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Carbon dioxide mitigation co-effect analysis of clean air policies: lessons and perspectives in China's Beijing–Tianjin–Hebei region

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Abstract

In 2018, the Beijing–Tianjin–Hebei (BTH) area launched the Blue Sky Protection Campaign (BSPC) to control atmospheric pollution. CO_2 emissions could be significantly reduced due to the co-effects of implementing the BSPC. This paper employs the Greenhouse Gas and Air Pollution Interactions and Synergies Asia model to quantitatively evaluate the CO_2 reductions when implementing the BSPC in the BTH region. The results indicate that CO_2 emissions can be reduced by 20.7 Mt (equivalently, a 19.7% reduction in the corresponding baseline scenario), 6.8 Mt (3.8%), and 80.2 Mt (9.2%) by 2020 for Beijing, Tianjin, and Hebei, respectively, as a co-benefit of the BSPC. By 2030, it is estimated that the CO_2 emission reductions will be 37.8 Mt (26.6%), 4.85 Mt (2.5%), and 69.9 Mt (8.6%) for Beijing, Tianjin, and Hebei, respectively. NO_x presents the highest co-effects with CO_2 in each region. From the key sector perspective, sectors of power and heating in Beijing, residential combustion in Tianjin, and industrial combustion in Hebei are the most important sector that presents the highest co-effects on CO_2 emission reductions due to the application of BSPC. We suggest that the implementation of BSPC, specifically the energy control measures in the power and heating, residential combustion, and industrial combustion sectors for Beijing, Tianjin, and Hebei, respectively, have high synergies and can simultaneously reduce CO_2 and other atmospheric emissions. The results contribute to city-level policymaking on facilitating air pollution control and climate change mitigation among different governmental departments.

1. Introduction

In recent decades, greenhouse gas and air pollutant emissions have been increasing rapidly in China as a result of the dramatic economic growth that relied on fossil fuels (Lei *et al* 2011, Zhao *et al* 2012). China surpassed the United States and became the world's largest carbon emitter in 2007 (Wen and Shao 2019). Substantial efforts have been made to reduce carbon emissions. Based on the 13th Five-Year Plan (FYP), China is making efforts to improve the proportion of non-fossils fuels in the total energy consumption to 15% by 2020, and decrease the share of coal consumption to below 58% by 2020 (Xu *et al* 2017). In addition, a national carbon trading scheme was launched in order to effectively cope with climate change through market-based mechanisms in

2017 (Lo 2013). The Chinese government has made ambitious commitments in terms of reducing CO_2 emissions. Specifically, the carbon intensity (measured by tons of CO_2 emissions per unit of GDP) of 2020 and 2030 is declared to decrease by 40%–45% and 60%–65%, respectively, compared with 2005 level (Xu *et al* 2017, Dong *et al* 2018). To achieve these goals, a series of measures have been taken to decrease the consumption of fossil fuels and develop cleaner energy such as hydropower, wind energy, and nuclear power (Liu *et al* 2015).

The Chinese government has also implemented some air pollutant control plans. In 2012, China's Ministry of Environmental Protection adopted the Air Quality Standards (DEP 2012), and $PM_{2.5}$ pollution was monitored in different regions. The Chinese government released the Air Pollution Prevention

