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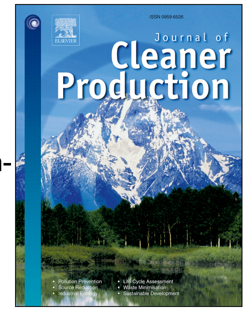

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Abstract

Since 2018, the Blue Sky Protection Campaign (BSPC) have been implemented at unprecedented levels to combat air pollution in the Beijing-Tianjin-Hebei (*JJJ*) region. In this study, the GAINS IV Asia (Greenhouse Gas and Air Pollution Interactions and Synergies) model is used to assess the potential for air pollution abatement, air quality improvement and associated costs of the BSPC in the JJJ region. The key findings are: 1) The total energy consumption under BSPC will decrease by 3%, 2%, and 6% for Beijing, Tianjin, and Hebei, respectively, by 2020 compared with the baseline scenario and Hebei is projected to experience the greatest changes in energy consumption both in absolute terms and in proportion. 2) Hebei would have the largest air pollution abatement. Compared to 2015, emissions of NO_x, $PM_{2.5}$, SO_2, and NH_3 under 2020 will be decrease by 31.3% 44.8%, 40.3%, and 10.7%, respectively. Residential and industrial combustion play vital contributions for pollution abatement, accounting for 52.3% together of Hebei's total. 3) Emissions of NO_x, $PM_{2.5}$, and SO_2 of Beijing will decrease by 21.2%, 58.7%, and 56.1% by 2020, compared to 2015. Transportation and residential sectors have key contributions to reductions. 4) The population-weighted annual $PM_{2.5}$ concentration would decrease to 41.4μg/m³, 49.4μg/m³, and 53.8μg/m³ by 2020 in Beijng, Tianjin, and Hebei, respectively. Finally, we recommend that actions of increasing nitrogen use efficiency of agricultural sector, super low emission standard in industrial sector, and switching off coal power plants are most cost-effective in air quality improvement during 2020-2025.

Keywords:
the Blue Sky Protection Campaign (BSPC); air pollution abatement; air quality; the Greenhouse Gas and Air Pollution Interactions and Synergies Asia (GAINS IV Asia) model; Jing-Jin-Ji

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1 Introduction

One of the side effects of China's rapid industrialization and urbanization was severe ambient air pollution. A total of 83% of the Chinese population lives in areas exceeding the World Health Organization's (WHO's) Level 1 interim target annual average of 35 μg/m^3 $PM_{2.5}$ (fine particulate matter ≤ 2.5 μm in aerodynamic diameter), leading to serious health concerns (Brauer et al., 2012; Ma et al., 2016; Brauer et al., 2016; Liu et al., 2016). As shown in Fig. 1, air pollution has become a common issue for urban areas in China, especially for the Beijing-Tianjin-Hebei (*Jing-Jin-Ji*; hereinafter, *JJJ*) region. Ambient air pollution ranks fifth among global mortality risk factors, having caused 4.2 million deaths and accounting for 7.6% of total global deaths in 2015, 52% of which occurred in China and India (Cohen et al., 2017).

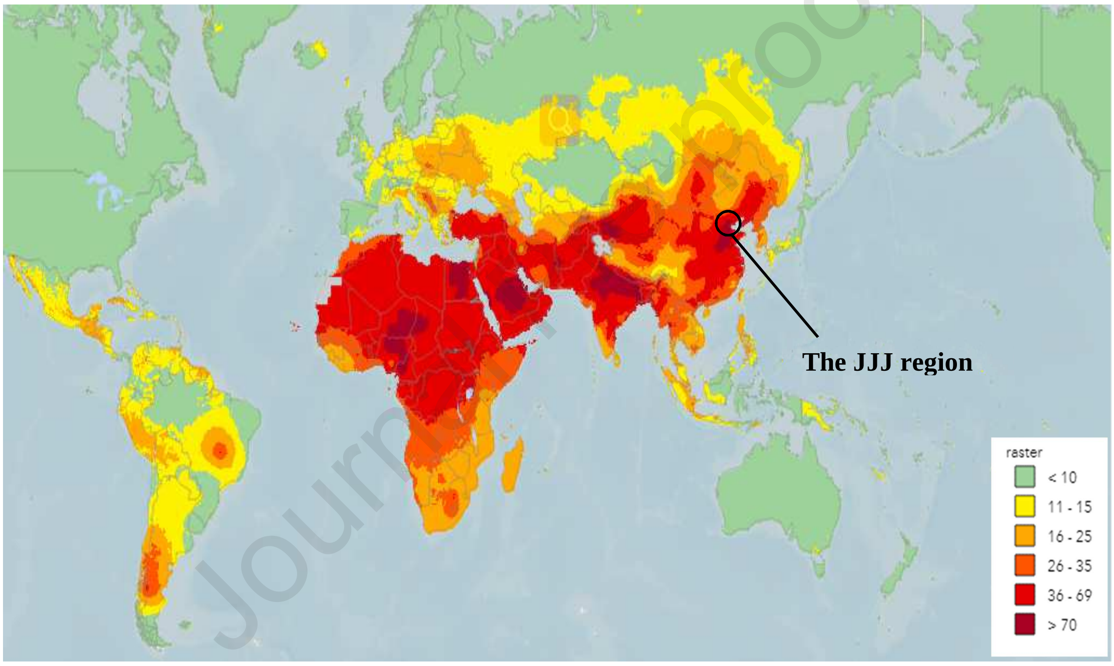

Fig. 1. Annual mean ambient $PM_{2.5}$ centration in 2016 (unit: μg/m^3; figure from the WHO; see http://maps.who.int/airpollution/).

China's government has implemented several strict policies to control air pollution (Feng and Liao, 2016; Yang et al., 2019) (see Fig. 2). The JJJ region is the key region experiencing the most severe air pollution problems (Fig. 1). In 2017, annual average $PM_{2.5}$ concentrations in the JJJ region ranged from 58 to 67 μg/m^3, much higher than the limit of 10 μg/m^3 recommended by the WHO Air Quality Guidelines (CNEMC, 2018). In 2012, the China State Council issued the Air Pollution Prevention and Control Action Plan 2013–2017 (APPCAP). Meanwhile, the JJJ region has undertaken intensive air pollution control policies, putting tremendous effort toward controlling centralized fossil fuel use in power plants, central heating, and industry and aiming to reduce the annual average ambient $PM_{2.5}$ by 25%. The JJJ region was the first to implement this policy on a large scale. Taking Beijing as an example, over 400,000 households implemented the *coal-to-electricity* policy in 2017 (Daily, 2017). In 2018, the Chinese government rolled out a three-year plan called the Blue Sky Protection Campaign (BSPC) to eliminate haze and reduce air pollution and finally achieve the dream of a Chinese blue sky. The target of this policy was for emissions of SO_2, NO_x, and $PM_{2.5}$ to decrease by 15%, 15%, and 18%, respectively, between 2015 and 2020 in the most heavily polluted regions of China (city clusters in the JJJ region and Yangtze River Delta (YRD)). Indeed, this policy has made significant improvements in terms of energy efficiency and the relocation or closure of selected pollution-heavy industries. Nevertheless, few studies have examined the effectiveness of these plans for a blue China.

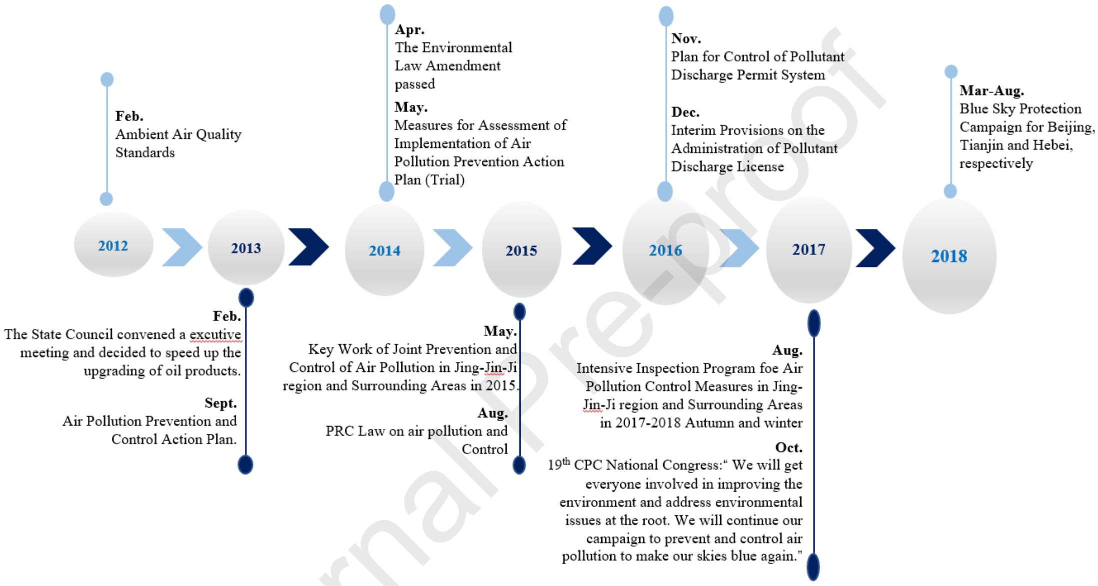

Fig. 2. Implemented events and policies to control air pollution in recent years.

