Analysis of the air pollution reduction and climate change mitigation effects of the Three-Year Action Plan for Blue Skies on the “2+26” Cities in China

Yun Shu [a, *], Jingnan Hu [a], Shaohui Zhang [b, c], Wolfgang Schöpp [c], Wei Tang [a], Jinhong Du [a], Janusz Cofala [c], Gregor Kiesewetter [c], Robert Sander [c], Wilfried Winiwarter [c, d], Zbigniew Klimont [c], Jens Borken-Kleefeld [c], Markus Amann [c], Haisheng Li [a, **], Youjiang He [a], Jinmin Zhao [a], Deyuan Xie [a]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

[b] School of Economics and Management, Beihang University, Beijing, 100191, China

[c] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria

[d] Institute of Environmental Engineering, University of Zielona Góra, Zielona Góra 65-417, Poland

[*] Corresponding author.

[**] Corresponding author.

E-mail address: shuyun@craes.org.cn (Y. Shu), atmosphere@craes.org.cn (H.S. Li)

Abstract

City clusters play an important role in air pollutant and greenhouse gas (GHG) emissions reduction in China, primarily due to their high fossil energy consumption levels. The “2+26” Cities, i.e., Beijing, Tianjin and 26 other perfectures in northern

China, has experienced serious air pollution in recent years. We employ the Greenhouse Gas and Air Pollution Interactions and Synergies model adapted to the "2+26" Cities (GAINS-JJJ) to evaluate the impacts of structural adjustments in four major sectors, industry, energy, transport and land use, under the Three-Year Action Plan for Blue Skies (Three-Year Action Plan) on the emissions of both the major air pollutants and CO_2 in the "2+26" Cities. The results indicate that the Three-Year Action Plan applied in the "2+26" Cities reduces the total emissions of primary $PM_{2.5}$, SO_2, NO_x, NH_3 and CO_2 by 17%, 25%, 21%, 3% and 1%, respectively, from 2017 to 2020. The emission reduction potentials vary widely across the 28 prefectures, which may be attributed to the differences in energy structure, industrial composition, and policy enforcement rate. Among the four sectors, adjustment of industrial structure attains the highest co-benefits of CO_2 reduction and air pollution control due to its high CO_2 reduction potential, while structural adjustments in energy and transport attain much lower co-benefits, despite their relatively high air pollutant emissions reductions, primarily resulting from an increase in the coal-electric load and associated carbon emissions caused by electric reform policies. Results provided in the paper demonstrate the need of integrating perfectural level decisions in efforts to abate air pollutants and CO_2.

Keywords

Air pollutants; Carbon dioxide; Emission reduction; "2+26" Cities; Co-benefit; GAINS model

1. Introduction

The large amounts of fossil energy that are consumed in association with the urbanization process in China lead to large quantities of air pollutants and greenhouse gases (GHGs) being emitted into the atmosphere every year, which causes air pollution and climate change. Studies have reported that provincial capitals consume 40% of the total energy use and contribute to nearly half of the emissions in China (Dhakal, 2009; Zheng et al., 2018). High air pollutant emissions lead to more complicated regional air pollution via the formation and transport of secondary air pollutants (Silver et al., 2018; Zhai et al., 2019). Over the past decades, heavy-haze episodes have frequently occurred across 74 major cities in China, and the "2+26" Cities (encompassing Beijing, Tianjin and 26 other prefectures in Jing-Jin-Ji and surrounding areas, shown in Figure 1a) are the most seriously polluted (Ministry of Ecology and Environment of the People's Republic of China, 2018). In 2017, nine out of the ten cities with the most air pollution were found among the "2+26" Cities. In addition, there is well-documented evidence that exposure to elevated levels of ambient $PM_{2.5}$ (fine particulate matter with an aerodynamic diameter of $\leq$2.5 μm) causes a notable burden on public health and economic development (Huang et al., 2018), although exact quantification remains lacking.

In light of the above, the Chinese government has successively promulgated a number of policies to reduce pollutant emissions and safeguard public health. For example, the State Council issued the Air Pollution Prevention and Control Action Plan (State Council of the People's Republic of China, 2013). According to the estimates (Li et al., 2017; Zheng et al., 2018), the emissions of SO_2, NO_x, and primary $PM_{2.5}$ decreased from 2013-2017. In consideration of the remarkable impacts of the Air

Pollution Prevention and Control Action Plan, the Chinese government released the Three-Year Action Plan for Blue Skies (Three-Year Action Plan) in 2018 (State Council of the People's Republic of China, 2018). The "2+26" Cities have implemented intensive air pollution control policies, thereby putting tremendous effort towards the control of centralized fossil fuel consumption of the power, industry, and transport sectors, aiming to greatly reduce the total emissions of major air pollutants and synergistically reduce GHG emissions.

In support of the Three-Year Action Plan, major structural adjustments in four key sectors, namely, industry, energy, transport, and land use, were implemented, covering various aspects, including elimination of the backward production capacity, implementation and updating of vehicle emission standards, substitution of clean fuels and strengthening of comprehensive straw utilization. Technical reduction measures were contained within the structural adjustment in each key sector. Detailed information regarding each measure is listed in Table S1. To address severe air pollutants and GHG emission-reduction pressure, many provinces, such as Beijing, Tianjin, Hebei, Henan, Shandong and Shanxi, have issued local action plans in line with national policies (The People's Government of Beijing Municipality, 2018; The People's Government of Hebei Province, 2018; The People's Government of Henan Province, 2018; The People's Government of Shandong Province, 2018; The People's Government of Shanxi Province, 2018; Tianjin Municipal People's Government, 2018).

Previously, air pollution control measures and policies have attained notable pollutant reduction effects. For example, Wang et al. (2014) found that with the implementation of the national control policies of the 11th and 12th Five-Year Plan, the national SO_2 and NO_x emissions decreased by 14% and by 10%, respectively, between 2010 and 2015. Cai et al. (2017) chose the Jing-Jin-Ji region as a case study and demonstrated that the Air Pollution Prevention and Control Action Plan resulted in reductions of 36%, 31% and 30% in SO_2, NO_x and $PM_{2.5}$ emissions, respectively. Zhang et al. (2019) assessed that with the implementation of the above 5-year action plan, the SO_2, NO_x, and primary $PM_{2.5}$ emissions in China were reduced by 16.4, 8.0, and 3.5 Tg, respectively. Amann et al. (2017) reported that effective improvement in the air quality in Delhi, India, requires collaboration with neighbouring states. Most of the current studies have covered only policy evaluations at the national, provincial or single-city level. City clusters, as the main areas of energy consumption, exhibit a large emission abatement space and are the core areas to achieve air pollution control goals (Hu and Fan, 2020; Luo et al., 2021). The “2+26” Cities, although accounting for only 2.9% of the land area of China, consume 21% of Chinese coal(National Bureau of Statistics, 2018b). The emission intensity per unit area is over 4 times the national average (Feng et al., 2019). However, few studies have examined the integrated impact of air pollution control policies on city clusters. In this regard, our study focuses on city clusters and fills this gap by considering the “2+26” Cities.

Relevant studies have revealed that many air pollution control measures may reduce GHG (mainly CO_2) emissions, in addition, many policies with the aim of reducing GHG emissions may reduce the emissions of air pollutants (Mao et al., 2014; Zeng et al., 2017). This occurs because most air pollutants and CO_2 share common sources, such as fossil fuel combustion. For example, energy-related measures in the Air Pollution Prevention and Control Action Plan have led to the co-reduction in CO_2 emission (Lu et al., 2019). Reasonable co-control effects in regard to GHGs, SO_2, NO_x and total suspended particulates (TSP) could be achieved via the implementation of energy-saving and carbon reduction policies in key sectors, such as the power plant, iron and steel, cement and transport sector (Jiang et al., 2020; Mao et al., 2014; Zhou et al., 2013).

In this study, we adopt the "2+26" Cities as the research object and employ the Greenhouse Gas-Air Pollution Interactions and Synergies model in the "2+26" Cities model (GAINS-JJJ) to quantitatively evaluate the impacts structural adjustments in four major sectors contained in the Three-Year Action Plan on the emissions of both the major air pollutants (i.e., primary $PM_{2.5}$, SO_2, NO_x, and NH_3) and CO_2. The GAINS-JJJ model was developed in collaboration with the International Institute for Applied System Analysis (IIASA) as a regional version of the GAINS model (Amann et al., 2011). First, an emission inventory of the "2+26" Cities for the base year of 2017 and an emission scenarios (baseline and policy) for 2020 and 2030 are developed. The Covid-19 related effects in energy consumption, transport and industry process are not considered in the projection. Second, a policy scenario based on a careful review of the Three-Year Action Plan is integrated into the GAINS-JJJ model, and the impacts of various policies are studied. Third, source-specific emission abatement of air pollutants and CO_2 emissions in 2020 are estimated, and measures or prefectures with high co-benefit potentials are identified. Finally, policy implications are analyzed to highlight further mitigation opportunities.

2. Materials and methods

2.1. Model description and data sources

The GAINS model is a widely applied policy assessment tool of the effects of air pollution and GHG emissions mitigation and the interactions between policies. The model calculates the emissions of air pollutants and GHGs based on international emission inventories and statistics as well as input obtained from collaborating national expert teams. Emissions are estimated with a technology-based methodology following Equation (1). Details of the GAINS model have been provided in the literature (Amann et al., 2011).

