Pathways toward $PM_{2.5}$ air quality attainment and its CO_2 mitigation co-benefits in China's northern cities by 2030

Abstract

Rapid economic development and urbanization have left millions of people in urban areas vulnerable to the adverse effects of air pollution. Reducing serious $PM_{2.5}$ pollution remains a major policy challenge for Chinese cities, such as the "2+26" Cities in the most polluted region of China, despite adopting various air pollution-control measures since 2017. In this study, we use a Greenhouse Gas and Air Pollution Interactions and Synergies model for the "2+26" Cities to explore feasible pathways for achieving the $PM_{2.5}$ air quality annual standard (35 μg/m^3) until 2030 by developing four future scenarios based on a 2017 emission inventory. The results show that by continuing the control policies from before 2020, including the Air Pollution Prevention and Control Action Plan from 2013 and the Three-Year Action Plan for Wining the Blue Sky Defense Battle from 2018, and implementing the policies likely to be proposed after 2020, the "2+26" Cities will not succeed in achieving the standard by 2030; furthermore, the amount of the population living below 35 μg/m^3 will not exceed 12%. Nevertheless, by combining the best available technologies, the regional average $PM_{2.5}$ concentration in the "2+26" Cities is 34 μg/m^3 by 2030, attaining the target; moreover, more than half of the population will experience air quality that conforms to the standard. Under this scenario, emissions of primary $PM_{2.5}$, SO_2, NO_x, NH_3 and NMVOCs are estimated to decrease by 75%, 69%, 76%, 32% and 52%, respectively, in 2017-2030. The emission reductions under alternative scenarios vary widely across cities, indicating the need for differentiated control strategies among cities. Considering the predominant contributions to emissions and the lack of effective control measures, fuel conversion, off-road, agricultural and solvent use sectors should be paid more attention to enable further emission reductions in future. In addition, CO_2 emission reduction co-benefits of implemented clean air action measures have been identified; however, the negative reduction effects of these measures should be given more attention (e.g., increased carbon emissions in the power sector from electrification of end-users).

Keywords: air quality; $PM_{2.5}$; emission scenario; GAINS; cities

1. Introduction

China's rapid economic development and urbanization have substantially relied on fossil fuels, resulting in severe environmental pollution, particularly air pollution and carbon emissions. A total of 83% of the population in China faces an exposure to more than the National Ambient Air Quality Standard (NAAQS) of 35 μg/m^3 annual mean $PM_{2.5}$ (Wang *et al.*, 2019; Wu *et al.*, 2017a), not to mention exceedance of the World Health Organization (WHO) Guidelines of 5 μg/m^3.

To protect public health, several air pollution control policies aiming to reduce the annual mean $PM_{2.5}$ have been implemented in China, such as the Air Pollution Prevention and Control Action Plan (Action Plan) in 2013 (State Council of the People's Republic of China, 2013) and the Three-Year Action Plan for Wining the Blue Sky Defense Battle (Three-Year Action Plan) in 2018 (State Council of the People's Republic of China, 2018). Consequently, national mean $PM_{2.5}$ has decreased by 32%

from 2013 to 2017 through substantial decreases in emissions of primary pollutants (21-59%) (Zhang *et al.*, 2019; Zheng *et al.*, 2018). Moreover, implementing energy-related measures from these clean air policies can also reduce 0.1-1.8 Gt anthropogenic CO_2 emissions each year (Shi *et al.*, 2022; Tibrewal and Venkataraman, 2020), as a co-benefit of the clean air policies. Simultaneously, cities in China account for over 70% of national energy use and energy-related emissions (Wang and Zheng, 2013), and play an increasingly important role in air pollution control and CO_2 emission mitigation. How the clean air actions reshape emissions in cities largely determine the national pollution mitigation pathway.

The "2+26" Cities in northern China (encompassing Beijing, Tianjin and 26 other prefectures in the Jing-Jin-Ji and surrounding areas, shown in Figure 1) are the most polluted areas in the country due to their large energy use, dense populations and long heating season (National Bureau of Statistics, 2018b). In 2017, the "2+26" Cities were the first to implement a clean household fuel substitution policy on a large scale (Ministry of Ecology and Environment of the People's Republic of China, 2017b). Furthermore, the Three-Year Action Plan issued in 2018 required that the "2+26" Cities reduced emissions of atmospheric pollutants by optimizing the structures of industry, energy, transportation, and land use and by strengthening regional cooperation on controlling heavy air pollution. These measures are anticipated to reshape the patterns of sectoral fuel use and emissions of air pollutants and CO_2, and consequently affect future regional air quality. Exploring future mitigation pathways for achieving the NAAQS in the "2+26" Cities and investigating the indirect impacts of clean air actions on CO_2 reductions, are therefore valuable for policymaking.

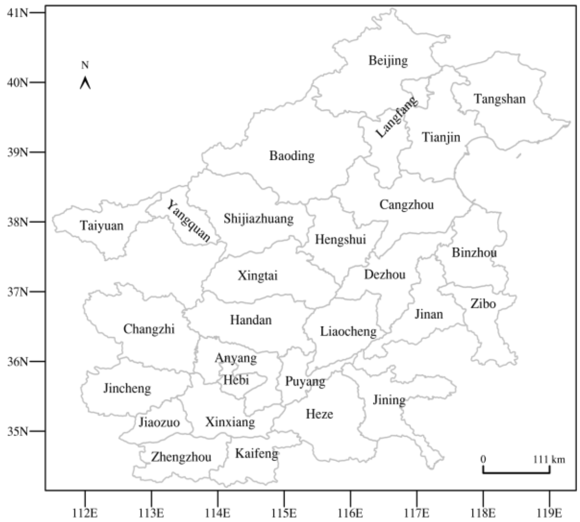

Figure 1 The “2+26” Cities, including Beijing, Tianjin, and 26 other municipalities

Early studies have evaluated and predicted future emissions and air quality trends at the national (Cai *et al.*, 2018; Cheng *et al.*, 2021a; Tong *et al.*, 2020; Xing *et al.*, 2011; Zhao *et al.*, 2014), provincial (Chang *et al.*, 2022; Madaniyazi *et al.*, 2015; Tong *et al.*, 2019) and city levels (Ling *et al.*, 2021). Xing *et al.* (2011), Wang *et al.* (2014) and Tong *et al.* (2019) projected emissions of $PM_{2.5}$, SO_2, NO_x, NH_3 and nonmethane volatile organic compounds (NMVOC) up to 2020/2030 based on policies from before 2013. Future emissions such as NO_x and NMVOC are projected to increase by 24-49% under the current policies compared to their base levels. After 2013, a series of stringent clean air actions (e.g., Action Plan) was implemented including strengthening industrial and vehicle emission standards, phasing out small and polluting factories and upgrades on industrial boilers, which may alter the future emission pathways. Thus, underestimations may be found in the ambitious air pollution control policies implemented since the Action Plan. The most recent projections (Chang *et al.*, 2022; Cheng *et al.*, 2021a; Tong *et al.*, 2020) have developed future emission scenarios based on a 2015 emission inventory, but they were mostly conducted at national or sub-national levels, which cannot identify the differences between cities and make region-specific local policies. In addition, a few studies examined CO_2 emission reduction co-benefits of implemented clean air policies.

In this work, based on new information about local emission factors in the "2+26" Cities in 2017 and on the constantly updated air pollution control policies, we present possible emission scenarios for primary $PM_{2.5}$, SO_2, NO_x, NH_3, nonmethane volatile organic compounds (NMVOC) and CO_2 and the potential impacts of emission changes on the regional $PM_{2.5}$ concentration and population exposure in the "2+26" Cities for 2030. A base case emission inventory is developed for 2017 using the Greenhouse Gas and Air Pollution Interactions and Synergies model adapted to the "2+26" Cities (GAINS–JJJ) (Yun *et al.*, 2022). Emissions under four future scenarios are developed considering the Three-Year Action Plan and progressive emission control policies. More specifically, three research questions are addressed: (1) Are the current policy measures in the "2+26" Cities adequate to reduce air pollution to the NAAQS by 2030? (2) What is the direction for prioritized control strategies considering the future evolution of sectoral emissions under policies? (3) How do air pollution control measures affect the CO_2 emissions at the city level?