and Control Action Plan (APPCAP) in 2013, so as to reduce urban PM_{10} levels by 10% and decrease the $PM_{2.5}$ concentrations of the Beijing–Tianjin–Hebei (BTH), the Pearl River Delta (PRD), and the Yangtze River Delta (YRD) by 15%–25% from 2012 to 2017 (Ma *et al* 2020). The APPCAP was the first plan that specified the air quality goals in China (APPCAP 2013) and it may have been one of the most influential environmental policies in the past 5 years (Cai *et al* 2017). Specifically, it was calculated that with the implementation of the APPCAP, the emissions of SO_2, NO_X, $PM_{2.5}$, and non-methane volatile organic compound (NMVOC) in 2017 had decreased by 36%, 31%, 30%, and 12%, with NH_3 emissions increased by 10% from the 2012 levels in BTH, respectively, based on the Weather Research and Forecasting model and Community Multiscale Air Quality model (Cai *et al* 2017). Also, results from Zhang *et al* (2018) indicated that the annual mean $PM_{2.5}$ concentration had decreased by more than 30% throughout the country since the implementation of the APPCAP using arithmetic mean and percentile methods. It has been concluded that under the APPCAP, industrial combustion and industry process play important roles in SO_2 reduction while it is the transportation sector dominates the NO_x reduction, and the industrial sources and domestic combustion sources contribute the most to the $PM_{2.5}$ reduction. It is worth noting that the APPCAP has reduced 352.7 Mt ($39.9 \pm 5.3\%$) of CO_2 emissions when compared to the emissions in 2012 (Lu *et al* 2019). In 2018, the Chinese government launched a 3 year plan named the Blue Sky Protection Campaign (BSPC) to reduce air pollution. The specific goals are to decrease SO_2 emissions, NO_x emissions, and $PM_{2.5}$ concentration by 15%, 15%, and 18%, respectively, compared with 2015 levels. In addition, the goal of helping reduce greenhouse gas emissions are also mentioned under the BSPC but with no controls specified. The BSPC mainly focuses on the three key regions of BTH, YRD and Fenwei Plain. Specific measures were designed to reduce emissions of atmospheric pollutants, with core contents in energy related measures, including eliminating highly polluting facilities, optimizing the energy structure, reducing the use of traditional fossil fuel in power, industrial, and residential sectors, and increasing the proportion of clean energy in total energy use. It is worth noting that these control policies would also have impacts on other air pollutants besides SO_2, NO_x, and $PM_{2.5}$. For example, Cai *et al* (2017) presented that implementing the APPCAP had decreased the emissions of NMVOC by 12% and increased NH_3 emissions by 10% by 2017, and would decrease NMVOC emissions by 22% and increase NH_3 emissions by 3% by 2020 from the 2012 levels in the BTH region. Maji *et al* (2020) concluded that the APPCAP had led to a reduction in CO concentration by 80 $\mu g\ m^3\ yr^{-1}$ while the O_3 concentration was increased by 1.3 $\mu g\ m^{-3}\ yr^{-1}$

from 2014 to 2018 in Beijing. In addition, many studies have shown the opposite trends of $PM_{2.5}$ and O_3 precursor emissions under the APPCAP (Fenech *et al* 2019, Zhao *et al* 2020). This is mainly because O_3 is a typical secondary pollutant and the increase in O_3 could be due to non-linear chemistry effects (e.g. NO_x Titration), as well as because of changes in $PM_{2.5}$ (Dong *et al* 2019). As the BTH region is one of China's most developed regions owing to its status in terms of economic development as well as one of the regions suffering from the most severe air pollution (Qi *et al* 2017, Hao *et al* 2018), both the APPCAP and the BSPC have identified the BTH region as a priority area for air pollution control and prioritized an investigation of the policy impacts. As policies that intended to address either air pollution or CO_2 mitigation may well impact on the other, generating co-effects or trade-offs (Rao *et al* 2016), it is important to investigate the existing indirect impacts of air pollution regulations on CO_2 mitigation and utilize the lessons learned from previous policies.