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

where, k, m, and p denote the activity type, abatement measure, and pollutant, respectively, E_p stands for the emissions of pollutant p, A_k denotes the activity data of type k, $ef_{k,m,p}$ is the emission factor of pollutant p for activity k after the application of control measure m, and $\chi_{k,m,p}$ denotes the penetration of control measure m targeting pollutant p of activity k.

The GAINS-JJJ model considers Jing-Jin-Ji and surrounding areas as a single region, which is further subdivided into 28 subregions corresponding to the “2+26” Cities. The estimated emissions in each of the prefectures considered in the GAINS-JJJ model are determined from activity data, emission factors and control strategies updated according to local information for the specific 28 prefectures. To reproduce the prefectural total emission inventory (unpublished data, hereafter referred to as the MEE database), the input data under the default baseline scenario of

“ECLIPSE_V6c_CLE_base” have been updated for the power, industrial, domestic, transport and agricultural sectors.

In the power sector, the energy consumption was calibrated based on data published by the World Resources Institute and the Global Coal Plant Tracker, which contains the power plant capacity and type for each prefecture. In the industrial sector, the fuel use and industrial process data were based on prefectural energy use patterns and product output retrieved from the China City Statistical Yearbook (National Bureau of Statistics, 2018a) and the China Energy Statistical Yearbook 2018 (National Bureau of Statistics, 2018b). Unfortunately, no subsectoral details were provided in these data sources, so it was necessary to formulate certain assumptions to construct subsectors based on process data. Information on the energy consumption for residential heating and cooking was taken from the MEE database. It was estimated that approximately 19 million households still relied on coal for heating and cooking purposes in the “2+26” Cities in 2017. In the transport sector, data on the registered number, mileage and emission standards of the different kinds of vehicles in the “2+26” Cities were taken from the MEE database and Yearbook of China Transportation & Communications (Ministry of Transport of the People's Republic of China, 2018), and applied to calibrate the fuel consumption in the transport sector in 2017. NH_3 emissions are mainly from agricultural production. The fertilizer consumption, livestock numbers (e.g., cows, pigs, sheep, and hens), and milk yields in the agriculture sector were calibrated, based on the 28 Prefectures Statistical Yearbooks and the Nutrient Flows in Food Chains, Environment and Resources Use (NUFER) model (Zhao et al., 2017). The emission factors for the different fuel types used to estimate the emissions in the power, industrial, domestic, transport and agricultural sectors were taken from the GAINS dataset (a full description is provided in Supplementary Section 1.1).

2.2. Emission scenarios

Two scenarios are constructed and analyzed in this study, i.e., baseline and policy scenarios, and the base year is set to 2017. For future projections, exogenous inputs, which follow the projections of the World Energy Outlook 2018 (International Energy Agency, 2018), are used for the model, these inputs are in line with China's recent economic growth during the Thirteenth Five-Year Plan period (State Council of the People's Republic of China, 2016). For example, the gross domestic product (GDP) in the "2+26" Cities increases by a factor of 1.3 to 1.6 between 2017 and 2020, and 1.9 to 2.8 between 2017 and 2030 (Figure S1). At the same time, the consumption of total primary energy is estimated to increase by a factor of 1.0 to 1.3 and 1.1 to 1.5, which indicates a decoupling between economic growth and energy consumption in the "2+26" Cities. We assumed no additional policy adoptions under the baseline scenario during the study period. Details on the establishment of the baseline scenario are provided in section 1.1 of the Supplementary information.

In support of the Three-Year Action Plan, major structural adjustments in four key sectors, namely, industry, energy, transport, and land use, were proposed (State Council of the People's Republic of China, 2018). A brief description of the policy scenario implemented in the model is summarized in Table S1 and further described in detail below.

Adjustment of industrial structure. Ineffective capacity (Table S1) in various industrial sectors, such as steel, cement, coke, glass and electrolytic aluminum, is phased out. Inefficient coal-fired power plants and small-scale coal mining are shut down. The change in activity data due to industry structural adjustment is calculated with Equation (2).

$$\Delta A = A_{BL} \times \frac{\Delta Ca}{Ca_{2017}} \qquad (2)$$

where ΔA is the change in activity data due to industry structural adjustment, A_{BL} denotes the activity data under the baseline scenario, ΔCa is the change in production capacity due to industry structural adjustment, and Ca_{2017} is the total capacity in 2017, which is retrieved from the statistical data contained in the Province Economic Yearbook 2018.

Adjustment of energy structure. Poor quality coal for residential heating purposes is replaced by natural gas and electricity. Here, we assume that the required electric loads are balanced by local coal-fired power plants due to the high reliance on coal for electricity generation in China (Wang et al., 2020). The fuel demand change in the residential and power sectors is calculated with Equations (3)-(6).

$$\Delta A_{Coal}^{Res} = \Delta N_{House} \times U_{Coal} \qquad (3)$$

$$\Delta A_{Ele}^{Res} = \frac{\Delta A_{Coal}^{Res} \times Eff_{Coal}^{Res} \times R_{Coal-Ele}}{Eff_{Ele}^{Res}} \qquad (4)$$

$$\Delta A_{Gas}^{Res} = \frac{\Delta A_{Coal}^{Res} \times Eff_{Coal}^{Res} \times R_{Coal-Gas}}{Eff_{Gas}^{Res}} \qquad (5)$$

$$\Delta A_{Coal}^{PP} = \frac{\Delta A_{Ele}^{Res}}{Eff_{Coal}^{PP} \times (1 - Eff_{Lose})} \qquad (6)$$

where ΔA_{Coal}^{Res} is the change in coal use in the residential sector, ΔA_{Ele}^{Res} is the change in electricity use in the residential sector, ΔA_{Gas}^{Res} is the change in natural gas use in the residential sector, ΔA_{Coal}^{PP} is the change in coal use in the power sector, ΔN_{House} is the change in the number of households due to energy structural adjustment, U_{Coal} is the average coal use per household obtained from Chinese household surveys (Zhi et al., 2009), Eff_{Coal}^{Res} is the energy efficiency of residential coal use, Eff_{Gas}^{Res} is the energy efficiency of residential gas use, Eff_{Coal}^{PP} is the energy efficiency of thermal coal use, Eff_{Loss} is the power loss rate across transmission and distribution networks, and $R_{Coal\text{-}Ele}$ and $R_{Coal\text{-}Gas}$ are the substitution ratios (State Council of the People's Republic of China, 2018) of coal by electricity and gas, respectively. All small coal-fired industrial boilers are eliminated, and the decreased energy use is redistributed across large coal-fired industrial boilers. Existing and newly built large boilers are all equipped with SO_2, NO_x, and particulate control devices as required by the new emission standard (Ministry of Ecology and Environment of the People's Republic of China, 2014). The fuel demand change in the large coal-fired boilers is calculated with Equation (7).

$$\Delta A_{Coal}^{L} = A_{Coal}^{S} \times \frac{Eff_{Coal}^{S}}{Eff_{Coal}^{L}} \quad (7)$$

where ΔA_{Coal}^{L} is the change in coal use of large coal-fired boilers, A_{Coal}^{S} is the baseline coal use of small coal-fired boilers, and Eff_{Coal}^{S} and Eff_{Coal}^{L} are the energy efficiencies of small and large coal-fired boilers, respectively.

Adjustment of transport structure. The Three-Year Action Plan mandated that all new light gasoline and diesel vehicles in the 2+26 cities must meet the China VI emission standard (similar to the Euro VI emission standard) in 2020. In the GAINS-JJJ model, the growth rate of vehicles reflects the addition of new vehicles to the current stock, and the same proportion of old vehicles (with outdated emission standards) is eliminated. The appropriate control strategies are applied to this new stock. Simultaneously, the same proportion of control strategies involving outdated emission standards is phased out. In addition, electric vehicles are introduced into the stock. Here, we assume that the required electricity is provided by local coal-fired power plants. The fuel demand change in the transport and power generation sectors is calculated with Equations (8)-(10). The road freight volume is proportionally replaced by rail freight options. For example, compared to 2017, the railway freight share increased by 40% in Hebei in 2020. The activity data corresponding to vehicle/rail mileage, vehicle/rail number and energy are adjusted in the GAINS-JJJ model accordingly to reflect this policy.

$$\Delta A_{Ele}^{Trans} = A_{BL-ele}^{Trans} \times \frac{\Delta Num_{Ele}}{Num_{Ele-2017}} \quad (8)$$

$$\Delta A_{Gasoline/Diesel}^{Trans} = \frac{\Delta A_{Ele}^{Trans} \times Eff_{Ele}^{Trans}}{Eff_{Gasline/Diesel}^{Trans}} \quad (9)$$

$$\Delta A_{Coal}^{PP} = \frac{\Delta A_{Ele}^{Trans}}{Eff_{Coal}^{PP} \times (1-Eff_{Lose})} \quad (10)$$

where ΔA_{Ele}^{Trans} is the change in fuel use of electric vehicles, $\Delta A_{Gasoline/Diesel}^{Trans}$ is the change in fuel use of gasoline or diesel vehicles, ΔA_{Coal}^{PP} is the change in coal use in the power sector, ΔNum_{Ele} is the change in electric vehicle number due to transport structural adjustment, $Num_{Ele-2017}$ is the electric vehicle ownership in 2017, which is retrieved from various sources during field surveys, and Eff_{Ele}^{Trans} and $Eff_{Gasline/Diesel}^{Trans}$ are the energy efficiencies of electric and gasoline/diesel vehicles, respectively.