The paper is structured as follows. In Section 2, the GAINS–JJJ model is described for the "2+26" Cities, followed by key assumptions behind the alternative policy scenarios and the resulting energy consumption and penetration levels of end-of-pipe control technologies. Section 3 summarizes the modelling results in terms of sector-and prefectural-specific changes in the emission levels. Thereafter, the likely impacts on air quality and population exposure from the alternative policy interventions are analyzed. The discussion and conclusion sections summarize the modelling insights and policy ideas derived from this study.

2. Methods

2.1. GAINS–JJJ model

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; Zheng *et al.*, 2016). As a 2+26 city-based version of the GAINS model, the GAINS–JJJ model contained a disaggregated representation of the Jing-Jin-Ji region and surrounding areas in 28 subregions. The model was used to calculate the emissions of air pollutants and CO_2 through a technology-based methodology following Equation (1). Details of the GAINS model are 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 denotes 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 estimated emissions in 2017 for each of the prefectures considered in the GAINS–JJJ model were updated for the power, industrial, domestic, transport agricultural and solvent sectors. More specifically, various parameters (e.g., energy consumption levels by fuel type and sector, industrial process activities, utilization rates of air pollution control technologies, and emission factors) were calibrated through key assumptions and various data sources (e.g., statistical reports, local surveys and field investigations); a more detailed description is provided in Supplementary Section 1.

The annual average $PM_{2.5}$ concentration in the "2+26" Cities was estimated with the GAINS–JJJ model, employing reduced-form source–receptor relationships derived from a European Monitoring and Evaluation Programme (EMEP) model with a spatial resolution of 0.5°×0.5° (Simpson *et al.*, 2012) and a Community Multiscale Air Quality (CMAQ) model with a 12×12 km grid within the region (Environmental Protection Agency). Calculation merging on the 0.5° grid and 12×12 km grids was accomplished via spatial interpolation of 0.5° transfer coefficients into the fine grid for smoothing. The $PM_{2.5}$ concentration at the receptor point was calculated by Equation (2) (Kiesewetter *et al.*, 2015). Modeled $PM_{2.5}$ concentrations were validated against ground-based observations in 28 cities (Figure S1). In general, reasonable agreement was achieved, with a correlation coefficient of 0.83, normalized mean bias of -4.27%, and root mean squared error of 6.63. The grid-specific $PM_{2.5}$ concentration was converted into a population-weighted average $PM_{2.5}$ concentration via Equation (3). In this study, we used gridded population data (National Aeronautics and Space Administration, 2018; WorldPop) in the calculation.

$$PM_{2.5}(j) = \delta_{PM_{2.5}}(j) + \sum_i \pi_i^j E_{PM_{2.5}}^i + \sum_i \alpha_i^j E_{NH_3}^i + \sum_i \upsilon_i^j E_{NO_x}^i + \sum_i \sigma_i^j E_{SO_2}^i \quad (2)$$

$$\rho_k(PM_{2.5}) = \sum_{j\in k} \frac{pop_j}{pop_k} PM_{2.5}(j) \quad (3)$$

where π_i^j, α_i^j, υ_i^j, and σ_i^j are the linear $PM_{2.5}$ transfer coefficients for primary $PM_{2.5}$, NH_3, NO_x, and SO_2, respectively, from source grid *i* to receptor point *j*; $E_{PM_{2.5}}^i$, $E_{NH_3}^i$, $E_{NO_x}^i$, and $E_{SO_2}^i$ are the total primary $PM_{2.5}$, NH_3, NO_x, and SO_2 emissions, respectively, in source grid *i*; $\delta_{PM2.5}(j)$ is the $PM_{2.5}$ constant in receptor point *j* based on source-receptor calculations representing both boundary conditions and nonlinear contributions in the EMEP simulations (Simpson *et al.*, 2012); $\rho_k(PM_{2.5})$ is the population-weighted average $PM_{2.5}$ concentration in city *k*; pop_j is the population of receptor point *j* living in city *k*; and pop_k is the total population of city *k*.

2.2. Development of future emission scenarios

The year 2017, for which the authors previously developed an emissions inventory (Yun *et al.*, 2022), was set as the base year. The year 2030 was selected as the target year, representing the medium-term future. In 2017, it was determined that 28 prefectures emitted 959–3050 kt air pollutants, which agreed reasonably well with the values reported in previous studies (Cai *et al.*, 2017; Li *et al.*, 2017; Zheng *et al.*, 2018); more details are presented in Section 1 and Table S1 in the Supplementary Information.

Four future scenarios were developed for the "2+26" Cities based on the 2017 emissions inventory that considered requirements for air pollution prevention in the policies at the provincial and national levels. These four scenarios were projected under the same future socioeconomic assumptions (Table S2). Table 1 lists the key assumptions of these scenarios. The current legislation (CLE) scenario only considered the existing control policies by the of 2017, including the 12^{th} Five-Year Plan for Environmental Protection during 2010–2015 (State Council of the People's Republic of

China, 2011) and the Action Plan from 2013 to 2017 (State Council of the People's Republic of China, 2013). On top of the CLE scenario, the other three future emission scenarios—air pollution legislation implemented before 2020 (Pre-2020), legislation that was anticipated to be implemented after 2020 (Post-2020), and the maximum technically feasible reduction (MTFR), represent low-, middle- and high-pollution-control ambitions, respectively.

Table 1. Definition of scenarios

Scenario	Description
CLE	Existing legislation implemented until 2017, i.e., the Action Plan
Pre-2020	Existing legislation implemented until 2017, after which implementation of measures in the Three-Year Action Plan
Post-2020	Existing legislation implemented until 2017, after which implementation of measures in the Three-Year Action Plan and the foreseeable emission control policies applied from 2020 onward
MTFR	Implementation of the best available technologies based on the Post-2020 scenario

The Pre-2020 scenario reflected the air pollution control policies and measures that were in place before 2020, such as the Action Plan and the Three-Year Action Plan (State Council of the People's Republic of China, 2018). Table S3 presents a list of the city-specific policies implemented by sectors for the Pre-2020 scenario. These measures included phasing out outdated technologies and capacities in various industries, such as iron, steel, cement, and plate glass, substituting household coal with electricity and natural gas, increasing the numbers of electric vehicles (EVs) and strengthening industrial and vehicle emissions standards. As a logical extension of the Pre-2020 scenario, the Post-2020 scenario further assumed that foreseeable emission control policies would gradually be applied from 2020 until 2030. Table S4 shows additional air pollution control policies implemented in the Post-2020 scenario relative to the Pre-2020 scenario. As indicated in the table, the extra policies implemented after 2020 mainly employed measures concerning four aspects: 1) decreasing the share of coal use while increasing that of clean and renewable energy (e.g., solar and wind) in power plants; 2) further eliminating outdated industrial capacities and banning new production capacity in industrial sectors; 3) implementing ultra-low emission retrofitting for key industries, such as iron, steel, cement and plate glass; and 4) implementing substitutions with low solvent products and installations of add-on removal technologies in solvent use. Based on the Post-2020 scenario, the MTFR scenario assumed the maximum application of technically feasible emissions reduction technologies. This scenario represented the highest levels of emissions control measures from the power, industrial, fuel conversion, transportation, residential, agricultural and solvent sectors. Details on policy evaluations and approaches for modifying technology penetration and activity data are provided in Section 3 in the Supplementary Information.