It is expected that the implementation of active clean air policies can achieve remarkable improvements in air quality (Cai et al., 2017; Wang et al., 2020; Wan et al., 2020; Yang et al., 2020), so understanding the effectiveness of air pollution control policies is important for future air pollution control in China. Several studies have examined historical air pollution control policies and their associations with the emission trends of SO_2, NO_x, and PM_{10} (Bernard et al., 2001; Clark et al., 2010; Li and Patiño-Echeverri, 2017; Wang et al., 2010; Zeng et al., 2019). Recent studies have reported significant $PM_{2.5}$ air quality improvements and associated health benefits from 2013 to 2017 in China under the APPCAP (Huang et al., 2018; Li et al., 2019; Wang et al., 2019; Xue et al., 2019). Meanwhile, the relative contributions of emission control and interannual meteorological variations to reductions in $PM_{2.5}$ concentrations have also been identified ((Ding et al., 2019). The majority of recent studies have focused on the impacts of the APPCAP, which was issued in 2013. Huang et al. (2018) analyzed national air quality monitoring and mortality data to estimate the health impacts of the APPCAP from 2013 to 2017 in 74 key cities in China using hierarchical Bayesian models. Their results showed that between 2013 and 2017, annual average concentrations of $PM_{2.5}$ decreased by 33.3%, those SO_2

decreased by 54.1%, and those of CO decreased by 28.2%, and no significant changes were seen in annual average concentrations of NO_x (9.7% reduction) or O_3 (20.4% increase) (Huang et al., 2018). In addition, there were 47,240 fewer deaths in 2017 than in 2013 (Huang et al., 2018). Using arithmetic mean and percentile methods, Zhang et al. (2018) indicated that the annual mean $PM_{2.5}$ concentration in China decreased by more than 30% since the implementation of the APPCAP. However, to the best of our knowledge, no prior research has involved a systematic analysis of the impacts of BSPC on air quality. Therefore, a comprehensive evaluation of the effectiveness of BSPC is urgently needed.

In the present study, the Greenhouse Gas and Air Pollution Interactions and Synergies East Asia (GAINS IV Asia)[2] model was used to examine the air quality and health effects of BSPC in the JJJ region of China. We attempted to address five questions: (1) What is the air pollutant emission inventory for 2015 in the JJJ region? (2) How much have air pollutant emissions in the JJJ region reduced since the implementation of BSPC? (3) How much do the control measures involved in this policy cost? (4) How much has this policy improved air quality? (5) How many years of life lost are affected by this policy? The methods and insights of this study can further contribute to similar assessments of air pollution control policymaking in other parts of China and the world.

This paper is organized as follows. Section 2 describes the model configuration, protocols, and evaluation database. Section 3 presents the modeling results and discussion, including emission estimates and air quality evaluations. Section 4 summarizes the conclusions and policy recommendation of this work.

2 Methodology

The GAINS IV Asia model, which was developed by the International Institute of Applied Systems Analysis (IIASA), is an integrated assessment model intended to assess the interactions and effectiveness of different air pollution control and greenhouse gas policies. This model considers activity pathways (power and heating plants, industry, domestic, transportation, etc.) and air pollution control measures for key pollutants in key emission sectors at five-year intervals (Amann et al., 2011). In the present study, we used the GAINS IV Asia model to simulate the effects of BSPC on energy structure, pollutant emissions, and air quality. The workflow of the GAINS IV Asia model used in this study can be found in Fig. 3.

As shown in Fig. 3, the first step of the present analysis involved simulating an actual emission scenario. We integrated original data from 2015 from the emissions inventory of each province into the GAINS IV Asia model and updated the parameters of the default baseline scenario of WEO-2018-CPS. Various air pollution sources (e.g., power, industry, transportation, residential buildings, and agriculture) and associated activities were considered. Specifically, parameters such as energy

[2] GAINS-IV Asia is the sub model of GAINS.

consumption by fuel types and sectors, industrial activities, the utilization rate of air pollution control technology, and other values and assumptions were calibrated. Second, we considered scenario-specific implications and requirements for reaching universal access to the emission control strategies considered in the examined policy packages. Analytically, we approached this step by running the GAINS IV Asia model over the implications for air pollutant emissions that would arise from the achievement (or absence) of the strategies outlined in the policy packages. For instance, in the policy scenario, measures were selected for each province individually. Third, the GAINS IV Asia model calculated the impacts of primary PM and precursors to secondary PM (i.e., SO_2, NO_x, NH_3, and volatile organic compounds) emissions on ambient $PM_{2.5}$ concentrations.

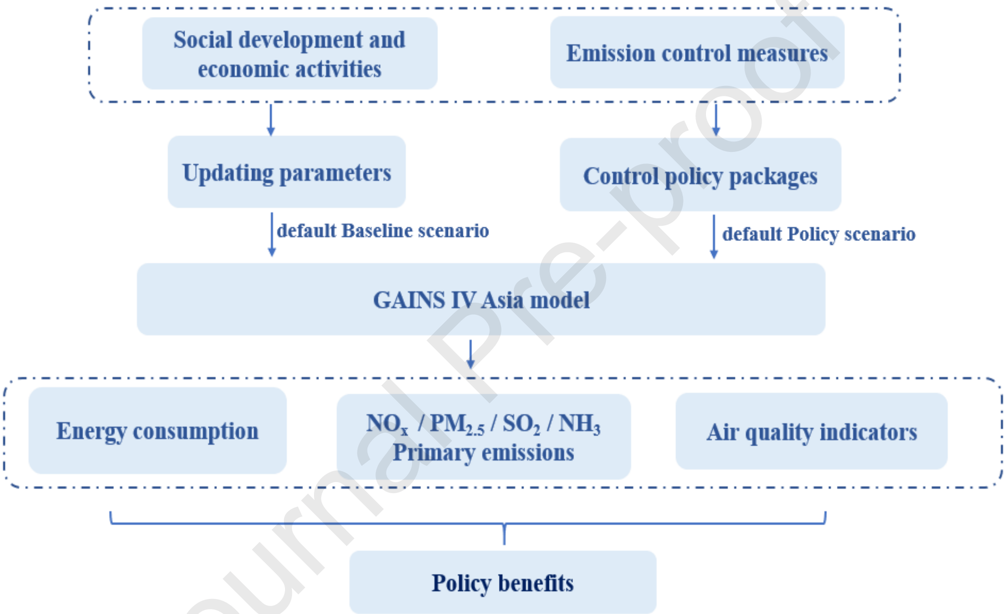

Fig. 3. The workflow of the GAINS IV Asia model in this study.

2.1 GAINS IV Asia model

2.1.1 Emission calculations

For each of the pollutants, the GAINS IV Asia model calculated emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures, and the extent to which such measures are applied.

$$E_{i,p} = \sum_{k} \sum_{m} A_{i,k} ef_{i,k,m,p} \chi_{i,k,m,p} \quad (1)$$

where:

i, k, m, and p = region, activity type, abatement measure, and pollutant, respectively.

$E_{i,p}$ = emissions of pollutant p in region i.

$A_{i,k}$ = activity level of type k (e.g., coal consumption in power plants) in region i.

$ef_{i,k,m,p}$ = emission factor of pollutant p for activity k in region i after application of control measure m.

$\chi_{i,k,m,p}$ = share of total activity type *k* in region *i* to which a control measure *m* is applied for pollutant *p*.

2.1.2 Emission control measures and their costs

The GAINS IV Asia model estimated emission control costs from the perspective of a social planner, with a focus on resource costs of emission controls to societies. Emission control costs are influenced by the allocation of emission control measures, which were calculated based on the assumption that, in a free market for emission control technologies, the same technology will be available to all regions at the same cost. Technological progress was also assumed with respect to the performance and cost data, based on literature estimates. For each of the 3,500 emission control options, this model estimated the costs of local application considering annualized investments (I^{an}) as well as fixed (OM^{fix}) and variable (OM^{var}) operating costs, and how they depend upon technology *m*, country *i*, and activity type *k* (Cofala and Syr, 1998; Klimont and Brink, 2006; Höglund-Isaksson et al., 2009). Unit costs of abatement (*ca*), related to one unit of activity (*A*), were calculated as:

$$ca_{i,k,m} = \frac{I^{an}_{i,k,m} + OM^{fix}_{i,k,m}}{A_{i,k}} + OM^{var}_{i,k,m} \qquad (2)$$

The cost per unit of abated emission (*cn*) of a pollutant *p* was calculated as:

$$cn_{i,k,m,p} = \frac{ca_{i,k,m}}{ef_{i,k,0,p} - ef_{i,k,m,p}} \qquad (3)$$

where $ef_{i,k,0,p}$ is the uncontrolled emission factor in the absence of any emission control measure (m = 0).