The synergistic effects between air pollution mitigation and CO_2 emission reduction has been confirmed by many studies (Mittal *et al* 2015, Peng *et al* 2017, Li *et al* 2019). Wagner and Amann (2009) applied the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model to assess the effectiveness of CO_2 reduction measures in the Kyoto Protocol and concluded that CO_2 reduction goals could be reached while reducing emissions of SO_2, NO_x, and $PM_{2.5}$ by an additional 5%. Shrestha and Pradhan (2010) explored the synergies in Thailand by using a cost optimization method, which showed that by reaching the target of decreasing CO_2 emissions by 30%, SO_2 would decrease by 43%. Many studies have suggested that policies targeting sources of air pollution can also lead to CO_2 reductions benefits. For China, Lu *et al* (2019) identified that the energy-related measures under the APPCAP had reduced $47.3 \pm 0.8\%$ of SO_2, $32.5 \pm 2.6\%$ of NO_x, $15.2 \pm 0.2\%$ of $PM_{2.5}$, and $39.9 \pm 5.3\%$ of CO_2 emissions, compared to the emissions in 2012 using the GAINS model, and suggested that $PM_{2.5}$ and NO_x had a high co-effect on reducing CO_2 emissions in the BTH region. Alimujiang and Jiang (2020) analyzed the co-effects of the electric vehicles promoting policy in Shanghai and discovered that substituting electric vehicles for conventional fuel ones could aid in both atmospheric pollutant reduction and CO_2 reduction. Yan *et al* (2013) analyzed the synergy between the reductions of atmospheric pollutant and CO_2 emissions under the Clean Development Mechanisms (CDMs), which aims to offer the opportunity for developed countries to make low-cost greenhouse gas reducing investments in developing countries. It was concluded that the coal to gas policy has a high CO_2 emission reduction co-effects. In addition, Yang *et al* (2018) concluded the measures for mitigating $PM_{2.5}$ pollution can have CO_2

reduction potentials based on a multi-objective analysis in China's iron and steel industry. Similar synergistic effects between air pollutants and CO_2 emissions have also identified by other studies under various air control policy (Dong *et al* 2019, Yu *et al* 2020).

The air pollution control measures under the BSPC aims to improve the air quality. To realize this goal, specific measures including clean energy transformation in the energy system is implemented in different sectors. It is clear that emissions of greenhouse gases, particularly CO_2, could benefit from this policy. As most studies focus on the air quality improvement after the implementation of the APPCAP, the impacts and co-effects of implementing the BSPC have not been evaluated. To the best of our knowledge, we provided the first study on the synergistic effects of the BSPC on CO_2 mitigation in the BTH region. In this research, the GAINS Asia model was applied to examine the CO_2 emission reductions, which is a co-effect of implementing the BSPC, in the BTH region of China. The results of the GAINS Asia model can provide a comprehensive CO_2 emission inventory for the year of 2015 in the BTH region, which is the most up to date one as far as we know. Future CO_2 emissions trends from different sectors after implementing the BSPC are also projected up to 2030 based on the model. We aim to answer these questions: (a) How much have CO_2 emissions reduced since the implementation of the BSPC in the BTH region? (b) Which factors contribute to the changes in CO_2 emissions? (c) What are the differences in synergies between different pollutants and the major sectors? This work will advance the scientific understanding of co-effects on CO_2 emissions when implementing air quality policy and will provide evidence of the synergies for future decision-making in air pollution control.

2. Materials and methods

2.1. Model description
The GAINS Asia model, which was developed by the International Institute of Applied Systems Analysis, is a comprehensive assessment system that evaluates the interactions and the effectiveness of different atmospheric management policies. This model takes into account activities (such as power, industry, transportation, etc) and air pollution controls for different pollutants from different source sectors at 5 year intervals (Amann *et al* 2011, Zhang *et al* 2016). We employed this model to assess the CO_2 emission reductions due to the co-effects of implementing the BSPC. Details regarding the emission calculation principle of the model are provided in section 1 of the supporting information.