Figure S2 shows the energy consumption in the “2+26” Cities in 2017 and under four future scenarios in 2030. As shown in Figure S2A, coal (57%) and liquid fuels (22%) remained the main primary energy sources in 2017. For other energy sources such as gas, biomass, renewables and electricity, contributed 8%, 2%, 1% and 10%, respectively, to the total consumption. Under the CLE scenario, the total energy use was projected to grow from 23912 PJ in 2017 to 29643 PJ in 2030, which is mainly attributed to the increase in liquid fuels, gas and electricity. Correspondingly, the coal fraction to the total consumption decreased to 44% by 2030 in the CLE scenario, while the fractions of liquid fuels, gas and electricity increased to 25%, 12% and 15%, respectively. Implementation of legislation already in place in 2020, i.e., Pre-2020 scenario, would slightly increase the total energy use compared to the CLE scenario, and the energy structure exhibited little change. Under the Post-2020 scenario, there was a decline in total energy use relative to the Pre-2020 scenario (reduced by 9%), mainly due to the reduction in coal use. The coal proportion in this scenario only accounted for 39% of the total consumption, and the shares of liquid fuels, gas, biomass, renewable and electricity use were estimated to be 25%, 13%, 2%, 3% and 18%, respectively. Since the MTFR scenario only considered the end-of-pipe control technology, its energy consumption patterns were the same as those of the Post-2020 scenario. In total, there are obvious decreases in coal use through 2030 under the alternative scenarios, and varying increases in the use of liquid fuels, gas, electricity and renewables.

The changes in sectoral energy consumption are presented in Figure S2B-F. It can be seen that power and industrial combustion sectors are two main energy consumers in the "2+26" Cities, and the energy consumption structures among sectors are different. Coal was the predominant fuel used in the power and industrial combustion sectors. Regarding the power sector, there were general decreases in the use of coal under various scenarios, except for a slight increase when comparing the CLE and Pre-2020 scenarios. The renewable fraction increased from 2% under the Pre-2020 scenario to 8% under the Post-2020 scenario, which could be attributed to the implementation of low-carbon energy transitions. Regarding the industrial combustion sector, due to the elimination of outdated industrial capacities, continuous decreases in the coal shares occurred under all four scenarios in 2030, relative to 2017 level. As for the transportation sector (including light- and heavy-duty vehicles and nonroad machines), about 90% of the total energy consumption stemmed from liquid fuel use, and the energy consumption structure was relatively stable for all emission scenarios. Driven by promotion of EVs, a decrease in liquid fuel use from CLE to Pre-2020 scenarios was observed along with an increase in electricity use.

Figures S3–S7 show the penetration levels of end-of-pipe control technologies for different air pollutants. Technology differentiations were comprehensively considered among the scenarios and subsectors. Taking ultra-low emission standard as an example, under the CLE and Pre-2020 scenarios strict emission control technologies realizing the requirement of the ultra-low standard, such as high-efficiency dust removal technologies (HED) for particulate matter (removal efficiencies of 98.9-99.8% (Chen, 2015; Wang *et al.*, 2016)), wet flue gas desulfurization (WFGD) for SO_2 (removal efficiencies of 97.5-99.5% (Shuai *et al.*, 2015; Xing *et al.*, 2020)) and selective catalytic reduction (SCR) for NO_x (removal efficiencies of 86.5-93.1% (Jin and Pan, 2016; Shuai *et al.*, 2015)), were only applied to coal-fired power plants by 2030, while under the Post-2020 scenario, the ultra-low emission technologies were used in all industries, including power, steel and iron, cement and glass. In the MTFR scenario, the penetration levels of the best available technologies from developed countries were assumed to reach 100% for all industry sectors. For NH_3 and NMVOC, we assumed no specific technologies in the CLE scenario, and moderate control applications in the Pre-2020 and Post-2020 scenarios. Under the MTFR scenario, more effective technologies, such as low nitrogen/ammonia feed and covered outdoor storage of manure in the livestock, urea substitution and organic fertilizer use in fertilizer application, as well as application of low solvent products (e.g., water-soluble solvents) and add-on control technologies (e.g., adsorption and incineration), were further considered.

Table S5 shows a list of the emission standards for on-road vehicles (including light- and heavy-duty vehicles) and nonroad machines for 2017 and four scenarios in 2030. Under the CLE scenario, there were no more stringent standards implemented after the China V and China IV emission standards for light-duty vehicles and heavy-duty vehicles, respectively. The China III emission standards for nonroad machines were implemented. In the Pre-2020 and Post-2020 scenarios, more strengthened emission standards, such as China VI for on-road vehicles and China IV for nonroad machines, were expected to be implemented by 2030. Under the MTFR scenario, China VIb emission standards for all on-road vehicles were implemented.

3. Results

3.1. Future emission trends

Figures 2 and 3 present the sectoral trends of the emissions in the “2+26” Cities in 2017 and the four scenarios in 2030, respectively. In 2017, the “2+26” Cities emitted a total of 959 kt of primary $PM_{2.5}$, 1037 kt of SO_2, 2921 kt of NO_x, 1290 kt of NH_3, 3050 kt of NMVOC and 1874 Mt of CO_2. Residential combustion (34%) is an important source of primary $PM_{2.5}$ due to its relatively low combustion efficiency (Duan *et al.*, 2014; Zheng *et al.*, 2018). Industrial combustion (29%), residential combustion (28%) and industrial processes (24%) were the top three contributors to SO_2 emissions. Transportation sector (40%), i.e., light-duty vehicles (5%), heavy-duty vehicles (26%) and nonroad machines (9%), contributed the most to NO_x emissions. Agricultural (85%) and solvent use (62%) sectors were the largest sources of NH_3 and NMVOC emissions, respectively. Due to the bulk coal consumptions (Figure S2), industrial combustion (35%) and power plants (30%) dominated CO_2 emissions.

Under the CLE scenario, regional primary $PM_{2.5}$, SO_2 and NO_x emissions in 2030 were expected to be reduced by 9–16% from their 2017 levels, which was inconsistent with previous studies reporting that the emissions of these pollutants would increase under business-as-usual scenario by 2030 (Ling *et al.*, 2021; Tong *et al.*, 2020). A possible reason for this discrepancy was that the updated emission inventory for the “2+26” Cities in 2017 took full account of the positive effects of the policies already implemented in 2017 on future emission reductions. In contrast, the emissions of NH_3, NMVOC and CO_2 were estimated to increase by 2–10%, reflecting the limited control measures on NH_3 and NMVOCs (Cheng *et al.*, 2021b; Zhang *et al.*, 2019) and increasing the energy use derived from coal (National Bureau of Statistics, 2018a) over the past few years. Under the Pre-2020 and Post-2020 scenarios, all pollutants in 2030 would be further reduced compared to the CLE scenario indicating the effectiveness of air pollution legislation implemented before and after 2020. Applying the best available technologies in the MTFR scenario would lead to decreases of 75%, 69%, 76%, 32% and 52% for primary $PM_{2.5}$, SO_2, NO_x, NH_3 and NMVOC emissions, respectively, relative to the 2017 levels. It should be noted that there was no change in CO_2 emissions when comparing the Post-2020 and MTFR scenarios due to their same structures and volumes of energy consumption.

Different sectors have different emission reduction potentials under various scenarios. Under the CLE scenario, the residential combustion sector was the largest contributor to the primary $PM_{2.5}$ and SO_2 reductions in 2017-2030 due to rapid urbanization (Zhao *et al.*, 2018) and the clean fuel substitution policy (Duan *et al.*, 2014). With the implementation of outdated industrial capacity elimination and ultra-low emission retrofit, industrial combustion and process sectors contributed more and more to the emission reductions under the Pre-2020, Post-2020 and MTFR scenarios. The fuel conversion sector contributed to most of the primary $PM_{2.5}$ reductions when comparing the Post-2020 and MTFR scenarios. This phenomenon occurred because the progress in ultra-low emission retrofits of the fuel conversion sector (e.g., refinery and coke making) often lagged behind the required schedule, resulting in relatively large reduction potentials of this sector (Bo *et al.*, 2021). Application of increasingly stringent vehicle standards to heavy-duty vehicles drove down transport NO_x emissions, which was the dominant driving force of the decrease in NO_x emissions under the CLE scenario in 2017-2030. Similar to primary $PM_{2.5}$ and SO_2, gradually increasing contributions of industrial combustion and process sectors to NO_x reductions were also observed under the alternative policy scenarios. At the same time, the NO_x emissions from nonroad machines increased due to the relatively less effective measures on nonroad engines (Wu *et al.*, 2017b). Owing to the implementation of the China IV standard under the MTFR scenario, nonroad machinery sector became the major driver of the reductions in NO_x emissions.