2.1.3 Air quality impacts of $PM_{2.5}$

The Unified European Monitoring and Evaluation Programme (EMEP) Eulerian model was used with the GAINS IV Asia model to link marginal changes in emission precursors of various sources to changes in impact-relevant air quality (Fagerli and Aas, 2008). For the GAINS IV Asia model, it has been found that the almost linear response in annual mean $PM_{2.5}$ toward changes in annual emissions of $PM_{2.5}$ and SO_2, as well as changes in seasonal NO_x and NH_3 emissions, can be represented as follow (Amann et al., 2011).

$$PM_j = k_{0,j} + \sum_i pm_i PP^A_{ij} + \sum_i s_i S^A_{ij} + C_0\left(\sum_i a_i A^S_{ij} + \sum_i n_i N^S_{ij}\right) + (1 - C_0)$$
$$\times \min\left\{\max\left\{0, k_{1,j} + c_1 \sum_i a_i A^W_{ij} - c_2 \sum_i s_i S^W_{ij}\right\}, k_{2,j} + c_3 \sum_i n_i N^W_{ij}\right\} \qquad (4)$$

where:

PM_j = annual mean concentration of $PM_{2.5}$ at receptor point *j*.

s_i, n_i, a_i, and pm_i = emissions of SO_2, NO_x, NH_3, and primary $PM_{2.5}$ in country *i*.

$\acute{A}^x_{ij}$, N^x_{ij}, S^x_{ij}, and PP^x_{ij} = matrices with coefficients for reduced (*A*) and oxidized (*N*) nitrogen, sulfur (*S*), and primary $PM_{2.5}$ (*PP*) for season *X*, where *X* = *W* (*winter*), *S* (*summer*), and *A* (*annual*)

c_0, c_1, c_2, and c_3 = model parameters derived by regression analyses.

$k_{0,j}$, $k_{1,j}$, and $k_{2,j}$ = constants to take background concentrations into account.

Furthermore, a simpler formulation has been used in the GAINS IV Asia model to perform reasonably well when only marginal changes in emissions around a reference point are considered (Equation 5). It is worth noting that the GAINS model includes $PM_{2.5}$ concentration from natural sources, primary PM, and the associated precursor pollutants (SO_2, NO_x, NH_3, etc.) via air pollution dispersion model.

$$PM_j = \sum_i pm_i PP_{ij}^A + \sum_i s_i S_{ij}^A + \sum_i a_i A_{ij}^A + \sum_i n_i N_{ij}^A + k_{0,j} \qquad (5)$$

2.2 Scenario descriptions

The base year used in the present study was 2015, as the GAINS IV Asia model simulates emission scenarios at five-year intervals. The year 2020 was selected as the main target year because BSPC will be implemented until 2020; thus, this choice of target year enabled consideration of policy benefits. The year 2025 was also included as a secondary target year to show the long-term trends of improvement.

Two scenarios were developed in the present study to simulate policy effects: the baseline scenario and the policy scenario. The baseline scenario (i.e., the no-policy scenario) assumed there was no BSPC for air quality improvement in the JJJ region. For this scenario, we projected the activities of energy, agricultural, and industrial processes in 2020 based on the goals of the 13^{th} Five-Year Plan (FYP) announced by the governments of the JJJ region and China’s renewable report. The demands in 2025 in the baseline scenario were evaluated based on the growth rate of demands in the scenarios from 2020 to 2025 of the WEO-2018-CPS projected by the GAINS IV Asia model.

Meanwhile, the policy scenario assumed that the JJJ region implemented BSPC so that this scenario could project the effects of this control policy from 2015–2020. Key sub policy package of BSPC can be found in Table SI in supporting information. Within this step, various air pollution sources (e.g., power, industry, transportation, residential building, and agriculture) and the associated activities would be considered. More specifically, parameters (e.g., energy consumption by fuel types and sectors, activities of the industrial process, and the utilization rate of air pollution control technology, and other values and assumptions) are predicted for 2020 using the consumption trends from yearbooks from each province. For example, the coal consumption in residential urban sector and commercial combustion sector is decreased by: a) in the urban residential heating sector, we assumed that 80% of heat demand is from district heating system (Li, 2016; Su et al., 2018; Xiong et al., 2015); b) hard coal grade 2 is used instead of hard coal grade 3 and increasing usage of natural gas and electricity. From 2020–2025, it was assumed that the three provinces/municipalities of the JJJ region would maintain the same levels of policy strictness, in that the governments would continue to implement specific policy measures at the same rate. The policy packages of the policy scenario are shown in Table SI 1 in supporting information.

2.3 Data sources

Data for this study was obtained from the China Guidebook for Air Pollution Emission Inventory (MEEC, 2015), the Provincial Economic Yearbooks (BSB, 2016; HSB, 2016; TSB, 2016), the China Statistical Yearbook (NBS, 2016), the 13th FYP of Energy Development (NEA, 2017a), the Clean Heating Plan for Winter in North China (2017–2021) (NEA, 2017b), the 13th FYP of Renewable Energy Development (NDRC, 2016), the 13th FYP of Industrial Transformation and Upgrading (GOHB, 2016), the 13th FYP for the Comprehensive Development of Transportation Systems (GOTJ, 2016; GOHB, 2017; GOBJ, 2016), the 13th FYP of Power Sector Development (PGC, 2016), and several state-of-the-art studies (Hu et al., 2016; Li, 2016; Su et al., 2018; Xiong et al., 2015; Zhang et al., 2015).

3 Results and discussion

3.1 Current emission status

Fig. 4 shows the primary emissions of NO_x, $PM_{2.5}$, SO_2, and NH_3 in 2015 in the updated baseline scenario, which totaled 2875 kt, 1167 kt, 1712 kt, and 1963 kt, respectively. Hebei was the biggest contributor to each type of pollutant emission, followed by Tianjin and Beijing, respectively.

Table 1 compares the present results concerning emissions with the findings of other studies. Our calculated NO_x emissions (2875 kt) in the JJJ region were higher than those calculated by the Multi-resolution emission inventory for China (MEIC), which estimated NO_x emissions to be 2621 kt in 2014. These results reflected an increasing trend. For one, polluting activity levels (e.g., vehicle population and fuel consumption) increased significantly. On the other hand, the use of different estimation methods and different data sources may also explain the difference between the present results and previous estimations.

With respect to $PM_{2.5}$ emissions, our estimate (1167 kt) did not significantly differ from those of the MEIC (951 kt in 2014) and Qi et al. (2017) who estimated $PM_{2.5}$ emissions to be 1090 kt in 2013 in the JJJ region. It is worth noting that Hebei accounted for 80% of total $PM_{2.5}$ emissions (940 kt), followed by Tianjin (115 kt) and Beijing (110 kt).

Our estimate of 1712 kt of SO_2 emissions (147 kt, 255 kt, and 1311 kt for Beijing, Tianjin, and Hebei, respectively) was almost the same as that of the MEIC (1713 kt) for 2014 and was lower than that of Qi et al. (2017) (2305 kt) for 2013. The observed fluctuations in annual SO_2 emissions were consistent with official data. According to the Ministry of Environmental Protection, because of the installation of flue-gas desulfurization devices, SO_2 emissions in China decreased for the first time in 2007 after rapidly increasing from 2002 to 2006 (Xu et al., 2009).

Our calculated NH_3 emissions (1963 kt) in the JJJ region were higher than those of other studies, as shown in Table 1. Non-industrial sources considered in our estimations were the main reason for this difference. In the present study, we mainly estimated NH_3 emissions from livestock and fertilizer applications, which are the largest emission sources for NH_3. Other sources, including ammonia-related chemical industries, on-road mobile sources, waste treatment, and fuel combustion, were also considered. For example, it is estimated that 12% of NH_3 emissions are due to vehicles in Shanghai (Chang et al., 2016) and biomass burning may contribute up to 12% of the global NH_3 emissions flux (Bari et al., 2003; Lamarque et al., 2010). Therefore, the estimation of NH_3 in this study is significantly higher than the MEIC. One reason is that GAINS covers emissions sources across all sectors. In addition, our results are comparable to the study of Cheng et al. (2018), which showed that the total NH_3 emissions from agricultural sources in the JJJ region were 1751 kt in 2014 based on the emission factor method.