Adjustment of land use structure. Good practices are applied to dust management of construction sites and bulk product storage and handling. Moreover, agricultural residue open burning (e.g., crop straw field burning) and chemical fertilizer use are reduced. Therefore, control strategies are adjusted to reflect the suppression of construction dust and the ban on agricultural waste burning. Additionally, the amount of chemical fertilizer in the agricultural sector is reduced to match the increased nitrogen use efficiency(State Council of the People's Republic of China, 2018).

2.3 Quantification of the CO_2 co-benefits

To compare the co-benefits between the emission reductions of CO_2 and air pollutants (including primary $PM_{2.5}$, SO_2, and NO_x) resulting from different measures, the ratio of the emission change in CO_2 to that of a certain air pollutant P is defined, as shown in Eq. (11). This index has been used in previous studies (Liu et al., 2013; Lu et al., 2019; Rive and Aunan, 2010) to estimate the magnitude of co-benefit effects. A higher value of R represents a higher co-benefit effect.

$$R = \frac{\Delta E_{CO2}}{\Delta E_P} \qquad (11)$$

where $\triangle E_{CO2}$ is the CO_2 emission reduction (Mt) and $\triangle E_P$ is the emission reduction in air pollutant P (kt).

3. Results

3.1. Base year emission inventory

In 2017, the anthropogenic emissions of primary $PM_{2.5}$, SO_2, NO_x, NH_3 and CO_2 in “2+26” Cities reached 972 kt, 1041 kt, 2923 kt, 1404 kt and 1891 Mt, respectively. To ensure consistency, the emissions estimated in this study are compared to other studies focusing on Jing-Jin-Ji and surrounding areas (Table S2). The emissions of primary $PM_{2.5}$, SO_2, NO_x and NH_3 agree reasonably well with those contained in the MEE database, but are lower than those of the MEIC inventory (Li et al., 2017). The activities of industrial products in this study account for only large scale enterprises, which may contribute to the lower emissions compared to the MEIC results.

Figure 1 shows the prefectural emissions in 2017. As expected, the total emissions of air pollutants and CO_2 vary widely across the "2+26" Cities, due to differences in demographic status and economic development level, in addition to urban and industrial structures. In general, the cities with large energy consumption amounts, such as Tangshan, Binzhou, Handan, Tianjin and Shijiazhuang (Figure S2), emit more air pollutants (except for NH_3) and CO_2. Among the "2+26" Cities, Tangshan dominated by coal, iron and steel production is the largest contributor to the emissions of primary $PM_{2.5}$ (12%), SO_2 (10%), NO_x (8%) and CO_2 (10%). Jining, an important base of agricultural products in China, contributes the largest share of NH_3 emissions (8%), followed by Heze (7%) and Cangzhou (7%).

In terms of sectoral emissions (Figure 2), residential combustion (33%) is an important source of primary $PM_{2.5}$ emissions due to its relatively low combustion efficiency and the lack of controls (Zheng et al., 2018), while industrial process contributes 21% and fuel conversion contributes 16% to the total emissions. Regarding SO_2, three groups of sources yield similar emissions: industrial combustion (29%), residential combustion (28%), and industrial process (25%). In comparison, the power sector (15%) is a smaller source, which is inconsistent with the findings reported in previous studies (Klimont et al., 2017). This occurs because pronounced SO_2 emission abatements occurred in China from 2013-2017 due to the ultralow-emission retrofitting of coal-fired power (Liu et al., 2020). Transportation (40%), especially heavy-duty diesel vehicles (25%), predominantly contributes to NO_x emissions, followed by industrial combustion and process (36%) and power plants (11%). In contrast to the above pollutants, more than 90% of the NH_3 emissions stem from agriculture, including livestock manure (pigs, poultry and other cattle) and synthetic fertilizer application (urea and ammonium bicarbonate application) (Figure S3d). In regard to CO_2, industrial combustion (34%) and power plants (29%) dominate the emissions, primarily due to the bulk coal consumption occurring in these two sectors (Table S3).

Most noteworthy, the sectoral contributions to the total emissions differ greatly across the “2+26” Cities. For example, residential combustion is a major emitter of $PM_{2.5}$ in cities on the North China Plain, such as Baoding, Cangzhou, and Hengshui, while it has a small contribution for the cities on the Central China Plain, such as Anyang, Zhengzhou, and Xinxiang, since residential home heating is not needed as much in winter in Central China. Furthermore, we select several subsectors that contribute considerably to air pollution and CO_2 emissions (Figure S3). As shown, in cities with conglomerated iron steel, coke and cement plants, such as Tangshan, Handan and Anyang, a large share of the emissions originates from five subsectors in industrial combustion and process, namely, agglomeration plant-sinter, basic oxygen furnace, industrial furnace, coke oven and cement and lime. In populous cities relying more on the tertiary industry, such as Beijing and Baoding, cooking and heating stoves in the residential sector and heavy-duty diesel vehicles and cars in the transportation sector are the prime sources of the emissions of primary $PM_{2.5}$, SO_2, NO_x and CO_2. The above sectoral disparity indicates the necessity for attention when planning future mitigations.

3.2. Policy-level simulation results analysis

3.2.1. Air pollutant and CO_2 emission reductions

Table 1 lists the estimated emissions of air pollutants and CO_2 from 2017 and 2020 to 2030 under the baseline and policy scenarios. The sectoral emissions of these pollutants from 2017-2030 are shown in Figure 3. Under the baseline 2020 scenario, the emissions of air pollutants (except for SO_2) in the "2+26" Cities increase due to the growth in the total primary energy use (Tables S3 and S4), while under the baseline 2030, despite an increase in total energy use, the emissions of air pollutants are reduced as a result of the decline in absolute volume of coal use (Tables S3 and S5). Emissions of CO_2 under both baseline 2020 and 2030 scenarios show an increase relative to the 2017 level. With the implementation of the Three-Year Action Plan, despite an increase in the total energy use (Table S6), the total emissions of primary $PM_{2.5}$, SO_2, and NO_x are obviously reduced by 17%, 25% and 21%, respectively, from 2017 to 2020, and the NH_3 and CO_2 emissions are also slightly lower (the NH_3 emissions are 3% lower, and the CO_2 emissions are 1% lower). However, further reductions after 2020 are modest without new clean air action: air pollutant emissions fall by only 3%-11% between 2020 and 2030; instead, CO_2 emissions are slightly increased by 2030. Analysing key sector emissions shows that the change patterns of the sectoral emissions result in varied source contributions after the implementation of the Three-Year Action Plan. For instance, the contribution of residential combustion decreases from 33% in 2017 to 25%

in the policy 2020 scenario and 19% in the policy 2030 scenario for primary $PM_{2.5}$, from 28% to 17% and 12% for SO_2 and from 6% to 4% and 5% for CO_2. In contrast, the power and non-road machinery sectors experience increasing trends; namely, the contribution of the power plants to SO_2 grows from 15% in 2017 to 23% in the policy 2020 scenario and 28% in the policy 2030 scenario, and the non-road machinery contribution to NO_x increases by 13% and 16%, respectively.

The sectoral contributions to the observed emission reductions by prefecture after implementing the Three-Year Action Plan in 2020 are shown in Figure S4. In terms of the cities or sectors, the higher the pollutant emissions are, the higher the reduction potential. From the city-specific perspective, a high mitigation potential is observed in Tangshan, Handan, Tianjin, Taiyuan and Jining due to their high total emissions. From the sector perspective, residential combustion is the largest contributor to $PM_{2.5}$ and SO_2 emission reductions, while transport, agriculture and industrial combustion are the largest contributors to the reduction in NO_x, NH_3 and CO_2 emissions, respectively. In addition, negative emission cuts occur in almost all prefectures, probably resulting from the increase in development and policy intervention.

3.2.2. Analysis of the implementation of individual policies

Structural adjustments of industry, energy, transportation and land use have been carried out since the implementation of the Three-Year Action Plan. Figure 4 shows the policy-specific contributions to emission reductions. Each measure is analyzed in terms of air pollutants and CO_2 emission reductions (Figure S5). Compared to the results of the baseline for 2020 scenario, the above four structural adjustment measures under the policy 2020 scenario reduced the primary $PM_{2.5}$ emissions by 173 kt, the SO_2 emissions by 245 kt, the NO_x emissions by 749 kt, the NH_3 emissions by 59 kt, and the CO_2 emissions by 168 Mt. However, it should be noted that certain structural measures attain a good air pollution reduction effect but simultaneously impose negative reduction effects on other pollutants, such as CO_2.

Adjustment of industrial structure. Industrial restructuring is an important source control measure for air pollution prevention (Zheng et al., 2016). A series of measures is considered, including the phasing out of outdated or inefficient technologies and capacities in sectors such as steel, cement, coke, glass, electrolytic aluminum and power. Extra capacity is no longer allowed in these areas. For example, 40 million tons of iron and steel, 5 million tons of cement, 10 million tons of coke, and 23 million weight boxes of flat glass were eliminated in Hebei Province from 2017-2020 due to outdated production capacity mitigation. In addition, a coal-fired power generation capacity of 1.5 GW may also be retired to improve the energy efficiency (The People's Government of Hebei Province, 2018). In comparison to the baseline 2020 scenario, these measures lead to a reduction of 50 kt (29% of the total abatements) in primary $PM_{2.5}$ emissions, 81 kt (33%) in SO_2 emissions, 150 kt (20%) in NO_x emissions and 135 Mt (80%) in CO_2 emissions in 2020. From Figure 4 and Figure S5, the emission reductions are especially remarkable in the industrial combustion and process sectors due to the phasing out of high-emission industrial capacity (such as iron and steel, cement and coke). Additionally, in the power sector, the SO_2, NO_x and CO_2 emissions show a slight decrease because of the elimination of coal-fired power generation capacity units.