The agricultural sector was the dominant driver of changes in NH_3 emissions, and it contributed the most to the emission reductions in the alternative scenarios. In the MTFR scenario, applying nitrification and urease inhibitors in fertilizer and enhanced manure management in livestock operations would cut 366 kt NH_3 emissions. Driven by activity growth and limited control measures, NMVOC emissions in solvent use and fuel production & distribution sectors increased obviously under CLE and Pre-2020 scenarios despite some decreases in residential sector due to clean household fuel policy. Under the Post-2020 scenario, the solvent use sector drove NMVOC emissions down owing to the substitution with low solvents and installation of add-on removal facilities. In addition to the main contributions to the reductions from the solvent use sector, the fuel production and distribution sector reduced NMVOC emissions by 22% under the MTFR scenario. With an ever-increasing demand for vehicle and power generation, transportation and power plant sectors contributed to the increase of CO_2 under the CLE scenario in 2017-2030. Phasing out outdated industrial capacity in industrial sector and deploying EVs in transportation sector under the Pre-2020 scenario were excepted to reduce CO_2 emissions compared to the CLE scenario. However, the emissions were obviously increased in power plants due to the increase in the coal-electric loads. This is consistent with those in earlier literature whereby the dominant coal-fired electricity of the total generation mix could generate negative benefits in reductions of fuel-cycle CO_2 emission for electrification policies relative to the original policy (Huo *et al.*, 2010; Wang *et al.*, 2020; Wu *et al.*, 2012). Besides the main contributions to the reductions from the industrial sectors, power plant sector drove CO_2 emissions down under Post-2020 scenario driven by the low-carbon energy transitions in power plants.

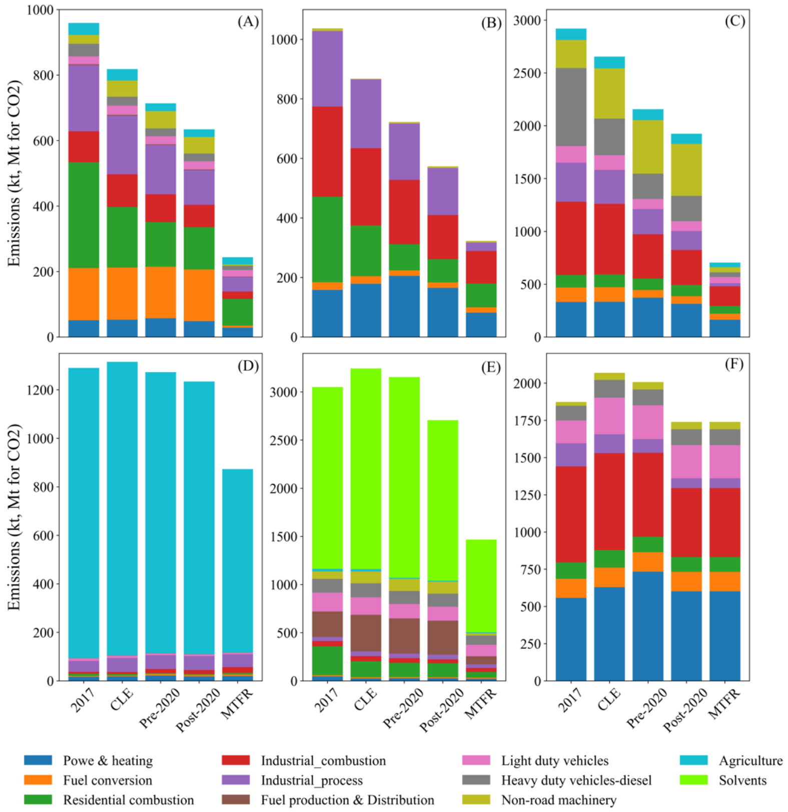

Figure 2. Sectoral emissions of major air pollutants and CO_2 for the base year 2017 and the four scenarios in 2030: (A) primary $PM_{2.5}$, (B) SO_2, (C) NO_x, (D) NH_3, (E) NMVOCs and (F) CO_2.

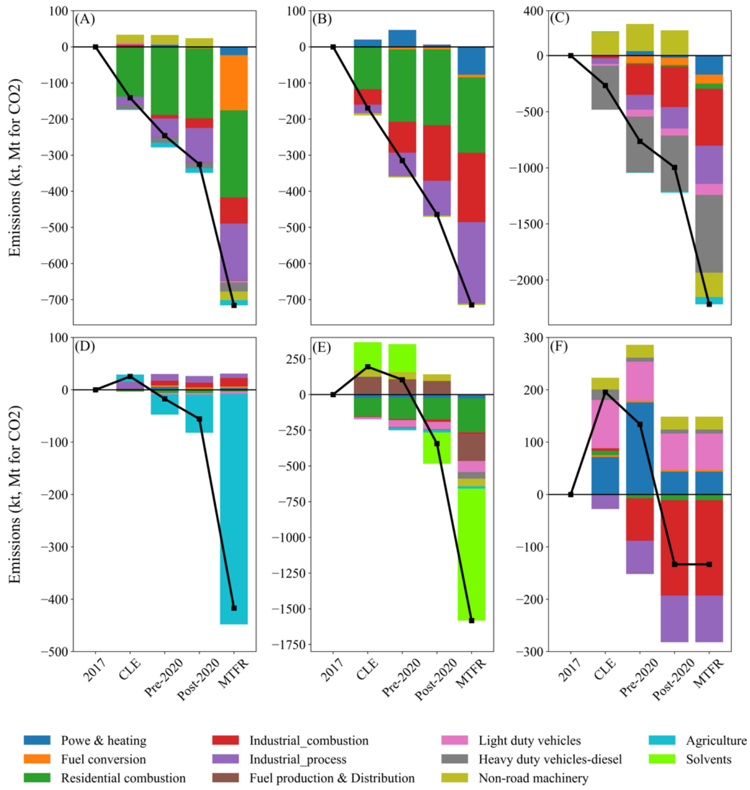

Figure 3. Changes in the emissions of major air pollutants and CO_2 under the four future scenarios compared to the base year 2017: (A) primary $PM_{2.5}$, (B) SO_2, (C) NO_x, (D) NH_3, (E) NMVOCs and (F) CO_2. The emission changes are shown by sector (bar chart) and as regional totals (black curve).

Figure 4 presents air pollutants and CO_2 emissions by prefecture for 2017 and under four scenarios in 2030. In this figure, the 2017 value is marked by black dots; the upper end of each color range indicates the emission level reached in that scenario; for example, the size of the yellow bar reveals emissions reduction from the MTFR to Post-2020 scenarios. It was observed that the emissions of air pollutants and CO_2 varied widely across cities owing to differences in industrial and energy structures (Luo *et al.*, 2021). The cities with large fossil fuel consumption amounts, such as Tangshan, Binzhou, Tianjin, Handan and Shijiazhuang (Figure S8), emitted more energy-related pollutants (e.g., primary $PM_{2.5}$, SO_2, NO_x and CO_2). As for NH_3 emissions, Jining, Heze and Cangzhou were high-emitting ones. Beijing and Tianjin contributed the largest share of total emissions for NMVOC, which was attributed to the large amount of solvent use (Li *et al.*, 2019). Given the differences in the emission patterns, the faction of emission reduction under alternative intervention scenarios revealed spatial disparity. Considering SO_2, the best available technologies from the MTFR scenario contributed to most of the emission reductions for Binzhou and Liaocheng cities; for the cities of Tangshan and Handan, additional policies in the Post-2020 scenario played pivotal roles in emission reductions. Thus, emission control strategies of cities need to be designed individually considering the local realities.

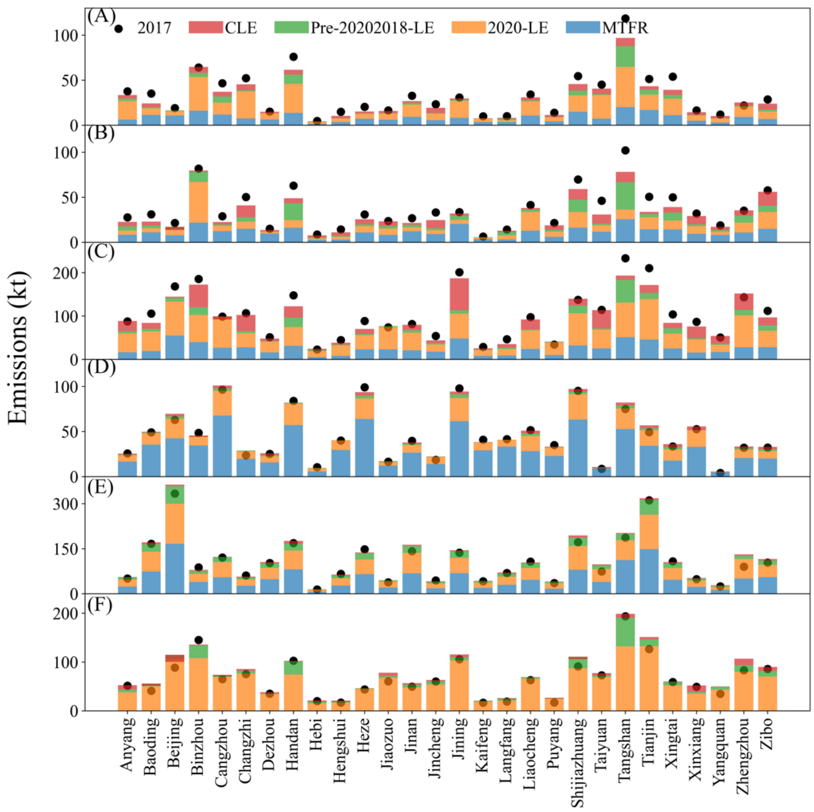

Figure 4. Prefectural emissions of the major air pollutants and CO_2 for 2017 and four scenarios in 2030: (A) primary $PM_{2.5}$; (B) SO_2; (C) NO_x; (D) NH_3; (E) NMVOC; and

(F) CO_2.

3.2. Future air quality improvements

Figure 5 shows the simulated $PM_{2.5}$ concentrations in the "2+26" Cities for 2017 and four scenarios in 2030. In 2017, the high $PM_{2.5}$ concentrations were observed in the central region due to the higher local emissions (Figure 4) and reduced ventilation caused by obstructions from the Yanshan and Taihang Mountains (Qu *et al.*, 2020). Elsewhere in the region, high levels coincided with cities with conglomerated industries (e.g., Tangshan and Binzhou) or areas with dense population (e.g., Zhengzhou). The regional annual mean concentration of $PM_{2.5}$ in 2017 was 57 μg/m^3, which was 1.6 times of the NAAQS grade II (i.e., 35 μg/m^3). With the implementation of recent legislation, the average $PM_{2.5}$ concentration over the "2+26" Cities decreased to 53 μg/m^3 in 2030 under the CLE scenario, which might be attributable to the emission reductions of primary $PM_{2.5}$, SO_2 and NO_x despite some increases in NH_3 and NMVOC emissions. As more stringent regulations and policies were applied under the Pre-2020 and Post-2020 scenarios, obvious improvements in air quality were made throughout the "2+26" Cities, following similar spatial patterns. On average, ambient $PM_{2.5}$ concentration decreased to 45 μg/m^3 under the Pre-2020 scenario and to 42 μg/m^3 under the Post-2020 scenario; however, this value remained above the national standard. When the best available technologies were fully implemented, emission reductions offered by the MTFR scenario would cause large parts of the region to comply with the national standard. The annual mean $PM_{2.5}$ concentrations in the "2+26" Cities could decline to 34 μg/m^3, thus achieving the target concentration by 2030.

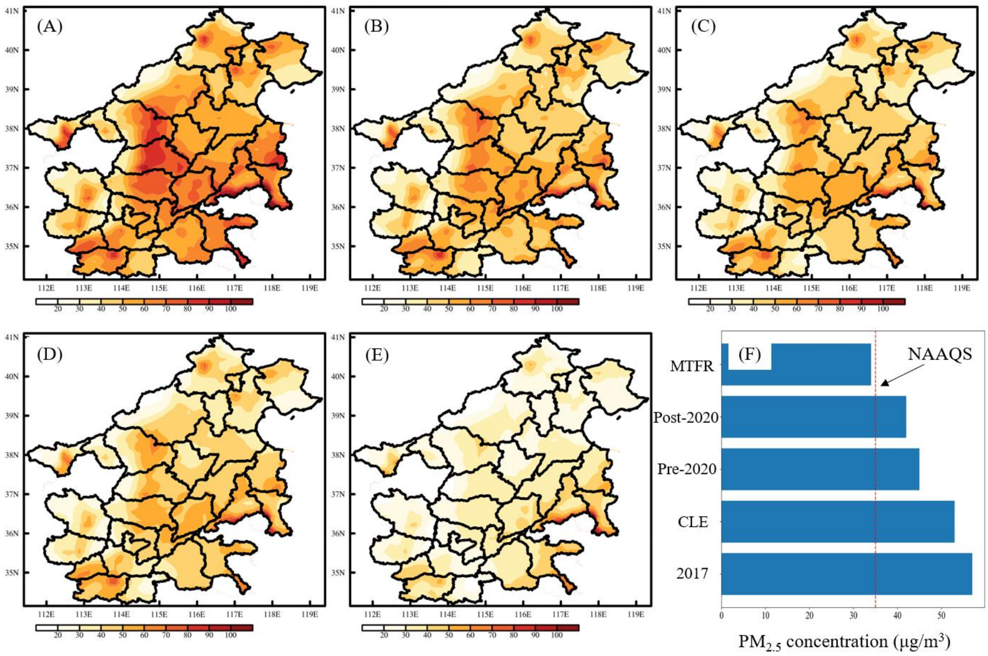

Figure 5. Spatial distributions of simulated $PM_{2.5}$ concentrations in the "2+26" Cities for 2017 (A) and four scenarios in 2030 (B–E), as well as corresponding annual mean $PM_{2.5}$ values (F).

Figure 6 exhibits the population exposure distribution in the "2+26" Cities for 2017 and the four scenarios in 2030. In 2017, the majority of the regional population (~98%) faced $PM_{2.5}$ pollution levels that exceeded NAAQS grade II. Almost 25% of the total population was exposed to air that exceeded the standard by a magnitude of over two times (>70 μg/m^3). Under the CLE scenario, the group with the highest exposure (i.e., >70 μg/m^3) would decrease to 19% in 2030, while 96% of the population would still be exposed to ambient concentrations above the standard. The stringent implementation of the Pre- and Post-2020 scenario legislation would bring approximately 9%–12% of the population within the exposure level under the secondary standard of 35 $\mu g/m^3$ annual mean $PM_{2.5}$; however, 4%–5% of people would still experience a $PM_{2.5}$ exposure above 70 $\mu g/m^3$. The full and effective implementation of advanced measures in the MTFR scenario could ensure that more than half of the population (53%) would be exposed to $PM_{2.5}$ concentrations below 35 $\mu g/m^3$, and few people would be exposed to extreme levels.

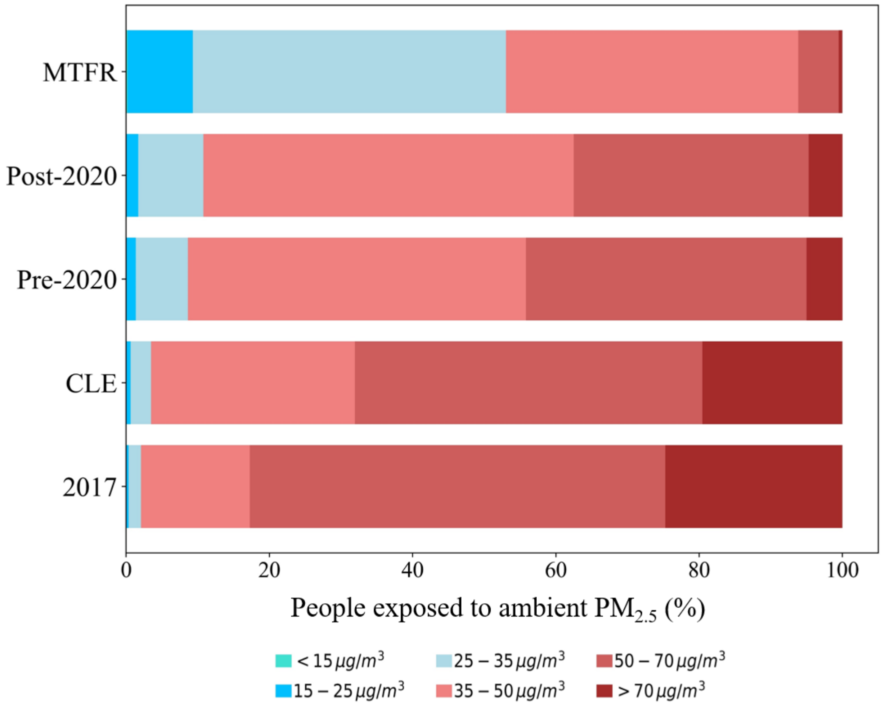

Figure 6. Distributions of population exposure in the "2+26" Cities for 2017 and under the four scenarios in 2030.

4. Discussion

4.1 Comparison with other studies

Significant air quality improvement and population exposure reduction are achieved over the "2+26" Cities from a more comprehensive application of best available technologies under the MTFR scenario. This strategy is sufficient to achieve the target of 35 μg/m^3 regionwide by 2030 and to provide NAAQS-compliant air quality to more than half of the population in the "2+26" Cities. A few studies have also explored future emission mitigations in the Jing-Jin-Ji region (Cai *et al.*, 2017; Lina *et al.*, 2015; Tong *et al.*, 2019). In those studies, emission reduction estimates are 31-69%, 44-57%, 50-72% and -3-1% for primary $PM_{2.5}$, SO_2, NO_x and NH_3, respectively, based on a range of energy-saving and end-of pipe control policies. In this study, the corresponding fractional reductions of the air pollutants under MTFR were 75%, 69%, 76% and 32%, respectively, relative to the 2017 levels. The comparison is only descriptive because of the different settings across studies regarding key parameters and temporal and spatial scales. Nevertheless, two things are clear from the comparison. First, emission reduction estimates from these studies are smaller than ours, because detailed local pollution control policies are considered in our work, as well as the different base year. Second, future actions focusing on NH_3 abatements in the agriculture sector should be implemented.

4.2. Policy implications

Driven by the increase in environmental policy stringency, air pollutant emissions in China have substantially decreased, especially those of primary $PM_{2.5}$, SO_2 and NO_x (Cheng *et al.*, 2021a; Silver *et al.*, 2018). Meanwhile, reduction potentials of sectors for these pollutants have also changed (Zheng *et al.*, 2019), which was confirmed by our results. In this work, control of primary $PM_{2.5}$, SO_2 and NO_x should be focused on fuel conversion and nonroad machinery sectors, while for NH_3 and NMVOC that used to be less controlled, agricultural and solvent use sectors contribute a large fraction of emission reductions in future.

The fuel conversion sector is estimated to account for 25% of primary $PM_{2.5}$ emissions in the Post-2020 scenario by 2030, becoming the largest source. Therefore, meeting ultralow emission standards is urgently required in refining and coke-making plants by installing or updating emissions control equipment for PM, SO_2 and NO_x and improving the quality of fuels and raw materials. The contributions of nonroad machines to NO_x emissions is estimated to increase from 9% in 2017 to 26% in 2030 under the Post-2020 scenario. Thus, more strengthened emissions standards, such as China V for off-road transport, should be implemented in the future. Regarding the agricultural sector, NH_3 emissions are predicted to grow in the future under the CLE scenario relative to 2017. Ambitious control policies must be enforced in the "2+26" Cities. On the one hand, applying slow-release fertilizers, nitrification and urease inhibitors in the crop production sector not only abates NH_3 emissions but also reduces nitrogen fertilizer use, decreasing implementation costs (Zhang *et al.*, 2015). On the other hand, manure management in livestock operations, such as deploying covered tanks for animal manure storage and transforming manure from a liquid form into a solid form prior to application on farmland, requires increased attention, affecting NH_3 emissions. Similar to the agricultural NH_3, there are limited regulations to date for controlling NMVOC emissions from the solvent use sector. In this context, tailored control measures for solvent use sector should be developed; for example, high solids, waterborne paints and powder coatings, should be strongly suggested for the surface coating, packaging and printing industries. The fuel production and distribution sector is another key contributor to reductions in NMVOC emissions. Recovery of gasoline vapor facility should be widely used in the petrochemical industry, especially for chemical terminals and oil depots. In addition to the above mentioned four sectors, the industrial combustion and process sectors still account for a large proportion of the emissions, although strict control measures, such as phasing out outdated capacities and strengthening emission standards, are being conducted. In future, quick upgrade to ultra-low emission standards in industrial sectors with relatively low emission standards, such as iron and steel, cement and plate glass sectors, is necessary.

The ratio of the emission change in CO_2 to that of a certain air pollutant (e.g., primary $PM_{2.5}$, SO_2, and NO_x) under Post-2020 scenario compared to 2017 level is applied to evaluate the CO_2 emission reduction co-benefits. Details on the quantification of the co-control effects are provided in section 4 of the Supplementary information. As shown in Figure S9, NO_x had the highest co-benefit with CO_2 in the "2+26" Cities. This finding is consistent with the results from (Feng *et al.*, 2018; Xu *et al.*, 2021), which indicated a stronger co-effect on the CO_2 emission reductions due to application of NO_x control measures. On the other hand, our model assessment suggests that electricity consumption resulted from electric policy leads to an increase in CO_2 emissions from power industry because the "2+26" Cities heavily rely on coal for electricity generation. Therefore, the fraction of the generation capacity taken by non-fossil fuels should be increased to balance electric loads resulted from clean air action plan with renewable energies, such as wind and solar power. Fortunately, the State Council's recent document Action Plan for Carbon Dioxide Peaking Before 2030 stipulates that by 2030, the total installed generation capacity of wind and solar powers will exceed 1200 gigawatts (State Council of the People's Republic of China, 2021). Consequently, the CO_2 induced by clean air action plans is expected to substantially decline in the near future.

In this study, we have identified a feasible pathway for achieving the 2030 target and proposed a series of effective measures. Different mitigation policies are needed in various prefectures to correspond with local conditions (Figure 4), especially in the context of regional joint prevention and control. In fact, the MEE has issued a campaign for the “2+26” Cities in 2017, namely, the one solution for one city initiative, to advance the working mechanism of joint air pollution prevention and control (Ministry of Ecology and Environment of the People's Republic of China, 2017a). Given the differences in industrial structures, pollution sources and governance conditions, a series of locally suited strategies has been designed for each city. Therefore, it is recommended for the one solution for one city approach to be promoted and implemented in other regions with severe regional air pollution, such as the Gangetic Plain in India (Rao *et al.*, 2021) and the western states in the United States (Bistline *et al.*, 2022). Differentiated control strategies between cities, such as the one solution for one city initiative, can potentially support regional joint prevention and control in those regions as well.

4.2. Uncertainties and limitations

Our study is subject to some uncertainties and limitations. First, emission estimates in the base year are uncertain due to limited information for energy consumption, removal technology penetrations and emission factors. Even though the GAINS–JJJ model contains updates retrieved from the literature based on local information in the "2+26" Cities, the underlying data for the different industries and processes in some prefectures are still not available. Second, we explored emission mitigation pathways based on the Three-Year Action Plan and progressive policies. A lack of detailed information regarding the quantification of specific measures under the Three-Year Action Plan impacts the results. Moreover, rapid economic growth and ambitious air pollution control actions in the "2+26" Cities can contribute to the uncertainties in projected emission estimates. Since we focus mostly on relative changes of alternative scenarios, these uncertainties are partially eliminated by a differential analysis. Third, ambient $PM_{2.5}$ concentrations simulated with the GAINS–JJJ model are unavoidably affected by the model representation of reduced-form source receptor relationships, which excludes $PM_{2.5}$ from primary and secondary organic aerosols (Kiesewetter *et al.*, 2015). This approach underestimates the air quality improvements under alternative policy interventions. Fourth, contribution of meteorology variation to the future air quality is considerable (Tong *et al.*, 2019). Due to computational limitations, only one meteorological year (2017) is chosen for the transfer coefficient calculations for the EMEP model and the CMAQ model, which adds uncertainty due to the interannual variability of meteorological conditions. Affected by unfavorable meteorological conditions, the "2+26" Cities may be at risk of exceeding the NAAQS of 35 $\mu g/m^3$, especially for those cities in southern regions (Figure 5E). Finally, estimated additional power CO_2 emissions caused by clean air actions are generated from local power plants in this study. In practice, the “2+26” Cities are power-loading centers that in part rely on interprovincial electricity transmission, especially for Beijing, mainly from Inner Mongolia and Shanxi through an extra high-voltage transmission connection. Thus, our results overestimate local CO_2 emissions in the “2+26” Cities. However, from a national perspective, the “2+26” Cities’ electricity consumption resulted from clean air action leads to increases in CO_2 emissions in the other regions that provide electricity to this region and thus will not increase total national impacts.

5. Conclusion

In this study, we consider the likely future evolution of air pollutants, CO_2 emissions, ambient $PM_{2.5}$ concentrations and resulting population exposures in the “2+26” Cities, and we explore pathways toward achieving the NAAQS II of 35 μg/m^3 by 2030. In addition to the current legislation, three future emission scenarios are developed to represent low, middle and high pollution control ambitions. The results clearly indicate that continuing the control policies before 2020 (e.g., strengthening industrial and vehicle emission standards, phasing out outdated technologies and capacities in various industries and substituting household coal with electricity and natural gas) and implementing the policies likely to be proposed after 2020 (e.g. decreasing the share of coal use in power plants, banning new production capacity in industrial sectors and implementing ultra-low emission retrofitting for key industries), will not be sufficient for reducing the $PM_{2.5}$ concentration below the national standard.

However, combining the best available technologies with the above policies will reduce primary $PM_{2.5}$, SO_2, NO_x, NH_3, NMVOCs and CO_2 by 75%, 69%, 76%, 32% 52% and 7%, respectively, relative to 2017 levels over the “2+26” Cities. Consequently, the regional annual mean level of $PM_{2.5}$ decreases from 57 μg/m^3 in 2017 to 34 μg/m^3 in 2030, attaining the 35 μg/m^3 target; moreover, more than half of the population in the region can experience air quality that conforms to the NAAQS.

Active clean air policies in the past decade had limited effects on reducing emissions from the fuel conversion, off-road, agricultural and solvent use sectors according to our results; thus, the “2+26” Cities should prioritize these sectors to enable further emission reductions in future. In addition, the industrial combustion and process sectors still account for a large proportion of the emissions; thus, it is necessary to quickly promote ultralow emission standards in the iron and steel, cement and plate glass industries in the future. In addition, the CO_2 emission reduction co-benefits of implemented clean air action measures have been identified, but the negative reduction effects of these measures should be given more attention (e.g., increased carbon emissions in the power sector from end-use electrification).

Application of the best available control technologies lead to significant reductions in air pollutants for the “2+26” Cities; however, their implementation puts high demands on economic resources. Further work is needed to select technologies that may reduce future air pollution at a low cost and to continue with the development of the optimization module in the GAINS–JJJ model.

Appendix A. Supplementary data

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

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.

Bistline, J.E.T., Blanford, G., Grant, J., Knipping, E., McCollum, D.L., Nopmongcol, U., Scarth, H., Shah, T., Yarwood, G., 2022. Economy-wide evaluation of CO_2 and air quality impacts of electrification in the United States. Nature communications 13, 6693-6705.

Bo, X., Jia, M., Xue, X., Tang, L., Mi, Z., Wang, S., Cui, W., Chang, X., Ruan, J., Dong, G., Zhou, B., Davis, S.J., 2021. Effect of strengthened standards on Chinese ironmaking and steelmaking emissions. Nature Sustainability 4, 811-820.

Cai, S., Ma, Q., Wang, S., Zhao, B., Brauer, M., Cohen, A., Martin, R.V., Zhang, Q., Li, Q., Wang, Y., Hao, J., Frostad, J., Forouzanfar, M.H., Burnett, R.T., 2018. Impact of air pollution control policies on future PM2.5 concentrations and their source contributions in China. J. Environ. Manage. 227, 124-133.

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.

Chang, S., Zeng, W., Zheng, Y., Wang, L., Song, Z., Zhu, Q., Luo, Y., Li, P., Li, Y., Liao, C., Zhang, Y., Yu, S., 2022. Emission mitigation pathways to achieve PM2.5 interim target III of the world health organization in the Pearl River Delta in 2035. Atmospheric Research 269, 106050.

Chen, X., 2015. Application of wet dust collector and its control system in Guohua Huizhou Power Plant. Resources Economization & Environment protection 7, 19-20.

Cheng, J., Tong, D., Zhang, Q., Liu, Y., Lei, Y., Yan, G., Yan, L., Yu, S., Cui, R.Y., Clarke, L., Geng, G., Zheng, B., Zhang, X., Davis, S.J., He, K., 2021a. Pathways of China's $PM_{2.5}$ air quality 2015-2060 in the context of carbon neutrality. National Science Review 8, 78-89.

Cheng, L., Ye, Z., Cheng, S., Guo, X., 2021b. Agricultural ammonia emissions and its impact on $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region from 2000 to 2018. Environ. Pollut. 291, 118162-118173.

Duan, X., Jiang, Y., Wang, B., Zhao, X., Shen, G., Cao, S., Huang, N., Qian, Y., Chen, Y., Wang, L., 2014. Household fuel use for cooking and heating in China: Results from the first Chinese Environmental Exposure-Related Human Activity Patterns Survey (CEERHAPS). Appl. Energ. 136, 692-703.

Environmental Protection Agency, CMAQ: The community multiscale air quality modeling system. US Environmental Protection Agency.

Feng, X.Z., Lugovoy, O., Qin, H., 2018. Co-controlling CO_2 and NO_x emission in China's cement industry: an optimal development pathway study. Advances in Climate Change Research 9, 34-42.

Huo, H., Zhang, Q., Streets, D.G., He, K.B., 2010. Environmental implication of electric vehicles in China. Envionmental Science & Technology 44, 4856-4861.

Jin, H., Pan, X., 2016. Case study on ultra-low emission modification project of nitrogen oxides in thermal power plants. Shandong Industrial Technology 11, 90-94.

Kiesewetter, G., Schoepp, W., Heyes, C., Amann, M., 2015. Modelling PM2.5 impact indicators in

Europe: Health effects and legal compliance. Environmental Modelling & Software 74, 201-211.

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.