Specifically, in our study, we estimated that the transportation sector accounted for the largest share for NO_x emissions (over 50%) in 2015 in the JJJ region, followed by industry (30%) and power (18%). More than half of energy-related $PM_{2.5}$ emissions originated from the residential sector. The energy sector was responsible for over 1546 kt of SO_2 emissions, with over 48% originating from industry and 48% originating from the power sector. The agricultural sector contributed significantly (over 95%) to NH_3 emissions.

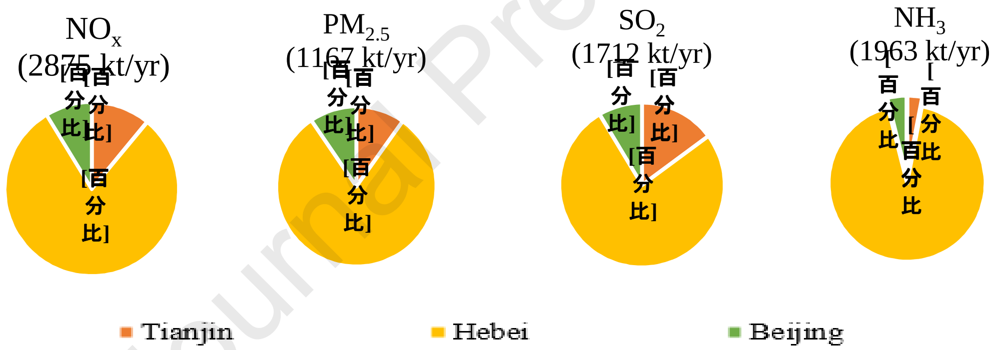

Fig. 4. Estimated anthropogenic emissions of the main air pollutants by regions, 2015.

Table 1 Comparison of emissions estimates for the JJJ region.

	Year	NO_x (kt)	$PM_{2.5}$ (kt)	SO_2 (kt)	NH_3 (kt)
Xu et al. (2015)	2010				1574
Qi et al., (2017)	2013	2686	1090	2138	
MEIC	2014	2621	951	1713	611
This study	2015	2875	1167	1712	1963

3.2 Energy consumption up to 2025

3.2.1 Energy consumption by key sectors

Fig. 5 shows energy emission trends in the baseline and policy scenarios.

In the baseline scenario, we projected that the total energy consumption in all three provinces/municipalities of the JJJ region will increase without the implementation of BSPC. If the policy goals of BSPC are achieved by 2020, the growth rate of energy consumption in the JJJ region has slowed and we projected that energy consumption will have decreased by 70 PJ (equivalent to a 3% reduction of consumption in the baseline scenario), 53 PJ (2%), and 563 PJ (6%) in Beijing, Tianjin, and Hebei, respectively. Projected overall energy consumption was still on the rise in both scenarios.

The impacts of air pollution control policies on energy consumption were mainly reflected in the industrial, residential, and transportation sectors. Specifically, the energy consumption of the industrial sector in Tianjin and Hebei was projected to be lower or basically the same in 2020 as in 2015, which is closely related to improving the industrial structure and related layout of steel, cement, coke, and other industries under BSPC. The projected residential energy consumption of each of the JJJ regions in 2020 under the policy scenario was lower than in 2015, regardless of population growth, mainly due to the replacement of heating and loose coal and the closure of small boilers. Although the energy consumption of light duty vehicles in each of the JJJ region is still growing rapidly, the growth rate has slowed down under the policy scenario. Overall, Hebei was projected to experience the greatest changes in energy consumption both in absolute terms and in proportion.

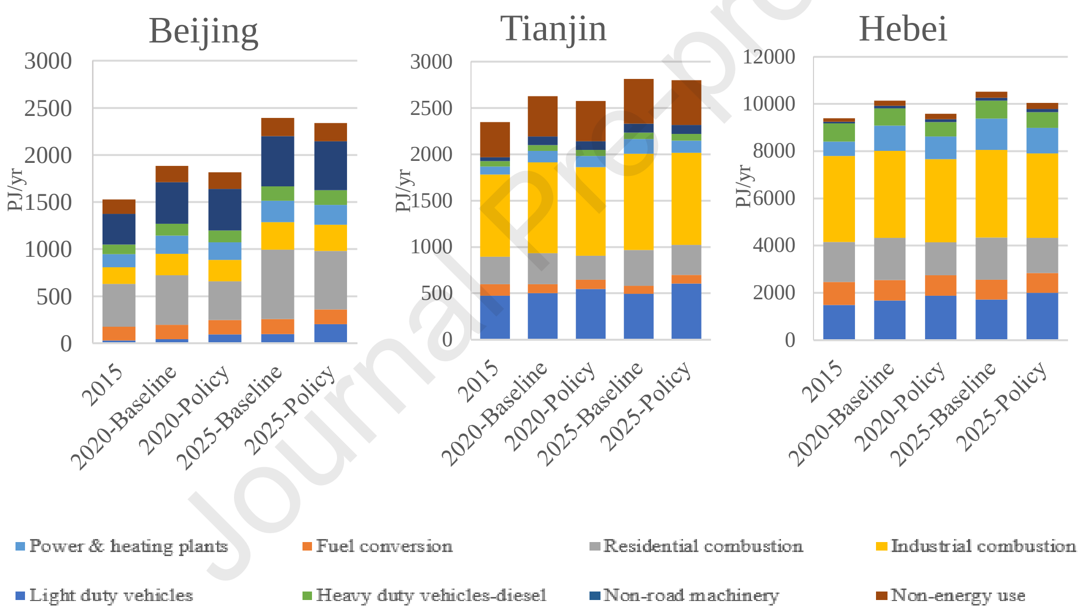

Fig. 5. Energy consumption by key sectors under different scenarios.

3.2.2 Energy consumption by key fuels

Fig. 6 shows the projected energy consumption by key fuels in different scenarios. Compared with the baseline scenario, it was projected that the percentage of coal and liquid fuel consumption (out of total energy consumption) would be significantly reduced in each region under the policy scenario. In terms of absolute quantity, the consumption of coal in the policy scenario in each of the JJJ region in 2020 is obviously lower than that in 2015, and the consumption growth rate of liquid fuels such as petroleum has also slowed down. The consumption of natural gas and electricity will increase significantly, most of which will be used for residential heating sectors and light duty vehicles. Hebei was projected to reduce the greatest amount of energy consumption of coal and liquid fuel in absolute terms (equivalent to a 12% reduction of the consumption in the baseline scenario). This indicates that the structure of energy consumption under BSPC would produce a transformation from conventional to cleaner energy sources, eliminating air pollutant emissions (Li and Patiño-Echeverri, 2017). In addition, it’s worth noting that the energy consumption in Tianjin in the 2025 baseline scenario is almost the same as in the 2025 policy scenario, which is mainly due to the fact that natural gas consumption in Tianjin is increasing at a faster rate than in Beijing and Hebei. This is consistent with data drawn from the 2018 statistical yearbook of the three provinces, which indicating that Tianjin's natural gas consumption grew at nearly twice the rate of Beijing and Hebei from 2015 to 2017, indicating the faster increase in the natural gas consumption in Tianjin.

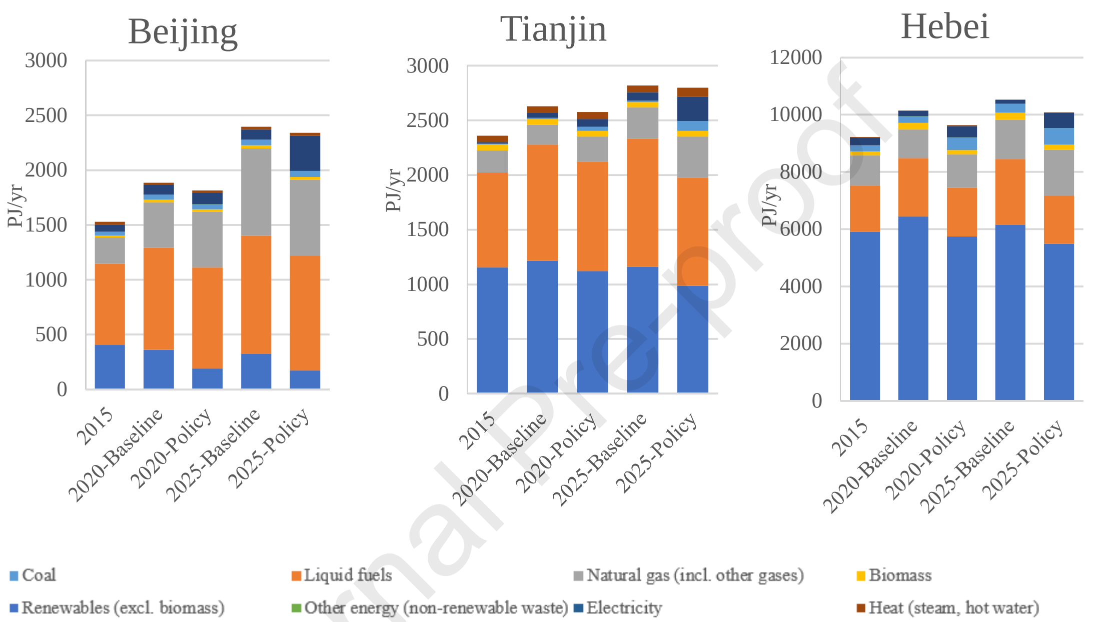

Fig. 6. Energy consumption by key fuels under different scenarios.