Adjustment of energy structure. The adjustment and optimization of the energy structure plays an important role in air pollutant and CO_2 emission reductions (Lu et al., 2019). Two aspects are considered to examine the effect of energy restructuring on emission reduction. On the one hand, coal use for residential heating is replaced by natural gas and electricity. According to the MEE database, the energy consumption in 10 million households in the “2+26” Cities transitioned from coal to electricity and natural gas from 2017-2020. On the other hand, all small coal-fired industrial boilers are eliminated, and the decreased energy use is redistributed across large coal-fired industrial boilers. Existing and newly built large industrial boilers are all equipped with advanced SO_2, NO_x, and particulate control devices. It is estimated that these measures lead to reductions of 96 kt (55% of the total abatements) in primary $PM_{2.5}$ emissions, 165 kt (67%) in SO_2 emissions, 292 kt (38%) in NO_x emissions, and 14 kt (8%) in CO_2 emissions, in addition to an increase of 9 kt in NH_3 emissions. In regard to the primary $PM_{2.5}$, SO_2 and CO_2 emissions, most of the reductions are caused by residential combustion, owing to the transition from domestic coal burning to electricity and natural gas utilization (Figure S5). Regarding NO_x, industrial combustion is the prime contributor to its emission reduction due to the elimination of small coal-fired industrial boilers and implementation of stringent control measures targeting large industrial boilers. It is noteworthy that a negative effect of the energy restructuring is mainly found in the power sector. This occurs because fuel substitution results in a sharp increase in the coal-electric loads (Wang et al., 2020) and associated emissions, especially CO_2 emissions. In addition, the slight increase in NH_3 emissions might be ascribed to the ammonia slip as a result of existing and newly built large industrial boilers being equipped with additional selective noncatalytic reduction systems.

Adjustment of transport structure. The transportation sector has been a notable contributor to NO_x emissions in China since 2015 due to the rapid growth of the vehicle population (Zheng et al., 2019). Strategies of old vehicle elimination, tightening of vehicle emission standards, and new-energy vehicle promotion have been introduced to develop city-level green transportation systems (Wu et al., 2017). In this study, China 6 emission standards are applied to light-duty and heavy-duty vehicles in 2020. Electric vehicles are introduced into the vehicle population, and the road freight volume is proportionally replaced by rail freight volume. For example, the number of electric vehicles in Beijing will reach 0.4 million by 2020 (The People's Government of Beijing Municipality, 2018). Consequently, these measures reduce the primary $PM_{2.5}$ emissions by 14 kt (8% of the total abatements), the NO_x emissions by 296 kt (40%), the NH_3 emissions by 4 kt (7%), and the CO_2 emissions by 19 kt (11%). Within transport structural adjustment, strengthening vehicle emission standards is a prominent contributor to NO_x abatements (177 kt, 24% of the total abatements). In contrast, the implementation of transport structural adjustment leads to an increase in emissions in the non-road machinery sector, which may be ascribed to the freight volume transition from trucks to rail. Moreover, the increase in CO_2 emissions in the power sector may be attributed to the increase in electric loads resulting from the introduction of electric vehicles.

Adjustment of land use structure. Adjustment of the land use structure focuses on the management of nonpoint source pollution, including the strengthening of comprehensive dust control measures, such as construction dust management and bulk product storage and handling, enhancement of comprehensive straw utilization, such as a ban on agricultural residue open burning, and reduction in fertilizer application on agricultural fields. For example, in 2020, the utilization rate of straw reached 100% in Beijing and Tianjin, 95% in Hebei, 89% in Henan, 92% in Shandong, and 85% in Shanxi. The nitrogen use efficiency in the "2+26" Cities was enhanced to higher than 40%. We estimate that these measures reduce the primary $PM_{2.5}$ emissions by 13 kt (8% of the total abatements), SO_2 emissions by 4 kt (2%), NO_x emissions by 10 kt (1%), and NH_3 emissions by 63 kt (107%, , as measures in energy are associated with an increase of NH_3 emissions). In contrast, the CO_2 emissions change little because the implemented land use structural adjustment measures are largely focused on emission control strategies, while the structural measures (e.g., fuel switching) are not employed. In regard to land use structure optimization, an increase in nitrogen use efficiency contributes most to the reduction in NH_3 emissions, and agriculture is the single sector predominantly contributing to the reduction of this air pollutant.

3.3. Co-benefits analysis

Table 2 illustrates the CO_2 co-benefits based on parameter R due to the different structural measures under the Three-Year Action Plan in 2017-2020. It is evident that industry structural adjustment attains the highest co-benefits of CO_2 reduction and air pollution control among the four structural measures, primarily due to its high CO_2 reduction potential (Figure 4). The co-reduction rate is approximately 2.7 $MtCO_2/ktPM_{2.5}$, 1.7 $MtCO_2/ktSO_2$, and 0.9 $MtCO_2/ktNO_x$, respectively. In comparison, the energy and transport structural adjustment measures yield much lower co-benefits, despite their relatively high air pollutant emission reductions. One reason for this finding is that the CO_2 abatements resulting from these two measures are small. Another contributing factor is the partial increase of CO_2 emissions due to measures implemented. Regarding land use structural adjustment, no co-benefits of CO_2 reduction are obtained since the emissions of CO_2 vary little under policy intervention. In addition, the reduction ratio of CO_2 to $PM_{2.5}$ emissions is the highest among the three air pollutants, which is consistent with the results of Lu et al. (2019) that $PM_{2.5}$ has the highest co-benefit with CO_2 in Beijing, Tianjin and Hebei Province.

Figure 5 shows the co-benefits of reducing CO_2 and air pollution in the "2+26" Cities from 2017 to 2020. The x- and y-axes represent the reduction amounts of CO_2 and major air pollutants (primary $PM_{2.5}$, SO_2 and NO_x). Each point in the coordinate system stands for the emission reductions of CO_2 and a certain air pollutant in a certain city. Details on the establishment of the co-control effects coordinate system are provided in section 2 of the Supplementary information. For the co-control effects of CO_2 and three air pollutants, most of the points are located in the first and second quadrants, indicating that most cities exhibit positive reduction effects for primary $PM_{2.5}$, SO_2 and NO_x. Among them, nearly half of the prefectures can contribute positively to the reduction in CO_2 and air pollutant emissions. Significant co-benefits are found in Tianjin, Beijing, Taiyuan and Xinxiang, which reduce the emissions of CO_2 and major air pollutants by 8-19 Mt and 3-39 kt, respectively. In contrast, the other half have seen negative reduction effects on CO_2 although they can reduce the air pollutant emissions simultaneously.

4. Discussion and policy implications

In the "2+26" Cities, we estimate that structural transformations in the four sectors industry, energy, transport and land use, introduced for air pollutant emissions mitigation, also yield co-benefits of CO_2 reduction. The diversity of the emission reduction potentials among the 28 cities (Figure S4) may be attributed to several factors. First, the emission reduction potential corresponds to the emission amount, which is mainly driven by energy consumption and economic scale (Ma, 2015); hence, Tangshan, Handan and Tianjin have relatively high mitigation potentials. Second, notable differences in industrial structure occur among the various cities. In cities with heavy industrial conglomeration (e.g., iron steel, coke and cement), such as Tangshan, Handan and Anyang, a large share of the reduction potential is attributed to industrial combustion and process. In populous cities heavily reliant on the tertiary industry, such as Beijing and Baoding, the residential and transportation sectors appear to be the major contributors to emission reductions. Third, the enforcement of structural adjustment policies varies. For example, the prefectures in Henan Province banned the addition of new production capacity in the coke, electrolytic aluminum, cement and glass industries, whereas Tianjin did not implement this restriction (The People's Government of Henan Province, 2018; Tianjin Municipal People's Government, 2018).

Our study contains a number of uncertainties and limitations. The first source of uncertainty originates from the lack of detailed information regarding the quantification of specific measures under the Three-Year Action Plan. For example, the effects of nonroad transportation control measures are not investigated here, which might result in an underestimation of the total benefits of the Three-Year Action Plan. Second, the uncertainties in the construction of the baseline scenario may also cause discrepancies. Specifically, simplifications and assumptions are required when projected energy use data are unavailable in certain prefectures. But the way the baseline and policy scenarios have been created integrates uncertain information in the same way, hence discrepancies between scenarios become more robust. Third, the emission factors introduce uncertainties. Even though the GAINS-JJJ model contains updates retrieved from the literature based on local information in China, individual emission factors for the different industries and processes in the "2+26" Cities are still not available.