2.2. Scenario settings
In this study, the base year is 2015 and the evaluated period covers 2015–2030 in 5 year intervals. Two

scenarios are proposed to study the policy effectiveness: the baseline scenario and the policy scenario. Based on the World Energy Outlook 2018 Current Policy Scenario (WEO-2018-CPS) projected by the GAINS Asia model, the baseline scenario in our study assumed that the BSPC is not implemented in the BTH region. We recalibrated the activities of energy, agricultural, and industrial processes for 2020 based on the trend from the 'WEO-2018-CPS' and the 13th FYP targets published by the BTH regional government and China's renewable report (NDRC 2016, NEA 2017a). The APPCAP is not part of our baseline scenario due to the 5 year interval evaluation and that the 2020 targets set for BSPC are in comparison with the year of 2015. Then, we made the changes in 2025 and 2030 link to the 2020 values based on the growth rate of demands between 2020 and 2030 from the 'WEO-2018-CPS'. The trends in both scenarios (2025 and 2030) are keep consistent with 'WEO-2018-CPS'.

The policy scenario assumes that the BSPC is implemented in the BTH region in order to predict the effects of this control policy from 2015 to 2020. The policy packages of the policy scenario are shown in table S1 (available online at stacks.iop.org/ERL/16/015006/mmedia) in section 2 of the supporting information. Specifically, the policy packages are divided into four categories: the power and industry sector (with core content such as improving industrial structure and the associated distribution for steel, cement, coke, glass, and coal power plants); the transport sector (with core content such as increasing the number of new energy vehicles and implementing national vi (B) standard gasoline and diesel for traffic vehicles); the building sector (with core content such as replacing untreated coal of heating by households); and the cross sector (such as the pollution controls for stationary sources). The policy packages of the BSPC and its corresponding emission control measures in the GAINS Asia model are summarized in table S2 in section 3 of the supporting information. Within the policy scenario setting step, various air pollution sources (e.g. power, industry, transportation, residential building, and agriculture) and associated activities will be considered. More specifically, parameters (e.g. energy consumption by different fuels and sectors, industrial process activities, and utilization rate of atmospheric pollution control technology) are forecasted for 2020 using the consumption trends from the yearbooks (NBS 2016, 2017, 2018, 2019). For example, a reduction in coal consumption by urban residents and commercial combustion sectors is attributed to the following factors: (a) in the urban residential heating sector, we assumed that 80% of the heat demand was derived from the district heating system (Xiong *et al* 2015); (b) hard coal grade 2 is applied instead of hard coal grade 3, and the usage of natural gas and electricity increased. These assumptions are consistent with the BSPC regulations. From 2020 to 2030, it is assumed

Table 1. Estimated emissions of major air pollutants in different scenarios.

Regions	Pollutants	2015	2020 Baseline	2020 Policy	2025 Baseline	2025 Policy	2030 Baseline	2030 Policy
Beijing	SO_2 (kt yr^{-1})	146.7	127.1	64.4	116.0	59.4	104.7	57.9
	NO_x (kt yr^{-1})	250.3	219.0	197.0	181.8	166.0	168.3	149.5
	$PM_{2.5}$ (kt yr^{-1})	110.6	96.1	45.7	86.2	39.5	76.8	39.0
Tianjin	SO_2 (kt yr^{-1})	255.0	183.9	159.9	164.2	147.3	149.8	126.4
	NO_x (kt yr^{-1})	315.5	259.3	248.7	220.5	214.5	195.9	186.2
	$PM_{2.5}$ (kt yr^{-1})	115.4	98.8	76.4	85.8	61.0	75.3	47.7
Hebei	SO_2 (kt yr^{-1})	1310.8	1029.1	782.8	941.7	703.6	768.2	564.3
	NO_x (kt yr^{-1})	2309.4	1798.1	1585.4	1431.9	1286.3	1197.4	1033.3
	$PM_{2.5}$ (kt yr^{-1})	940.6	868.2	519.0	791.7	474.9	666.4	424.7
BTH	SO_2 (kt yr^{-1})	1712.5	1340.1	1007.1	1221.9	910.3	1022.7	748.6
	NO_x (kt yr^{-1})	2875.2	2276.4	2031.1	1834.2	1666.8	1561.6	1369.0
	$PM_{2.5}$ (kt yr^{-1})	1166.6	1063.1	641.1	9637	575.4	818.5	511.4

that the same levels of policy strictness will be maintained in the BTH region and the governments will continue to implement specific policy measures at the same rate. The detailed ways to determine the key parameters and default parameters of the GAINS Asia model used in our study are present in section 4 of the supporting information.