3.3 Air pollutant emission reduction

Efforts included in BSPC to reduce air pollution span all key sectors in the policy scenario. With this policy’s focus on energy consumption and with additional policies to increase air pollution control and monitoring, emissions of all pollutants were predicted to fall. We present our results concerning each pollutant by sectors below.

3.3.1 Projection for NO_x by key sectors

Projected NO_x emissions in the JJJ region are shown by key sectors in Fig. 7. In 2015, the NO_x emissions in Hebei were much higher than in Beijing and Tianjin (approximately 2309 kt, 250 kt, and 315 kt, respectively). Fig. 7 also shows the primary emission tendencies in the baseline and policy scenarios. The total NO_x emissions in all three provinces/municipalities were projected to decrease without the implementation of BSPC in the baseline scenario. If the policy goals are achieved by 2020 in the JJJ region, NO_x emissions were projected to reduce by 22 kt (equivalent to a 10% reduction of the emissions in the baseline scenario), 11kt (4.1%), and 213 kt (12%), respectively, in Beijing, Tianjin, and Hebei. Total emissions in the JJJ region were projected to reduce by 246 kt (equivalent to a 11% reduction of the emissions in the baseline scenario), with Hebei accounting for 86.7% of the total emissions. Hebei emits eight times as much NO_x as Beijing and Tianjin. The main reason for this difference is that Hebei hosts the most of industrial processes and heavy-duty diesel vehicles in the JJJ region.

The contribution of the policy to the above reductions mainly comes from the transportation sector, in which, in 2020, the NO_x emissions of heavy-duty diesel vehicles under the policy scenario in the JJJ region will be reduced by 105 kt compared to the baseline scenario, while the emissions of light duty vehicles will also be reduced by 28 kt. Fully implementation of these control policies on the transportation sector was projected to reduce NO_x emissions by 54% of the total NO_x emissions reductions in the JJJ region. In addition, the policy has also reduced emissions from the residential combustion sector, accounting for 26% of the total NO_x emissions reductions.

Further, BSPC has reduced emissions from industrial combustion, power and heating, and agricultural sectors to a certain extent, and the contributions of policy measures in these sectors were relatively even. However, the focus of future reductions in NO_x emissions in the JJJ region is on the transportation sector, especially heavy-duty diesel vehicles.

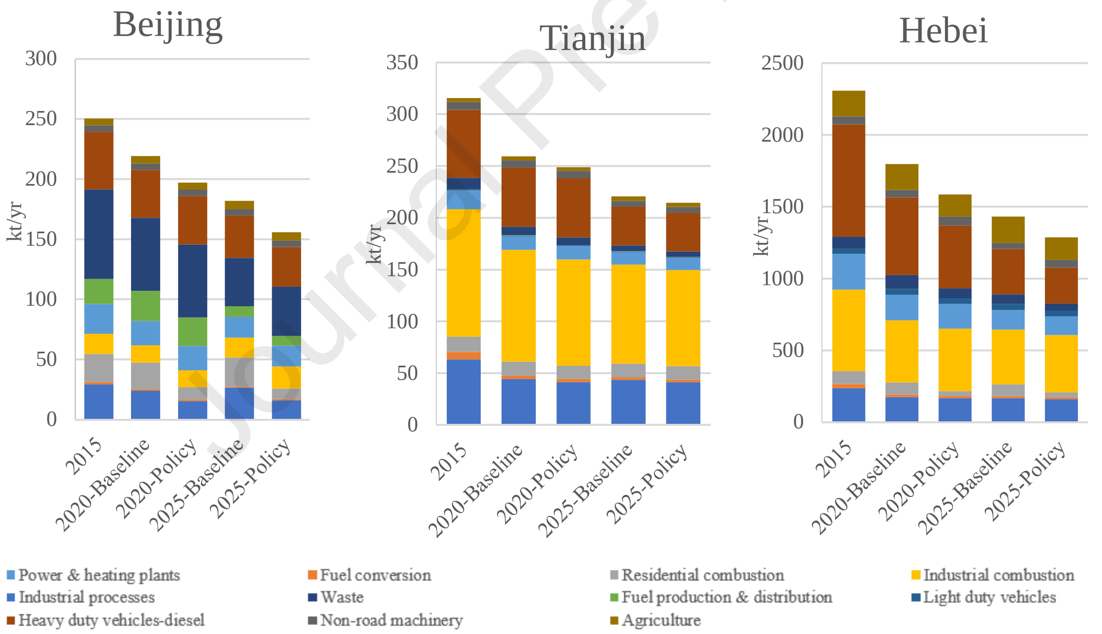

Fig. 7. NO_x emissions by key sectors.

3.3.2 Projections for $PM_{2.5}$ by key sectors

Nearly all air-related emission control policies have treated the reduction of $PM_{2.5}$ as the main target. $PM_{2.5}$ emissions in the JJJ region are shown by key sectors in Fig. 8. In 2015, the $PM_{2.5}$ emissions in Hebei were much higher than those in Beijing and Tianjin (approximately 941 kt, 111 kt, and 116 kt, respectively). Emissions of $PM_{2.5}$ in Beijing, Tianjin, and Hebei are expected to constantly decrease between 2015 and 2025 without the implementation of BSPC. In the baseline scenario, emissions of $PM_{2.5}$ were projected to reach 1063.1 kt by 2020 in the JJJ region (96.1 kt in Beijing, 98.8 kt in Tianjin, and 868.2 kt in Hebei). If only the JJJ region implements BSPC, a significant reduction of $PM_{2.5}$ emissions (422 kt; 39.7%) was projected to occur by the end of 2020. In addition, the projected reduction of $PM_{2.5}$ emissions in Hebei was much higher than that in Beijing or Tianjin in each scenario, implying that BSPC will play a major role in the reduction of $PM_{2.5}$ emissions in Hebei. With the continued implementation of this policy, emission reductions in the JJJ region show the potential for improvement between 2020 and 2025.

As shown in Fig. 8, primary $PM_{2.5}$ emissions in the JJJ region were projected to decrease from 2015 to 2025 in both scenarios but were projected to decrease more in the policy scenario than in the baseline scenario. Residential combustion of coal was the largest contributor to primary $PM_{2.5}$ emissions. As Hebei is the largest emitter in the JJJ region, industrial processes and power and heating plants in Hebei also affect $PM_{2.5}$ emissions to some extent. Specifically, due to the implementation of the BSPC under the policy scenario, the transformation of residential heating from coal to cleaner fuels (i.e., natural gas and electricity) in 2020 was projected to contribute to 74% of the reduction in $PM_{2.5}$ emissions in the JJJ region. This finding also reflects the vital role of replacing coal with gas in reducing air pollution. Industrial processes comprise another major source of pollution. The BSPC can reduce emissions from industrial processes to a certain extent, but this decline is relatively limited. Other pollution sources, such as waste and agriculture, make limited contributions to $PM_{2.5}$ reduction.

