total of 258 8000 tons of backward steel production capacity will be phased out. | Policy 1&3&4 |
| I-2 | | | NO _x , SO ₂ , VOC | A total of 177 110 00 tons of backward cement production capacity will be phased out. | Policy 1&3&4 |
| I-3 | | | All | The PRD prioritizes the development of the modern service industry. The development of advanced manufacturing for high-tech industries will be accelerated. | Policy 1 |
| P-1 | Stationary sources end-of-pipe control | Power | SO ₂ | Employing desulfurization bypass in new thermal power is forbidden; by the end of 2014, remove all flue gas desulfurization facility bypass in the serving coal-fired furnace in Guangdong Province; the integrated desulfurization rate of the coal-fired thermal plants with power >125 000 kW capacity will reach >95%. | Policy 1 |
| P-2 | | | NO _x | By the end of 2014, the active coal-fired thermal power plant of >125 000 kW will complete low NO _x combustion and flue gas denitrification transformation (excluding CFB boiler generation units); if CFB discharge cannot stably reach emission standards, installation of the denitrification facilities is required; the comprehensive denitration efficiency will exceed 85%. | Policy 1 |
| P-3 | | | PM _{2.5} | From July 1, 2014, all coal-fired units in the PRD region will follow special soot emissions limits established in <i>Thermal Power Plant Air Pollutant Emission Standard (GB 13223-2011)</i> ; other regions will follow soot emissions limits set in this standard. | Policy 1 |
| P-4 | | NO _x | Dry, low NO _x combustion technologies in gas-fired units will be widely adopted. | Policy 1 | |
| P-5 | | Industry (boiler) | SO ₂ | Less than 0.6% of sulfur content will be allowed in coal burned in industrial boilers and kilns. | Policy 1 |
| P-6 | | Industry (boiler) | SO ₂ | FGD installation will be required in industrial boilers exceeding 20 t/h capacity. | Policy 1&5 |
| P-7 | | Industry (boiler) | NO _x | LNB installation will be required in >35t/h capacity boilers; SNCR installation will be promoted in >65 t/h capacity boilers. | Policy 1&5 |
| P-8 | | Industry (boiler) | PM _{2.5} | Coal-fired industrial boiler flue gas will be treated. | Policy 1&5 |
| P-9 | | Industry (ceramics) | SO ₂ | | Policy 1 |

Table 1. (Continued.)

| Measure No. | Types | Sectors | Target pollutants | Measures | Sources |
|-------------|----------------|-----------------------|---|--|----------|
| P-10 | | | PM _{2.5} | By the end of 2015, the kilns used by building ceramics manufacturers with >700 0000 m ² /year capacity and sulfur content >0.5% will be replaced by clean energy facilities or FGD and dust removal facilities will be installed; the emissions should satisfy the <i>Emission standard of air pollutants for ceramics industry (GB 25464-2010)</i> . | Policy 1 |
| P-11 | | Industry (flat glass) | SO ₂ | By the end of 2015, the kilns used by flat glass manufacturers with >700 0000 m ² /year capacity and sulfur content >0.5% will be replaced by clean energy facilities or FGD and dust removal facilities | Policy 1 |
| P-12 | | | PM _{2.5} | will be installed; emissions levels should satisfy <i>Emission standards of air pollutants for the flat glass industry (GB 26453-2011)</i> . | Policy 1 |
| P-13 | | Industry (cement) | NO _x | LNB and SNCR facilities will be installed in active dry cement clinker production lines of greater than 2000 t/d capacity; active dry cement clinker production lines of less than 2000 t/d (excluding 2000) capacity in Guangdong Province must gradually adopt the LNB. | Policy 1 |
| P-14 | | Industry (sinter) | SO ₂ | By the end of 2015, FGD installation in steel-sintering machines in Guangdong Province will be completed. | Policy 1 |
| P-15 | | Industry (steel) | PM _{2.5} | Particulate end-of-pipe control measures will be implemented in three steel companies in the PRD and in surrounding areas. | Policy 6 |
| P-17 | Mobile sources | Transport | NO _x , PM _{2.5} , SO ₂ , VOC | 1. By the end of 2017, the yellow-label cars in Guangdong Province will be nearly eliminated. 2. With central government approval, the PRD will advance the implementation of Euro5 emissions standards for light gasoline vehicles and the province will implement Euro5 diesel emissions standards. | Policy 1 |
| V-1 | VOC control | Industry | VOC | 1. By the end of 2017, all key enterprises in the areas of oil refining, organic chemicals and pharmaceutical chemicals will fully develop LDAR technologies; oil refining and chemical companies will be equipped for comprehensive organic waste treatment. 2. Enterprises producing coatings, inks, adhesives, and pesticides will apply chrysalis airtight integration technologies for uniform collection, volatilization and purification at a >90% purification rate. 3. By the end of 2014, all gas stations, oil depots, tankers and tank areas will meet oil and gas recycling management and on-line monitoring requirements. | Policy 1 |
| V-2 | | | VOC | The use of organic solvents will be gradually reduced, and the use of liquid or low-volatile architectural coatings, wood coatings and adhesives will be promoted. The PRD will achieve >50% usage of liquid paints or paints generating low VOC emissions; for new motor vehicle painting projects, >80% usage of liquid paints and other low-emission VOC coatings will be achieved. | Policy 1 |

Policy 1: Guangdong Action Plan.

Policy 2: Industrial Boiler Pollution Control Work Plan for Guangdong Province 2012–2015.

Policy 3: announcement of the elimination of backwards and over-capacity industries in Guangdong Province in 2013 and 2014.

Policy 4: Guangdong Energy Saving and Low-Carbon development Action Plan 2014–2015.

Policy 5: Guangdong Province '12th five year plan' after half of the total amount of major pollutants emission reduction.

Policy 6: the air pollution management program for the PRD and the surrounding's key industries.

obtained by multiplying the satellite-based $PM_{2.5}$ concentrations by the CMAQ simulated $PM_{2.5}$ ratios in 2013 and 2017. The gridded satellite-derived $PM_{2.5}$ concentrations were obtained from Zheng *et al* (2015), who developed a linear mixed-effects (LMEs) model to make the gridded surface $PM_{2.5}$ estimation. More details about the satellite retrieval can be found in the supplementary information. We applied the CMAQ model V.5.0.1, with the CB05 chemical mechanism and AERO6 aerosol module, and the offline-coupled weather research and forecasting (WRF) model V.3.5.1 to perform the air quality simulation which was further employed to obtain the $PM_{2.5}$ ratios. It should be noted that open biomass burning was not considered in this study. Moreover, anthropogenic emissions outside of Guangdong Province remain constant for the 2013 and 2017 $PM_{2.5}$ simulations; thus, the calculated changes are a response solely to the emissions reductions in Guangdong Province (including PRD and non-PRD cities). Full details regarding the CMAQ modeling are presented in the supplementary information.

2.3. Health benefits evaluation

Both mortality and morbidity were considered to represent the health benefits of air pollution control in the PRD region. The $PM_{2.5}$ concentrations estimated in the previous section were utilized in health impact functions (equations (1) and (2)) to calculate the health outcomes. For long-term mortality, we employed the IER functions developed by Burnett *et al* (2014) to perform the health benefits estimations due to the limitations of a $PM_{2.5}$ cohort study in China. The IER mortality estimation is based on four leading causes of deaths: ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), stroke and lung cancer (LC). These four specific diseases share the same health impact function but with varied parameters (table S6).

The relative RR for mortality estimation was calculated as,

$$RR(C) = \begin{cases} 1 + \alpha \left(1 - e^{-\gamma(C-C_0)^\delta} \right), & \text{if } C > C_0 \\ 1, & \text{else} \end{cases} \quad (1)$$

where C is the annual $PM_{2.5}$ concentrations in 2013 and 2017; C_0 is the counterfactual concentration; and α , γ , and δ are parameters used to describe the shape of the concentration-response curve, as presented in table S6.

For morbidity, we selected cardiovascular and respiratory hospital admissions as health endpoints for evaluation. The log-linear response function was applied to estimate health outcomes (equation (2)). The relative RR for morbidity estimation was calculated as

$$RR = e^{\beta x} \quad (2)$$

where β is the parameter to describe the curve, also listed in table S6.

The above RR was then converted to the attributable fraction (AF), defined as,

$$AF = \frac{RR - 1}{RR} \quad (3)$$

Based on equation (3) (Ostro 2004), the health outcomes attributable to $PM_{2.5}$ can then be estimated as,

$$E = AF \times B \times P \quad (4)$$

where B is the baseline incidence of the given health effect and P is the LandScan global population database for 2010 at 1 km resolution. The baseline incidence of the corresponding health endpoints (as shown in table S6) is mainly estimated from data in the Health Statistics Yearbook of Guangdong Province 2012 (Department of Health of Guangdong Province 2013).

3. Results

3.1. Energy consumption

Fossil fuel combustion is the primary source of air pollutants (Zhang *et al* 2007b, Guan *et al* 2014). The power, industry, residential and transportation sectors constitute the total fossil fuel consumption in the PRD region. In 2012, approximately 160 million tons of standard coal equivalent (tce) fossil fuels were consumed in the PRD, accounting for 74% of the overall in Guangdong Province. The power sector was the largest consumer, using 44% of the fuel (figure 2). Industry in the PRD was sustained by extensive fuel consumption, accounting for almost 38% of the fuel. The residential and transportation sectors shared the rest, representing 18% of the total. Coal and coal-derived products were the dominant energy sources, accounting for 66% of energy, almost all of which (~99.5%) was consumed in the power and industry sectors (figure 2). Petroleum was the second largest fuel type (27% of the total), which mainly supported the industry, residential and transportation sectors. Natural gas was consumed less, representing 6% of the fuel. Biomass, mainly used in rural areas, had a noticeable share (i.e. 24%) in the residential sector, which accounted for 1% of the total energy consumption.

Reducing dependence on fossil fuels is an essential part of emissions abatement to improve air quality. By employing the energy elasticity of GDP (Bhattacharyya 2011), the energy demands in the power and industry sectors were estimated to increase by 22% and 28%, respectively, from 2012 to 2017. To curb the increasing consumption of fossil fuels, the Action Plan proposed several measures to reshape the energy and industrial structures. For example, to reduce the fossil fuel consumption in the power sector, the Guangdong

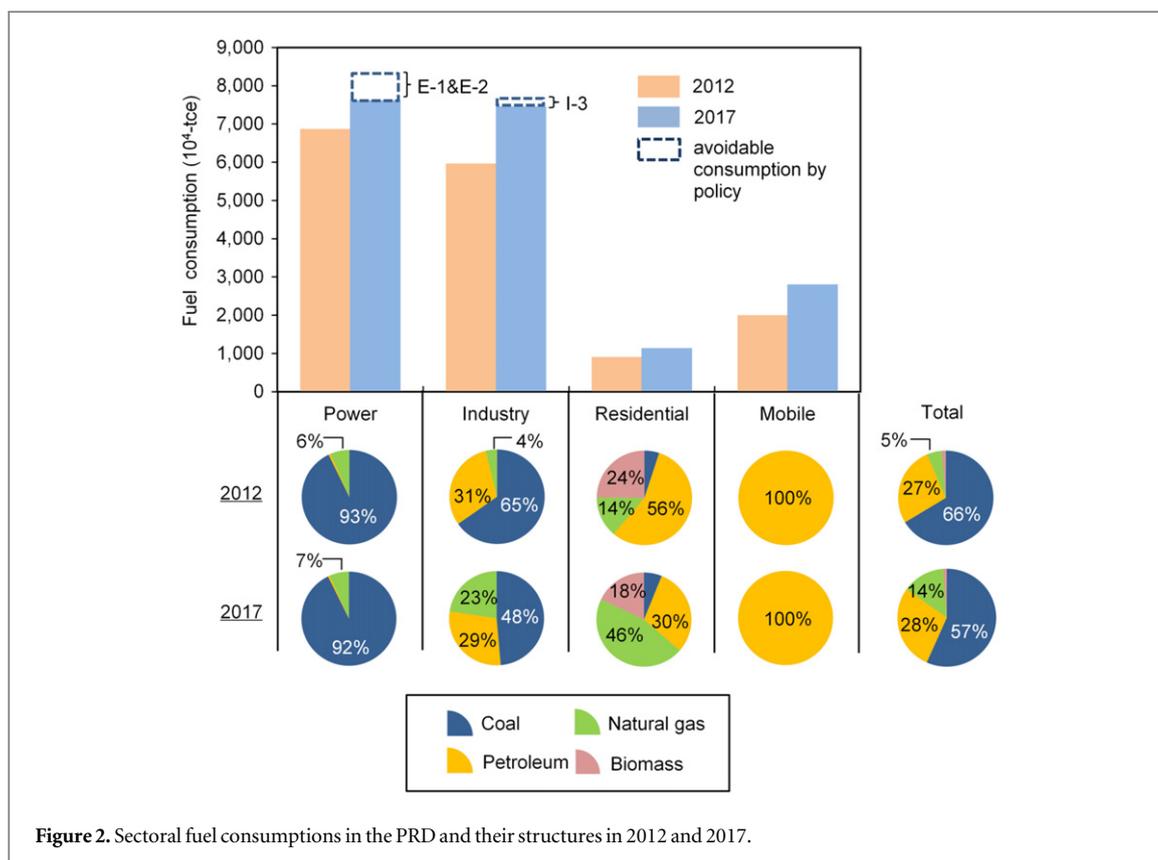


Figure 2. Sectoral fuel consumptions in the PRD and their structures in 2012 and 2017.

government advocated the development of non-fossil fuel based electricity (i.e., nuclear and renewable) and an increase in electricity transfer from neighboring provinces (table 1, E-1 and E-2). The above measures would reduce fuel demand by 11% in the power sector compared to that forecast by the electricity elasticity coefficient (as shown in figure 2). Modifying the industrial structure (table 1, I-3) would also be effective in reducing fossil fuel consumption and therefore allow a decrease in the pollution levels (figure 2). In fact, since the 11th FYP, the Guangdong government has determined to prioritize the development of modern service industry in the PRD region (Pearl River Delta Reform and Development Plan (2008–2020)). To improve air quality, this policy was further stressed in the Action Plan, which is capable of reducing fuel consumption compared to that forecast by the elasticity coefficient. For the urban and rural residential sectors, we derived their energy demands in 2017 through a simple extrapolation by utilizing the linearity of both sectors' short term growth trend. For mobile sources, the energy consumptions for on-road and off-road vehicles in 2017 were estimated using the method described in Zheng *et al* (2014). On this basis, fuel consumption for the power, industry, urban residential and rural residential sectors was expected to increase by 11%, 25%, 35% and 13%, respectively, considering both demand increases and the influence of policy.

Shrinking the proportion of coal in the energy system and switching coal to natural gas is another important task in the Plan. A series of stringent

measures have been prompted to control coal use. For example, by the end of 2017, all urban districts in Guangdong Province are forbidden to burn raw coal, washed coal, coal slurry, briquettes, coke, charcoal, coal, coal tar, fuel oil, residual oil and combustible waste (table 1, E-5). Meanwhile, the Guangdong government is planning to increase the natural gas supply, aiming to raise the supply capacity up to approximately 50 billion m³. Urban households will be given priority access to the clean energy, rendering natural gas to become the dominant primary energy source for the residential sector (46%, figure 2), though in rural households, 80% of fuel will still be supported by coal and biomass. For the industrial sector, small coal boilers with capacities <10t/h are required to complete the energy replacement by the end of 2017 as these small boilers contribute to almost 30% of all of SO₂ and PM_{2.5} emissions, but are responsible for less than 20% of heating. Natural gas would be the primary substitute. As a result, the share of coal in the industry sector would decline from 65% to 48%, whereas the share natural gas would increase from 4% to 23%. From the PRD perspective, though coal and its derived products will continue to dominate the energy supply, the total consumption of coal based energy will remain almost constant at approximately 10 000 tce. Natural gas consumption, however, will go up to ~27 billion m³ accounting for 14% of the total energy consumption in 2017 (figure 2).

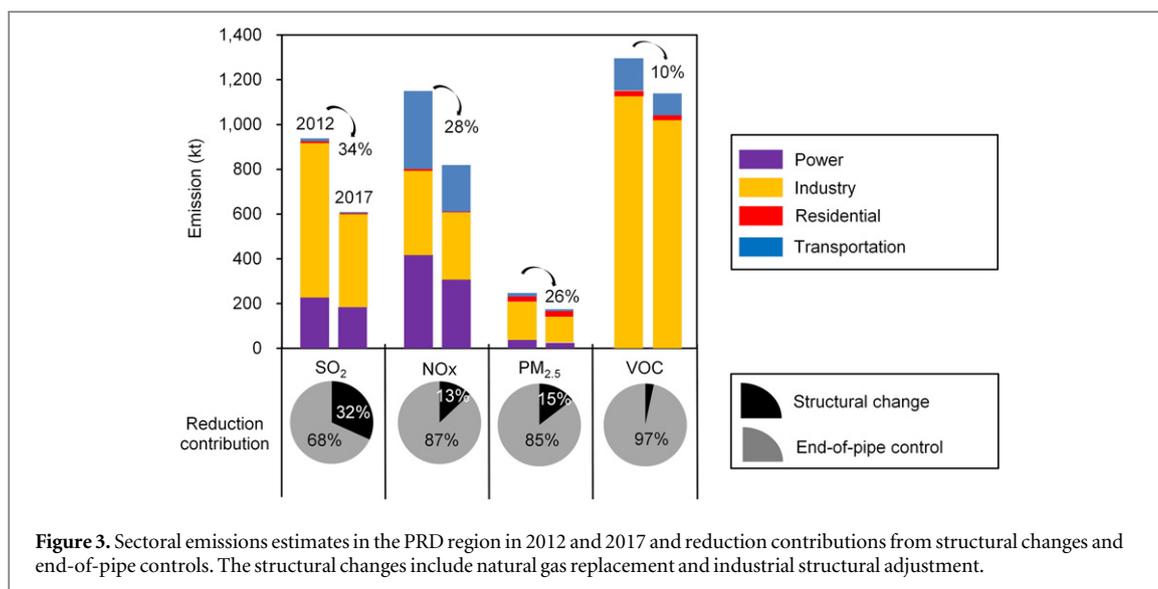


Figure 3. Sectoral emissions estimates in the PRD region in 2012 and 2017 and reduction contributions from structural changes and end-of-pipe controls. The structural changes include natural gas replacement and industrial structural adjustment.

3.2. Emissions reduction

Figure 3 presents the emissions estimates for SO₂, NO_x, PM_{2.5}, and VOC from different sectors in 2012 and 2017. According to the MEIC model, anthropogenic emissions in the PRD region in 2012 were 948 kt SO₂, 1158 kt NO_x, 261 kt PM_{2.5}, and 1305 kt VOC. Industry is the largest emitter of SO₂, PM_{2.5}, and VOC, contributing 73.5%, 67%, and 86.1% of the total emissions, respectively, though its coal consumption is less than that of the power. Lower control efficiency levels and the restricted coverage of end-of-pipe control devices in industry are responsible for the higher emissions (table S2). The power, industry, and transportation sectors almost equally contributed to the NO_x emissions in 2012. The above emissions estimates are basically consistent with previous estimates made in the PRD region (Zheng *et al* 2009, Lu *et al* 2013).

With the implementation of the Action Plan, SO₂, NO_x, PM_{2.5}, and VOC emissions in the PRD are expected to be reduced by 34%, 28%, 26%, and 10% respectively in the period 2012–2017 (figure 3). Table S7 presents the individual emissions abatement levels for each measure. Two types of measures are simultaneously working on this emissions reduction process, end-of-pipe controls and structural modifications (including the energy structure and industrial structure optimization). As shown in figure 3, end-of-pipe controls contribute the majority of emissions reductions, accounting for 68% of SO₂, 87% of NO_x, 85% of PM_{2.5}, and 97% of VOC. Because efficient removal equipment was not widely deployed across Guangdong in 2012, increasing the coverage of upgraded end-of-pipe controls such as FGD (flue gas desulfurization), SCR (selective catalytic reduction), ESP (electrostatic precipitator) and LNB (low NO_x combustion technology) will effectively reduce emissions, leading to its dominant role in total emission abatements. In particular, measures targeting the main combustion

sources that lacked efficient treatment in 2012 will be most effective. For example, according to the Action Plan, over 90% of coal power plants are required to be equipped with SCR and LNB by 2017. Achieving this goal would correspond to nearly 100% coverage of this technology in terms of coal combustion and is expected to cut ~153 kt NO_x, becoming the biggest contributor to NO_x reductions (table 2, P-6). Industrial boilers, another important combustion source of air pollutants, will be better controlled in 2017 by both the energy structure improvement and upgrade of pollution control equipment. Specifically, using natural gas rather than coal industrial boilers is expected to decrease SO₂ and PM_{2.5} emissions by 255 kt (40% of total reductions, table 2, E-4) and 18.7 kt (20% of total reductions, table 2, E-4), respectively. Raising the FGD penetration rate (table 2, P-2) and upgrading the PM removal equipment from wet scrubbers to electrostatic precipitators (table 2, P-8) could further reduce 178 kt SO₂ (25% of total reductions) and 34.5 kt PM_{2.5} (25% of total reductions) in industrial boilers. For NO_x and VOC, measures in the transportation sector would also be crucial, accounting for nearly 30% of both controls. Relative to SO₂, NO_x, and PM_{2.5} measures, VOC control is expected to be less effective, especially for solvent use which is the greatest source of emissions, and is the most challenging component for VOC control. Because of the wide application (e.g. architectural paints/coatings, printing inks, furniture production), the emission sources of VOC are more widely dispersed and include some small factories that lack control measures. Such conditions require a more scientific and stricter supervision system to achieve the control targets. In contrast, due to the lack of a national emissions standard, VOC regulations lack strict supervision even though the local government has issued several regulations for different industries (Zheng *et al* 2013). As a result, many policies did not achieve the expected performance (Zheng

Table 2. Sectoral contributions and the top five control measures contributing to emissions reductions in the PRD region.

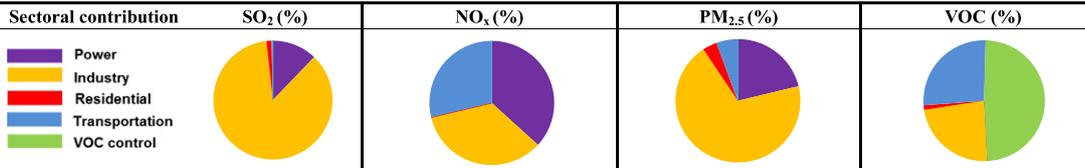
| Sectoral contribution | SO ₂ (%) | NO _x (%) | PM _{2.5} (%) | VOC (%) | | | |
|--|---------------------|---------------------|-----------------------|------------|-----------------------|------------|---------|
|  | | | | | | | |
| Policy No. | SO ₂ (t) | Policy No. | NO _x (t) | Policy No. | PM _{2.5} (t) | Policy No. | VOC (t) |
| E-4 | 255,000 | P-2 | 153,000 | P-8 | 34,500 | V-1 | 64,000 |
| P-6 | 178,000 | P-17 | 136,000 | P-3 | 20,500 | P-17 | 44,000 |
| P-1 | 74,900 | I-2 | 65,600 | E-4 | 18,700 | E-4 | 27,000 |
| P-5 | 51,800 | E-4 | 53,500 | I-2 | 7,900 | V-2 | 16,000 |
| P-9 | 31,300 | P-7 | 25,500 | P-17 | 5,500 | I-2 | 11,000 |

Table 3. The avoided health outcomes attributable to the Action Plan induced air quality improvement in each year after 2017.

| | Health benefits per year | | |
|---------------------------|--------------------------|-------|-------|
| | Mean | Lower | Upper |
| Death | 2920 | 1523 | 4636 |
| LC | 402 | 195 | 489 |
| COPD | 271 | 162 | 339 |
| Stroke | 1295 | 450 | 1967 |
| IHD | 952 | 716 | 1841 |
| Hospital admission | 4367 | 466 | 7996 |
| Respiratory | 1958 | 0 | 3754 |
| Cardiovascular | 2409 | 466 | 4242 |

et al 2013). Based on the above, we conservatively evaluate the effectiveness of VOC control policies because the corresponding management system cannot keep pace.

Measures targeting air pollution might have the co-benefit of CO₂ reduction. Without the Action Plan, annual CO₂ emissions in Guangdong are expected to surge from ~430 to ~495 million tons, increasing by ~15%. Implementation of the Action Plan would effectively curb this surge, reducing the increase from 15% to 6%. Natural gas replacement plays an important role in this emissions restriction. To ensure a sustainable natural gas supply, various sources have been proposed, including extraction from the sea and importation from the international market and western China. However, the long-range transfer will inevitably induce methane leakage, the primary component of natural gas, and therefore might increase GHG emissions elsewhere.

Emissions reductions in Guangdong Province outside of the PRD were also evaluated. Tables S1 and S2 list the parameters used to make the emissions estimates for these two years and measure-by-measure emissions abatements are presented in table S7. In summary, though the extent of emission reduction is estimated to be lower in the non-PRD region, SO₂, NO_x, PM_{2.5} and VOC emissions in 2017 are expected

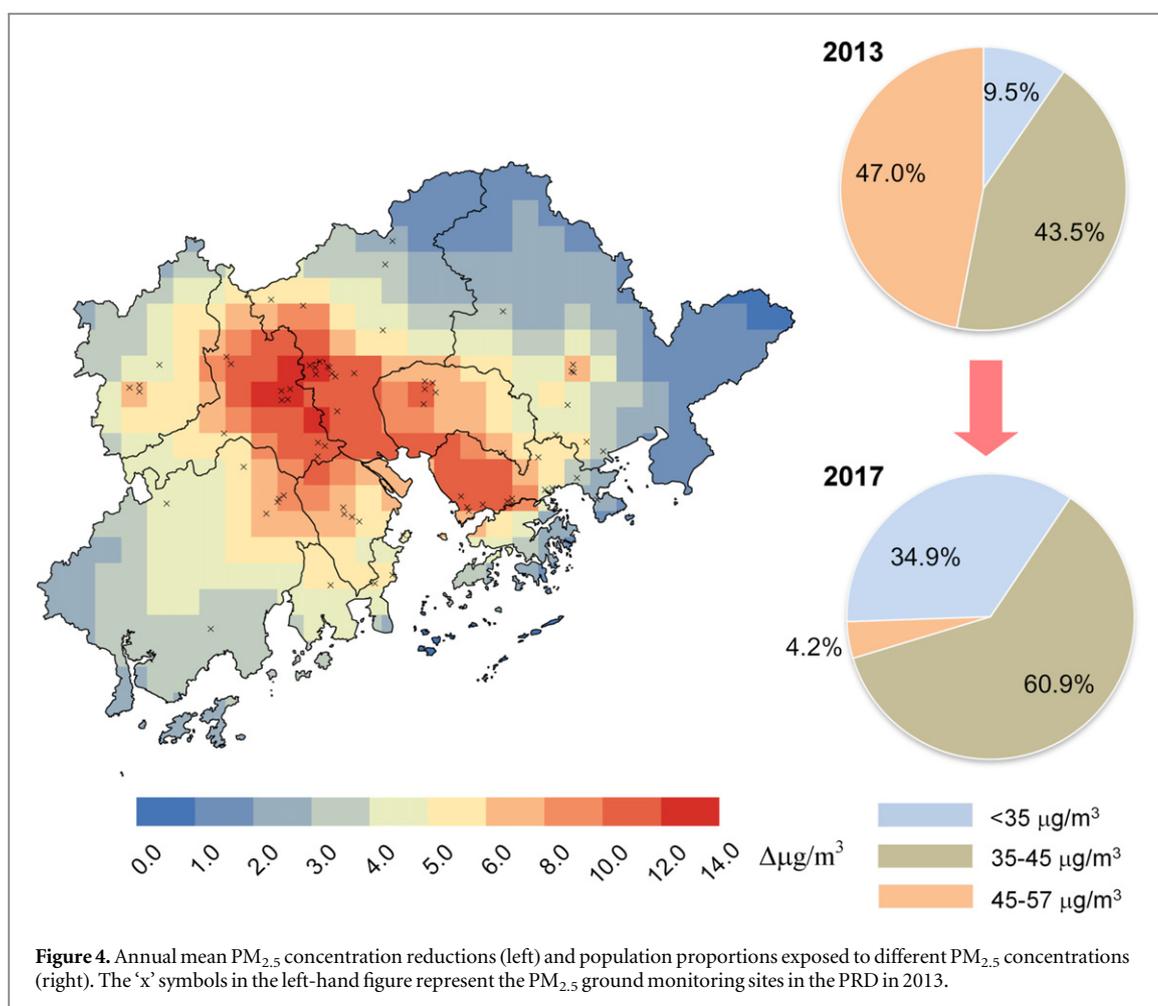
to decrease by 20%, 21%, 6% and 6%, respectively, compared to the 2012 levels.

3.3. Air quality improvement and health benefits estimation

PM_{2.5} is the primary air pollutant in the PRD region (Department of Environmental Protection of Guangdong Province 2014). Based on the satellite derived data, the annual average PM_{2.5} concentration at the monitoring sites was estimated to be 46 μg m⁻³ in 2013 (figure S1), which exceeds the recommended interim-3 target of the World Health Organization (WHO) (35 μg m⁻³) by 32%. Secondary PM_{2.5} (based on the CMAQ model) accounts for 42% of the total (table S8). More than 51 million residents (~91% of the total PRD population, figure 4, right) live in the places where PM_{2.5} concentrations exceed 35 μg m⁻³.

Imposing the Action Plan and its related policies is expected to reduce the annual average PM_{2.5} concentration by 17% (from 46 μg m⁻³ to 38 μg m⁻³) and such a reduction would help the PRD region achieve the 15% reduction target set by the central government. All of the components in the PM_{2.5} modeling simulations indicate a downward trend, but they vary greatly, ranging from a 1.5% decrease for NO₃⁻ to 22.8% for other fine PM. The primary PM_{2.5} decreased proportionately to the emission change (e.g. BC), whereas the secondary PM_{2.5} exhibited a less-than-proportional reduction (e.g. SO₄²⁻), especially for nitrate due to the relatively limited emission reduction of VOCs.

Almost all PRD residents (>99%) will benefit from the improved air quality, with the largest improvement reaching 11.3 μg m⁻³ (figure 4, left). In particular, the percentage of people living with concentrations of more than 35 μg m⁻³ will be reduced from 90.5% in 2012 to 65.1% in 2017, lifting more than 14.4 million people from poor PM_{2.5} air quality (figure 4, right). Such air quality improvement is capable of preventing more than 2900 premature deaths and 4300 hospital admissions on the basis of the health



benefit estimation using concentration-response functions, representing 8% and 14% of the respective total health outcomes in 2012 (table 3).

3.4. Air pollution control in the post-Action Plan period in the PRD

Though we find that the Action Plan has shown promise in achieving the targets, the efforts toward air pollution control should continue beyond the Action Plan, as more than 33 million (~65% of total population in the PRD) people will still be living with $>35 \mu g m^{-3}$ $PM_{2.5}$. This outcome is obviously far from the ultimate goal of protecting the human health of local residents. However, further pollution control may become more difficult as the reduction space of end-of-pipe treatment increasingly approaches the ceiling. Furthermore, continuing the end-of-pipe dominated approach to pollution control would result in sharp increases in the cost of reduction (Pinder and Adams 2007). Therefore, to achieve efficient pollution control, a transition from an end-of-pipe dominated system to a structurally focused control should be implemented in the post-Action Plan period in the PRD. In particular, important sources that are omitted from the Action Plan should be given greater attention. Moreover, further efforts should give simultaneous consideration to the issue of climate change, a

longer health threat, which seems distant but has already shown consequences, to achieve a win-win situation.

Structural reduction instead of the end-of-pipe treatment will play a more important role in the post-Action Plan period and therefore deserves greater attention. After the Action Plan, the polluting energy sources such as coal will still retain a noticeable share in the energy system (57% of the fossil fuel) and some highly polluting industries, such as ceramics, will not have been restricted. Therefore, structural changes such as the accelerating elimination of heavily polluting industry and the development of renewable energy would be effective means to reduce pollution following implementation of the Action Plan. In addition to the air quality related advantage, more renewable energy would be beneficial to climate change mitigation as massive natural gas application has the potential to increase GHG as a result of methane leakage (Alvarez *et al* 2012). Moreover, the overall climate effect of substitution from coal to gas is highly uncertain, depending on the particular sources of replacement (e.g., power plants release SO_2 but very small amounts of black carbon, whereas biofuel combustion emits large amounts of black carbon but less SO_2) (Bond *et al* 2013).

In a broader approach to pollution control, pollution in rural areas must be given greater attention. Rural households contributed 10% of primary PM_{2.5} emissions in 2012 which is consistent with a previous study (Huang *et al* 2014). However, the health impacts from residential cooking could be enormous as residents typically spend more than 90% of their time indoors (Spengler and Sexton 1983, Zhang and Smith 2007). Moreover, solid fuels consumed in rural households are commonly inefficiently combusted in open cooking stoves, without any control measure, and the impacts will likely be worse because of the higher concentrations in an enclosed indoor space (Spengler and Sexton 1983, Zhang and Smith 2007). However, in the Action Plan, pollution from rural households has not received sufficient attention; no specific measure has been prescribed to reduce solid fuel combustion in rural households. As a result, solid fuels (coal and biomass) would still comprise ~80% of rural households' energy system after the Action Plan. Therefore, from a health perspective, replacing solid fuels with clean energy in rural households is imperative and requires urgent implementation in the post-Action Plan period.