2.3. Quantification of CO_2 co-effects
Two indicators are introduced to evaluate the synergistic effects of CO_2 and air pollutants under the BSPC. The indicator of S_1, which is named the 'degree of co-effect', represents the ratio of CO_2 reduction to one pollutant reduction (equation (1)).

$$S_1 = \frac{\Delta E_{CO_2}}{\Delta E_p}. \tag{1}$$

ΔE_{CO_2} equals the CO_2 emission reduction (Mt). ΔE_P represents the pollutant reduction (Kt).

S_1 and S_2 has been suggested in some studies to assess the synergistic level (Nathan and Kristin 2010, Liu *et al* 2013, Lu *et al* 2019). The higher S_1 is, the stronger the co-effect is. However, S_1 could be high when both ΔE_{CO_2} and ΔE_P are low in certain cases, indicating low reduction potentials. And also S_1 could be low when there are large changes in both air pollutant and CO_2 emissions. Therefore, the 'relative degree of co-effect' indicator S_2 has been used as the indicator for assessing the synergies in our study.

$$S_2 = \frac{\frac{\Delta E_{CO_2}}{E_{CO_2}}}{\frac{\Delta E_p}{E_p}}. \tag{2}$$

E_{CO_2} is the CO_2 emissions (Mt). E_p represents the pollutant p emissions (Kt). When we implement the BSPC, assuming the same effect of pollutant reduction level, the greater the indirect emission reduction ratio of CO_2, the higher the co-effects. This means the higher is S_2, the greater is the CO_2 mitigation potential of decreasing one-unit pollutant.

2.4. 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 (GOBJ 2016, GOHB 2016, GOTJ 2016), the 13th FYP of Power Sector Development (PGC 2016), and several state-of-the-art studies (Xiong *et al* 2015, Zhang *et al* 2015, Su *et al* 2018).
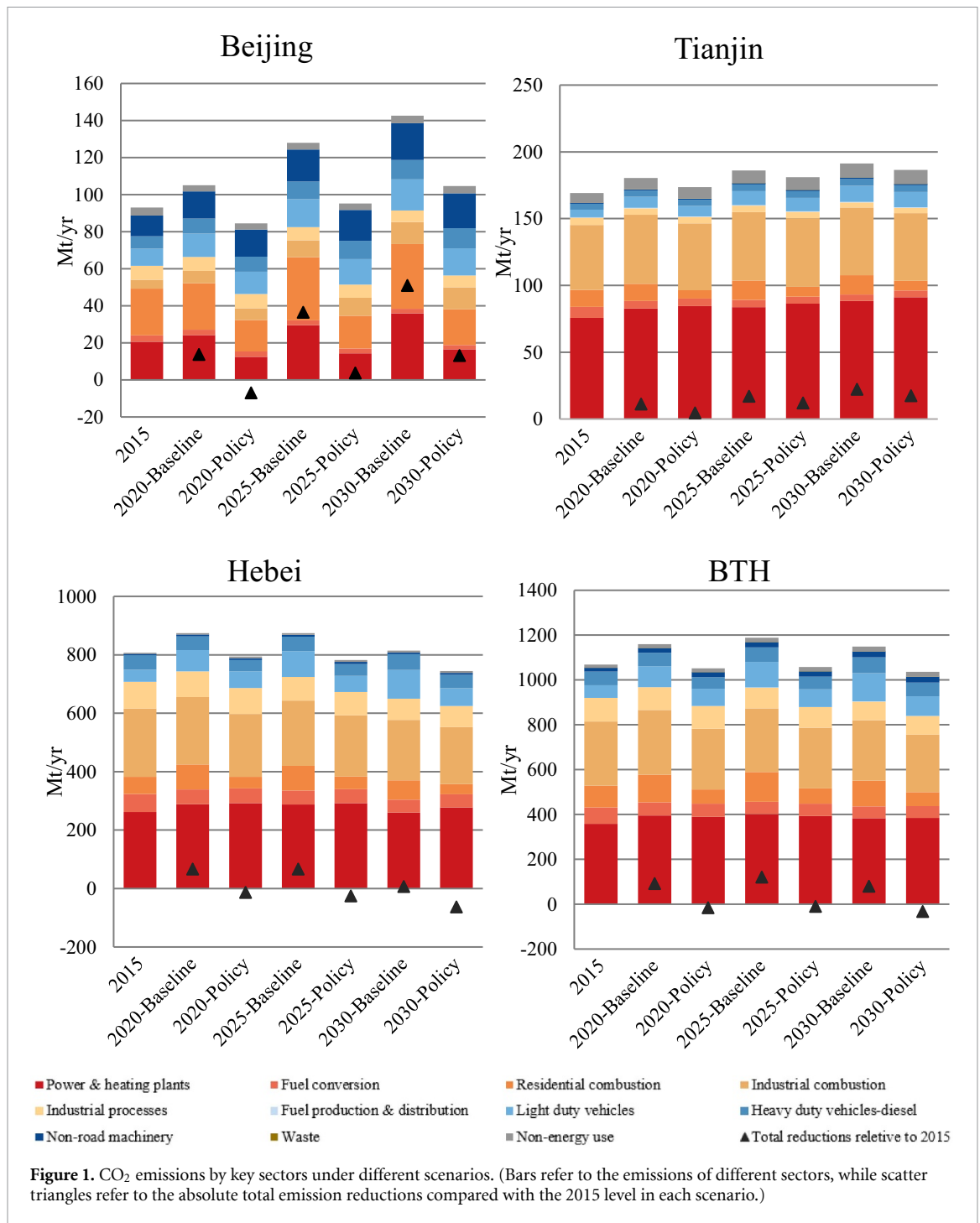
2.5. Uncertainty
All analyses conduced for this study are based on the meteorology of 2015. It is known that the interannual variability in meteorological conditions causes variations for individual years. In addition, in absence of local information from each province, the baseline projection of economic activities for each province up to 2030 has been developed from international data sources. Activity projections, especially the future development of the most polluting activities in Hebei (production levels of the various sectors in heavy industry, agricultural activities, etc) have important impacts on future emission projections and the mitigation potential. Further work that incorporates local information will be required to enhance the robustness of the findings.

3. Results and discussion
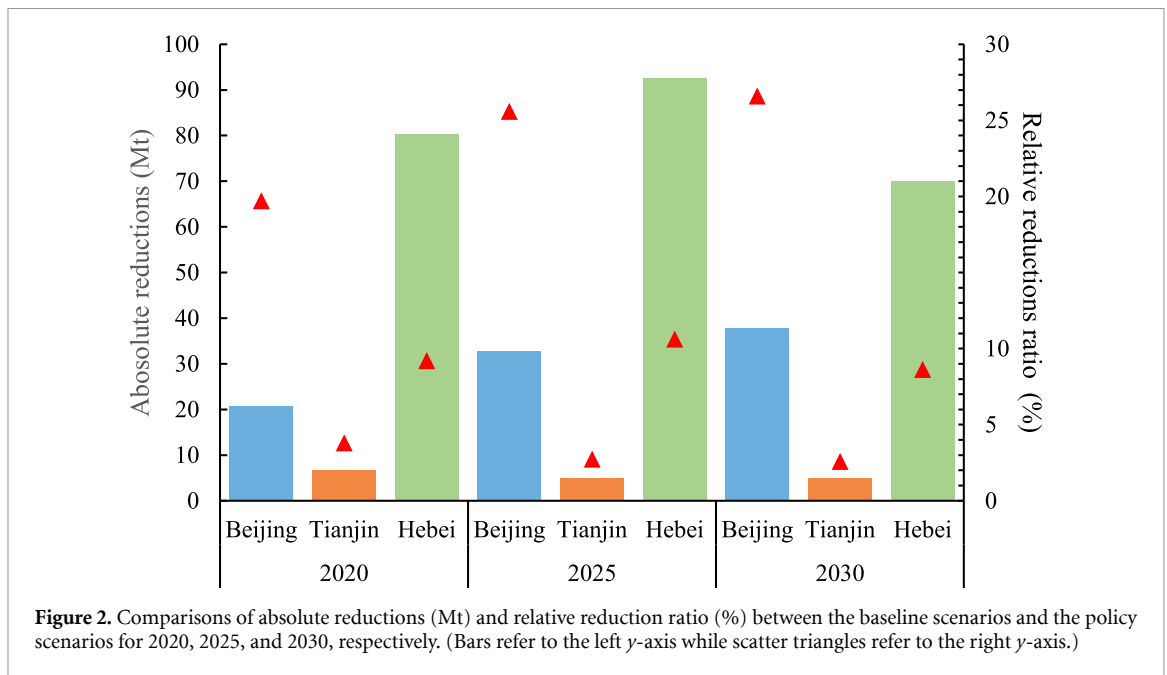
3.1. Projection for CO_2 emission by key sectors
Table 1 presents the projected major pollutants (SO_2, NO_x, and $PM_{2.5}$) emissions under different scenarios, which have been concluded in our forthcoming published studies (Xu *et al* 2020). Details regarding the

Figure 1. CO_2 emissions by key sectors under different scenarios. (Bars refer to the emissions of different sectors, while scatter triangles refer to the absolute total emission reductions compared with the 2015 level in each scenario.)

emissions of these air pollutants in different sectors and scenarios of each region are shown in figures S1–S3 of the supporting information. Compared to the emissions in the 2020 baseline scenario, the BSPC would reduce emissions of SO_2 by 62.7 kt (equivalent to a 49% reduction of the emissions in the corresponding baseline scenario), 24 kt (13%), and 246.3 kt (23.9%), respectively, in Beijing, Tianjin, and Hebei by 2020. NO_x emissions reduce by 22 kt (10%) in Beijing, 11 kt (4.1%) in Tianjin, and 213 kt (12%) in Hebei by 2020. $PM_{2.5}$ emissions reduce by 50.4 kt (52%), 22 kt (23%), and 349 kt (40%) for Beijing, Tianjin, and Hebei by 2020, respectively. In addition,

the emissions of SO_2, NO_x, and $PM_{2.5}$ are also lower in the policy scenarios than in the baseline scenarios for 2025 and 2030. The BSCP can significantly reduce air pollutant emissions in the BTH region.

The predicted CO_2 emissions of the BTH region in the baseline and policy scenarios are presented in figure 1. In 2015, Hebei produced substantially more CO_2 than Beijing and Tianjin (about 807 Mt, 92 Mt, and 169 Mt, respectively). Figure 1 shows the primary emission tendencies in the baseline and policy scenarios. CO_2 emissions of Beijing are expected to grow significantly if the BSPC is not implemented, and it is projected to increase by 14%, 39%, and 55% relative

Figure 2. Comparisons of absolute reductions (Mt) and relative reduction ratio (%) between the baseline scenarios and the policy scenarios for 2020, 2025, and 2030, respectively. (Bars refer to the left *y*-axis while scatter triangles refer to the right *y*-axis.)