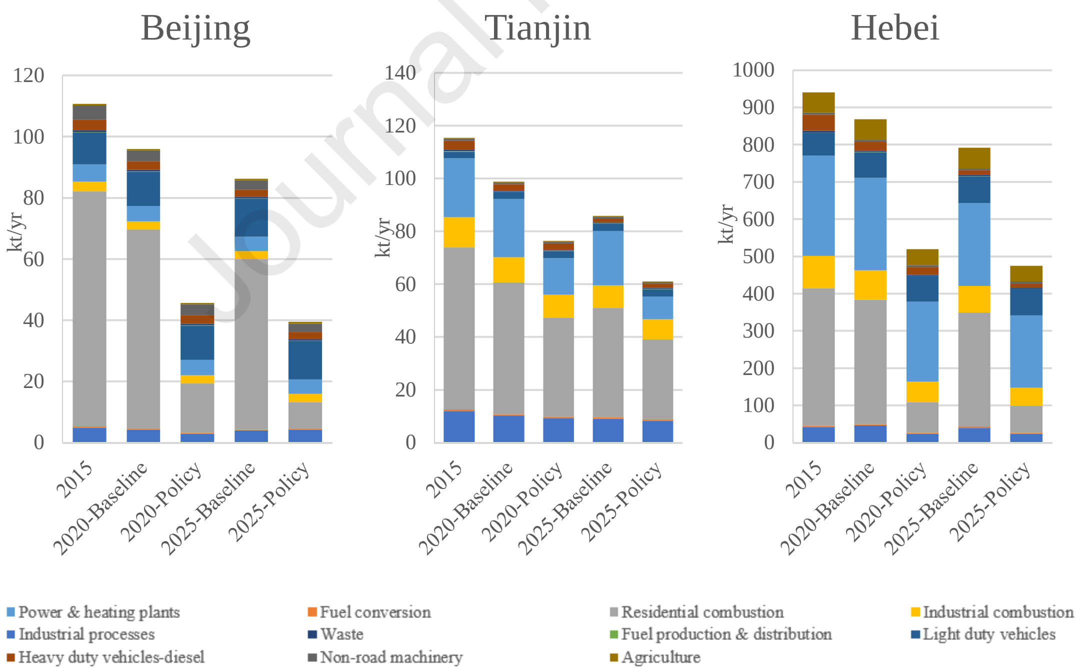

Fig. 8. $PM_{2.5}$ emissions by key sectors.

3.3.3 Projections for SO_2 by key sectors

SO_2 emissions in the JJJ region are shown by key sectors in Fig. 9. In 2015, SO_2 emissions were much higher in Hebei than in Beijing and Tianjin (approximately 1311 kt, 147 kt, and 255 kt, respectively). Fig. 9 also shows the primary emission tendencies of the baseline and policy scenarios. Overall SO_2 emissions were projected to decrease in all three provinces/municipalities without the implementation of BSPC in the baseline scenario. However, projections indicated that the rate of decline will be faster if the policy goals are achieved by 2020 in the JJJ region. Specifically, SO_2 emissions were projected to reduce by 62.7 kt (equivalent to a 49% reduction of the emissions in the baseline scenario), 24 kt (13%), and 246.3 kt (23.9%), respectively, in Beijing, Tianjin, and Hebei. Total emissions in the JJJ region were projected to reduce by 333 kt (equivalent to a 24.8% reduction of the emissions in the baseline scenario), with Hebei accounting for 74% of the total emissions. Hebei emits five to six times as much SO_2 as Beijing and Tianjin. The main reason for this difference is that Hebei hosts most of the industrial combustion and residential combustion in the JJJ region.

Industrial and residential combustion are significant sources of SO_2 emissions. It is particularly noteworthy that most of the contribution of BSPC to the reduction of SO_2 emissions is projected to result from controls on residential combustion. As opposed to the relatively advanced terminal SO_2 control measures in industry settings, control on untreated coal combustion in the residential sector comprise the focus of efforts toward future reduction of SO_2 emissions in the JJJ region, especially in Hebei. Fully implementation of BSPC was projected to reduce SO_2 emissions by 300.4 kt (64.2%) within the residential combustion sector in the JJJ region by 2020. Hebei was projected to reduce the most pollutant emissions in absolute terms, accounting for 73.6% of the total reduction in the residential sector; this finding was consistent with the policy goal for Hebei to replace the untreated coal use of eight million households with electricity and natural gas. Beijing was projected to reduce the pollutant emissions significantly; this finding was consistent with the energy structure of Beijing, in that coal use has declined sharply and the transformation of the residential heating from coal to cleaner fuels since 2015. These results are consistent with the conclusions from Chen and Chen, (2019), which shows that a shift from coal to natural gas or electricity is of great importance for the reductions of SO_2.

In addition to residential combustion, BSPC was also projected to contribute to a certain degree of reduction in SO_2 emissions from industrial combustion and power and heating plants. However, this decline is expected to be relatively low. Overall, the focus of controlling SO_2 emissions is relatively simple and concentrated in the residential sector. In contrast, the power and heating, industrial, transportation, and other sectors hold little potential for further reductions in SO_2 emissions.

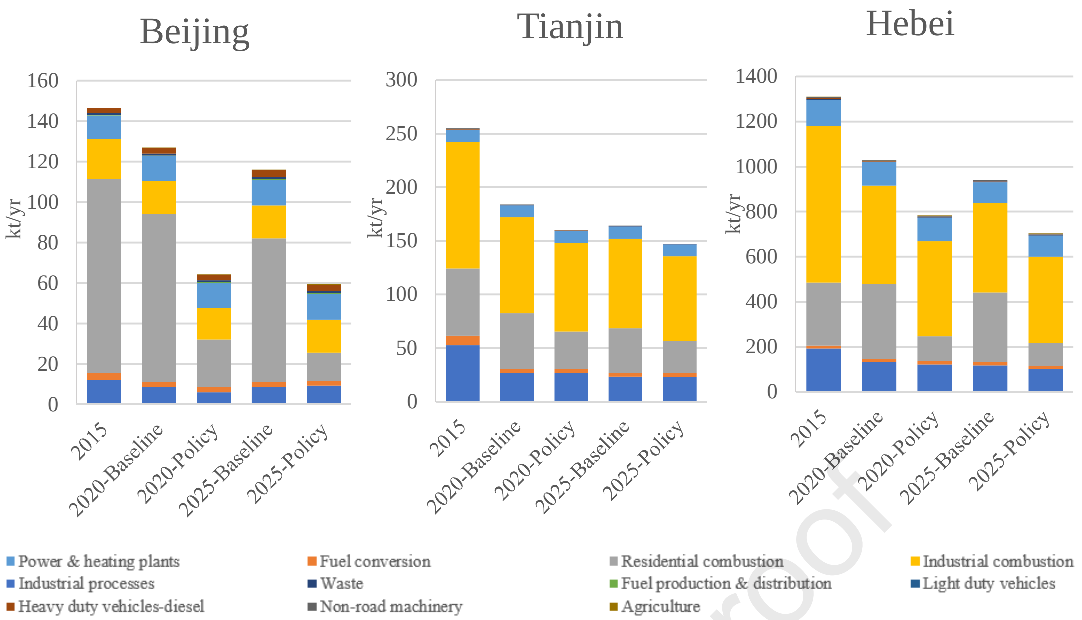

Fig. 9. SO_2 emissions by key sectors

It's no wonder that the emissions of air pollutants are lower in the policy scenarios than in the baseline scenarios due to implementing the BSPC. However, it's worth noting that emissions of NO_X, $PM_{2.5}$, and SO_2 decrease in all three provinces in the 2020-baseline scenario compared to 2015. This is in consistent with the conclusions drawn from Meng and Zhou, (2020), which suggested that the air pollution emission level reached the peak in 2015 and then decreased with a fluctuating and slow process in the JJJ region. Similar reductions of air pollutants in the JJJ region without implementing the BPSC are also found in other researches (Fan et al., 2020; Li et al., 2020; Maji et al., 2020). For example, Fan et al. (2020) concluded that emissions of $PM_{2.5}$, SO_2, and NO_x all decrease with the year between 2014 and 2019 based on long-period monitoring data with high temporal resolution (hourly) recorded. Therefore, all this shows that even if BPSC is not implemented (as suggested in the baseline scenario), the emissions of pollutants in the 2020 baseline scenario will be lower than that of 2015. Besides, it's worth noting that the effect of emission reduction in Tianjin is lower than Beijing and Hebei, which is mainly because Beijing's restrictions are more stringent than Tianjin's in terms of the residential combustion sector and the reduction potentials in Hebei are higher than those in Tianjin under the BSPC.

3.3.4 Projections for NH_3 by key sectors

NH_3 emissions in the JJJ regions are shown by key sectors in Fig. 10. In 2015, NH_3 emissions were much higher in Hebei than in Beijing and Tianjin (approximately 1827 kt, 77 kt, and 59 kt, respectively). Fig. 10 also shows the primary emission tendencies of the baseline and policy scenarios. In contrast to NO_x, $PM_{2.5}$, and SO_2 emissions, total NH_3 emissions were projected to increase in all three provinces/municipalities without the implementation of BSPC in the baseline scenario. If the policy goals of BSPC are achieved by 2020 in the JJJ region, it is projected that

NH_3 emissions will not significantly change in Beijing while NH_3 emissions in Tianjin and Hebei will be reduced by 4.1 kt (6.6%) and 240.5 kt (12.9%), respectively. Most of these reductions come from Hebei, primarily because Hebei was projected to increase its nitrogen fertilizer use efficiency to 40% in the policy scenario (higher than the national standard level of 33%), thereby reducing fertilizer use and leading to lower releases of NH_3 to the atmosphere.