Li, M., Zhang, Q., Zheng, B., Tong, D., Lei, Y., Liu, F., Hong, C., Kang, S., Yan, L., Zhang, Y., Bo, Y., Su, H., Cheng, Y., He, K., 2019. Persistent growth of anthropogenic NMVOC emissions in China during 1990-2017: dynamics, speciation, and ozone formation potentials. Atmospheric Chemistry and Physics 19, 8897-8913.

Lina, M., Tatsuya, N., Yuming, G., Shilu, T., 2015. Projecting fine particulate matter-related mortality in east China. Environ. Sci. Technol. 49, 11141-11150.

Ling, H., Qing, L., Jian, X., Lishu, S., Liang, L., Qian, W., Yangjun, W., Chaojun, G., Hong, Z., Qiang, Y., Sen, Z., Guozhu, Z., Li, L., 2021. Strategies towards $PM_{2.5}$ attainment for non-compliant cities in China: A case study. J. Environ. Manage. 298, 113529-113540.

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.

Madaniyazi, L., Nagashima, T., Guo, Y., Tong, S., 2015. Projecting fine particulate matter-related mortality in east China. Environ. Sci. Technol. 48, 11141-11150.

Ministry of Ecology and Environment of the People's Republic of China, 2017a. National Research Program for Key Issues in Air Pollution Control. Ministry of Ecology and Environment of the People's Republic of China (MEE).

Ministry of Ecology and Environment of the People's Republic of China, 2017b. Work plan for air pollution control in Jing-Jin-Ji region and surrounding areas in 2017. Ministry of Ecology and Environment of the People's Republic of China (MEE).

National Aeronautics and Space Administration, 2018. Global Rural-Urban Mapping Project. National Aeronautics and Space Administration.

National Bureau of Statistics, 2018a. China Energy Statistical Yearbook. China Statisties Press.

National Bureau of Statistics, 2018b. China Statistical Yearbook 2018. China Statistics Press.

Qu, L., Liu, S., Ma, L., Zhang, Z., Du, J., Zhou, Y., Meng, F., 2020. Evaluating the meteorological normalized $PM_{2.5}$ trend (2014-2019) in the "2+26" region of China using an ensemble learning technique. Environ. Pollut. 266, 115346.

Rao, N.D., Kiesewetter, G., Min, J., Pachauri, S., Wagner, F., 2021. Household contributions to and impacts from air pollution in India. Nature Sustainability 4, 859-867.

Shi, Q., Zheng, B., Zheng, Y., Tong, D., Liu, Y., Ma, H., Hong, C., Geng, G., Guan, D., He, K., Zhang, Q., 2022. Co-benefits of CO_2 emission reduction from China's clean air actions between 2013-2020. Nature Communications 13, 5061-5069.

Shuai, W., Li, L., Cui, Z., Wu, J., Mo, H., 2015. Analysis of primary air pollutant emission characteristics and reduction efficiency for ultra-low emission coal-fired power plants based on actual measurement. China Electric Power 48, 131-137.

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.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyíri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.P., Valdebenito, Á., Wind, P., 2012. The EMEP MSC-W chemical transport model – technical description. Atmospheric Chemistry and Physics 12, 7825-7865.

State Council of the People's Republic of China, 2011. Announcement for "12th Five-Year" National Environmental Protection. State Council of the People's Republic of China.
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. State Council of the People's Republic of China.
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.
State Council of the People's Republic of China, 2021. Announcement for Action Plan for Carbon dioxide Peaking before 2030. People.cn, Beijing.
Tibrewal, K., Venkataraman, C., 2020. Climate co-benefits of air quality and clean energy policy in India. Nature Sustainability 4, 305-313.
Tong, D., Cheng, J., Liu, Y., Yu, S., Yan, L., Hong, C., Qin, Y., Zhao, H., Zheng, Y., Geng, G., Li, M., Liu, F., Zhang, Y., Zheng, B., Clarke, L., Zhang, Q., 2020. Dynamic projection of anthropogenic emissions in China: methodology and 2015–2050 emission pathways under a range of socio-economic, climate policy, and pollution control scenarios. Atmospheric Chemistry and Physics 20, 5729-5757.
Tong, D., Geng, G., Jiang, K., Cheng, J., Zheng, Y., Hong, C., Yan, L., Zhang, Y., Chen, X., Bo, Y., Lei, Y., Zhang, Q., He, K., 2019. Energy and emission pathways towards $PM_{2.5}$ air quality attainment in the Beijing-Tianjin-Hebei region by 2030. Sci. Total Environ. 692, 361-370.
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, Q., Wang, J., Zhou, J., Ban, J., Li, T., 2019. Estimation of $PM_{2.5}$-associated disease burden in China in 2020 and 2030 using population and air quality scenarios: a modelling study. The Lancet Planetary Health 3, 71-80.
Wang, S., Zhao, B., Cai, S.Y., Klimont, Z., Nielsen, C.P., Morikawa, T., Woo, J.H., Kim, Y., Fu, X., Xu, J.Y., Hao, J.M., He, K.B., 2014. Emission trends and mitigation options for air pollutants in East Asia. Atmospheric Chemistry and Physics 14, 6571-6603.
Wang, W.G., Zheng, G.G., 2013. Annual report on actions to address climate change (2013): Forcus on low-carbon urbanization. Social Sciences Academic Press, China.
Wang, X., Zhu, L., Wang, D., Wang, K., 2016. Application of wet electrostatic dust removal technology in coal-fired power plants. China Electric Power 49, 157-160.
WorldPop, Worldpop country datasets. WorldPop.
Wu, R., Dai, H., Geng, Y., Xie, Y., Masui, T., Liu, Z., Qian, Y., 2017a. Economic impacts from $PM_{2.5}$ pollution-related health effects: A case study in shanghai. Environ. Sci. Technol. 51, 5035-5042.
Wu, Y., Yang, Z., Lin, B., Liu, H., Wang, R., Zhou, B., Hao, J., 2012. Energy consumption and CO2 emission impacts of vehicle electrification in three developed regions of China. Energy Policy 48, 537-550.
Wu, Y., Zhang, S., Hao, J., Liu, H., Wu, X., Hu, J., Walsh, M.P., Wallington, T.J., Zhang, K.M., Stevanovic, S., 2017b. On-road vehicle emissions and their control in China: A review and outlook. Sci. Total Environ. 574, 332-349.
Xing, J., Lu, X., Wang, S., Wang, T., Ding, D., Yu, S., Shindell, D., Ou, Y., Morawska, L., Li, S., Ren, L., Zhang, Y., Loughlin, D., Zheng, H., Zhao, B., Liu, S., Smith, K.R., Hao, J., 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 117, 29535-29542.

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

Xu, M., Qin, Z., Zhang, S., 2021. Carbon dioxide mitigation co-effect analysis of clean air policies: lessons and perspectives in China's Beijing–Tianjin–Hebei region. Environmental Research Letters 16, 15006-15017.

Yun, S., Jingnan, H., Shaohui, Z., Wolfgang, S., Wei, T., Jinhong, D., Janusz, C., Gregor, K., Robert, S., Wilfried, W., Zbigniew, K., Jens, B.-K., Markus, A., Haisheng, L., Youjiang, H., Jinmin, Z., Deyuan, X., 2022. 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. J. Environ. Manage. 317, 115455-115465.

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 PM2.5 air quality in China from 2013 to 2017. Proc. Natl. Acad. Sci. U.S.A. 116, 24463-24469.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51-59.

Zhao, B., Zheng, H., Wang, S., Smith, K.R., Lu, X., Aunan, K., Gu, Y., Wang, Y., Ding, D., Xing, J., Fu, X., Yang, X., Liou, K.N., Hao, J., 2018. Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005-2015. Proceedings of the National Academy of Sciences of the United States of America 115, 12401-12406.

Zhao, Y., Zhang, J., Nielsen, C.P., 2014. The effects of energy paths and emission controls and standards on future trends in China's emissions of primary air pollutants. Atmospheric Chemistry and Physics 14, 8849-8868.

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.