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Co-benefits of carbon and pollution control policies on air quality and health till 2030 in China

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ABSTRACT

Facing the dual challenges of climate change and air pollution, China has made great efforts to explore the co-control strategies for the both. We assessed the benefits of carbon and pollution control policies on air quality and human health, with an integrated framework combining an energy-economic model, an air quality model and a concentration–response model. With a base year 2015, seven combined scenarios were developed for 2030 based on three energy scenarios and three end-of-pipe control ones. Policy-specific benefits were then evaluated, indicated by the reduced emissions, surface concentrations of major pollutants, and premature deaths between scenarios. Compared to the 2030 baseline scenario, the nationwide $PM_{2.5}$- and O_3-related mortality was expected to decline 23% or 289 (95% confidence interval: 220–360) thousand in the most stringent scenario, and three quarters of the avoided deaths were attributed to the end-of-pipe control measures. Provinces in heavily polluted and densely populated regions would benefit more from carbon and pollution control strategies. The population fractions with $PM_{2.5}$ exposure under the national air quality standard (35 μg/m^3) and WHO guideline (10 μg/m^3) would be doubled from 2015 to 2030 (the most stringent scenario), while still very few people would live in areas with the WHO guideline achieved for O_3 (100 μg/m^3). Increased health impact of O_3 suggested a great significance of joint control of $PM_{2.5}$ and O_3 in future policy-making.

1. Introduction

With the rapid economic development and urbanization, China is facing the dual challenges of air pollution and climate change. In 2015, the annual average of $PM_{2.5}$ (particles with aerodynamic diameter smaller than 2.5 μm) concentration in more than 80% of areas in China exceeded the National Ambient Air Quality Standard (NAAQS) of 35 μg/m^3 (equal to the World Health Organization (WHO) air-quality first Interim Target), resulting in over a quarter of the global $PM_{2.5}$-related deaths (Burnett et al. 2018). As the top carbon emitter in the world, China has pledged to peak its carbon emissions by 2030 or earlier at the 2015 Paris Agreement. The country set a goal to reduce the carbon dioxide (CO_2) emissions per unit of GDP by 60%-65% over the 2005 level by 2030 (NDRC, 2015). As air pollutants and greenhouse gases come often from similar sources, great efforts have been made to identify co-control strategies to mitigate air pollution and carbon emissions. The country has conducted the National Action Plan for Prevention and Control of Air Pollution (NAPPCAP) and pushed forward a series of toughest-ever measures (SCPRC, 2013), including improvement of energy and industrial structures, implementation of tightened emission standards, and other supportive policies. Significant benefits in air quality and health were achieved from 2013 to 2017 (Zhang et al., 2019a,b; Zheng et al. 2018). Meanwhile, the climate policies targeting CO_2 emissions can simultaneously reduce air pollution (Li et al. 2019a; West et al. 2013). For instance, the launch of national Emission Trading System (ETS) for carbon in electricity (NDRC, 2017) marks a new stage of using market-oriented economic means to achieve CO_2 targets. Enterprises subject to a CO_2 cap are encouraged to improve energy

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efficiency and to use renewable energy, which is beneficial for cutting the emissions of air pollutants.

A series of studies have estimated the future emissions and air quality in China, based on emission forecasting and chemistry transport modeling. Amann et al. (2008), Klimont et al. (2009) and Xing et al. (2011) predicted the air pollutant concentrations up to 2020/2030 based on the emissions of 2005. Cai et al. (2018) investigated the impacts of air pollution controls on $PM_{2.5}$ concentrations and their source contributions based on a 2013 emission inventory. Underestimations were commonly found in the rapid economic growth and ambitious emission reduction policies implemented since NAPPCAP. After 2015, in particular, the government paid specific attention to coordinating controls of $PM_{2.5}$ and ozone (O_3) pollution, and restrained the emissions of their common precursors such as NO_X and non-methane volatile organic compounds (NMVOCs). Although China is struggling on co-control strategies these years, most studies evaluated either energy or end-of-pipe control (EPC) measures. Peng et al. (2018) evaluated the electrification of transportation and residential sectors in 2030 and found that accelerated electrification can mitigate both air pollutant and carbon emissions. Li et al. (2018) quantified the co-benefit of carbon pricing policy with different targets of carbon intensity reduction, and indicated that the health benefit would rise with increased policy stringency. Neither of them considered relative contribution or co-benefit of aggressive EPC measures. Accordingly, a comprehensive analysis on the impacts of both carbon and air pollution control policies with the latest available data and legislations integrated, is of great significance for future decision making.

Besides air quality improvement, the air pollution controls are expected to further reduce health risks. For decades, burdens of diseases attributable to air pollution have become the focus of many studies. Some have shown that long-term exposure to ambient $PM_{2.5}$ was associated with high risk of mortality, and have developed methods of estimating the relative risk (RR) at specific air pollutant concentration levels (Burnett et al. 2014; Burnett et al. 2018). Change in anthropogenic emissions is an important driving force for air pollution-related health impacts. A recent study identified implementation of tightened emission standards, upgrades on industrial boilers, phasing out outdated industrial capacities, and promotion of clean fuels in residential sector as the major effective measures in reducing $PM_{2.5}$ health burdens since NAPPCAP (Zhang et al., 2019a,b). Although $PM_{2.5}$ was found to contribute more to premature mortality than O_3, the latter deserves increasingly attention because of the aggravated O_3 pollution and its negative impact on human health such as cardiovascular and respiratory diseases. Yet limited studies tried to quantify the comprehensive health impact of both $PM_{2.5}$ and O_3 changes attributed to the emission reduction. Li et al. (2019a) examined the co-benefits of climate policy targeting CO_2 emissions on air quality and human health associated with $PM_{2.5}$ and O_3. Xie et al. (2019) compared the health impacts from $PM_{2.5}$ and O_3 pollution in 2030, but did not evaluate the cause-specific mortality or any policy contribution to those impacts.

In this study we developed a comprehensive framework combined an energy-economic model, a regional atmospheric chemistry model and an integrated exposure–response model, to evaluate the impacts of China's carbon and air pollution control policies on emissions, air quality and human health in near future. Based on a 2015 emission inventory, first, possible future scenarios were designed with an economic model to predict the emissions of air pollutants and CO_2 till 2030. Besides conventional climate policies and air pollution control measures, we mainly stressed the national Emission Trading System for carbon, accelerated end-use electrification strategy and ultra-low emission retrofit in key industries. All those strategies were gradually released after 2015. We then applied the Weather Research and Forecasting Model-Community Multiscale Air Quality Model (WRF-CMAQ) and the epidemiological concentration–response relationships to simulate the changes in air pollutant concentrations and premature mortalities for selected scenarios. Finally, the benefits of individual policies on emissions, air quality, and associated health burdens were evaluated through comparisons between scenarios.

2. Materials and methods

2.1. Development of the emission inventory for 2015

The 2015 emission inventory was developed with a bottom-up method described in our previous studies (Xia et al. 2016; Zhao et al. 2011; 2012a; 2012b; 2013). Targeted species included gaseous pollutants (SO_2, NO_X, NMVOCs, CO, NH_3), aerosols (PM_{10}, $PM_{2.5}$, element carbon (EC), organic carbon (OC)), and CO_2. The research domain covered 31 provinces in mainland China (see the details in Fig. S1 in the Supplement). The inventory contained five main categories: power generation (including electricity generation and heat production), industry (cement, iron & steel plants, other industrial boilers, and other non-combustion processes), transportation (on-road and off-road subcategories), residential combustion (fossil fuel and biomass burning subcategories), and agriculture. The annual emissions were calculated by province using Eq. (1) and then aggregated to the national level:

$$E_{i,j} = \sum_k \sum_m \sum_n A_{i,j,k,m} \times EF_{i,j,k,m} \times R_{j,k,m,n} \times (1 - \eta_{i,n}) \tag{1}$$

where i, j, k, m, and n stand for species, province, sector, fuel/technology type and emission control technology; A is the activity level, either energy consumption or industrial/agricultural production; EF is the unabated emission factor; R is the penetration rate of the relevant emission control technology; and η is the removal efficiency of the technology.

The activity levels were collected mainly from governmental statistical yearbooks, including China Statistical Yearbook (NBS, 2016a), China Energy Statistical Yearbook (NBS, 2016b), China Industrial Economy Statistical Yearbook (NBS, 2016c), as well as yearbooks for other specific economic sectors such as chemical industry, light industry, and agriculture. Emission factors were updated based on previous emission inventory studies (Xia et al. 2016; Zhao et al. 2013) by incorporating the more recent published data (He et al. 2018; Jiang et al. 2018; Li et al. 2019b). Especially for coal-fired power plants, we used the latest provincial emission factors based on the data from continuous emission monitoring systems (CEMS), environmental statistics and pollutant emission permits (Cui et al. 2018; Zhang et al., 2019a,b).

2.2. Development of future scenarios

Based on the 2015 emission inventory, totally seven combined scenarios were developed from three energy and three emission control scenarios to estimate the future emissions till 2030 (Table 1).

To predict the future change in activity level, we developed a business-as-usual scenario (BAU), an emission trading system for carbon scenario (ETS) and an accelerated end-use electrification scenario (EES). BAU was based on the current legislations of energy conservation by the end of 2017. We fully considered the national guidance for future development (NDRC and NEA, 2016) and developed the non-linear relation between future activity levels and various factors including historical energy consumption and product output, per capita GDP, population, and urbanization rate. All these assumptions were under the constraints of the base case developed in an economic-energy model (Cao et al. 2019), especially for the energy use and CO_2 emission cap. More information on the economic model and major activity level predictions are given in Sect. 2 in the Supplement. ETS and EES have been identified as important measures for achieving the national goal of carbon emission mitigation (Chang et al. 2020; Li et al. 2018; Peng et al. 2018). We followed the principles of ETS-NoA scenario in Cao et al. (2019) and developed the ETS scenario, considering emission trading as an effective means of economic stimulus for carbon reduction. The system covered two energy-intensive sectors (electricity and cement),

Table 1
Description of the energy and emission scenarios.

Energy scenarios	Description		Emission scenarios	Description
BAU	BAU is set up based on current legislation and implementation status (until the end of 2017)		BAU-BC	Under BAU, BC assumes that all current end-of-pipe pollution control (until the end of 2015) will continue during 2015–2030
			BAU-SC	Under BAU, SC assumes that more progressive control policies will be released and implemented.
			BAU-ULC	Under BAU, ULC assumes that ultra-low emission retrofit will be conducted for major high-polluted industries besides policies in SC
ETS	ETS builds a carbon emission trading system covering electricity and cement sectors without considering carbon tax and auction		ETS-BC ETS-ULC	Under ETS, emission control measures are the same as BAU-BC and BAU-ULC, respectively
EES	EES assumes a 30% growth of electricity use on industry, transport and residential sectors compared to ETS.		EES-BC EES-ULC	Under EES, the emission control measures are the same as BAU-BC and BAU-ULC, respectively.
	HEES	The power generation mix is the same as BAU.	HEES-ULC	Under HEES, the end-of pipe control measures are the same as BAU-ULC
	LEES	Coal-fired electricity is further reduced 40% compared to BAU	LEES-ULC	Under LEES, the end-of pipe control measures are the same as BAU-ULC.

and free quotas of permits were allocated to enterprises. An emission cap was considered by generating a reduction in carbon intensity of 62.5% in 2030 compared to 2005, the midpoint of China's 60–65% commitment (NDRC, 2015). As a result, the share of coal-fired electricity generation would decline from 54% in BAU to 45% (see the details in Table S3 in the Supplement). For EES, the government has promoted the substitution of electricity for fossil fuels, driving the continuous optimization of the end-use energy structure and narrowing the gap of electrification process between China and developed countries. With the same power mix as ETS, we assumed a 30% growth in the fossil fuel replacement with electricity for transportation, residential burning and industry, and the electrification rates for end-use energy consumption would accordingly be elevated, as shown in Table S3. The growth in electricity rate was loosely calibrated with the prediction by the State Grid (see Sect. 2.2 of the Supplement for details). On the demand side, the total electricity generation would increase from 8571 in ETS to 9948 TWh in EES. To assess the significance of decarbonization of the electricity supply, a sensitivity analysis was further conducted with two additional electrification cases (HEES and LEES), which were separately dependent on the coal-intensive power mix in BAU and a more decarbonized one with the coal-fired electricity further reduced 40% compared to BAU, respectively.

For pollution control, a basic control scenario (BC), a strict control scenario (SC) and a scenario with fully implementation of ultra-low emission control (ULC) were applied. In BC, the emission controls were conservatively assumed following existing legislations by the end of 2015, and the scenario evaluated the continuous effect of policies before China's 13th Five-year Plan period (2015–2020). SC would conduct progressive EPC measures for all the air pollutant sources. Existing policies issued after 2015 were fully considered, including "13th Five-Year Plan for Energy Saving and Emission Reduction" (SCPRC, 2017), "Three-year Action Plan to Fight Air Pollution" (SCPRC, 2018), and specific action plans for NMVOCs and diesel trucks (MEE, 2019a; 2019b). Outdated equipment would be eliminated or replaced with more advanced manufacturing and emission control technologies. The comparison between BC and SC thus highlighted the benefit of China's most recent policies on air pollution control. The difference between SC and ULC was mainly in industry, with the ultra-low emission retrofit faithfully implemented in the latter. The Ministry of Ecology and Environment (MEE) has released the ultra-low emission limits at 35, 50, and 10 mg/m^3 for the flue gas concentrations of SO_2, NO_X and $PM_{2.5}$, respectively, for power sector and sintering (MEP, 2015; MEE, 2019c). In ULC we assumed that ultra-low emission retrofit would be enforced not only on power, but also on iron & steel, cement, plate glass, brick, nonferrous metal production, and other coal-fired industrial boilers. Multiple ultra-low emission standards and recommended emission control technologies were collected from available government documents and the strictest provincial/municipal standards were applied in ULC. For example, the limits of SO_2, NO_X and $PM_{2.5}$ were 50, 100 and 10 mg/m^3 for coal-fired industrial boilers and 30, 50, and 10 mg/m^3 for cement, respectively. Although the actual progress of emission controls may differ by region, we assumed that all the selected industrial sectors in the whole country would meet the ultra-low emission standards by 2030. More details of the ultra-low emission standards and the implementation progress by scenario are documented in Sect. 2.3 and 2.4 in the Supplement. The relative changes of emission factors for typical industrial sectors in different pollution control scenarios in 2030 are shown in Figure S5 in the Supplement. The emission factors for non-electricity industries with ultra-low emission retrofit in ULC would be 30%-80% smaller than those in SC.

2.3. Model description and evaluation

We used CMAQ v5.1, a regional air quality model developed by US Environmental Protection Agency (USEPA), to simulate the nationwide air quality for 2015 and future scenarios in 2030. The model has been proven to perform well in Asia (An et al. 2013; Hu et al. 2017; Zhou et al. 2017). Double nesting domains were employed as shown in Fig. S6 in the Supplement. Domain 1 covered most of East Asia with a horizontal resolution at 81 × 81 km, and Domain 2 covered the entire China with 27 × 27 km. The simulation adopted the Lambert projection with two true latitudes of 40°N and 25°N, and the origin of domain was set at 110°E, 34°N. The Carbon Bond Mechanism (CB05) and AERO5 mechanisms were used for the gas-phase chemistry and aerosol module, respectively. The simulation period covered 12 months for a year, with a spin-up time of 7 days for each month to reduce the impact of initial condition on the simulation.

WRF v3.4 was applied to generate the meteorological field and the outputs were transferred by meteorology chemistry interface professor (MCIP) into CMAQ chemistry transport module. Meteorological initial and boundary conditions were obtained from the National Centers for Environmental Prediction (NCEP) datasets. Ground observations at 3-h intervals at 351 meteorological stations in Domain 2 were downloaded from National Climatic Data Center (NCDC). Statistical indicators including bias, index of agreement (IOA), and root mean squared error (RMSE) were used to evaluate the WRF performance (Emery et al., 2011). The discrepancies between simulations and ground observations were within acceptable range (Fig. S7).

We followed the temporal and spatial patterns of the Multi-resolution Emission Inventory for China (MEIC, http://www.meicmodel.org/) to allocate our annual emission inventories for 2015 and 2030 by province and sector. For anthropogenic emissions outside China, we adopted MIX v1.1 (0.25°×0.25°) for 2010 and re-gridded it to our model resolution. The biogenic emissions were from the Model Emissions of Gases and Aerosols from Nature developed under the

Monitoring Atmospheric Composition and Climate project (MEGAN-MACC, Sindelarova et al. 2014) and the emission inventory of Cl, HCl, and lightening NO_X were from the Global Emissions Initiative (GEIA, Price et al. 1997). The model performance was evaluated by comparing the simulated concentrations for 2015 with available observation data from the China National Environmental Monitoring Center (CNEMC), i.e., the measured concentrations of $PM_{2.5}$, O_3, SO_2 and NO_2 at 1252 air quality monitoring sites across the country.

Four future scenarios (BAU-BC, ETS-BC, EES-BC, and EES-ULC) were selected for simulation to explore the changed air quality and associated health burdens from varied energy and pollution control strategies, and BAU-BC was determined as the 2030 baseline for analysis. The 2015 meteorological field was applied for the simulation in 2030. To limit the uncertainty from nonlinear response of concentration to emission change, we made an extra BAU-ULC simulation when assessing the contribution of individual policy. The concentration reductions of three policies (ETS, EES, and EPC) were calculated as the differences between BAU-BC and ETS-BC, ETS-BC and EES-BC, and BAU-BC and BAU-ULC, respectively. The reduced concentrations were then added together with EES-ULC to obtain a concentration of an approximate base case with no extra energy or pollution control through 2030 (No-C). The policy-specific concentration reductions were finally normalized by the difference between BAU-BC and No-C, to represent the contributions of individual polices to air quality improvement. The policy-related health benefits were evaluated in the similar way.

2.4. Evaluation of health impact from air pollution exposure

The number of premature deaths attributed to long-term exposure of $PM_{2.5}$ and O_3 can be calculated with Eq. (2):

$$\Delta M = PAF \times y \times Pop \tag{2}$$

where ΔM represents mortality burdens for a specific disease attributable to ambient $PM_{2.5}$ and O_3 under different scenarios; y is the baseline age-sex-disease-specific mortality rate in each province/geographic region; *Pop* is the exposed population of specific age and sex in each grid cell; and *PAF* is the population attributable fraction calculated as $PAF = 1 - 1/RR$, where *RR* represents relative risk for a specific disease.

Concentration-response (C-R) models represent the relationships between exposure and attributable mortalities. We applied the Integrated Exposure-Response model (IER) developed by Burnett et al. (2014) to calculate RR for $PM_{2.5}$. The model has been widely used in many studies (Xie et al. 2016; Yue et al. 2020; Zheng et al. 2019; Zheng et al. 2017). Five leading health endpoints caused by $PM_{2.5}$ long-term exposure were considered, including ischemic heart disease (IHD), stroke (STK), lung cancer (LC) and chronic obstructive pulmonary disease (COPD) for adults (age of 25–85), and acute lower respiratory infections (ALRI) for children under 5 years old. The RR for each endpoint was calculated depending on $PM_{2.5}$ concentration:

$$RR(C) = \begin{cases} 1, C < C_0 \\ 1 + \alpha \times \left(1 - e^{-\beta(C - C_0)^{\gamma}}\right), C \geq C_0 \end{cases} \tag{3}$$

where C is the annual average $PM_{2.5}$ exposure concentration for each grid simulated by WRF-CMAQ, C_0 is the counterfactual concentration below which no additional health risk is assumed; α, β and γ are the parameters describing the shape of C-R curves in the age-sex-disease-specific group. We relied on the 2015 Global Burden of Disease (GBD) IER parameter estimates reported by Cohen (2017) for α, β, γ and C_0.

For the health impact related to long-term exposure of O_3, we focused on the mortality risk from cardiovascular (CVD) and respiratory (RESP) diseases for adults of 25–85. A log-linear relationship (Lelieveld et al. 2013) was used to estimate premature mortalities attributable to O_3 pollution:

$$RR = e^{\beta(C - C_0)} \tag{4}$$

where C is the annual average daily maximum 8-h O_3 concentration (AMDA8) based on the WRF-CMAQ simulation (we took the 90th percentile of AMDA8 in the whole year as the exposure concentration); C_0 is the threshold concentration, which was calculated as the average of 33.3–41.9 ppb (Lim et al. 2012), i.e., 37.6 ppb, to be consistent with GBD 2010 and Lelieveld et al. (2015); and β is the change of certain death risk per ppb O_3 increment, which can be derived from epidemiological cohort studies or be calculated by RR as $\beta = \ln(RR)/\Delta C$ (Lelieveld et al. 2013). The applied RR for CVD and RESP are 1.03 (95% confidence interval (CI): 1.01–1.05) and 1.12 (95% CI: 1.08–1.16) for per 10 ppb increase of AMDA8 (Turner et al. 2016).

The national baseline age-sex-disease-specific mortality rates for IHD, STK, COPD, LC, ALRI, CVD and RESP for 2015 were obtained from the GHDx database (https://vizhub.healthdata.org/gbd-compare/). The provincial baseline rates were estimated based on the relationships between provincial and national rates as shown in Xie et al. (2016), and were assumed to remain unchanged till 2030. The population distribution at 1-km horizontal resolution across mainland China for 2015 was obtained from the Resource and Environment Science Data Center of Chinese Academy of Sciences (http://www.resdc.cn) and was re-gridded to our model resolution at 27 km. The provincial age-sex-specific proportions of the total population were gained from 2016 statistic yearbooks. Based on the historical trend, the provincial population in 2030 (Table S2 in the Supplement) was estimated through the logistic regression, with the same spatial distribution as 2015 remained. The 95% CIs of premature deaths calculated in this study were only from those of RRs.

In order to test the uncertainty of health impact assessment, we used another two C-R models for $PM_{2.5}$ and one for O_3 long-term exposure. The Global Exposure Mortality Model (GEMM) developed by Burnett et al. (2018) was used to calculate $PM_{2.5}$-related premature mortalities due to non-communicable diseases (NCDs) and lower respiratory infections (LRIs), denoted as GEMM NCD + LRI. For better comparison with IER model, GEMM 5-COD model was provided based on the same endpoints (i.e., STK, IHD, COPD, LC and ALRI). The RR of GEMM model is calculated by following equation:

$$RR(C) = e^{\frac{\theta \times log\left(\frac{z}{\alpha}+1\right)}{1+exp\{-(z-\mu)/\nu\}}}, z = \max(0, C - 2.4\mu g/m^3) \tag{5}$$

where θ, α, μ and ν are parameters that determine the shape of the mortality-$PM_{2.5}$ association, provided by GEMM framework (Burnett et al. 2018). We took 2.4 $\mu g/m^3$ as the counterfactual concentration in this model.

For O_3, we used an older C-R model with RR of 1.04 (95% CI: 1.013–1.067) for RESP (Jerrett et al. 2009) and 1.01 (95% CI: 1.00–1.02) for CVD (Atkinson et al. 2016) for every 10 ppb increase of average daily 1-h maximum O_3. The relationship recommended by USEPA (20:15:8 for the 1-h maximum: 8-h maximum: daily average) was applied to convert O_3 concentration into the same metric (Bell et al. 2005).

For each model above, we took the same baseline mortality rates of specific diseases and exposure concentrations to estimate the premature mortality with Eq. (2), thus any difference was attributable to the choice of C-R models.

3. Results

3.1. The emissions of air pollutants and CO_2 2015–2030

The emissions in 2015 are provided by province in Table S1 and are compared with other studies by sector in Fig. S2 in the Supplement. Smaller SO_2 and NO_X emissions in this study resulted partly from the incorporation of CEMS data of power sector, and our estimation was only 38–45% of those with a traditional bottom-up approach for the sector (Zheng et al. 2018; Zheng et al. 2019). The $PM_{2.5}$ emissions were 15–20% higher than other studies due mainly to the elevated activity levels and emission factors in residential combustion and biomass burning used in this work. The inter-annual changes in emissions of major air pollutants (SO_2, NO_X, $PM_{2.5}$, and NMVOCs, Fig. 1) and CO_2 (Fig. 2) between different scenarios during 2015–2030 indicated potentially great benefit of pollution control. In BAU-BC, the emissions of SO_2, NO_X, and $PM_{2.5}$ were expected to peak around 2022–2025 and to decrease by 2%-20% till 2030 compared to the 2015 level. In contrast, NMVOCs and CO_2 were estimated to increase by 18% and 13% as few control measures had been proposed before 2016.

The tightened EPC strategies (BAU-SC) could lead to 30–45% reduction in the national total emissions for major air pollutants, and around 10% additional reduction would be achieved with ultra-low emission retrofit in key industries. In BAU-ULC, the SO_2, NO_X, $PM_{2.5}$, and NMVOCs emissions were estimated at 44%, 55%, 54%, and 57% of BAU-BC. Industry contributed most to the emission reduction by 5.2, 4.1, 2.5, and 11.8 Tg for the four pollutants, respectively. For the non-electricity industrial sources with ultra-low emission retrofit (iron & steel, cement, plate glass, brick, nonferrous metal production, and industrial boilers), the emissions of major pollutants in ULC were estimated at 13%-86% of the SC level for 2030, as summarized in Table S9 in the Supplement. With stringent legislations and emission standards for industry, transportation would dominate the NO_X emissions by 2030, and the residential combustion might become the largest source of primary $PM_{2.5}$, while industrial solvent use would still be the largest contributor to NMVOCs. For NH_3 and CO_2, no EPC measures were considered in any scenario, thus their emission variations were attributed mainly to the changed activity levels.

Compared to the end-of-pipe control, the ETS and EES were found to have clear but smaller effects on air pollutant abatement. In ETS-BC, the SO_2, NO_X, $PM_{2.5}$ and NMVOCs emissions would decline 6%, 7%, 2% and 1% in 2030 compared to BAU-BC. Accelerated end-use electrification can further reduce the emissions by 5% for NMVOCs, and 10%-20% for other pollutants in EES-BC. The emissions of SO_2, NO_X, $PM_{2.5}$ and NMVOCs were estimated at 35%, 46%, 52% and 49% of BAU-BC in EES-ULC when considering both carbon and pollution control measures.

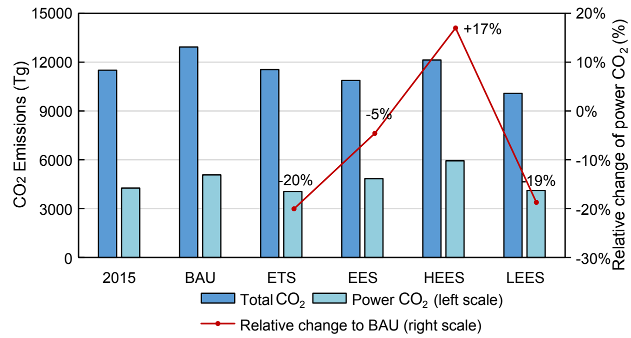


Fig. 2. The total CO_2 emissions and those from power sector under different scenarios. The red line refers to relative changes in CO_2 emissions from power sector compared to BAU in 2030. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The comparisons of air pollutant and CO_2 emissions between different studies are shown in Figs. S8 and S9 in the Supplement, respectively. Our baseline emissions in 2030 were 20–60% lower than the most conservative scenarios in other studies for SO_2, NO_X and $PM_{2.5}$, while 3–5% higher for NMVOCs. A possible reason could be the underestimation of energy efficiency improvement in those studies, as earlier reference years were commonly taken in those studies. Moreover, our smaller SO_2 and NO_X emissions with CEMS data incorporated in the base year 2015 also accounted for the disparity for the future estimates. The emissions of major pollutants in EES-ULC were close to or slightly higher than other estimates in the most stringent scenarios, as we focused on the compliance of ultra-low emission retrofit, rather than assuming a complete penetration of best available control technologies. Regarding CO_2, we predicted that the national emissions in EES would peak in 2025–2030 with an estimate of 10.8 Pg in 2030. The result was comparable with other available studies which implied that the emissions would peak around 2030 at 10–12 Pg.

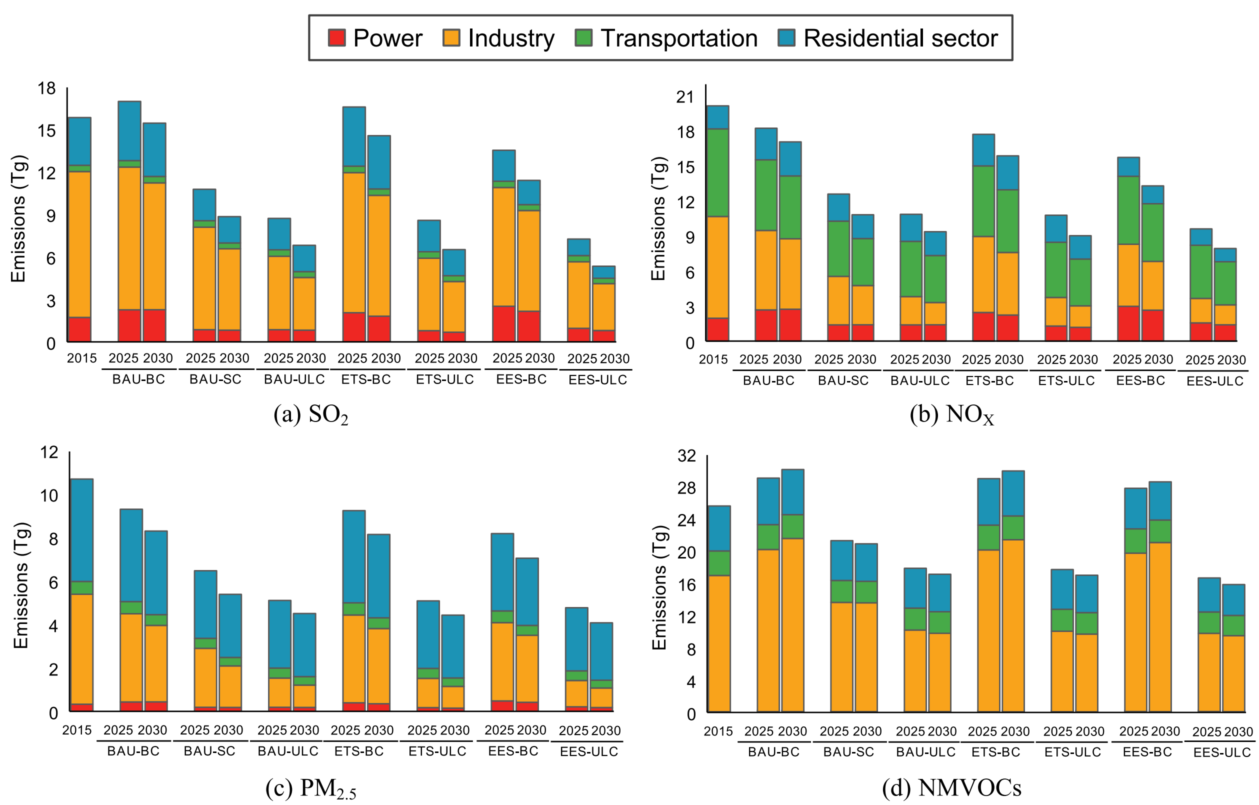


Fig. 1. The national emissions for 2015 and the seven scenarios in 2030 for SO_2 (a), NO_X (b), $PM_{2.5}$ (c), and NMVOCs (d).

As shown in Fig. 2, ETS would reduce 20% of CO_2 emissions from power sector, leading to an over 10% reduction in the total amount. Increased electricity demand in EES would produce nearly 15% additional emissions from the sector. Electrification based on coal-intensive electricity (HEES) would increase carbon emissions from power sector by 17%, although the total emissions could still be lower than those in BAU due to the reduced emissions from end-use sectors. A smaller share of coal-fired power generation in LEES could lead to a 19% reduction in power emissions and reduce the total CO_2 emissions by 22% compared to BAU, as the optimization of electricity mix would offset the effect of

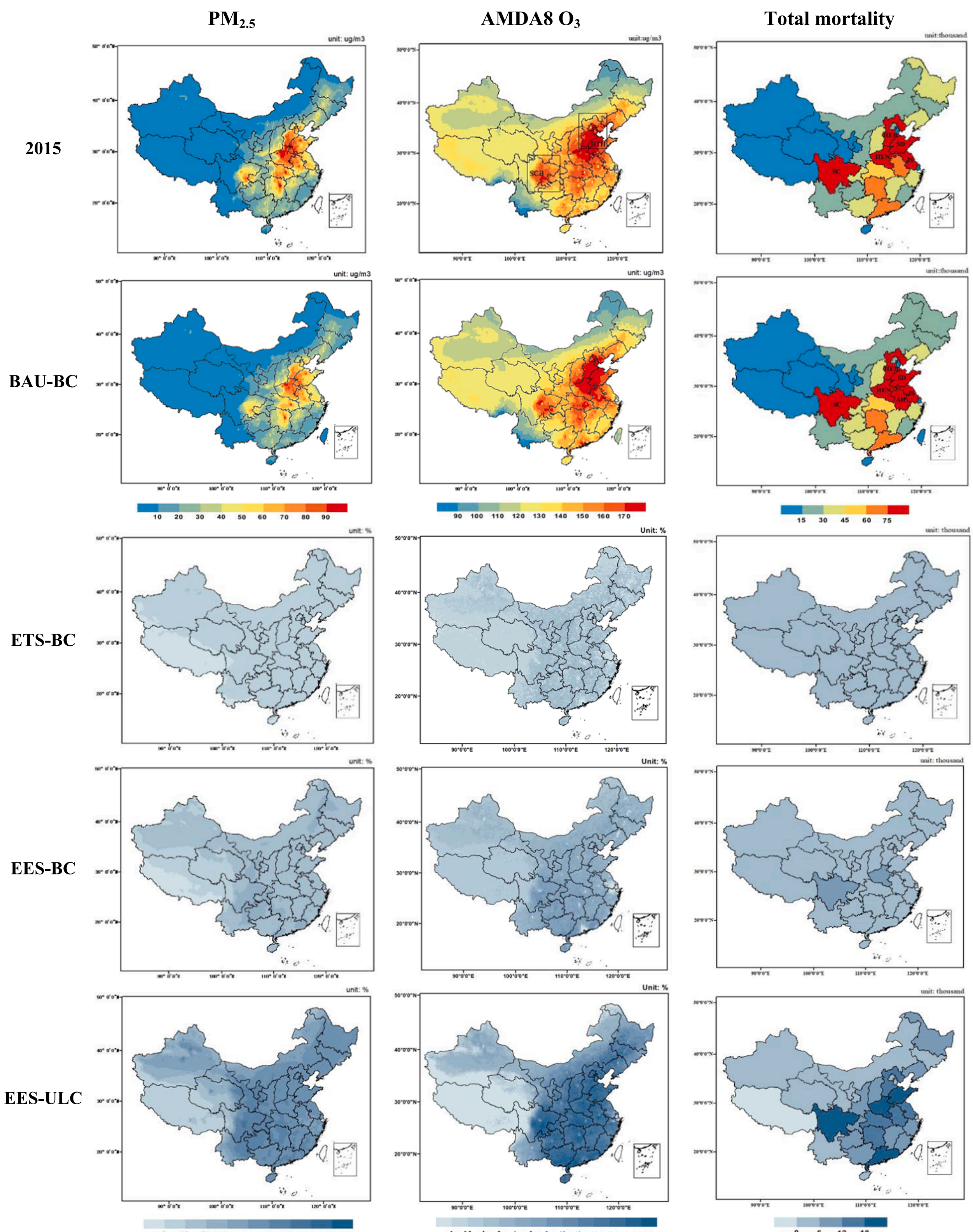


Fig. 3. The simulated annual concentrations and total premature deaths related to $PM_{2.5}$ and O_3 for 2015 and BAU-BC in 2030, and the changes between BAU-BC and other selected scenarios in 2030.

the power generation growth on emissions. The result confirmed that accelerated electrification could effectively reduce the total carbon emissions when coupled with a decarbonized electricity system, which has been identified as a key economy-wide strategy to address air pollution and carbon mitigation goals (Peng et al. 2018). As power generation is the major contributor to carbon emissions, there is still great potential for mitigation in the future by promoting the use of renewable electricity.

3.2. Air quality and health impact in future scenarios

3.2.1. The spatial–temporal changes in the simulated concentrations

Table S7 in the Supplement compares the simulated and observed concentrations by species and month for 2015. The normalized mean biases (NMB) and normalized mean errors (NME) of the four concerned species (SO_2, NO_2, $PM_{2.5}$ and O_3) were ranged between −17%-34% and 12%-19%, respectively. The root mean squared errors (RMSE) were within 7–25 μg/m^3 and the correlation coefficients (r) of annual mean concentrations were over 0.8 between observations and simulations. Compared to previous studies (Cai et al. 2018; Zhang et al., 2019a,b), the biases were further reduced and within acceptable range, indicating that the model reasonably reproduced the seasonal and spatial variations of the ambient air pollutant concentrations in China.

Fig. 3 illustrates the spatial patterns of the simulated surface concentrations of $PM_{2.5}$ and AMDA8 for 2015 and 2030 baseline (BAU-BC), as well as the changes relative to baseline for another three selected scenarios. Similar $PM_{2.5}$ patterns were found for 2015 and BAU-BC, i.e., higher pollution would appear in areas with dense population and heavy industries, especially for Henan (83 μg/m^3 in 2015) and Shandong (73 μg/m^3 in 2015). The $PM_{2.5}$ concentrations in BAU-BC 2030 would be lower than those of 2015 due mainly to the reduced emissions through existing energy and emission control policies. With the EPC measures frozen at current status, ETS and EES would lead to 3% and 16% reduction in the annual average concentration of $PM_{2.5}$, respectively. The $PM_{2.5}$ would drop significantly in most regions in EES-ULC, with the national annual average reduced 46% compared to BAU-BC. More prominent reduction (over 40%) would occur in heavily polluted areas, e.g., Henan, Shandong, Sichuan, and Hunan Provinces (see their locations in Fig. S1). With coal-intensive energy consumption and higher pollution level in 2015, more efforts would be required in those regions to fulfill the ultra-low emission standards, resulting in larger emission abatement of primary particles and gaseous precursors, as summarized in Table S8 in the Supplement.

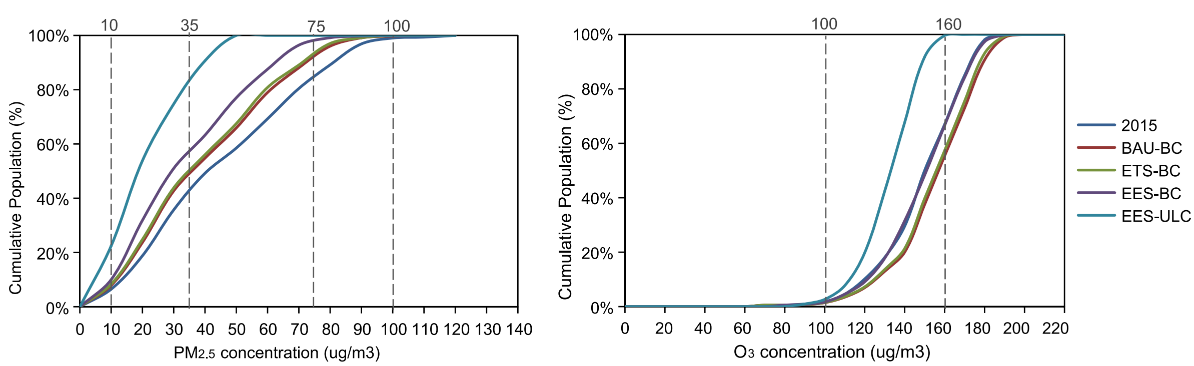
Relatively high O_3 concentrations would appear in east, central China and the Sichuan Basin (SCB). Attributed to the strong non-linear response of O_3 formation to the emissions of its precursors (NO_X and NMVOCs), the nationwide average concentration would increase in BAU-BC compared to 2015, and it would slightly decrease in ETS and EES, implying the limited benefit of carbon policy on O_3. The stringent air pollution control strategies in EES-ULC proved more effective in reducing O_3 pollution, indicated by over 10% reduction in annual AMDA8 for most regions. Similar with $PM_{2.5}$, areas with higher concentrations could benefit more from pollution control, e.g., the reduction in annual AMDA8 could be over 28 μg/m^3 in the Beijing-Tianjin-Hebei region (BTH) and over 25 μg/m^3 in central China (see Fig. S1 for the region) compared to BAU-BC.

3.2.2. The health impact

Fig. 4 illustrates the cumulative distribution of the population under different exposure levels of $PM_{2.5}$ (a) and O_3 (b) by scenario. In 2015, more than 60% of the population was exposed to the concentration over the NAAQS of $PM_{2.5}$ (35 μg/m^3), and only 6% people lived in regions where the concentration could meet the WHO guideline of 10 μg/m^3. Additional 6% of the population would live with good air quality (less than35 μg/m^3) in 2030 BAU-BC. With carbon policy implementation, the population fraction with exposure below 35 μg/m^3 would increase to 51% and 57% in ETS-BC and EES-BC, respectively. People exposed to annual $PM_{2.5}$ concentrations exceeding the NAAQS would further decline significantly to less than 15% by 2030 in EES-ULC, and the fraction with exposure less than 10 μg/m^3 would be elevated to 22%. By incorporating carbon and ultra-low emission policy, in other words, the fraction of people exposed to the $PM_{2.5}$ concentrations under the NAAQS would be doubled from 2015 to 2030.

For O_3, about 30% of people lived in regions that failed to meet the NAAQS for annual AMDA8 (160 μg/m^3) in 2015. The population exposure would get worse in BAU-BC and ETS-BC, and would be improved back to a similar level as 2015 by accelerating the end-use of electrification (EES-BC). With faithful implementation of ULC, the population exposure level would decline significantly and almost all the people would live in areas with the NAAQS achieved across the country. However, the situation could hardly change that almost all of population would still live in areas with AMDA8 over the WHO threshold of 100 μg/m^3.

In BAU-BC, the premature mortality attributable to long-term $PM_{2.5}$ exposure was estimated at 1.06 million (95% CI: 0.56–1.62) in 2030, and the deaths of IHD, STK, COPD, LC and ALRI would reach 438.2 (231.6–681.3), 351.2 (170.7–550.4), 181.8 (103.1–263.4), 86.4 (55.0–117.8) and 3.1 (2.1–4.0) thousand, respectively. The fractions of mortality by disease were similar to Gao et al. (2018). The mortality of O_3 would be much lower than $PM_{2.5}$, with the total death calculated at 218.5 (95% CI: 137.1–288.6) thousand, and cardiovascular and respiratory diseases would contribute 59.6 (20.9–94.4) and 158.9 (116.2–194.2) thousand, respectively. The total $PM_{2.5}$- and O_3– related deaths in BAU-BC 2030 added up to 1.28 million (95% CI: 0.70–1.91), slightly larger than 1.24 million (95% CI: 0.69–1.85) in 2015 due to the increased mortality of O_3. Fig. 3 shows the provincial distribution of



(a) $PM_{2.5}$ (b) O_3

Fig. 4. The cumulative distributions of annual mean $PM_{2.5}$ (a) and O_3 (b) exposures under different scenarios.

total mortality in 2015 and BAU-BC in 2030, and the avoided deaths in three pollution control scenarios compared to BAU-BC (see the detailed numbers in Table S10 in the Supplement). Provinces with higher concentration and larger population density would suffer more health burdens. In BAU-BC, the total deaths related to $PM_{2.5}$ and O_3 exposure in Henan, Shandong, Hebei, Jiangsu, and Sichuan would reach 134.2, 126.4, 91.0, 88.9, and 87.8 thousand, respectively, accounting collectively for 41% of the total mortalities in the whole country. The implementation of ETS and accelerated end-use electrification could lead to 13.2 (10.3–16.9) and 79.3 (61.9–100.7) thousand avoided deaths in ETS-BC and EES-BC, respectively. The nationwide mortality was expected to drop sharply by 288.6 (220.2–360.4) thousand or 23% in EES-ULC compared to BAU-BC, and $PM_{2.5}$- and O_3-related avoided deaths were 235.2 (185.3–292.8) and 53.4 (34.9–67.5) thousand, respectively. Provinces with higher pollution concentration and population density would gain more benefits from air quality improvement. The largest reduction in mortalities would appear in Henan (22.7 thousand), Sichuan (21.6 thousand), Shandong (20.4 thousand), and Guangdong (14.3 thousand) for $PM_{2.5}$, and in Shandong (4.9 thousand), Henan (4.8 thousand), Guangdong (4.6 thousand), and Hebei (4.1 thousand) for O_3 in EES-ULC. For the three most economically-developed regions in China, BTH, YRD, and PRD (see the definitions and locations in Fig. S1) would occupy 8%, 15%, and 5% of the national total population and 9%, 17%, and 4% of the total premature deaths in BAU-BC, respectively. The $PM_{2.5}$- and O_3-related avoided deaths from the improved air quality in EES-ULC were estimated to account for 8%, 13%, and 5% of the national total, respectively.

We compared our estimates in mortalities for 2015 and 2030 with other studies in Fig. S10 and Table S11 in the Supplement, respectively. Our estimate in $PM_{2.5}$-related deaths for 2015 was close to other studies, while that for O_3 was smaller than most other estimates due mainly to the different choices of threshold concentration. For the future health effect, the clear variation of simulated concentrations under different scenario assumptions resulted in large difference in the estimated premature deaths.

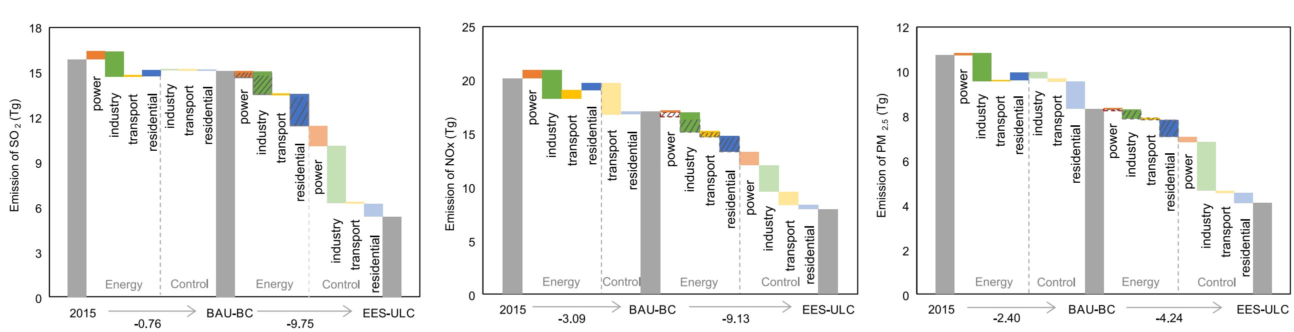
3.3. The policy-specific benefits on environment and health

Fig. 5 decomposes the driving forces of SO_2, NO_X and $PM_{2.5}$ emission changes into two categories of policy control (energy-driven and pollution control-driven) from 2015 to 2030, based on an index decomposition analysis (Zheng et al. 2018).

The emissions of SO_2, NO_X, and $PM_{2.5}$ are expected to decrease by 0.76, 3.09 and 2.40 Tg from 2015 to BAU-BC in 2030, respectively (Fig. 5). For energy-driven change, on one side, emission reductions were mainly achieved in industry. Energy policies issued by the end of 2017 would restrain the production of steel, cement, and other coal-intensive industries through elimination of outdated facilities. The policies would continue improving the industrial structure and reducing industrial emissions by 1.2–2.7 Tg for SO_2, NO_X and $PM_{2.5}$ in 2030. The elevated activities especially for power generation and transportation would be the main sources of growing emissions. Assuming the frozen pollution controls at the 2015 level, on the other side, the effect of EPC on emissions would be limited in power and industry sectors. Transportation was the main source for NO_X reduction due to the increased share of China Ⅳ (equivalent to Euro IV) vehicles. Residential sector contributed greatly to primary $PM_{2.5}$ reduction with the elimination of high-pollution stoves.

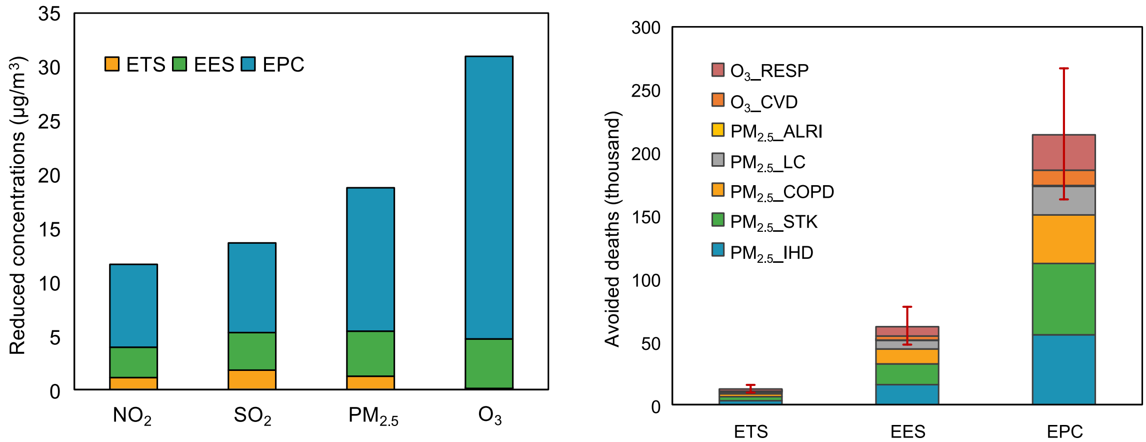
Decomposition of emission changes between BAU-BC and EES-ULC indicated the comprehensive effects of changed energy and pollution control on the national emissions (Fig. 5). For power sector, ETS was estimated to reduce SO_2, NO_X, and $PM_{2.5}$ by 0.46, 0.50, and 0.09 Tg. The benefit could be partially or totally offset by additional emissions from power generation due to accelerated end-use electrification. With faithful implementation of ultra-low emission retrofit, 45–60% of emission reduction could be achieved for the three species. Industry was identified as the dominant source of emission abatement from the tightened end-of-pipe control, and the emission reductions were 3.8, 2.5, and 2.2 Tg for SO_2, NO_X, and $PM_{2.5}$, respectively. The benefit came most from the increased use of advanced pollution control technologies to meet the stringent emission standards. The energy-related reduction was estimated at 30–42% of the three species, caused mainly by optimizing energy structure and improving energy efficiency. For residential sector, the energy policies including replacing coal with electricity and reducing biomass burning would lead to 0.8–2.1 Tg emission reduction for the three species. Promoting clean stoves would also result in additional 22–38% reduction of emissions. For transportation, the emission reduction (particularly for NO_X) would mainly be achieved through tightened emission standards (China V and VI, equivalent to Euro V and VI, respectively) and fleet turnover (i.e., old vehicles would be banned or replaced with cleaner ones subject to tightened standards).

Fig. 6 shows the reduced concentrations of the concerned air pollutants and the avoided excess deaths attributable to the three targeted policies (ETS, EES, and EPC). Enhanced EPC measures were found to contribute most to air quality and public health improvements. They were estimated to account for over 60% of the reduction in air pollutant concentrations, especially for $PM_{2.5}$ and AMDA8 with the annual average reduction of 13 and 26 $\mu g/m^3$, respectively (Fig. 6a). The avoided national $PM_{2.5}$- and O_3-attributable excess deaths due to EPC would reach 174.0 (136.7–216.1) and 40.2 (26.3–51.0) thousand, i.e., three quarters of the total avoided death from reduced $PM_{2.5}$ and O_3, respectively (Fig. 6b). The implementation of ETS for carbon would have limited benefit on air pollution, and would only contribute 4%-5% to the total abatement in $PM_{2.5}$- and O_3-related mortalities. Accelerated end-use electrification would contribute 20% to the improved air quality. The annual average concentrations of $PM_{2.5}$ and O_3 would decline 4.2 and 4.6 $\mu g/m^3$, resulting in 22% and 20% of the total avoided deaths for $PM_{2.5}$ and O_3 long-term exposure, respectively.



(a) SO_2 (b) NO_X (c) $PM_{2.5}$

Fig. 5. The drivers of the emission changes for selected air pollutants between 2015 and two scenarios in 2030.



(a) Concentration (b) Mortality

Fig. 6. The policy-specific contributions to the reduced concentrations of selected pollutants (a) and to the avoided excess deaths (b).

4. Discussions

4.1. Comparison of health impacts with various C-R models

Choice of C-R models and exposure concentrations can lead to disparity in health risk assessment. Maji et al. (2018) found that the $PM_{2.5}$-related deaths may range from 0.8 to 1.3 million with different C-R models. The large variation in mortality estimates indicated high uncertainties lying in health burden analysis methods. We applied three C-R models for $PM_{2.5}$ and two for O_3 to test the uncertainty in mortality estimation, as described in Sec. 2.4. Table 2 summarizes the results of health impact assessment with different C-R models. The larger GEMM hazard ratio as well as higher baseline mortality rates of NCD + LRI resulted in about two-fold increase of $PM_{2.5}$-related mortalities over IER results. The avoided deaths in EES-ULC compared with BAU-BC were estimated to be 736 (95% CI: 681–786), 585 (502–654) and 235 (18–293) thousand for GEMM NCD + LRI, GEMM 5-COD and IER, respectively. This comparison suggested that application of GEMM model would elevate 30%-120% of the health risk from air pollution, as well as the avoided mortality from energy/environmental policies. As the range of $PM_{2.5}$ exposure in China could be larger than that considered in GEMM (84 μg/m^3), we believed IER would be more applicable for the country. The latter has been relatively well developed for mortality estimation and has been widely used in quantifying the impact of environmental policies and air quality standards on health burden (Li et al. 2019a; Liu et al. 2016; Maji et al. 2018; Peng et al. 2017; Yue et al. 2020; Zheng et al. 2019). In addition, the evaluation of police-specific health benefit could be less affected by the choice of C-R models, as the estimated contributions of ETS, EES and EPC to the avoided deaths remained almost unchanged at 4%, 22% and 74% with three models, respectively.

Although elevated O_3 level was demonstrated to result in negative impacts on human health, epidemiological studies on long-term O_3 exposure were still limited in China. Similar to $PM_{2.5}$, there could be large variation in O_3-associated mortality estimates with different C-R models, threshold concentrations and matrices for O_3 exposure. For the two models we used in this study, we preferred to the newer one (Turner et al. 2016) due to its advantages against the former. The model applied RR derived from multi-pollutant models adjusted for $PM_{2.5}$ and NO_2, and improved O_3 exposure data by incorporating observation and CMAQ model outputs (Malley et al. 2017). As indicated in Table 2, the avoided deaths from carbon and pollution control policies estimated with the Turner et al. (2016) C-R model were two to three times of those with an old C-R model (Atkinson et al. 2016; Jerrett et al. 2009) in 2030 for the whole country. Higher mortality burden estimated with the new C-R model revealed an increased risk of O_3 pollution than previously expected. Although the long-term exposure to $PM_{2.5}$ still dominated the health impact, promotion of O_3 mitigation strategy would be increasingly important to effectively reduce the health damage related to air pollution in China.

Table 2
$PM_{2.5}$- and O_3-related premature mortalities in 2030 with different C-R models (thousand deaths with 95% CIs).

C-R model	BAU-BC	ETS-BC	EES-BC	EES-ULC
IER	1061 (562, 1617)	1053 (556, 1606)	996 (510, 1533)	826 (377, 1324)
GEMM NCD + LRI	2206 (2026, 2380)	2172 (1995, 2345)	1993 (1829, 2153)	1470 (1345, 1594)
GEMM 5-COD	1638 (1399, 1856)	1612 (1377, 1827)	1471 (1255, 1670)	1053 (897, 1202)
O_3-Turner	219 (137, 289)	216 (135, 285)	205 (128, 271)	165 (102, 221)
O_3-Jerrett	133 (36, 217)	132 (35, 214)	126 (34, 205)	105 (28, 173)

4.2. Uncertainties and limitations

Uncertainty in this study could be classified into three major sources. First, there were uncertainties in emission prediction. Although the energy-use information and driving factors of economic growth were thoroughly covered in the energy-economic model, there were still uncertainties in energy consumption and future price prediction for an actual market. The pure ETS covered only two sectors based on current announcement, and it could underestimate emission reduction potential for air pollutants, as more complicated ETS carbon-tax hybrid system might be promoted in the future, following the routes of developed countries. Moreover, the EES based on ETS was treated as an administrative intervention of a 30% growth of electrification on the demand side, with few economic constraints considered.

Second, the model bias related to chemical reactions, atmospheric dispersion and deposition had inevitable impact on the simulation of surface concentrations. The comparison between observation and simulation indicated 7–17% underestimation of nationwide SO_2, NO_2 and $PM_{2.5}$ concentrations for 2015. Such modeling bias can be partially offset, as our study decomposed the policy-specific benefits based on the relative changes in the simulated concentrations between scenarios. Besides, uncertainty in future concentration prediction could come from the fixed meteorological field used in the simulation. Some researchers have claimed that the future climate change would bring challenges on air quality improvement (Liu et al. 2019; Xing et al. 2020). Wang et al. (2013) found that higher temperature, lower PBL height, and reduced ventilation rate would increase the emissions of biogenic VOCs and thereby elevate the O_3 concentration. Hong et al. (2019) indicated that the higher temperature and less precipitation in the future would increase O_3 while lower PBL height and wind speed would increase $PM_{2.5}$. Therefore, application of the 2015 meteorological field might underestimate the concentrations of air pollutants for 2030.

Third, uncertainty existed in the C-R model including the shape of C-R curves and the threshold concentration. The widely used C-R models were generally developed on the basis of epidemiological studies in the US and Europe. Uncertainty should always be kept in mind when they were used for China. To be focused on the evaluation of policy-specific contributions, moreover, we assumed no change in spatial distribution of population and baseline mortality rate in the future, and ignored the population aging in China. Such assumptions might lead to a possible underestimation in health benefit due to higher risk for elderly.

Despite of the uncertainties above, this study illustrates the importance of carbon and pollution control policies on air quality improvement and health risk reduction. It helps better policy making for climate change mitigation and air pollution control in the future.

5. Conclusions

This study provides a comprehensive framework combining an energy-economic model, an air quality model and C-R models to quantify the impacts of future carbon and pollution control policies on air quality and health burden in China. As a combined effect of ETS, EES and ULC polices (EES-ULC), the national emissions of SO_2, NO_X, primary $PM_{2.5}$ and NMVOCs would decline 48–65% compared to the baseline scenario 2030 (BAU-BC), resulting in 46% and 13% reduction of annual $PM_{2.5}$ concentration and AMDA8 for O_3 over the country, respectively. The nationwide $PM_{2.5}$- and O_3-related mortalities were expected to be reduced by 235.2 (185.3–292.8) and 53.4 (34.9–67.5) thousand, i.e., 22% and 24% of the total deaths in the baseline, respectively. Provinces with higher pollution concentrations and population density would gain more benefits in health burdens. The population fractions with $PM_{2.5}$ exposure under the NAQQS (35 μg/m^3) and WHO guideline (10 μg/m^3) would be doubled from 2015 to 2030, and almost all the people would live in areas with the NAQQS achieved for O_3 (160 μg/m^3). However, still very few people would live in areas with the WHO guideline achieved for O_3 (100 μg/m^3).

Compared to end-of-pipe controls, the energy policies included in this work contributed smaller to the reduced air pollution and associated health risks. A pure ETS covering power and cement sectors was estimated to reduce the concentrations of the concerned species (SO_2, NO_2, $PM_{2.5}$, and O_3) by 0–13%. Accelerated end-use electrification could bring more significant benefit on carbon and air pollutant emissions when switching to a decarbonized power system. EES was estimated to be responsible for 20%–22% of the total avoided $PM_{2.5}$- and O_3-related mortalities. Tightened end-of-pipe controls would contribute most to air quality improvement and avoided health damage, accounting for three quarters of the total avoided mortalities compared to the baseline in 2030. It should be noted, however, that the energy policies could be conservatively assumed and their contribution to air quality improvement might be underestimated, as China recently pledged to peak its carbon emissions before 2030 with more aggressive plans being determined.

With dual challenges of climate change and air pollution, relying on single policy of carbon or air pollution control would hardly meet the both targets or be economically impossible. ETS and EES could be the key economic-wide strategies to address the carbon emission goals in 2030, and were confirmed to have co-benefits on air pollution and human health. The combination of legislation enforcement and economic stimulus would become an important way for China to gain more progress in air quality and climate change. With an increased risk of O_3 pollution, moreover, the coordinating control of O_3 and $PM_{2.5}$ is of great significance to reduce the health damage from air pollution in China.

CRediT authorship contribution statement

Jinzhao Yang: Methodology, Investigation, Formal analysis, Data curation, Visualization, Software, Writing - original draft. **Yu Zhao:** Conceptualization, Methodology, Resources, Writing - review & editing. **Jing Cao:** Resources. **Chris P. Nielsen:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Amann, M., Jiang, K. J., Hao, J. M., Wang, S. X., Zhuang, X., Wei, W., Deng, Y. X., Liu., H., et al. GAINS-Asia: Scenarios for cost-effective control of air pollution and greenhouse gases in China. International Institute for Applied Systems Analysis (IIASA), 2008, Laxenburg, Austria, available at: https://iiasa.ac.at/web/home/research/researchPrograms/air/Asia.html. Accessed 13 September 2020.

An, X., Sun, Z., Lin, W., Jin, M., Li, N., 2013. Emission inventory evaluation using observations of regional atmospheric background stations of China. Journal of Environmental Sciences 25, 537–546.

Atkinson, R.W., Butland, B.K., Dimitroulopoulou, C., Heal, M.R., Stedman, J.R., Carslaw, N., Jarvis, D., Heaviside, C., et al., 2016. Long-term exposure to ambient ozone and mortality: a quantitative systematic review and meta-analysis of evidence from cohort studies. BMJ Open 6, e009493. https://doi.org/10.1136/bmjopen-2015-009493.

Bell, M.L., Dominici, F., Samet, J.M., 2005. A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. Epidemiology 16, 436–445.

Burnett, R.; Chen, H.; Szyszkowicz, M.; Fann, N.; Hubbell, B.; Pope, C.A., III; Apte, J.S.; Brauer, M., et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proceedings of the National Academy of Sciences of the United States of America 2018; 115: 9592-9597.

Burnett, R.T.; Pope, C.A., III; Ezzati, M.; Olives, C.; Lim, S.S.; Mehta, S.; Shin, H.H.; Singh, G., et al. An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. Environmental Health Perspectives 2014; 122: 397-403. https://doi.org/10.1289/ehp.1307049.

Cai, S., Ma, Q., Wang, S., Zhao, B., Brauer, M., Cohen, A., Martin, R.V., Zhang, Q., et al., 2018. Impact of air pollution control policies on future $PM_{2.5}$ concentrations and their source contributions in China. Journal of Environmental Management 227, 124–133. https://doi.org/10.1016/j.jenvman.2018.08.052.

Cao, J., Ho, M.S., Jorgenson, D.W., Nielsen, C.P., 2019. China's emissions trading system and an ETS-carbon tax hybrid. Energy Economics 81, 741–753. https://doi.org/10.1016/j.eneco.2019.04.029.

Chang, S., Yang, X., Zheng, H., Wang, S., Zhang, X., 2020. Air quality and health co-benefits of China's national emission trading system. Applied Energy 261, 114226. https://doi.org/10.1016/j.apenergy.2019.114226.

Cohen, A.J., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6.

Cui, J., Qu, J., Bo, X., Chang, X., Feng, X., Mo, H., Li, S., Zhao, Y., et al., 2018. High resolution power emission inventory for China based on CEMS in 2015. China Environmental Science 38, 2062–2074 (in Chinese).

Emery, C, Tai E, Yarwood G. Enhanced Meteorological Modeling and Performance Evaluation for Two Texas Ozone Episodes. Final Report Submitted to Texas Natural Resources Conservation Commission, Prepared by ENVIRON, International Corp., Novato.2011.

Gao, M., Beig, G., Song, S., Zhang, H., Hu, J., Ying, Q., Liang, F., Liu, Y., et al., 2018. The impact of power generation emissions on ambient PM2.5 pollution and human health in China and India. Environment International 121, 250–259. https://doi.org/10.1016/j.envint.2018.09.015.

He, K., 2018. Technical Manual for Emission Inventories from Urban Air Pollution Sources. Tsinghua University, China.

Hong, C., Zhang, Q., Zhang, Y., Davis, S.J., Tong, D., Zheng, Y., Liu, Z., Guan, D., et al., 2019. Impacts of climate change on future air quality and human health in China. Proceedings of the National Academy of Sciences of the United States of America 116, 17193–17200.

Hu, J., Li, X., Huang, L., Ying, Q., Zhang, Q., Zhao, B., Wang, S., Zhang, H., 2017. Ensemble prediction of air quality using the WRF/CMAQ model system for health effect studies in China. Atmospheric Chemistry and Physics 17, 13103–13118. https://doi.org/10.5194/acp-17-13103-2017.

Jerrett, M.; Burnett, R.T.; III, C.A.P.; Ito, K.; Thurston, G.; Krewski, D.; Shi, Y.; Calle, E., et al. Long-Term Ozone Exposure and Mortality. The New England Journal of Medicine 2009; 360:1085-1095. https://doi.org/10.1056/NEJMoa0803894.

Jiang, C., Song, X., Zhong, Y., Sun, Y., Lei, Y., 2018. Emissions Inventory and Characteristics of NOx from Cement Industry. Environmental Science 39, 4842–4848 (in Chinese).

Klimont, Z., Cofala, J., Xing, J., Wei, W., Zhang, C., Wang, S., Kejun, J., Bhandari, P., et al., 2009. Projections of SO2, NOx and carbonaceous aerosols emissions in Asia. Tellus B: Chemical and Physical Meteorology 61, 602–617.

Lelieveld, J., Barlas, C., Giannadaki, D., Pozzer, A., 2013. Model calculated global, regional and megacity premature mortality due to air pollution. Atmospheric Chemistry and Physics 13, 7023–7037.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371.

Li, M., Zhang, D., Li, C.-T., Mulvaney, K.M., Selin, N.E., Karplus, V.J., 2018. Air quality co-benefits of carbon pricing in China. Nature Climate Change 8, 398–403. https://doi.org/10.1088/1748-9326/ab26ca.

Li, M., Zhang, D., Li, C.-T., Selin, N.E., Karplus, V.J., 2019;. Co-benefits of China's climate policy for air quality and human health in China and transboundary regions in 2030. Environmental Research Letters 14. https://doi.org/10.1038/s41558-018-0139-4.

Li, M., Zhang, Q., Zheng, B., Tong, D., Lei, Y., Liu, F., Hong, C., Kang, S., et al., 2019. Persistent growth of anthropogenic non-methane volatile organic compound (NMVOC) emissions in China during 1990–2017: drivers, speciation and ozone formation potential. Atmospheric Chemistry and Physics 19, 8897–8913. https://doi.org/10.5194/acp-19-8897-2019.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., AlMazroa, M. A., Amann, M., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. The Lancet 380, 2224–2260.

Liu, J., Han, Y., Tang, X., Zhu, J., Zhu, T., 2016. Estimating adult mortality attributable to PM2.5 exposure in China with assimilated PM2.5 concentrations based on a ground monitoring network. Science of the Total Environment 568, 1253–1262. https://doi.org/10.1016/j.scitotenv.2016.05.165.

Liu, S., Xing, J., Zhao, B., Wang, J.D., Wang, S.X., Zhang, X.Y., Ding, A.J., 2019. Understanding of aerosol–climate interactions in China: Aerosol impacts on solar radiation, temperature, cloud, and precipitation and its changes under future climate and emission scenarios. Current Pollution Reports 5, 36–51.

Maji, K.J., Dikshit, A.K., Arora, M., Deshpande, A., 2018. Estimating premature mortality attributable to PM2.5 exposure and benefit of air pollution control policies in China for 2020. Science of the Total Environment 612 (683–693). https://doi.org/10.1016/j.scitotenv.2017.08.254.

Malley, C.S., Henze, D.K., Kuylenstierna, J.C.I., Vallack, H.W., Davila, Y., Anenberg, S.C., Turner, M.C., Ashmore, M.R., 2017. Updated Global Estimates of Respiratory Mortality in Adults ≥30 Years of Age Attributable to Long-Term Ozone Exposure. Environmental Health Perspective 125, 087021.

Ministry of Ecology and Environment of the People's Republic of China (MEE), 2019a. Notice on Issuing the Comprehensive Treatment of Volatile Organic Compounds in Key Industries, Beijing, China.

Ministry of Ecology and Environment of the People's Republic of China (MEE), National Development and Reform Commission (NDRC), Ministry of Industry and Information Technology (MIIT), 2019b. Notice on Issuing the Action Plan for Combating Pollution of Diesel Truck, Beijing, China.

Ministry of Ecology and Environment of the People's Republic of China (MEE), National Development and Reform Commission (NDRC), Ministry of Industry and Information Technology (MIIT), 2019c. Opinions on Advancing the Ultra-Low Emissions in the Steel Industry, Beijing, China.

Ministry of Environmental Protection of the People's Republic of China (MEP), National Development and Reform Commission (NDRC), National Energy Administration (NEA), 2015. In: Work Plan for Fully Implementing Ultra-low Emissions and Energy Conservation in Coal-Fired Power Plants, Beijing, China.

National Bureau of Statistics (NBS). China Statistical Yearbook 2000-2016. China Statistics Press, 2016a, Beijing, China.

National Bureau of Statistics (NBS). China Energy Statistical Yearbook 2000-2016. China Statistics Press, 2016b, Beijing, China.

National Bureau of Statistics (NBS). China Industrial Economy Yearbook 2000-2016. China Statistics Press, 2016c, Beijing, China.

National Development and Reform Commission (NDRC), China Intended Nationally Determined Contributions. 2015. https://www.fmprc.gov.cn/ce/cese/chn/zgxw/t1278289.htm. Accessed 23 January 2021.

National Development and Reform Commission (NDRC), National Carbon Emission Trading Market Construction Programme for Electric Power Sector. 2017. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171220_960930.html. Accessed 23 January 2021.

National Development and Reform Commission (NDRC) and National Energy Administration (NEA), Strategy of Energy Production and Consumption (2016-2030). 2016. https://www.ndrc.gov.cn/fggz/fzzlgh/gjjzxgh/201705/t20170517_1196767.html. Accessed 23 January 2021.

Peng, W., Yang, J., Lu, X., Mauzerall, D.L., 2018. Potential co-benefits of electrification for air quality, health, and CO_2 mitigation in 2030 China. Applied Energy 218, 511–519. https://doi.org/10.1016/j.apenergy.2018.02.048.

Peng, W., Yang, J., Wagner, F., Mauzerall, D.L., 2017. Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China. Science of the Total Environment 598, 1076–1084.

Price, C., Penner, J., Prather, M., 1997. NOx from lightning: 1. Global distribution based on lightning physics. Journal of Geophysical Research: Atmospheres 102, 5929–5941.

Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J.-F., Kuhn, U., et al., 2014. Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years. Atmospheric Chemistry and Physics 14, 9317–9341. https://doi.org/10.5194/acp-14-9317-2014.

State Council of the People's Republic of China (SCPRC), Notice of the General Office of the State Council on Issuing the Air Pollution Prevention and Control Action Plan. 2013. http://www.mee.gov.cn/zcwj/gwywj/201811/t20181129_676555.shtml. Accessed 13 September 2020.

State Council of the People's Republic of China (SCPRC), Notice of the General Office of the State Council on Issuing the 13th Five-Year Plan on Energy Saving and Emission Reduction, 2017. http://www.mee.gov.cn/zcwj/gwywj/201812/t20181217_748249.shtml. Accessed 23 January 2021.

State Council of the People's Republic of China (SCPRC), Notice of the General Office of the State Council on Issuing the Three-year Action Plan to Win the Blue Sky Defense. 2018. http://www.mee.gov.cn/zcwj/gwywj/201807/t20180704_446068.shtml. Accessed 13 September 2020.

Turner, M.C.; Jerrett, M.; Pope, C.A., 3rd; Krewski, D.; Gapstur, S.M.; Diver, W.R.; Beckerman, B.S.; Marshall, J.D., et al. Long-Term Ozone Exposure and Mortality in a Large Prospective Study. Am J Respir Crit Care Med 2016; 193: 1134-1142. https://doi.org/10.1164/rccm.201508-1633OC.

Wang, Y., Shen, L., Wu, S., Mickley, L., He, J., Hao, J., 2013. Sensitivity of surface ozone over China to 2000–2050 global changes of climate and emissions. Atmospheric Environment 75, 374–382.

West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., et al., 2013. Co-benefits of Global Greenhouse Gas Mitigation for Future Air Quality and Human Health. Nature Climate Change 3, 885–889.

Xia, Y., Zhao, Y., Nielsen, C.P., 2016. Benefits of China's efforts in gaseous pollutant control indicated by the bottom-up emissions and satellite observations 2000–2014. Atmospheric Environment 136, 43–53. https://doi.org/10.1016/j.atmosenv.2016.04.013.

Xie, R., Sabel, C.E., Lu, X., Zhu, W., Kan, H., Nielsen, C.P., Wang, H., 2016. Long-term trend and spatial pattern of $PM_{2.5}$ induced premature mortality in China. Environment International 97, 180–186. https://doi.org/10.1016/j.envint.2016.09.003.

Xie, Y., Dai, H., Zhang, Y., Wu, Y., Hanaoka, T., Masui, T., 2019. Comparison of health and economic impacts of $PM_{2.5}$ and ozone pollution in China. Environment International 130, 104881. https://doi.org/10.1016/j.envint.2019.05.075.

Xing, J., Wang, S.X., Chatani, S., Zhang, C.Y., Wei, W., Hao, J.M., Klimont, Z., Cofala, J., et al., 2011. Projections of air pollutant emissions and its impacts on regional air quality in China in 2020. Atmospheric Chemistry and Physics 11, 3119–3136.

Xing, J., Lu, X., Wang, S., Wang, T., Ding, D., Yu, S., Shindell, D., Ou, Y., et al., 2020. The quest for improved air quality may push China to continue its CO_2 reduction beyond the Paris Commitment. Proceedings of the National Academy of Sciences of the United States of America 117, 29535–29542.

Yue, H., He, C., Huang, Q., Yin, D., Bryan, B.A., 2020. Stronger policy required to substantially reduce deaths from PM2.5 pollution in China. Nature. Communication 11, 1462.

Zhang, Q.; Zheng, Y.; Tong, D.; Shao, M.; Wang, S.; Zhang, Y.; Xu, X.; Wang, J., et al. Drivers of improved PM2.5 air quality in China from 2013 to 2017. Proceedings of the National Academy of Sciences of the United States of America 2019; 116: 24463-24469. www.pnas.org/cgi/doi/10.1073/pnas.1907956116.

Zhang, Y., Bo, X., Zhao, Y., Nielsen, C.P., 2019b. Benefits of current and future policies on emissions of China's coal-fired power sector indicated by continuous emission monitoring. Environmental Pollution 251, 415–424. https://doi.org/10.1016/j.envpol.2019.05.021.

Zhao, Y., Nielsen, C.P., Lei, Y., McElroy, M.B., Hao, J., 2011. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. Atmospheric Chemistry and Physics 11, 2295–2308.

Zhao, Y., Nielsen, C.P., McElroy, M.B., 2012a. China's CO2 emissions estimated from the bottom up: Recent trends, spatial distributions, and quantification of uncertainties. Atmospheric Environment 59, 214–223.

Zhao, Y., Nielsen, C.P., McElroy, M.B., Zhang, L., Zhang, J., 2012b. CO emissions in China: Uncertainties and implications of improved energy efficiency and emission control. Atmospheric Environment 49, 103–113.

Zhao, Y., Zhang, J., Nielsen, C.P., 2013. The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO2 in China. Atmospheric Chemistry and Physics 13, 487–508.

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., et al., 2018. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. Atmospheric Chemistry and Physics 18, 14095–14111. https://doi.org/10.5194/acp-18-14095-2018.

Zheng, H., Zhao, B., Wang, S., Wang, T., Ding, D., Chang, X., Liu, K., Xing, J., et al., 2019. Transition in source contributions of $PM_{2.5}$ exposure and associated premature mortality in China during 2005–2015. Environment International 132, 105111. https://doi.org/10.1016/j.envint.2019.105111.

Zheng, Y., Xue, T., Zhang, Q., Geng, G., Tong, D., Li, X., He, K., 2017. Air quality improvements and health benefits from China's clean air action since 2013. Environmental Research Letters 12, 114020. https://doi.org/10.1088/1748-9326/aa8a32.

Zhou, Y., Zhao, Y., Mao, P., Zhang, Q., Zhang, J., Qiu, L., Yang, Y., 2017. Development of a high-resolution emission inventory and it evaluation and application through air quality modeling for Jiangsu Province. China. Atmospheric Chemistry and Physics 17, 211–233.