The agricultural sector is the most significant source of NH_3 emissions. The impacts of pollution control policies on NH_3 emissions are mainly reflected in the agricultural sector. Fully implementation of these policies on the agricultural sector was projected to reduce NH_3 emissions by 3.9 kt (8.8%) in Tianjin and 232.4 kt (12.6%) in Hebei by 2020. Hebei was projected to reduce the most pollutant emissions in absolute terms whereas Beijing was projected to reduce the least; this result was consistent with the agricultural structure of Beijing, in that the sown rea of farm crops in Beijing is the smallest in the JJJ region.

NH_3 emissions from agriculture account for over 80% of total emissions, even reaching 95%in Hebei. Therefore, the focus of controlling NH_3 emissions is relatively simple and concentrated in the agricultural sector (i.e., increasing nitrogen fertilizer use efficiency).

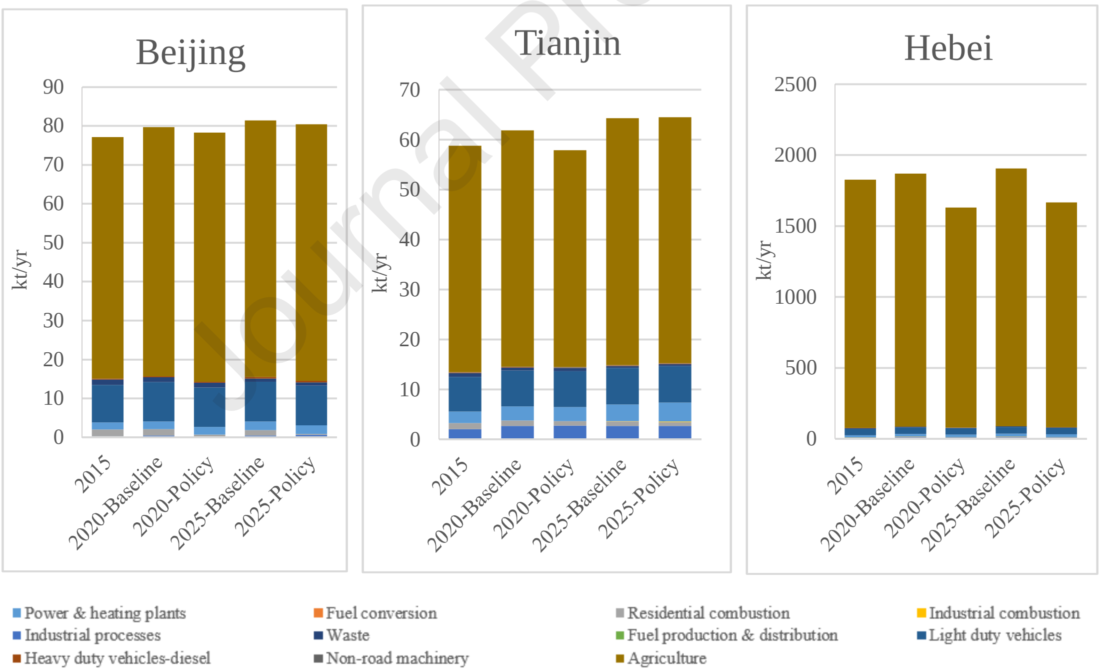

Fig. 10. NH_3 emissions by key sectors

3.4 All air pollutant emissions control costs

Emission control costs are shown by sectors in Fig. 11. These costs refer to the implementation costs of all pollutant control measures; the additional equipment costs required to change energy consumption mode or production mode are not considered.

Overall, the costs of pollutant emission controls showed an increasing trend in the JJJ region. In the 2020 policy scenario, these costs were projected to be approximately 1.27 times, 1.42 times, and 1.59 times those of 2015 in Beijing, Tianjin, and Hebei, respectively. Most of these costs occur in industry and power emission controls in Tianjin and Hebei, while the transportation sector costs the most in Beijing; this finding is consistent with the energy structure of the JJJ region, in that most industry of the JJJ region remains in Hebei while little remains in Beijing.

Costs in the power sector were projected to remain at approximately 35% in Tianjin and 23% in Hebei, while the proportion of industrial processes in both regions were projected to gradually decrease. One reason for this is that the adjustments in industrial structure reduce some high-pollution emission sources, thus reducing the costs of emission control measures required by these sources. Also, the cost of pollutant control in the transportation sector in the base period is low in Tianjin and Hebei, but the growth rate is very fast in the future. In the 2020 Policy scenario, the emission control cost of the transportation sector will be 1.79 and 1.65 times that of the base period for Tianjin and Hebei, respectively. In Beijing, the costs of pollutant controls in the transportation sector are the largest source of the total costs, accounting for 65% in 2015 and 80% in the 2020 policy scenario. Conversely, emissions control costs in residential heating stoves in each of the JJJ region are declining due to changes in energy utilization patterns. Emission control costs of other sectors, including waste, agriculture, and fuel conversion, were very low. It is worth noting that this study only calculated the costs of pollutant control technology; the costs of actual policy implementation were higher.

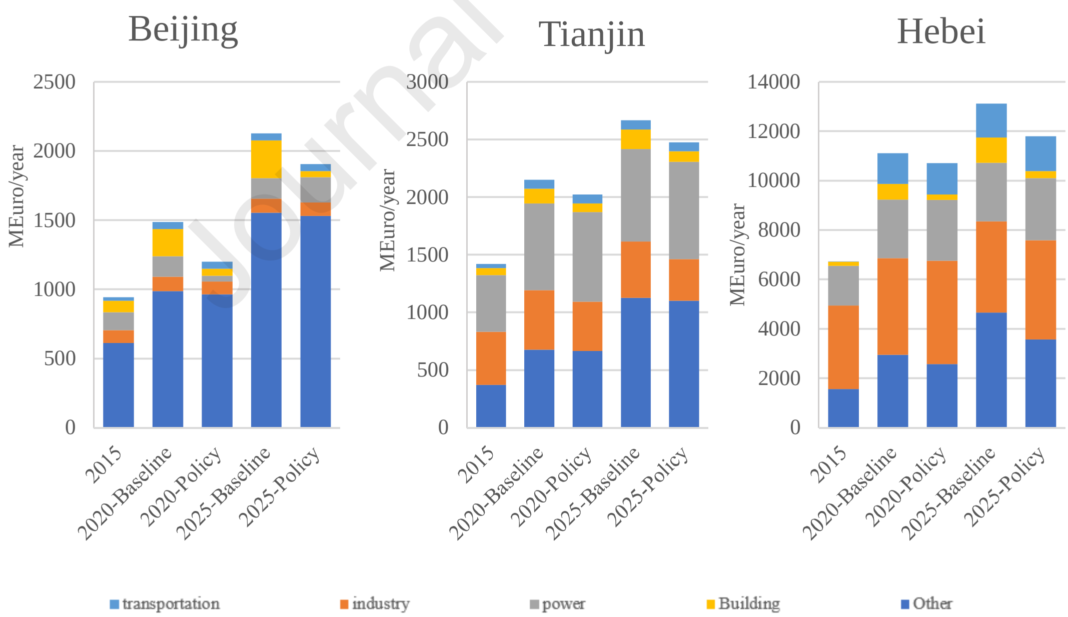

Fig. 11. Air pollutant emission control costs by key sectors

3.5 Ambient air quality impacts

Changes in emissions resulting from BSPC were projected to have profound benefits for ambient air quality in the JJJ region, as shown in Fig. 12. Under the 2020 policy scenario, concentrations of $PM_{2.5}$ calculated by the grids od maps shown in the GAINS IV Asia model were projected to reduce significantly in Beijing, Tianjin, and Hebei. In the baseline case, population-weighted annual $PM_{2.5}$ concentrations were projected to decline by 11.7%, 10.0%, and 11.6% by 2020 in Beijing, Tianjin, and Hebei, respectively; BSPC was projected to enhance these improvements to 47.9%, 28.2%, and 31.2%, relative to 2015. Note that all these calculations were performed under the assumption of constant maintenance of the meteorological conditions in 2015 and the population-weighted annual $PM_{2.5}$ concentration is equal to the quotient of PM_j (Equation 5) and population, in which the demographic data are based on statistical yearbooks for Beijing, Tianjin, and Hebei, and IEA WEO 2018 CPS scenario of GAINS.

Thereby, the measures of BSPC were projected to reduce the population-weighted mean exposure of $PM_{2.5}$ from 78.7μg/m³, 68.2μg/m³, and 77μg/m³ in the baseline projection to 41.4μg/m³, 49.4μg/m³, and 53.8μg/m³ in 2020 for Beijing, Tianjin, and Hebei, respectively (i.e., by 28.45μg/m³, 12.35μg/m³, and 15μg/m³ for each province/municipality). The average $PM_{2.5}$ concentration in the JJJ region would reach 48.2μg/m³, BSPC is expected to play a significantly positive role in improving air quality in the JJJ region.