Although total emissions of air pollutants and CO_2 in the "2+26" Cities have decreased in 2017-2030, many cities still fail to meet the $PM_{2.5}$ requirements in the National Ambient Air Quality Standards and are facing CO_2 emission-reduction pressure. Based on the analytical results, several policy implications are highlighted. First, cities as the main areas of energy consumption, are the best implementers of environmental policy. However, most studies usually refer to air pollution control among relatively large regions, such as provinces (Zhang et al., 2018; Zheng et al., 2015). They are often not practical in implementation because there are usually quite differences for industrial and energy structures among the cities within the same province, which are strongly associated with local emission patterns and trends (Figures 1 and 2). Thus, a precision scheme of air pollution control among cities is much needed. Second, the emission reductions are mainly contributed by the industrial, residential, transportation and agricultural sectors (Figure S4). Further reductions are still necessary for these sectors because they remained major sources of pollutant emissions in 2020 and/or even in 2030 (Figure 3). Specifically, quantitative emission control indicators regarding non-road machinery are recommended for incorporation into relevant policy documents, as the emissions of NO_x contributed by the non-road machinery sector have experienced increasing trends following policy implementation. Also, emission reductions of ammonia are fairly small, as measures were limited to one single element of the available portfolio in agriculture, and the important emission source of animal husbandry and manure management still offers large potential for abatement and air quality improvement (Zhao et al., 2017). Third, structural reduction measures are reported to achieve the overall co-benefits of reducing air pollution and carbon emissions (Jiang et al., 2020). The adjustment of industrial structure successfully abating air pollutants and CO_2 emissions should be prioritized (Figure 4, Figure S5 and Table 3). For example, Tangshan city could foster more capital- and technology-intensive industries and could restrict the scale of energy-intensive industries. As such, industry relocation should occur towards less-developed areas, and this should be carefully considered in regard to pollutant emissions issues. Fourth, electric consumption reforms, such as the coal-to-electricity policy and new-energy vehicle promotion, have contributed to notable emission reductions in certain sectors. This shift, however, has resulted in an increase in the coal-electric loads and associated emissions, especially CO_2 emissions (Figure 4). Thus, the government is encouraged to match large-scale renewable generation (such as wind power and solar power) with an additional electric load. Last but not least, in the "2+26" Cities more than half of the prefectures show an increase of CO_2 emissions (Figure 5). Generally, in local governments, air pollutant reduction policies receive much attention, while GHG reduction is often treated as a subsidiary benefit during policy design(Jiang et al., 2013). Therefore, in order to achieve China's aims of a peak in carbon emissions by 2030 and net-zero emissions by 2060 (United Nations Framework Convention on Climate Change, 2020), also local governments should place the same emphasis on both GHG emissions and air pollution control. For instance, strengthening the coordination and cooperation between government bodies and divisions and defining explicit GHG emissions reduction goals in energy-related policies are necessary to achieve comprehensive and notable co-benefits locally.

5. Conclusion

In this paper, we applied the GAINS-JJJ model to evaluate the impacts of structural adjustments to industrial, energy, transport and land use structure under the Three-Year Action Plan on the emissions of both the major air pollutants and CO_2. With the implementation of the Three-Year Action Plan, the total emissions of primary $PM_{2.5}$, SO_2, and NO_x were reduced by 17%, 25% and 21%, respectively, from 2017 to 2020.

In addition, the NH_3 and CO_2 emissions also slightly decreased (NH_3 emissions by 3% and CO_2 emissions by 1%). However, further reductions after 2020 are modest without new clean air action: air pollutant emissions are expected to fall by only 3%-11% between 2020 and 2030; instead, CO_2 emissions are slightly increased by 2030. Among the four sectors, adjustment of industrial structure attains the highest co-benefits of CO_2 reduction and air pollution control due to its high CO_2 reduction potential. In contrast, a sharp increase in the coal-electric loads and associated emissions due to electricity consumption reform resulted in much lower co-benefits of the energy and transport structural adjustment measures. In the "2+26" Cities, nearly half of the prefectures have seen increasing CO_2 emissions while reducing air pollutant emissions, demonstrating the need of integrating perfectural level decisions in efforts to abate air pollutants and CO_2. Thus, further policies should consider the potential incompatibility between any new and existing policies.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

This research was funded by the National Key R&D Program of China (2017YFC0213000), the World Bank Group under project (7196868 and 7192186), and National Natural Science Foundation of China (71904007).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://www.sciencedirect.com.

Table/Figure Captions

Table 1 Air pollutant and CO_2 emissions in 2017, baseline (2020 and 2030) and policy (2020 and 2030) scenarios in "2+26" Cities

Table 2 Co-benefits between the total emission reductions of CO_2 and air pollutants from various structural measures during 2017-2020 in the "2+26" Cities

Figure 1 Prefectural emissions in baseline 2017 scenario. (a) geographical location of the "2+26" Cities, (b) primary $PM_{2.5}$, (c) SO_2, (d) NO_x, (e) NH_3, (f) CO_2.

Figure 2 Prefectural emissions by key sectors in the baseline 2017 scenario. (a) primary $PM_{2.5}$, (b) SO_2, (c) NO_x, (d) NH_3, (e) CO_2

Figure 3 Air pollutant and CO_2 emissions by key sectors in the baseline and policy scenarios in 2017-2030.

Figure 4 Contribution of each structural policy under the policy 2020 scenario to the emission reductions compared with the baseline 2020 scenario. (a) adjustment of industrial structure, (b) adjustment of energy structure, (c) adjustment of transport structure, (d) adjustment of land use structure. Note: The positive horizontal axis shows the reduction amount, and the negative horizontal axis shows negative emission reduction and refers to an increase in the emissions.

Figure 5 CO_2 reduction versus the major air pollutant emission reductions in the "2+26" Cities in 2017-2020. (a) emission reductions of CO_2 and primary $PM_{2.5}$, (b) emission reductions of CO_2 and SO_2, (c) emission reductions of CO_2 and NO_x

References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling &

Software 26, 1489-1501.

Amann, M., Purohit, P., Bhanarkar, A.D., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Kiesewetter, G., Klimont, Z., Liu, J., Majumdar, D., Nguyen, B., Rafaj, P., Rao, P.S., Sander, R., Schöpp, W., Srivastava, A., Vardhan, B.H., 2017. Managing future air quality in megacities: A case study for Delhi. Atmospheric Environment 161, 99-111.

Cai, S., Wang, Y., Zhao, B., Wang, S., Chang, X., Hao, J., 2017. The impact of the "Air Pollution Prevention and Control Action Plan" on $PM_{2.5}$ concentrations in Jing-Jin-Ji region during 2012-2020. Sci. Total Environ. 580, 197-209.

Dhakal, S., 2009. Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 37, 4208-4219.

Feng, Y., Ning, M., Lei, Y., Sun, Y., Liu, W., Wang, J., 2019. Defending blue sky in China: Effectiveness of the "Air Pollution Prevention and Control Action Plan" on air quality improvements from 2013 to 2017. J. Environ. Manage. 252, 109603-109616.

Hu, W., Fan, Y., 2020. City size and energy conservation: Do large cities in China consume more energy? Energy Economics 92, 104943.

Huang, J., Pan, X., Guo, X., Li, G., 2018. Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality monitoring and mortality data. The Lancet Planetary Health 2, e313-e323.

International Energy Agency, 2018. World Energy Outlook 2018.

Jiang, P., Chen, Y., Geng, Y., Dong, W., Xue, B., Xu, B., Li, W., 2013. Analysis of the co-benefits of climate change mitigation and air pollution reduction in China. J. Clean. Prod. 58, 130-137.

Jiang, P., Khishgee, S., Alimujiang, A., Dong, H., 2020. Cost-effective approaches for reducing carbon and air pollution emissions in the power industry in China. J. Environ. Manage. 264, 110452-110464.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schöpp, W., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmospheric Chemistry and Physics 17, 8681-8723.

Li, M., Liu, H., Geng, G., Hong, C., Liu, F., Song, Y., Tong, D., Zheng, B., Cui, H., Man, H., Zhang, Q., He, K., 2017. Anthropogenic emission inventories in China: a review. National Science Review 4, 834-866.

Liu, F., Klimont, Z., Zhang, Q., Cofala, J., Zhao, L., Huo, H., Nguyen, B., Schöpp, W., Sander, R., Zheng, B., Hong, C., He, K., Amann, M., Heyes, C., 2013. Integrating mitigation of air pollutants and greenhouse gases in Chinese cities: development of GAINS-City model for Beijing. J. Clean. Prod. 58, 25-33.

Liu, J., Zheng, Y., Geng, G., Hong, C., Li, M., Li, X., Liu, F., Tong, D., Wu, R., Zheng, B., He, K., Zhang, Q., 2020. Decadal changes in anthropogenic source contribution of PM2.5 pollution and related health impacts in China, 1990–2015. Atmospheric Chemistry and Physics 20, 7783-7799.

Lu, Z., Huang, L., Liu, J., Zhou, Y., Chen, M., Hu, J., 2019. Carbon dioxide mitigation co-benefit analysis of energy-related measures in the Air Pollution Prevention and Control Action Plan in the Jing-Jin-Ji region of China. Resources, Conservation

& Recycling: X 1, 100006-100016.

Luo, X., Sun, K., Li, L., Wu, S., Yan, D., Fu, X., Luo, H., 2021. Impacts of urbanization process on $PM_{2.5}$ pollution in "2+26" cities. J. Clean. Prod. 284, 124761-124781.

Ma, B., 2015. Does urbanization affect energy intensities across provinces in China?Long-run elasticities estimation using dynamic panels with heterogeneous slopes. Energy Economics 49, 390-401.

Mao, X.Q., Zeng, A., Hu, T., Xing, Y.K., Zhou, J., Liu, Z.Y., 2014. Co-control of local air pollutants and CO_2 from the Chinese coal-fired power industry. J. Clean. Prod. 67, 220-227.

Ministry of Ecology and Environment of the People's Republic of China, 2014. Emission standard of air pollutants for boiler.(GB 13271-2014).

Ministry of Ecology and Environment of the People's Republic of China, 2018. Report on the state of the ecology and environment in China.

Ministry of Transport of the People's Republic of China, 2018. Yearbook of China Transportation & Communications.(Beijing).

National Bureau of Statistics, 2018a. China City Statistical Yearbook.(Beijing).

National Bureau of Statistics, 2018b. China Energy Statistical Yearbook.(Beijing).

Rive, N., Aunan, K., 2010. Quantifying the Air QualityCobenefits of the CleanDevelopment Mechanism in China. Environ. Sci. Technol. 44, 4368-4375.

Silver, B., Reddington, C.L., Arnold, S.R., Spracklen, D.V., 2018. Substantial changes in air pollution across China during 2015–2017. Environmental Research Letters 13, 114012-114020.

State Council of the People's Republic of China, 2013. Notice of the general office of the state council on issuing the air pollution prevention and control action plan. http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm. (15-December 2021).

State Council of the People's Republic of China, 2016. Outline of the 13th Five-Year Plan for National Economic and Social Development of the People's Republic of China. http://www.gov.cn/xinwen/2016-03/17/content_5054992.htm. (31-December 2021).

State Council of the People's Republic of China, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm?trs=1. (3-July 2020).

The People's Government of Beijing Municipality, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. http://www.beijing.gov.cn/zhengce/zhengcefagui/201905/t20190522_61552.html. (31-December 2020).

The People's Government of Hebei Province, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. http://hbepb.hebei.gov.cn/xwzx/szfwj/201808/t20180828_66737.html. (31-December 2020).

The People's Government of Henan Province, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. https://www.henan.gov.cn/2018/09-21/692225.html. (31-December 2020).

The People's Government of Shandong Province, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. http://www.sdein.gov.cn/dtxx/hbyw/201808/t20180808_1444314.html. (31-December 2020).

The People's Government of Shanxi Province, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. http://www.shanxi.gov.cn/sxszfxxgk/sxsrmzfzcbm/sxszfbgt/flfg_7203/szfgfxwj_7205/201808/t20180806_468873.shtml. (31-December 2020).

Tianjin Municipal People's Government, 2018. Notice of the State Council on printing and distributing the three-year action plan for winning the blue-sky defense war. http://www.tj.gov.cn/sy/jrgz/202005/t20200520_2479345.html. (31-December 2020).

United Nations Framework Convention on Climate Change, 2020. China's nationally determined contribution. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/ChinaFirst/China'sFirstNDCSubmission.pdf. (30-December 2020).

Wang, J., Zhong, H., Yang, Z., Wang, M., Kammen, D.M., Liu, Z., Ma, Z., Xia, Q., Kang, C., 2020. Exploring the trade-offs between electric heating policy and carbon mitigation in China. Nature communications 11, 6054-6065.

Wang, S., Xing, J., Zhao, B., Jang, C., Hao, J., 2014. Effectiveness of national air pollution control policies on the air quality in metropolitan areas of China. Journal of environmental sciences 26, 13-22.

Wu, Y., Zhang, S., Hao, J., Liu, H., Wu, X., Hu, J., Walsh, M.P., Wallington, T.J., Zhang, K.M., Stevanovic, S., 2017. On-road vehicle emissions and their control in China: A review and outlook. Sci. Total Environ. 574, 332-349.

Zeng, A., Mao, X., Hu, T., Xing, Y., Gao, Y., Zhou, J., Qian, Y., 2017. Regional co-control plan for local air pollutants and CO_2 reduction: Method and practice. J. Clean. Prod. 140, 1226-1235.

Zhai, S., Jacob, D.J., Wang, X., Shen, L., Li, K., Zhang, Y., Gui, K., Zhao, T., Liao, H., 2019. Fine particulate matter ($PM_{2.5}$) trends in China, 2013–2018: separating contributions from anthropogenic emissions and meteorology. Atmospheric Chemistry and Physics 19, 11031-11041.

Zhang, N.N., Ma, F., Qin, C.B., Li, Y.F., 2018. Spatiotemporal trends in $PM_{2.5}$ levels from 2013 to 2017 and regional demarcations for joint prevention and control of atmospheric pollution in China. Chemosphere 210, 1176-1184.

Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., Xu, X., Wang, J., He, H., Liu, W., Ding, Y., Lei, Y., Li, J., Wang, Z., Zhang, X., Wang, Y., Cheng, J., Liu, Y., Shi, Q., Yan, L., Geng, G., Hong, C., Li, M., Liu, F., Zheng, B., Cao, J., Ding, A., Gao, J., Fu, Q., Huo, J., Liu, B., Liu, Z., Yang, F., He, K., Hao, J., 2019. Drivers of improved $PM_{2.5}$ air quality in China from 2013 to 2017. Proceedings of the National Academy of Sciences 116, 24463-24469.

Zhao, Z.Q., Bai, Z.H., Winiwarter, W., Kiesewetter, G., Heyes, C., Ma, L., 2017. Mitigating ammonia emission from agriculture reduces $PM_{2.5}$ pollution in the Hai River Basin in China. Sci. Total Environ. 609, 1152-1160.

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., Peng, L., Qi, J., Yan, L., Zhang, Y., Zhao, H., Zheng, Y., He, K., Zhang, Q., 2018. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. Atmospheric Chemistry and Physics 18, 14095-14111.

Zheng, H., Zhao, B., Wang, S., Wang, T., Ding, D., Chang, X., Liu, K., Xing, J., Dong, Z., Aunan, K., Liu, T., Wu, X., Zhang, S., Wu, Y., 2019. Transition in source contributions of $PM_{2.5}$ exposure and associated premature mortality in China during 2005-2015. Environ. Int. 132, 105111.

Zheng, J., Jiang, P., Qiao, W., Zhu, Y., Kennedy, E., 2016. Analysis of air pollution reduction and climate change mitigation in the industry sector of Yangtze River Delta in China. J. Clean. Prod. 114, 314-322.

Zheng, S., Yi, H., Li, H., 2015. The impacts of provincial energy and environmental policies on air pollution control in China. Renewable and Sustainable Energy Reviews 49, 386-394.

Zhi, G.R., Peng, C., Chen, Y., Liu, D., 2009. Deployment of coal briquettes and improved stoves possibly an optionfor both environment and climate. Envionmental Science & Technology 43, 5587-5591.

Zhou, Y., Zhang, H., Cai, B.F., He, J., 2013. Synergetic reduction of local pollutants and CO_2 from cement industry. Environment Science & Technology 36, 164-180.

Figure 1

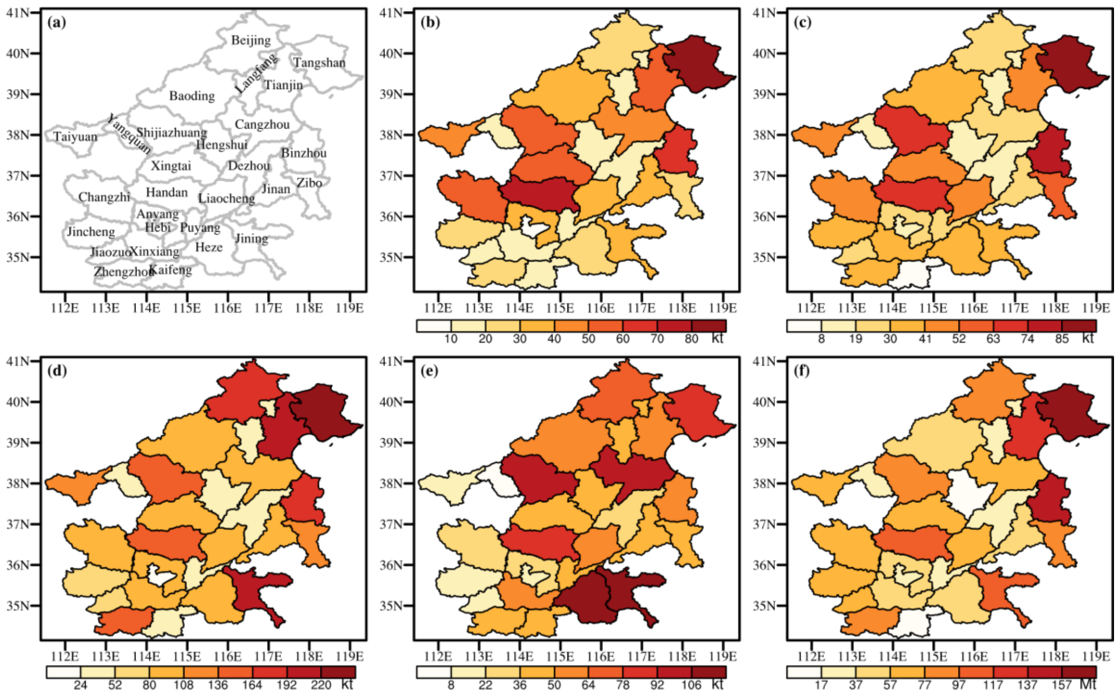


Figure 1

Figure 2

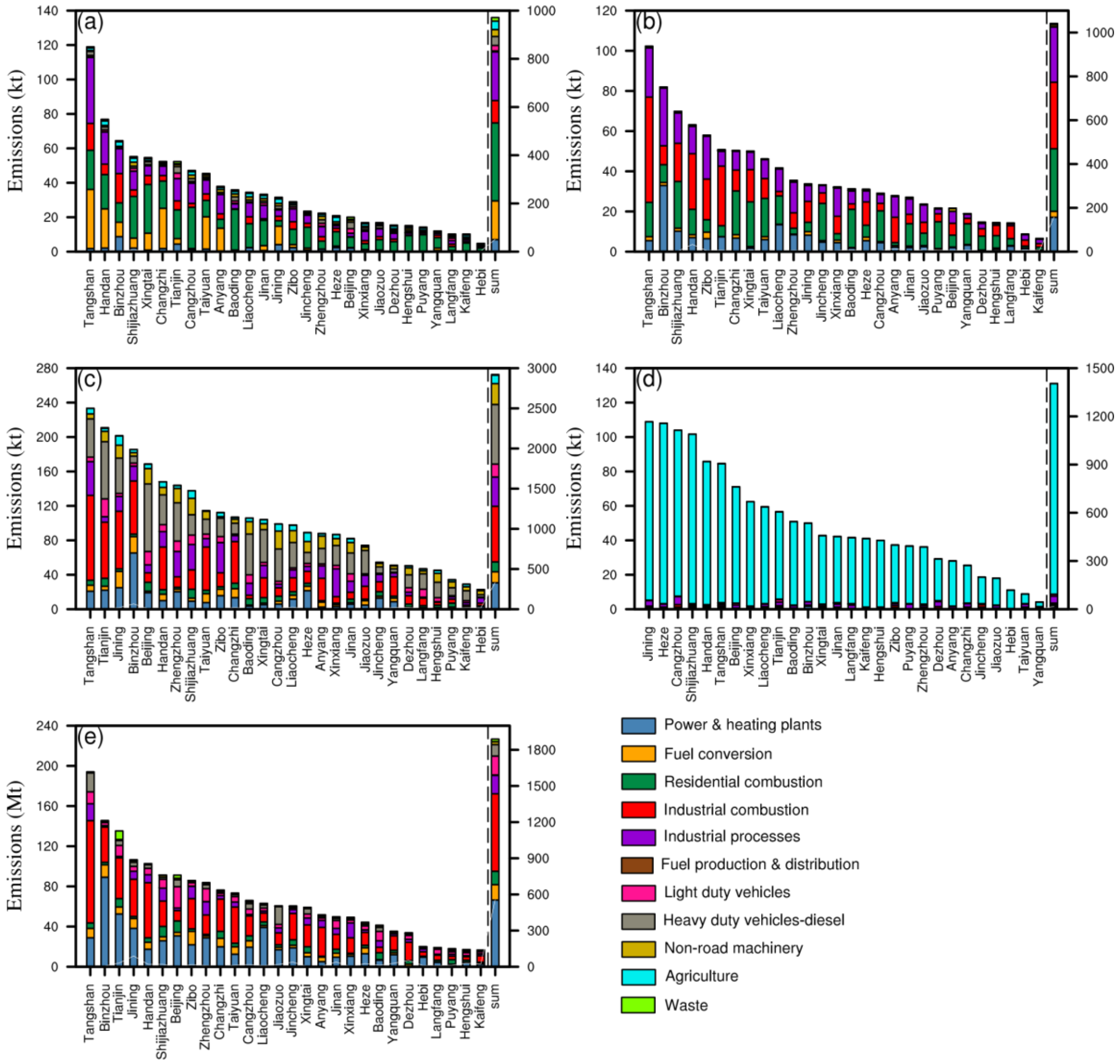


Figure 2

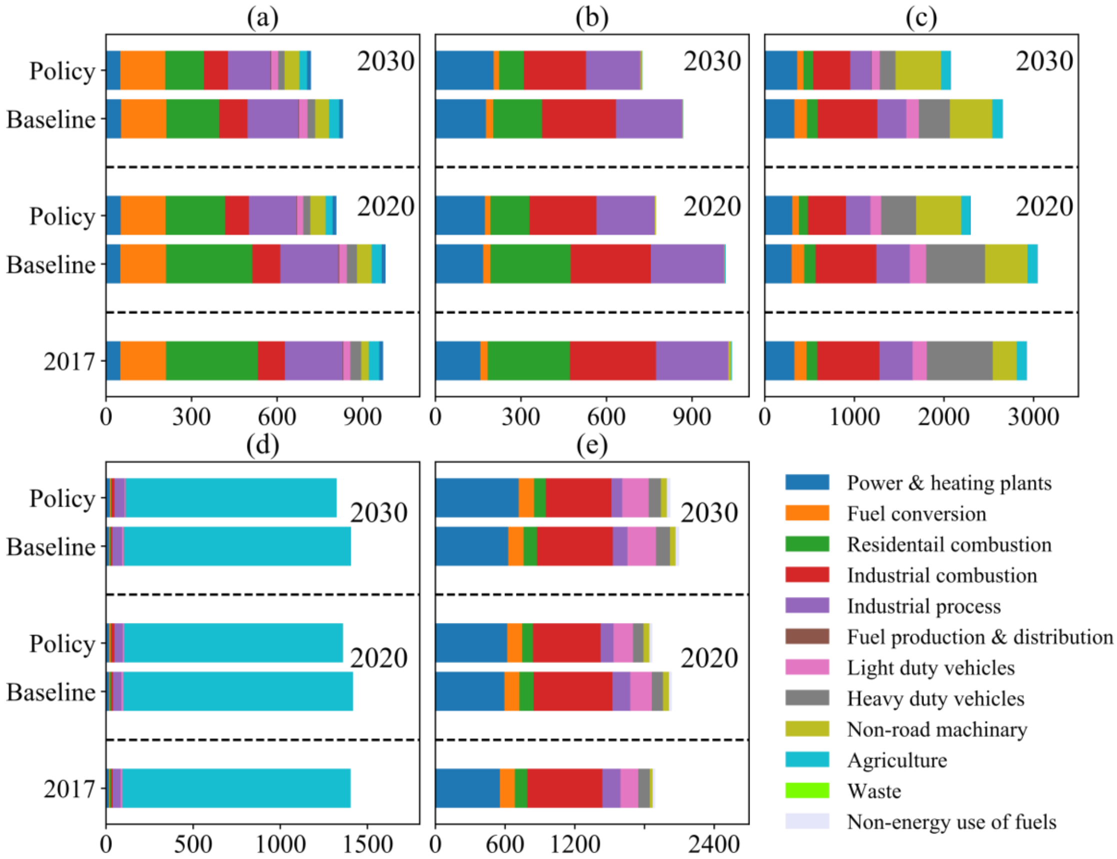

(a)
(b)
(c)
(d)
(e)
Policy
Baseline
Policy
Baseline
2017
2030
2020
0 300 600 900
0 300 600 900
0 1000 2000 3000
0 500 1000 1500
0 600 1200 2400
Power & heating plants
Fuel conversion
Residentail combustion
Industrial combustion
Industrial process
Fuel production & distribution
Light duty vehicles
Heavy duty vehicles
Non-road machinary
Agriculture
Waste
Non-energy use of fuels