Along with the air pollution control strategy, the government must establish a corresponding control management system to support policy implementation. China's pollution control system frequently adopts strict control measures without creating the conditions for strict implementation. In terms of the PRD, a typical example of this relates to VOC control. Zheng *et al* (2013) found that previous control policies for the wood furniture industry, a major source of VOC emissions in the PRD, have not been well implemented. Many factories either did not install the VOC control devices required by the new policy or the installed control devices were not set up to work regularly or efficiently (Zheng *et al* 2013). Designing a scientific pollution supervision system for air pollution management is in practice more important for VOC control.

Another important issue that should be addressed in the post-Action Plan period is regional air pollution transport from the non-PRD region. To seek new sources of economic growth, the Guangdong government is determined to develop heavy industries in its western and eastern areas (People's Government of Guangdong Province 2014). These can be expected to generate substantial levels of air pollutants and will inevitably affect air quality in the cities of the PRD. As a pioneer of regional air pollution control, the PRD area has experience in regional cooperation at the city level (Zhong *et al* 2013). This cooperation mechanism should be extended to the non-PRD region in the post-Action Plan period to enable a common basis of development for both the economy and environment. Additionally, experience of developed countries, e.g., the Prevention of Significant Deterioration (PSD) approach proposed by the US EPA, would also provide

numerous practical solutions to this issue (<http://www.epa.gov/NSR/psd.html>).

4. Discussion and conclusions

In many Western countries, there is a common call for 'evidence based' policies, including in the field of environmental policy. China launched its near-term air pollution control policy, the 'Action Plan', in 2013 without a full evaluation of its prospective impacts. The present study provides the first quantification of air pollution improvement and the associated health benefits, focusing on the PRD area.

The case study of the impacts of the Action Plan in the PRD area was conducted by employing state-of-the-art methods. A measure-by-measure emissions reduction analysis showed that the Action Plan would reduce SO₂ by 323 kt, NO_x by 324 kt, PM_{2.5} by 68.6 kt, and VOC by 136 kt, with 68%, 87%, 85%, and 97% of these reductions coming from the end-of-pipe treatment. The total emissions abatement was estimated to induce a 17% reduction in PM_{2.5} concentrations, indicating that the Action Plan has the potential to achieve the target put forward by the central government (i.e., a 15% reduction of PM_{2.5} concentration). Such PM_{2.5} air quality improvement would help more than 14.4 million people be free of poor air quality conditions and avoid 2920 deaths and 4367 hospital admissions annually.

However, we also note that more than 33 million people (~65% of the total population in the PRD) would still be living in poor air quality after the Action Plan, with annual concentrations of PM_{2.5} >35 µg m⁻³. Notably, the annual average of 35 µg m⁻³ is only the minimum requirement of the WHO. Indeed, 10 µg m⁻³ is the goal recommended by the WHO that allows health risks to remain at an acceptable level. Accordingly, the impacts of the Action Plan would still fall short of the ultimate objective of protecting the health and welfare of the public (Xu *et al* 2013). Though end-of-pipe technologies would contribute the majority of emissions reductions in this round, we argue that the opportunities for their adoption in the future will be more limited, and further control measures in the post-Action Plan period should place greater emphasis on structural change. Together with transformation of the control approach, pollution from rural areas and the non-PRD region are two additional sources that need to be seriously considered in the post-Action Plan period. Moreover, the establishment of a corresponding supervisory system for enforcement and monitoring is not only essential to achieving the goal of the Action Plan but also extraordinarily important for further air quality management, especially for VOC control.

It has been more than a year since the Action Plan was released by the Guangdong government, and progress has been made. For example, in 2014 the natural

gas supply capacity increased to 35 billion m³, 2.5 million tons of steel (representing more than 20% of the total in 2012) and 4.43 million tons of cement (representing nearly 5% of the total in 2012) have been phased out, and more than 680 thousand yellow label vehicles (corresponding to nearly 20% of the total in 2013) have been removed in Guangdong Province. All these changes are believed to contribute to a 10.5% reduction in the annual mean PM_{2.5} concentration over the PRD region from the 2013 level (Department of Environmental Protection of Guangdong Province 2015), indicating that the target set by the central government (i.e., 15%) is achievable.

The PRD is one of the earliest regions to initiate air pollution control in China (Zhong et al 2013) and therefore has experienced relatively lower pollution levels than other key regions. The central government, consequently, required this region to fulfill the tasks associated with the Action Plan one year ahead of schedule and to reach the required air quality standards as early as possible. Therefore, to some extent, the pathway undertaken by the PRD can provide a helpful reference for other regions in China. The measure-by-measure emissions abatement evaluation conducted here may help not only the case study PRD region, but the remainder of China, to develop and implement effective air pollution control policies.

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