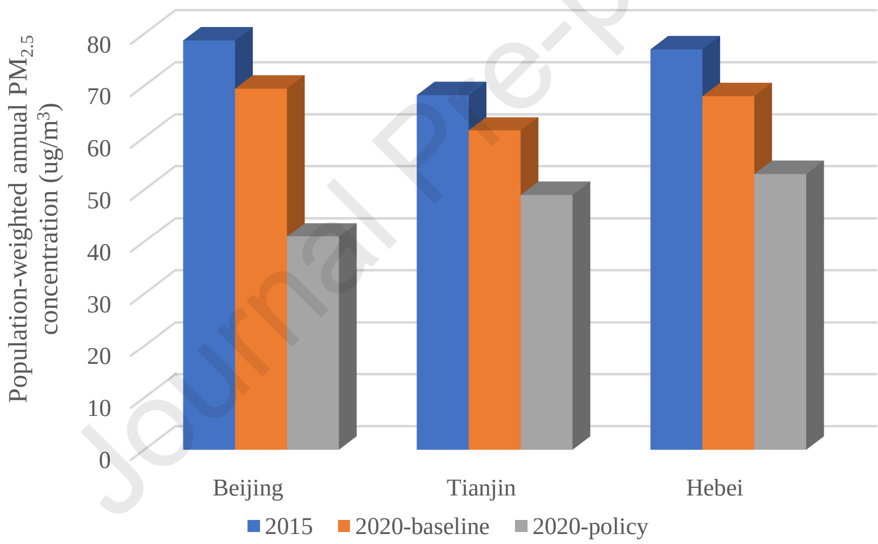

Fig. 12. Population-weighted annual $PM_{2.5}$ concentration in Beijing, Tianjin, and Hebei in 2015, for the baseline and policy projection in 2020.

3.6 Comparison with other studies

Our results identified the significant air quality improvement after the implementation of BSPC based on the relevant air quality control theoretical and technical aspects. So far, the recent existing literature have focused on studying the environmental impacts of the APPCAP or the pollution-control policy in a particular sector (Feng and Liao, 2016; Yang et al., 2019; Zhang et al., 2019; Wang and Wei, 2020; Yang et al., 2020). Under the implementation of APPCAP from 2013 to 2017, the average annual reduction in $PM_{2.5}$ concentration was 37.3% for the JJJ region, 35.2% for the YRD region, and 26.1% for the Pearl River Delta (PRD) region (Huang et al., 2018). In addition, the average annual SO_2 concentration decreased by 54.1% in the three regions with the largest reduction occur in the JJJ region by 63.5% and no significant change in NO_2 concentrations was evident in the three regions (Huang et al., 2018). Furthermore, it can be concluded that after implementing the APPCAP, the largest reductions in $PM_{2.5}$, PM_{10}, and SO_2 were found in the JJJ region. Similar results can be found in other studies (He et al., 2020; Zhang et al., 2018; Zhao et al., 2021) and this may be primarily due to their dominant heavy chemical industry and coal-dominated energy structure in JJJ (Feng et al., 2019; Liu and Miu, 2017). Specifically, for JJJ, in the study of Zhang et al. (2018), it has been concluded that the implementation of the APPCAP could decrease the $PM_{2.5}$ concentration by about 40% in the JJJ region from 2013 to 2017. In addition, significant reductions of $PM_{2.5}$, PM_{10}, NO_2, and SO_2 by 7.4, 8.1, 2.4, and 1.9 μg /m^3/year were observed in Beijing from 2014 to 2018 after implementing the APPCAP, respectively (Maji et al., 2020). From the key sector perspective, Zhang et al. (2019) concluded that the primary $PM_{2.5}$ emissions will be reduced by 27%, 16%, and 20% in Beijing, Tianjin, and Hebei by 2020 after implementing the residential “coal-to-electricity” policy. In these studies, the estimates are based on a more generally defined research scope and therefore do not include a comprehensive analysis of each sector. The comparison is only descriptive because of the different settings across studies regarding policy scenarios, health end points, key parameters, and temporal and spatial scales. However, from the indicators chosen for this comparison, three things are clear: First, the reductions on all pollutant emissions under the BSPC are significant while the emission control costs are lower. Second, the $PM_{2.5}$ concentration will decrease considerably under the BSPC while still exceeding the WHO interim Target-1. Third, control measures in the residential combustion sector would achieve greater reduction benefits than other sectors. This comparison also clarifies our study’s academic contribution in that our analysis aims to comprehensively evaluate the air pollutant emissions and air quality in each key sector in the JJJ region before and after the implementation of the BSPC to determine its effectiveness. To the best of our knowledge, no prior research has involved a systematic analysis of the impacts of BSPC. The atmospheric pollution control concepts and methods proposed herein have broad applicability for the implementation of BSPC-like policy in other regions worldwide.

4 Conclusion and policy implications

There is an urgent need to improve air quality in China’s JJJ region. BSPC has been implemented on a large scale over the 13th FYP period. Using the GAINS IV Asia model, this study evaluated the environmental impacts of BSPC in the JJJ region. Among the three provinces/municipalities of the JJJ region, we estimated that Hebei would obtain the greatest reductions in absolute terms of each kind of air pollutant, including NO_x, SO_2, $PM_{2.5}$, and NH_3. It is expected that emissions of NO_x, $PM_{2.5}$, SO_2, and NH_3 in Hebei will be reduced by 724 kt (equivalent to a 31.3% reduction of the emissions in 2015 in the baseline scenario), 21 kt (44.8%), 528 kt (40.3%), and 196.3 kt (10.7%), respectively, by 2020 if the JJJ region implements the control policies of BSPC as planned. In addition, NO_x, $PM_{2.5}$, SO_2, and NH_3 emissions in Tianjin were projected to reduce by 66 kt 21.2%), 39 kt (33.8%), 95 kt (37.2%), and 1 kt (1.7%), respectively, while the emissions in Beijing were projected to reduce by 53.3 kt (21.2%), 64.9 kt (58.7%), 82.3 kt (56.1%), and 1 kt (1.2%). These reductions are expected to be more remarkable in 2025 if policy implementation is sustained after 2020. In addition, with implementation of these policies in the JJJ region, the costs of pollutant emission controls in 2020 were projected to be approximately 1.27 times, 1.42 times, and 1.59 times that of 2015 in Beijing, Tianjin, and Hebei, respectively. Furthermore, this study assessed the impacts of these policies on ambient air quality in the JJJ region. With the implementation of these policies in the JJJ region, the measures of BSPC were computed to reduce population-weighted annual $PM_{2.5}$ concentrations to 35.3μg/m³, 46.8μg/m³, and 49.6μg/m³ in Beijing, Tianjin, and Hebei, respectively, by 2020. Meanwhile, net reductions were projected to reach 34.1μg/m³, 14.6μg/m³, and 8.7μg/m³ in these provinces/municipalities compared to the 2020 baseline scenario. BSPC should be implemented, as it is expected to bring significant environmental benefits to the JJJ region.

A GAINS IV Asia model analysis indicated that effective implementation of BSPC will produce profound benefits in terms of improving air quality in the JJJ region. Regarding emission controls for each pollutant, this analysis showed that controls of SO_2 emissions are relatively simple and concentrated in the residential sector, while controls of NO_x emissions have a greater capacity for emission reduction. The focus of efforts to reduce future NO_x emissions in the JJJ region is on the transportation sector, especially heavy-duty diesel vehicles. However, reductions in NO_x emissions can also arise from improvements in industrial and power structures, replacement of untreated coal, and increases in the utilization of chemical fertilizers. Policies concerning the replacement of coal with gas or electricity play a vital role in reducing $PM_{2.5}$ emissions in the JJJ region. Other major sources of $PM_{2.5}$ emissions include industrial processes.

In the actual implementation of BSPC, switching from coal to cleaner fuels (i.e., natural gas and electricity) in residential combustion would have great potential to reduce pollution in the JJJ region. Increasing nitrogen use efficiency and managing both heavy-duty diesel and light duty vehicles are also essential in controlling pollutant emissions in the future. In addition, controlling industrial emissions (including the processing and burning of low-sulfur fuels) and coal-fired power plants is important in improving the air quality in Tianjin and Hebei. These controls are recommended as key measures of future air quality management in the JJJ region.

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Highlights

1 Integrated policy assessment for the Blue Sky Protection Campaign are provided.

2 Policy have essential on pollution abatement and energy transition.

3 BSPC have large co-benefits between emission mitigation and energy saving.

4 Residential combustion plays a key contribution for pollution abatement.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: