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Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China

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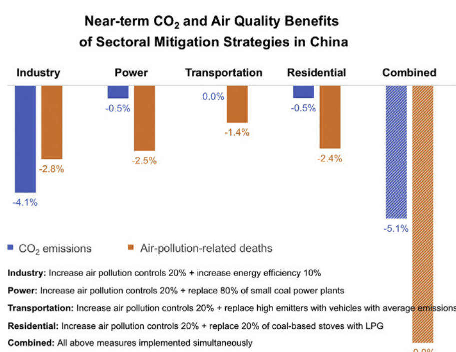
HIGHLIGHTS

- First evaluation of air quality and CO_2 benefits of sectoral mitigation strategies
- Industrial, power, residential and transport sectors examined
- Reductions in air-pollution-related mortalities are evaluated.
- CO_2 reductions due to industrial energy efficiency improvements are evaluated.
- Largest immediate benefits for health and climate found in industrial sector

GRAPHICAL ABSTRACT



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ABSTRACT

China is the world's top carbon emitter and suffers from severe air pollution. We examine near-term air quality and CO_2 co-benefits of various current sector-based policies in China. Using a 2015 base case, we evaluate the potential benefits of four sectoral mitigation strategies. All scenarios include a 20% increase in conventional air pollution controls as well as the following sector-specific fuel switching or technology upgrade strategies. Power sector (POW): 80% replacement of small coal power plants with larger more efficient ones; Industry sector (IND): 10% improvement in energy efficiency; Transport sector (TRA): replacement of high emitters with average vehicle fleet emissions; and Residential sector (RES): replacement of 20% of coal-based stoves with stoves using liquefied petroleum gas (LPG). Conducting an integrated assessment using the regional air pollution model WRF-Chem, we find that the IND scenario reduces national air-pollution-related deaths the most of the four scenarios examined (27,000, 24,000, 13,000 and 23,000 deaths reduced annually in IND, POW, TRA and RES, respectively). In addition, the IND scenario reduces CO_2 emissions more than 8 times as much as any other scenario (440, 53, 0 and 52 Mt CO_2 reduced in IND, POW, TRA and RES, respectively). We also examine the benefits of an industrial efficiency improvement of just 5%. We find the resulting air quality and health benefits are still among the largest of the sectoral scenarios, while the carbon mitigation benefits remain more than 3 times larger than any other scenario. Our analysis hence highlights the importance of even modest industrial energy efficiency improvements and air pollution control technology upgrades for air quality, health and climate benefits in China.

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1. Introduction

The rapid economic growth in China over the past few decades has been fueled by a growing use of energy, especially coal. Such a coal-intensive economic development path not only leads to worsening air quality and severe public health risks (Global Burden of Disease Study 2013, 2015), but also makes China the world's top emitter of carbon. Driven by record-high smog events in recent years, the Chinese government has made air pollution control one of its top priorities and introduced the Action Plan on Prevention and Control of Air Pollution in September 2013 (State Council, 2013). Meanwhile, as part of global efforts to tackle climate change, China has pledged, by 2030, to peak its carbon emissions and increase the share of non-fossil energy to 20% (National Development and Reform Commission, 2015). China is thus currently facing two environmental challenges simultaneously: reducing local air pollution and resulting health impacts on the one hand, and curbing carbon emissions and tackling global climate change on the other hand.

Due to the urgency to shift towards a low-carbon development pathway while improving air quality, there has been an increasing government emphasis on coordinating the strategies to mitigate air pollution and carbon emissions in China (National Development and Reform Commission, 2014). Such coordination is essential, because some measures to address local air pollution can bring long-term climate co-benefits while others can bring climate disbenefits. Examples of win-win strategies to curb air pollution and carbon emissions include energy efficiency measures and scaling up renewable energy (Plachinski et al., 2014; Markandya et al., 2009; Buonocore et al., 2016). Strategies beneficial only for air quality include installation of end-of-pipe control devices. Measures that lead to a tradeoff between air quality and climate goals include increasing the production of synthetic natural gas (SNG) which can reduce emissions of air pollutants from solid fuel use at the expense of higher carbon footprints (Qin et al., in press). It is hence critical to understand the air quality and climate implications of different policy options in order to optimize strategies to simultaneously address the two challenges.

Air pollution and climate policies in China are generally sector-oriented. Existing air pollution control policies emphasize regulating pollution sources in the power and transportation sectors, e.g. tightening the emission standards for thermal power plants and vehicles. In comparison, less attention has been paid to the industrial and residential sectors, despite the significant contribution of these two sectors to local air pollution and public health risks (Lin et al., 2015; Li et al., 2015a; Liu et al., 2016; Li et al., 2015b; Zhou et al., 2010; Wang et al., 2015; Archer-Nicholls et al., 2016). China's climate plan, as indicated by their “intended nationally determined contributions”, INDC (National Development and Reform Commission, 2015), continues to focus most attention on decarbonizing the power sector and controlling carbon emissions in key industrial sectors, such as steel and non-ferrous metal. There are also targets to curb emissions from buildings and the transport sector, by improving building energy efficiency and encouraging public transportation respectively. When comparing China's air pollution and climate plans side by side, one can identify a few policies that are included in both plans, such as a shift away from coal to cleaner fuels in the power and residential sectors. As a result, there is a growing literature on potential air quality and climate co-benefits of various interventions in China. However, most prior studies focus only on one sector (e.g. power (Wang et al., 2016; Zhang et al., 2012; Peng et al., in press), industry (Zhang et al., 2015a; Zhang et al., 2014; Ma et al., 2016), transportation (Geng et al., 2013), residential (Xing et al., 2015; Edwards et al., 2004)) and/or one region (e.g. Shanxi province (Aunan et al., 2004), Henan province (Wang et al., 2016), Shenyang city (Geng et al., 2013)). Here we fill a gap in the literature by applying one standard integrated assessment method to compare the air quality and climate benefits of a variety of policy options in various emission sectors throughout the whole country.

Existing literature on co-controlling air pollutant and carbon emissions in China generally takes a longer-term perspective, i.e. analyzing future scenarios to inform infrastructure investment decisions and technology choices over the coming decades (Wang et al., 2016; Zhang et al., 2015a; Zhang et al., 2014; Ma et al., 2016; Xing et al., 2015; Wang et al., 2016; Zhang et al., 2015b; Nam et al., 2013). However, a near-term perspective is also critical in order to better understand what is possible with existing technology and to guide immediate policy making. First, due to the high priority on improving air quality at present, some air pollution control policies are likely to be implemented irrespective of their climate implications. Examining the climate impacts of near-term air pollution policies is hence important to identify those with climate benefits, and avoid lock-in of those with climate disbenefits. Second, some co-control strategies that are effective in the long term may not play an important role in the near term. For instance, increasing the penetration of low-carbon generation is a widely acknowledged win-win strategy for both air pollution control and carbon emissions reduction. However, given the dominance of coal in China's current power system and the resulting inflexibility to rapidly adjust electricity output, integrating large amounts of intermittent wind and solar generation is difficult to achieve immediately. In addition to technical challenges, there are institutional barriers, since the existing electricity market practices in China, such as transmission planning and dispatch order, are designed for a coal-dominated system and thus are not renewable-friendly (Lu et al., 2016; Davidson et al., 2016). Therefore, here we take a near-term perspective, and focus on measures that are technically feasible now and are addressed in current policies.

In this study, we assess the air quality, health and climate impacts of immediately implementing measures in four individual sectors (industry, power, transportation and residential), as well as the impacts of simultaneously implementing all measures across the four sectors. We consider two categories of policy options in each sector. The first category is to increase the implementation level of conventional air pollution control strategies used in each sector beyond the level of current implementation, but within a range that is highly feasible with existing technology. Examples include installing end-of-pipe control devices on power and industrial plants, upgrading to less polluting industrial kilns, and improving fuel quality. The second category includes technology upgrades and fuel switching options that are mentioned in China's Action Plan for air pollution control. In the industrial sector, we focus on energy efficiency improvement measures that are in line with China's ongoing efforts (e.g. the target in the 12th Five-year Plan is to lower energy use per unit industrial added value in 2015 by 21% from 2010 levels (State Council, 2012)). In the power sector, we consider an accelerated implementation of the policy that has been in place since 2007 to replace old, inefficient, dirty coal units with larger, more efficient, cleaner ones (State Council, 2007). In the transportation sector, we target high emitters and replace them with vehicles with average fleet emissions, since one goal in the Action Plan is to replace all the vehicles that cannot comply with the China 1 standard (“yellow label cars”) by 2017 nationally. In the residential sector, we replace 20% of coal-based cooking and heating stoves with those fueled by liquefied petroleum gas (LPG). Increasing the use of cleaner fuel, especially LPG, to displace residential bulk coal burning is considered a major air pollution control policy opportunity in highly polluted regions, especially the Beijing-Tianjin-Hebei region (Beijing City Government, 2013; Anon, 2015a; Anon, 2016). For instance, Beijing started a LPG subsidy program in 2013, which, by 2015, had helped all rural residents access LPG (Anon, 2015b). Displacing 20% of coal-based stoves (currently mainly used in rural areas) with LPG-based ones thus may be achievable by expanding such an initiative nationwide.

2. Methods

We conduct an integrated assessment to evaluate a 2015 base case (BASE), and various counterfactual scenarios that assume immediate implementation of measures in each or all of the four sectors. For BASE and other scenarios, we estimate the associated carbon emissions, as well as the health-related air quality impacts using the WRF-Chem air pollution model and epidemiological concentration-response relationships. We focus on ambient fine particulate matter ($PM_{2.5}$, particulate matter with diameter 2.5 μm or less), the air pollutant with the largest impact on human health (Global Burden of Disease Study 2013, 2015). While our emission scenarios are designed for the year 2015, we use 2014 meteorological fields for air quality simulations because 2015 was a strong El Nino year and 2015 meteorological conditions are therefore not representative of typical conditions over China (Chang et al., 2016). We also conduct supplementary simulations using alternative meteorological fields in 2010 and 2015, the most recent La Nina and El Nino year, respectively, to examine the range of influence of variations in meteorology (see Discussion and Section 4.4 in Supplementary materials).

2.1. Emission scenarios

Our BASE scenario is based on a province-level emission scenario developed by the International Institute for Applied Systems Analysis (IIASA) with the GAINS (Greenhouse Gas—Air Pollution Interaction and Synergies) model for the year 2015 (Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants, ECLIPSE V5a (International Institute for Applied Systems Analysis, 2015)). This BASE scenario has a coal-intensive energy structure and assumes the implementation of air pollution control strategies that are consistent with China's 12th Five-year Plan (2010–2015). We then design five counterfactual scenarios (Table 1), which include four sectorial scenarios that target each of the four sectors (industry, power, transportation and residential sectors), and a combined scenario in which all the measures in the four sectorial scenarios are implemented simultaneously. In each sectorial scenario, we consider the effect of a 20% increase in the implementation level of conventional air pollution control strategies (e.g. end-of-pipe controls, higher quality fuel such as lower sulfur coal, less polluting kilns, etc.; see Supplementary Table 1 for a summary of air pollution control strategies that are considered), along with the following sector-specific fuel switching or technology upgrade policies. Power sector (POW): 80% replacement of small coal power plants with larger more efficient ones; Industry sector (IND): 10% improvement in energy efficiency, equivalent to a 10% reduction in emission intensity; Transport sector (TRA): replacement of high emitters with average vehicle fleet emissions; and Residential sector (RES): replacement of 20% of coal-based stoves with those using liquefied petroleum gas. The combined scenario (COMB) combines all the measures in the four sectorial scenarios, hence representing the effect of simultaneous implementation of the policies across all four sectors. In addition to these main scenarios, we also conduct supplementary industrial scenarios with 5% and 20% energy efficiency improvements as a sensitivity analysis to cover the range of plausible improvements (Supplementary Figs. 9 and 10).

The emission factors for CO_2 and air pollutants are consistent with the ECLIPSE V5a scenario developed by IIASA. Though we do not consider the carbon and efficiency penalty associated with the operation of end-of-pipe control devices in the main results, we include a sensitivity analysis in Supplementary Fig. 11.

2.2. Regional atmospheric chemistry simulation

For BASE and the five counterfactual scenarios, we simulate air quality using WRF-Chem v3.6, a regional air pollution model that can simulate the transport, mixing, and chemical transformation of fine particulate matter ($PM_{2.5}$). We thus consider both primary $PM_{2.5}$ and secondary $PM_{2.5}$ formed from precursors (e.g. SO_2, NO_x and NH_3). A detailed description of the model is summarized in Grell et al. (2005). We conduct simulations in East Asia using January, April, July and October 2014 meteorology. To test the effect of alternative meteorological conditions, we conduct supplementary simulations using BASE and IND emissions, but with 2010 and 2015 meteorological fields. We choose these two years as the most recent La Nina and El Nino year, respectively. These simulations thus represent a range of possible meteorological conditions over China.

The WRF-Chem simulations use 27×27 km^2 horizontal resolution with 31 vertical layers from the surface to 50 hPa (the surface layer is ~30 m deep). We use RADM2 gas-phase chemistry (more details in Grell et al. (2005)). The aerosol module is based on the Modal Aerosol Dynamics Model for Europe (MADE) (Ackermann et al., 1998), with secondary organic aerosols being incorporated by means of the Secondary Organic Aerosol Model (SORGAM) (Schell et al., 2001). Major inputs to the model include meteorological fields, chemistry initial and boundary conditions and emissions. The meteorological fields are based on National Centers for Environmental Prediction (NCEP) FNL (National Centers for Environmental Prediction and National Weather Service NOAA U. S. Department of Commerce, 2000) data and nudged towards the NCEP FNL data every 6 h. The chemistry initial and boundary conditions are provided by the global chemistry transport model, MOZART-4 (Emmons et al., 2010). Since the emissions scenarios developed using GAINS only estimate changes in annual total provincial

Table 1
Scenario summary.

Scenario	Targeted sector	A. Conventional air pollution control strategies	B. Fuel switching/Technology upgrade
BASE	Based on IIASA–developed scenario for 2015, ECLIPSE V5a		
IND	Industry	Increase the total implementation of currentair pollution control strategiesby an additional 20% with a maximum of 100% penetration*	Increase energy efficiency by 10%
POW	Power		Replace 80% subcritical coal units with ultra–/supercritical coal units
TRA	Transportation		Replace high emitters with average vehicle fleet emissions
RES	Residential		Replace 20% of coal–based residential cooking and heating stoves with LPG
COMB	All	Combine all above measures	

*Essentially reduce the share of the units/vehicles with no air pollution control technologies by 20% and within that 20% scale up the implementation of pollution control strategies proportional to their implementation in the BASE scenario.

emissions, we follow the spatial and temporal pattern of the Multi-resolution Emission Inventory (MEIC) (Wang et al., 2014) for the year 2012 ($0.25 \times 0.25°$) to allocate annual provincial emissions hourly to individual grid boxes (more details in Section 1.2 in the Supplementary materials). For anthropogenic emissions outside China, we use Hemispheric Transport of Air Pollutants (HTAP) v2 emissions for the year 2010 (Anon). HTAP dataset consists of 0.1×0.1 degree emissions of air pollutants in the northern hemisphere. Biogenic emissions are calculated online based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006). Fire emissions are taken from the Global Fire Emissions Database (GFED) v4 (Randerson et al., 2015). All anthropogenic emissions are emitted to the model surface layer. More information can be found in Supplementary Table 2.

We evaluate our simulation using observational data from the monitoring network of the Ministry of Environmental Protection in China (Ministry of Environmental Protection) and the U.S. State Department China Air Quality Monitoring Program (US Department of State, 2014) (more details in Supplementary Table 3 and Fig. 1).

2.3. Evaluating health impacts from air pollution exposure

For four diseases associated with long-term exposure to $PM_{2.5}$ (ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer), we use the following equation to calculate the mortality changes resulting from changes in air pollution levels for each scenario relative to BASE:

$$\Delta \text{Mortality}_d = I_{d,\text{BASE}} \cdot \text{Pop} \cdot \left(\frac{RR_d(C_s)}{RR_d(C_{\text{BASE}})} - 1 \right)$$

For each province, Pop is the total adult population aged 25 and above. We use provincial total population in 2014 based on China's Statistical Yearbook (National Bureau of Statistics of China, 2015). The age and spatial distributions of the population within each province are assumed to be the same as those in 2010, based on the most recent county-level census data (All China Marketing Research Co. Ltd, 2013). $I_{d,BASE}$ is the disease-specific (d) annual BASE mortality rate in the total adult population, based on the 2013 Global Burden of Disease (GBD) dataset (Global Burden of Disease Study 2013, 2015). RR_d (C_s) and RR_d (C_{BASE}) are the relative risks (RR) of disease d for adult population (>25 years old) at the $PM_{2.5}$ levels of C_s in scenario s and C_{BASE} in BASE, respectively. RR are also consistent with the GBD database (Burnett et al., 2014). We use a four-month average of the simulated population-weighted, provincial-averaged $PM_{2.5}$ concentrations to estimate annual mean exposures (more details in Section 1.4 in the Supplementary materials). Sensitivity analyses on linear RR functions are presented in Supplementary Fig. 12.

3. Results

3.1. Air quality impacts

3.1.1. Air pollutant emissions

3.1.1.1. BASE. For national total emissions in BASE, the industrial sector is a large source of annual total emissions for most air pollutants, including SO_2 (64%), NO_x (37%), CO (44%), PM_{10} (51%), $PM_{2.5}$ (45%) and VOC (51%) (Fig. 1). Such a significant role of industrial emissions is also found in other recent emission inventories (Hawkins et al., 2013; Zhao et al., 2011) and near-term projections for China (Ohara et al., 2007). Due to tightened emission standards for power plants in China, electricity generation is only the third largest source of SO_2 (16%) and NO_x (20%) emissions in BASE, and its contribution to other air pollutant emissions is small. The transportation sector is a large source of NO_x (38%) and VOC (21%) emissions, but a relatively minor source of other pollutants. However, recent research indicates that vehicle

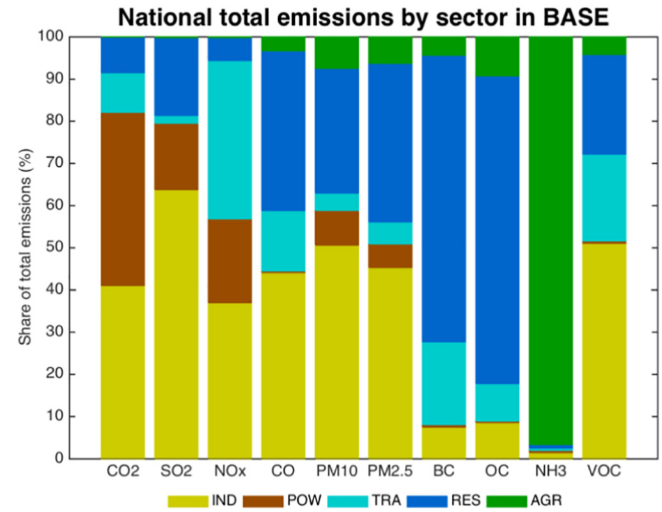

Fig. 1. Contribution of five sectors (industry, power, transportation, residential and agriculture) to national annual total emissions in BASE.

emissions in China, especially from heavy-duty diesel vehicles, may be underestimated in emission inventories (Huo et al., 2012; Wu et al., 2012; Wang et al., 2012). This may occur because inventories assume adequate enforcement of emission standards which recent evidence indicates may not actually be taking place. The residential sector contributes to substantial direct emissions of particles (especially 68% of BC, and 73% of OC), as well as some CO (38%) and VOC (24%) emissions, mainly due to residential coal burning. The agricultural sector, which is not the focus in this study, is the dominant source of NH_3 emissions (97%).

3.1.1.2. Reduction in five scenarios. Among the four sectorial scenarios, we observe the greatest reduction in the IND scenario for national total SO_2 (12%), CO (16%), PM_{10} (8%), $PM_{2.5}$ (7%) and VOC (5%) (Fig. 2). Increasing the implementation level of conventional air pollution control strategies, which include both end-of-pipe control technologies and technology improvements (e.g. upgrade industrial kiln type), can significantly reduce SO_2, NO_x, CO and PM emissions from the industry sector. A 10% improvement in industrial energy efficiency can further reduce the emissions of all the pollutants. The POW scenario reduces 5% of SO_2, 10% of NO_x, 6% of PM_{10} and 4% of $PM_{2.5}$. For SO_2 and NO_x, the reductions are driven not only by increased installation of control devices on power plants, but also by displacing small dirtier coal units with large cleaner ones. For PM, since almost all the power plants in BASE are already equipped with end-of-pipe control technologies, the PM reduction in the POW scenario is only due to the displacement of small coal units. The RES scenario reduces primary PM emissions of BC and OC the most, due to both improved air pollution control and switching from coal-based to LPG-fueled stoves. In the TRA scenario the emission reduction is <10% for all air pollutants. This is partly because the TRA sector emits a smaller fraction of total emissions of most pollutants (except NO_x) than other sectors. In addition, since high emitters only account for 10% of the total vehicle fleet and 30% of the total transportation emissions in the BASE case (on average, the emission factors of air pollutants are 10 times higher for high emitters than the average vehicle fleet), the emission reduction achieved by replacing these high emitters with average vehicle emissions is relatively small. To understand how effective these sector-oriented measures are in curbing emissions in their targeted sectors, we present the emission reductions as compared to BASE sectorial emissions in Supplementary Fig. 5.

In the COMB scenario, the emission reduction is the sum of the emission reductions in the four sectorial scenarios. We estimate that the reductions from taking all measures across the four sectors are 21% for SO_2, 20% for NO_x, 27% for CO, 19% for PM_{10}, 17% for $PM_{2.5}$, 23% for BC, 13% for OC and 13% for VOC. Since the agricultural sector is not affected

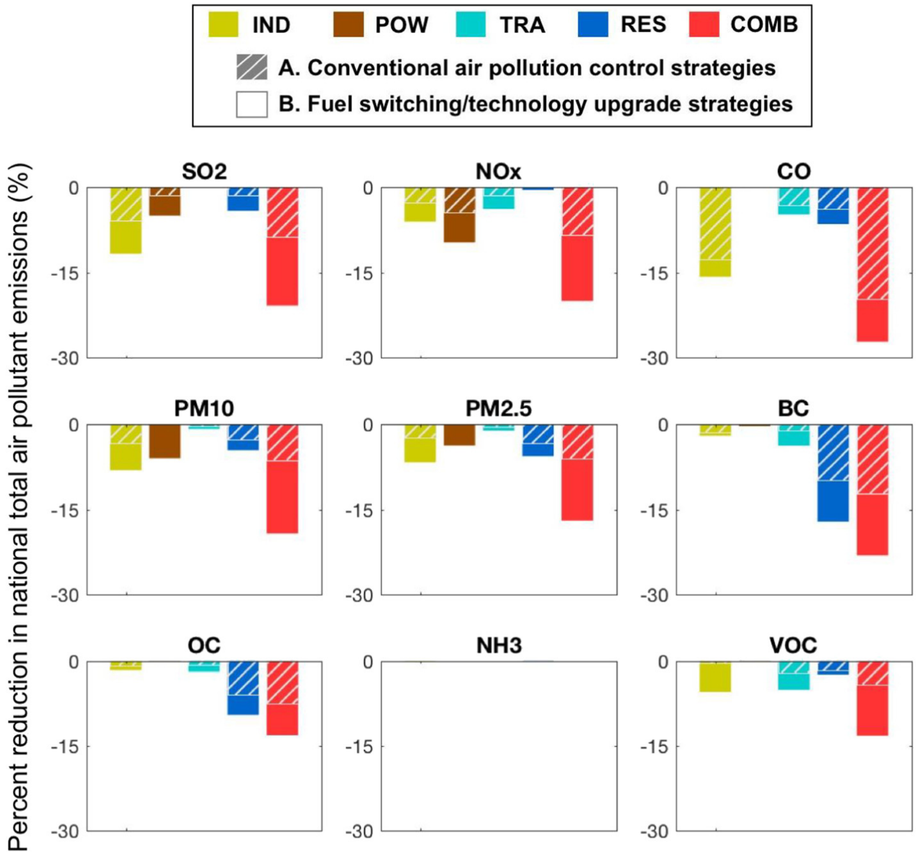

Fig. 2. Percent reduction in annual, national total air pollutant emissions in five scenarios as compared to BASE. The dashed bars represent the reductions achieved by increasing the implementation of conventional air pollution strategies by an additional 20%. The solid bars represent the reductions achieved by sector-specific fuel switching/technology upgrade measures.

in our counterfactual scenarios, we observe negligible changes in NH_3 emissions.

3.1.2. Simulated $PM_{2.5}$ concentrations

3.1.2.1. BASE. We compare our BASE simulation results with observations, and find that our simulations capture the day-to-day $PM_{2.5}$ variation for four representative months in 2014 in Beijing (Fig. 3b) and 30 other cities in China (Supplementary Figs. 1–4). We find our simulation results fit well with the observations in April and July, but underestimate the concentrations in January and October in some sites (more discussions in Section 2.2 in the Supplementary materials).

In BASE, we find that the surface $PM_{2.5}$ concentrations are higher in January and October, and over eastern and southwestern China

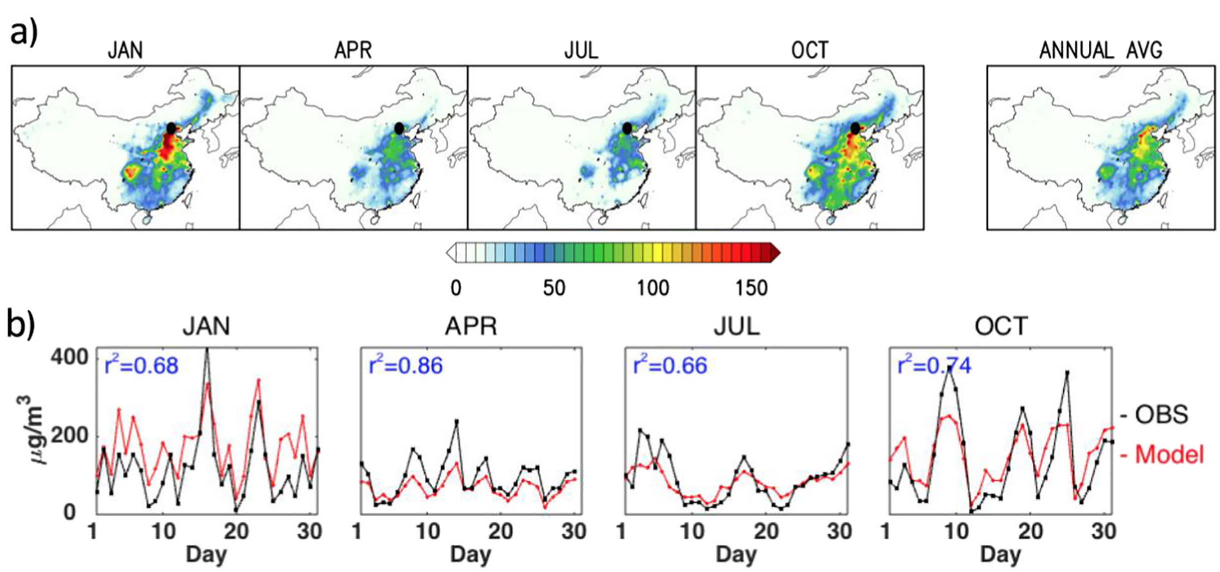

Fig. 3. BASE $PM_{2.5}$ concentrations. a) Monthly and annual mean simulated surface $PM_{2.5}$ (unit: μg/m^3). b) Comparison of modeled and observed daily mean $PM_{2.5}$ concentrations in Beijing in 2014 (black dots in panel a).

(Fig. 3a). Such patterns are not only driven by seasonal and spatial variations in emissions (e.g. higher residential emissions in winter; more details see Supplementary Fig. 6), but also affected by varying meteorological conditions such as prevailing seasonal winds (10 m monthly mean wind fields in Supplementary Fig. 7). The annual mean $PM_{2.5}$ levels are the highest in the North China Plain (NCP) region (>100 μg/m^3), with the concentrations in many East and Central China regions higher than 70 μg/m^3.

3.1.2.2. Reduction in five scenarios. Of the four sectorial scenarios, we find the $PM_{2.5}$ concentration reduction achieved in the IND scenario is the largest throughout China in all four seasons (Fig. 4). In comparison, the RES scenario is most effective in lowering $PM_{2.5}$ in the NCP region especially during winter. Quantitatively, in the IND scenario, we observe a 1– 4 μg/m^3 reduction in annual mean $PM_{2.5}$ in East and Central China (2–5%). The reduction in some NCP regions can reach 5–6 μg/m^3 (~6% reduction). Across four months, the absolute reduction in $PM_{2.5}$ concentration is the greatest in October, largely due to the high BASE concentrations in this month. Though the BASE pollution level is also high in January, smaller $PM_{2.5}$ reductions are observed in January than in October. This may be explained by the critical role of meteorological factors (e.g. wind transport and stable synoptic meteorological conditions) in wintertime $PM_{2.5}$ in many polluted regions (e.g. Beijing (Zheng et al., 2015) and North China (Gao et al., 2016)), which may make the $PM_{2.5}$ in January appear to be less sensitive to changes in emissions (see Supplementary Fig. 7 for monthly mean wind fields). Compared to the IND scenario, the $PM_{2.5}$ reductions achieved in the POW and TRA scenario have similar spatial and seasonal patterns, but are smaller in magnitude due to a smaller reduction in most air pollutant emissions. We find that the RES scenario can substantially lower the annual mean $PM_{2.5}$ over the NCP regions (8–12 μg/m^3, or 7-11%), mainly driven by the large reduction in January. This is because burning coal for heating during winter contributes to significant primary PM emissions and resulting particle pollution in the NCP regions. The air quality improvement is thus significant from improving coal-based stoves and switching to cleaner LPG. Reducing residential emissions to improve local air pollution in the NCP region is also found to be of great importance in Liu et al., 2016.

If all the measures are implemented simultaneously across the four sectors, we find that the annual reduction in the COMB scenario is roughly 3–22 μg/m^3 over North, East and Central China, i.e. an 11–20% reduction as compared to the BASE $PM_{2.5}$ levels. Significant $PM_{2.5}$ reduction can be achieved in all four months. This indicates potentially large improvements in surface fine particle pollution by implementing all the near-term policy measures that are considered here. Compared to BASE, we find that population-weighted national average concentrations of $PM_{2.5}$ of the IND, POW, TRA, RES and COMB scenarios are 4.5%, 3.5%, 2.3%, 4.4% and 15% lower (Fig. 5a).

3.1.3. Air-pollution-related deaths

Nationally, we estimate the premature deaths associated with the exposure to ambient particulate matter in BASE to be 0.94 million in 2014, which is comparable to the estimate in the Global Burden of Disease study (central estimate: 0.92 million in 2013) (Global Burden of Disease Study 2013, 2015). Among the four sectorial scenarios, we find that the IND scenario reduces air-pollution-related deaths the most (2.8% reduction from the BASE level, or a central estimate of 27,000 cases), followed by the POW (2.5% reduction, or 24,000 cases), RES (2.4% reduction, or 23,000 cases) and TRA (1.4% reduction, or 13,000 cases) scenarios (Fig. 5b; the uncertainty ranges based on 95% confidence interval of relative risks are presented in Supplementary Fig. 12). However, the regional distributions of the health benefits vary across scenarios (Fig. 4). While IND, POW and TRA scenarios avoid premature deaths in many provinces throughout eastern and

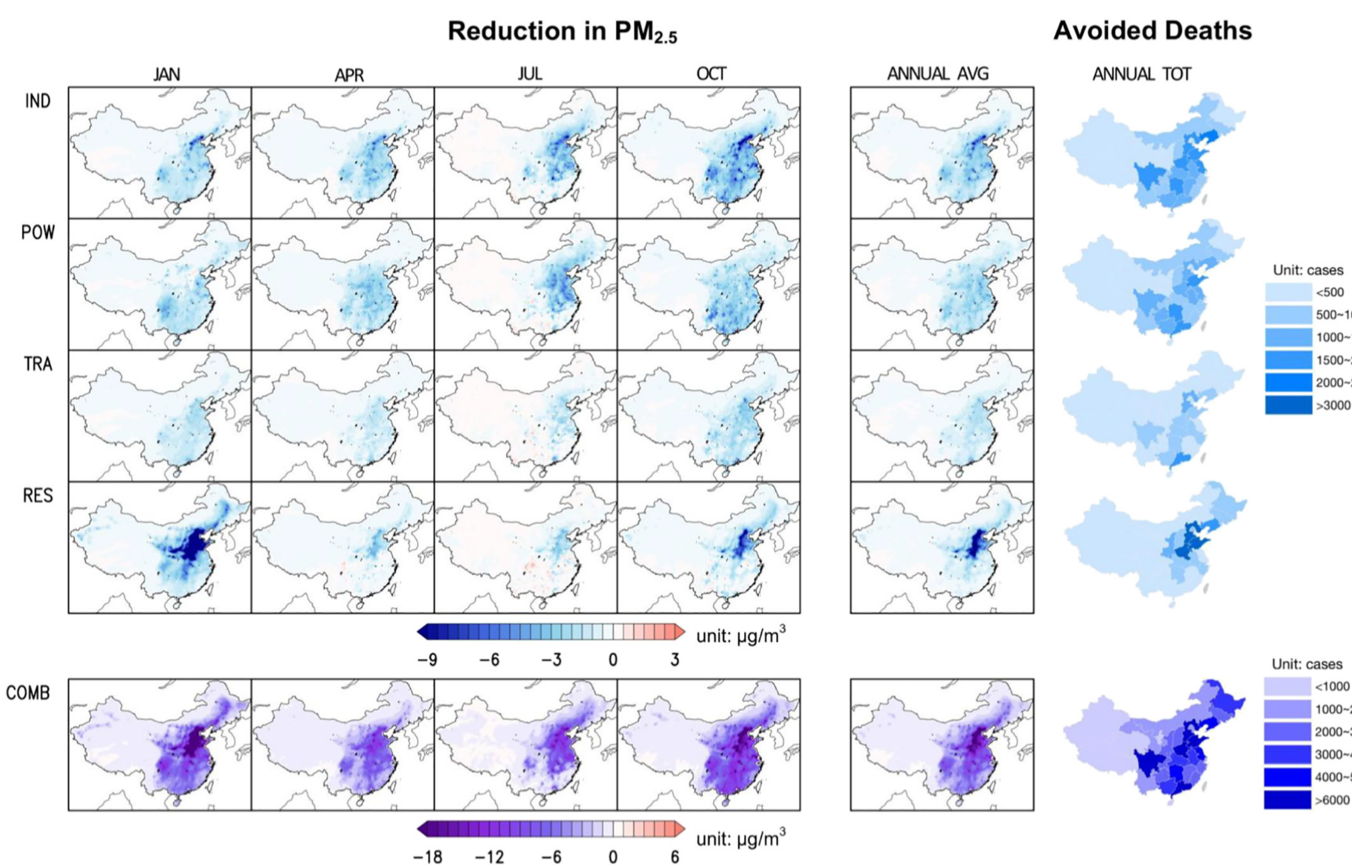

Fig. 4. Reduction in monthly and annual mean $PM_{2.5}$ concentrations (first five columns), and the resulting annual avoided premature mortalities by province (last column).

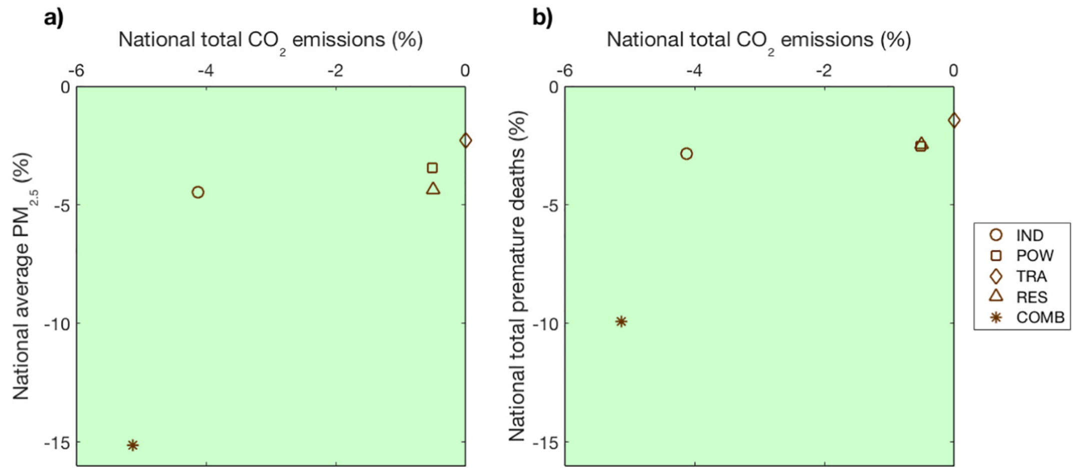

Fig. 5. Air quality and climate benefits achieved in five scenarios as compared to BASE. a) Percent reduction in national total CO_2 emissions and percent reduction in national average $PM_{2.5}$ (population-weighted). b) Percent reduction in national total CO_2 emissions and percent reduction in national total premature deaths. The smaller reduction in national total premature deaths compared with the reduction in national average $PM_{2.5}$ is largely due to the nonlinearity of relative risk functions and that a majority of the emission reductions occur in highly polluted regions.

southern China, the health benefits in the RES scenario are concentrated in the NCP regions. These spatial patterns of the health benefits are consistent with the patterns of $PM_{2.5}$ improvement found in the previous section.

Simultaneously implementing all the measures in all four sectors in COMB would lead to a 10% reduction in national total premature mortality due to air pollution exposure (central estimate: 93,000 cases). The magnitude of the avoided deaths in COMB is slightly larger than that obtained by summing the benefits achieved from the four sectorial scenarios individually. This is because in many provinces, nonlinearity in atmospheric chemistry and transport leads to a larger reduction in fine particulate concentrations when emissions from all sectors are reduced simultaneously (Supplementary Fig. 8a). The resulting lower concentrations imply a lower position on the concave human premature mortality relative risk curve with fewer associated deaths (Supplementary Fig. 8b).

3.2. Carbon emissions

In BASE (Fig. 1), the power and industrial sector each account for roughly 40% of national total carbon emissions. The contributions are much smaller for the residential (8%) and transportation sectors (9%). Since the energy efficiency improvement measures in the industry sector can avoid energy use and the associated carbon emissions, we find significant carbon emissions reduction in the IND scenario (4.1% reduction from the national total BASE level, or 440 million tons; See Fig. 5). We also find a small reduction in the POW (~0.5% reduction, or 53 million tons) and RES scenario (~0.5% reduction, or 52 million tons), due to efficiency improvements resulting from replacing subcritical coal units with more efficient supercritical units and replacing coal-based stoves with more efficient LPG-based stoves. As a result, we estimate a 5.1% reduction in carbon emissions (540 million tons) in COMB that can be achieved by implementing all the measures in four sectors. We also discuss the potential increase in carbon emissions due to the reduced efficiency from operating air pollution end-of-pipe control devices (see Discussion and Supplementary Fig. 11).

4. Discussion

Here we discuss four major sources of uncertainties, with details presented in Section 4 in the Supplementary materials.

First, our analysis indicates that air quality, health and climate benefits are significant even with small improvements in industrial energy efficiency and technology upgrades. To consider a range of plausible efficiency improvements, we also assess lower and higher industrial efficiency improvement scenarios (Supplementary Figs. 9 and 10). Our main IND scenario considers 10% efficiency improvement and 20% increase in the implementation level of conventional air pollution control strategies. These improvements can reduce 2.8% air-pollution-related deaths and 4.1% carbon emissions nationally. If we lower the efficiency improvement target to 5% and keep the same increase in the implementation level of air pollution control strategies, we find a 2% reduction in both the air-pollution-related deaths and carbon emissions nationally. This magnitude of health benefits is still comparable to the other three sectorial scenarios, while the carbon emissions reduction remains much greater than the other scenarios. A more ambitious efficiency improvement of 20% can further increase the benefits, leading to a 5% reduction in air-pollution-related deaths and an 8% reduction in carbon emissions. Therefore, energy efficiency improvements and technology upgrades in the Chinese industrial sector, even at a small scale, can be an effective near-term strategy to curb both air pollution impacts and carbon emissions.

Second, our main results do not consider the potential reduction in plant efficiency due to the operation of air pollution control technologies. The potential efficiency penalty may lead to an increase in carbon emissions in our sectorial scenarios, and is especially relevant for the industry (IND) and power (POW) scenarios for which end-of-pipe control technologies are more available. Based on a sensitivity analysis of the effect of efficiency penalties (Supplementary Fig. 11), we find that the IND scenario still results in a net reduction in carbon emissions due to large reductions obtained from energy saving measures, while the POW scenario leads to a net increase when the operation of pollution control devices reduces their efficiency by >2%. This is because we assume an increased installation of end-of-pipe control devices on power plants. The carbon emissions in the power sector are hence sensitive to the assumptions on the efficiency penalty.

Third, the evaluation of the health benefits from air pollution abatement is sensitive to the shape of the relative risk (RR) functions (Pope et al., 2015). Our main results use concave RR functions, consistent with recent epidemiological evidence that RR per unit increase in $PM_{2.5}$ decreases as concentrations increase. This implies that the same increment of pollution abatement may yield smaller health benefits in highly polluted areas than in relatively clean regions. Given that many parts of

China are highly polluted in BASE, the health benefits that can be achieved in our sectorial scenarios are sensitive to the assumption about the shape of the RR functions. Applying linear RR risk functions would increase the scale of air-pollution-related deaths in BASE, as well as the magnitude of the reduction achieved in these scenarios (Supplementary Fig. 12). However, recent evidence indicates that a linear RR function is not correct for high pollution levels typically observed in eastern China.

Finally, the $PM_{2.5}$ concentrations are affected by meteorological conditions, such as wind transport and wet deposition from precipitation. Our main simulations use emission scenarios developed for 2015 and meteorological fields for 2014. We test the sensitivity of our results to year-to-year variations in the meteorological conditions by conducting additional simulations that use the same BASE and IND emissions, but with the meteorological fields for 2010 and 2015 (the most recent La Nina and El Nino year, respectively). We find that different meteorological fields result in different BASE $PM_{2.5}$ concentrations (Supplementary Fig. 13), as well as the absolute reductions achieved in the IND scenario compared to BASE (Supplementary Fig. 15). However, in terms of the percent reduction in IND compared to BASE, for both the national-averaged $PM_{2.5}$ and national total avoided deaths, we find similar results across the three sets of simulations for 2014, 2010 and 2015 (Supplementary Fig. 16). In addition, the percent reduction based on the 2014 results (main results) are between those for 2010 and 2015. Our sensitivity analyses hence indicate that our results on the relative air quality and health impacts across scenarios are robust under various meteorological years.

5. Conclusion

Our study evaluates the air quality and climate benefits of immediate implementation of measures targeting four emission sectors in China. At the national level, we find that the IND scenario reduces both national air-pollution-related deaths (2.8%) and carbon emissions (4.1%) the most of the four scenarios examined (Fig. 5). Our results hence highlight the importance of industrial energy efficiency improvements and technology upgrades to simultaneously improve air quality and public health while addressing climate change. Improving industrial energy efficiency has drawn growing attention as a strategy to tackle China's air pollution and carbon emissions in recent years. The Action Plan on Prevention and Control of Air Pollution encourages the displacement of inefficient coal-based industrial boilers, as well as upgrading industrial kilns to lower their air pollutant emissions. It also requires all new energy-intensive projects to comply with advanced energy efficiency standards. Besides the air pollution control plan, improving industrial energy efficiency is also included in China's climate plan. Based on the Climate Change Action Plan for the Industrial Sector (2012 − 2020) (Ministry of Industry and Information Technology, 2013), China aims to reduce the carbon emissions per unit industrial added value in 2020 by 50% as compared to the 2005 level. Achieving such a target will require both industrial sector structure adjustment (e.g. limiting the growth of high energy-intensity industries), as well as substantial improvements in energy efficiency through technology upgrades.

While it is challenging to estimate the costs to improve energy efficiency in the industrial sector, and these costs likely vary greatly among specific industries depending on their current level of efficiency, prior literature has found large energy savings potential in major Chinese industrial sectors by implementing cost-effective measures (Zhang et al., 2015a; Zhang et al., 2014; Zhang et al., 2015b; Kong et al., 2015; Ma et al., 2015). These measures could save energy, hence leading to reductions in CO_2 and air pollutant emissions that are comparable or larger than those examined in our analysis. For instance, for China's cement industry, Zhang et al. (2015a) found that cost-effective energy efficiency measures can avoid 17% of energy use, leading to a 5%, 3%, 15% and 12% reduction of national total CO_2, PM, SO_2 and NO_x in 2030. For the iron and steel industry in China, Zhang et al., (2014) estimate that cost-effective energy efficiency measures can avoid 22% of energy use, hence reducing as much as 21%, 16%, 19% and 2% CO_2, SO_2, NOx and PM_{10} respectively in 2030. For pulp and paper industry in China, Kong et al. (2015) found the cost-effective reduction potential in 2010 to be 27% for total fuel consumption, 17% for CO_2, 7% for SO_2, and 9% for NO_x emissions. For ammonia industry, Ma et al. (2015) estimated the cost-effective reduction potential in 2012 to be 14% for energy use, and 14%, 7%, 9% and 7% for CO_2, SO_2, NO_x and PM_{10} emissions, respectively. These analyses demonstrate that it is not only technically possible, but also cost-effective to achieve the energy efficiency improvement targets examined in our IND scenarios and to harness the resulting air quality, health and climate benefits. Our study hence provides a scientific basis in support of near-term energy efficiency and technology improvement measures in the industrial sector to cost-effectively mitigate the emissions of both air pollutants and carbon dioxide.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.03.287.

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