Figure 3

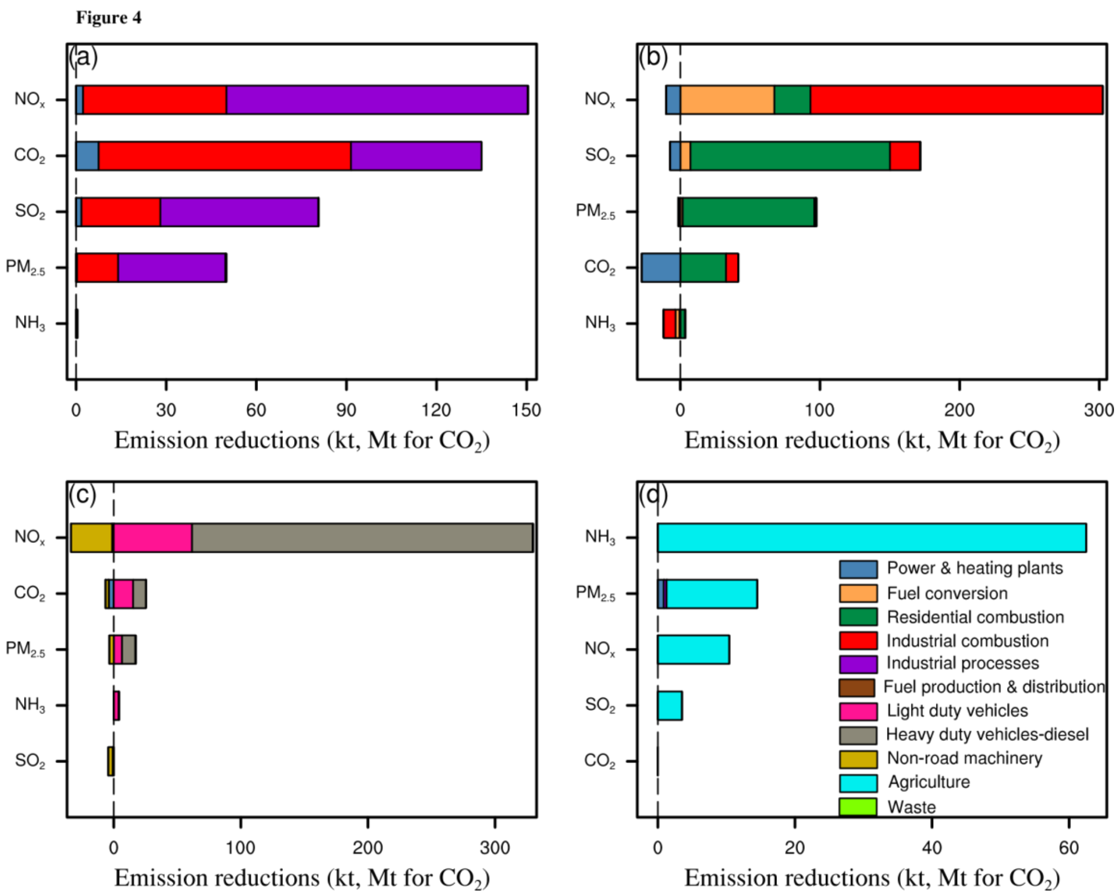


Figure 4
(a)
NO_x
CO_2
SO_2
$PM_{2.5}$
NH_3
0 30 60 90 120 150
Emission reductions (kt, Mt for CO_2)
(b)
NO_x
SO_2
$PM_{2.5}$
CO_2
NH_3
0 100 200 300
Emission reductions (kt, Mt for CO_2)
(c)
NO_x
CO_2
$PM_{2.5}$
NH_3
SO_2
0 100 200 300
Emission reductions (kt, Mt for CO_2)
(d)
NH_3
$PM_{2.5}$
NO_x
SO_2
CO_2
Power & heating plants
Fuel conversion
Residential combustion
Industrial combustion
Industrial processes
Fuel production & distribution
Light duty vehicles
Heavy duty vehicles-diesel
Non-road machinery
Agriculture
Waste
0 20 40 60
Emission reductions (kt, Mt for CO_2)

Figure 4

Figure 5 (a)

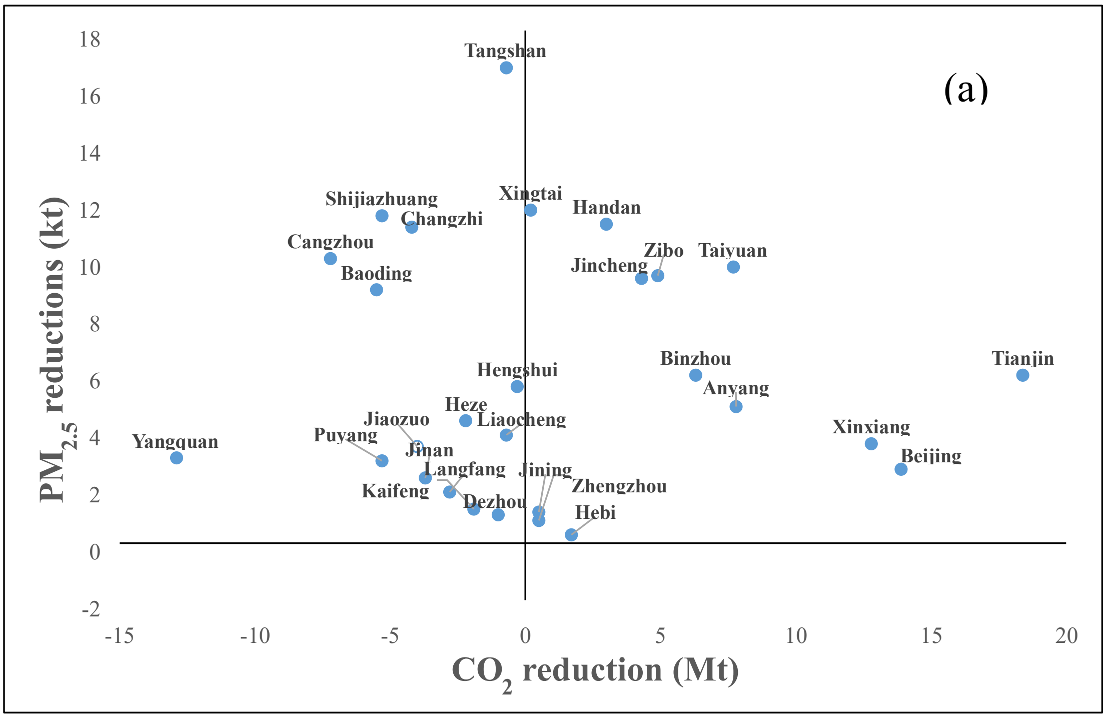


Figure 5 (a)

Figure 5 (b)

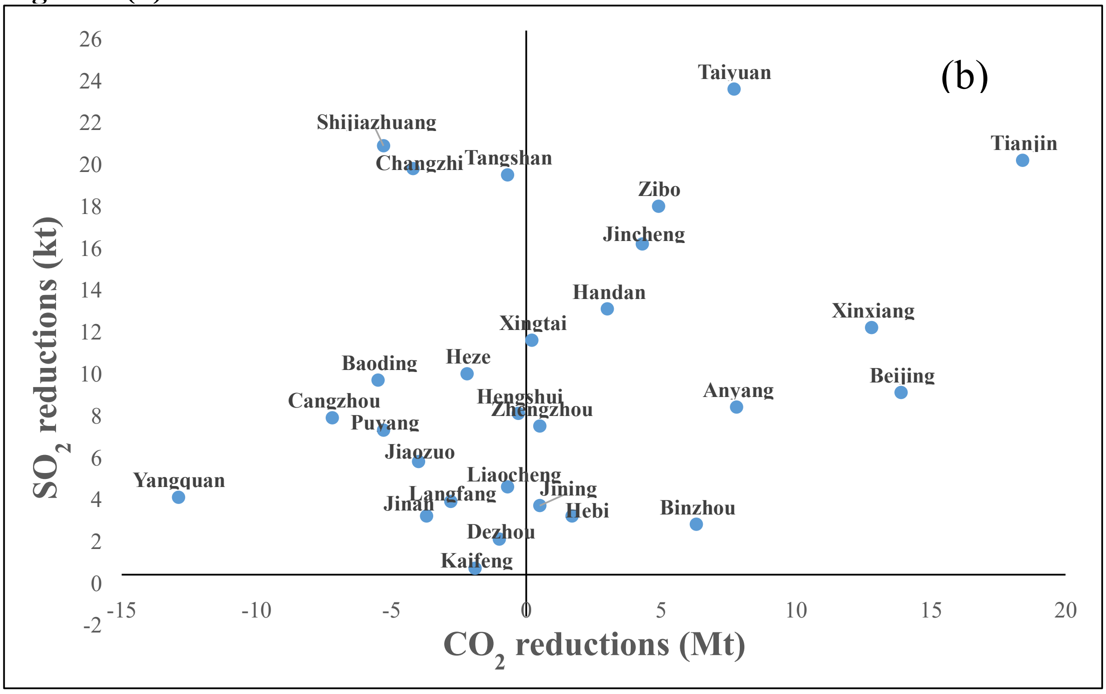
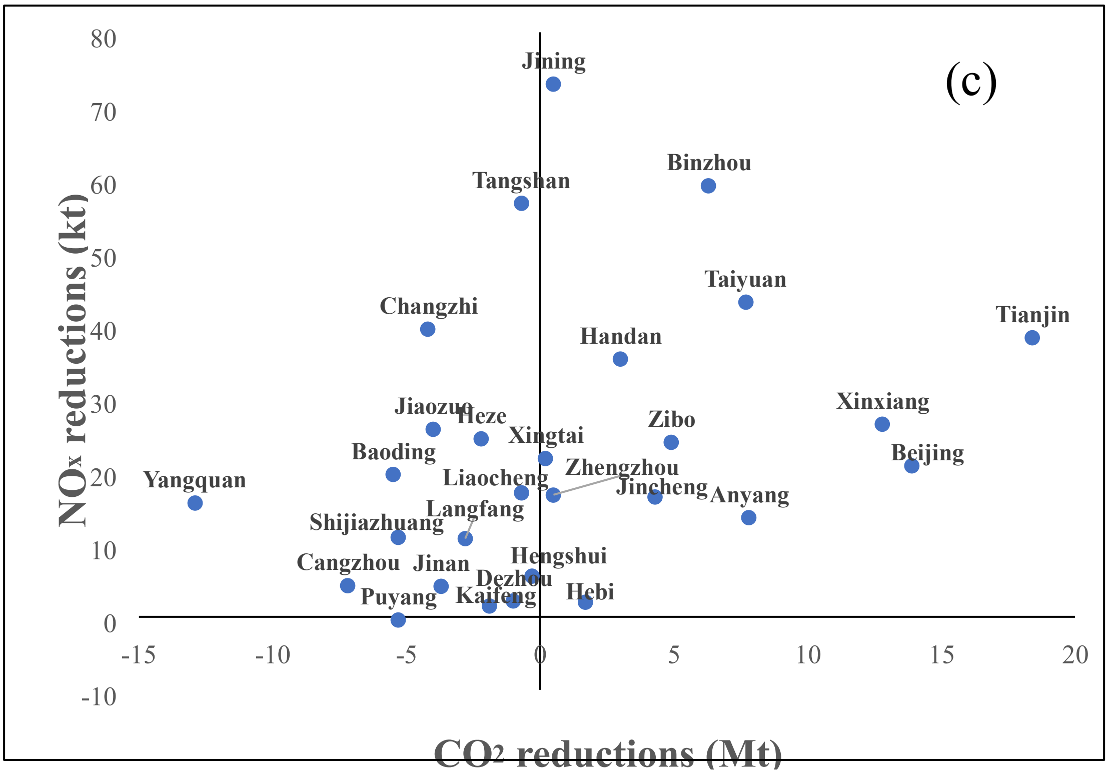


Figure 5 (b)

Figure 5 (c)

1 

2 Figure 5 (c)