to 2015 by 2020, 2025 and 2030, respectively. For Tianjin and Hebei, the increases in the baseline scenarios for 2020, 2025, and 2030 are all within 11% when compared with 2015. The larger increases of relative change in CO_2 emissions in Beijing under the baseline scenarios are probably due to the large size and strong growth of the Beijing's economy driving further residential consumption (Wen and Wang 2019, Jiang *et al* 2019b, Wei *et al* 2020). If the BTH area achieves the policy targets by 2020, it is predicted that Beijing, Tianjin, and Hebei will reduce CO_2 emissions by 20.7 Mt (equivalent to a 19.7% reduction in the corresponding baseline scenario), 6.8 Mt (3.8%), and 80.2 Mt (9.2%), respectively. CO_2 emissions from the BTH area would be reduced by 107.7 Mt (9.3%), of which Hebei accounts for 74.5%. By 2030, it is expected that Beijing, Tianjin, and Hebei will reduce their emissions by 37.8 Mt (26.6%), 4.85 Mt (2.5%), and 69.9 Mt (8.6%) compared with the 2030 baseline scenario, respectively (figure 2). It is worth noting that Tianjin and Hebei presents smaller reductions by 2030 compared with 2020 and 2025. On the one hand, it is due to that the baseline scenario slightly decreases by 2030 in Hebei, generating smaller policy benefits. On the other hand, for both Tianjin and Hebei, it is mainly because by 2030, increased levels of activity will require more power plants to be built for the increasing power generation requirements, leading to a smaller reduction potential. CO_2 emissions from the BTH area in 2030 would be reduced by 112.6 Mt (9.8%), of which Hebei accounts for 62.0%. From 2020 to 2030, the absolute emission reductions and the relative emission reduction ratio of CO_2 will remain relatively stable in each of the BTH region. Specifically, Beijing: 21–35 Mt (20%–25%); Tianjin: 5–6.7 Mt (2.5% to 3.8%); Hebei: 70–92 Mt (9%–11%) (figure 2). This indicates that the indirect effects

of BSPC on CO_2 emission reductions is stable and continuous. In each scenario, the emissions of Hebei would be several times higher than those of Beijing and Tianjin. The high emissions are mainly due to the fact that most of the industrial activity occurs in Hebei, and therefore, a greater amount of fossil fuels are consumed.

In addition, it is worth noting that although significant reductions in CO_2 emissions have been projected in Beijing when compared with the corresponding baseline scenario of each year, the CO_2 emissions in the 2030 policy scenario only show a slight increase compared to those in 2015. This shows that after the implementation of the BSPC, Beijing's CO_2 emissions have remained at a relatively stable level from 2015 to 2030. Further, in the BTH region, the CO_2 emissions have also remained at a stable level since 2015, suggesting that the CO_2 emission in BTH area peaked in 2015. This is consistent with the conclusions drawn from Zhao *et al* (2018), indicating that the increasing CO_2 emission trends in the BTH region from 2000 to 2014 and Yuan (2019), which show that the CO_2 emissions presents a downward trend from 2014 to 2016 based on a 2 year interval study in the BTH region. And then the CO_2 emissions will keep relatively stable (decrease within 1% compared with 2015) in 2020 and 2025, and decrease slightly by 3% in 2030 under the BSPC compared with 2015 in the BTH region. The CO_2 emissions under the policy scenarios in each region will not change significantly from 2015 to 2030 under the BSPC, however, the APPCAP would significantly reduce 352.7 Mt (39.9 ± 5.3%) of CO_2 emissions from 2012 to 2017 (Lu *et al* 2019). This also indicates that the peak for CO_2 emissions would have come in the BTH region. Compared with the study of Tao *et al* (2019) which suggests that China's total CO_2 emissions will peak by 2030, it could be

concluded that the relatively stable CO_2 emissions in the BTH region contribute to the peak of CO_2 emissions being achieved before 2030 in China and the CO_2 emissions from the BTH region have a positive effect on controlling China's total CO_2 emissions.

The CO_2 emissions of the power and heating sector, which is a significant source of CO_2 emissions in the BTH region, accounts for 22.4%, 44.7%, and 32.5% of the total emissions in 2015 for Beijing, Tianjin, and Hebei, respectively. CO_2 emissions in the power and heating sector in Beijing would decline by 49% and 54% compared with the baseline scenario for 2020 and 2030, respectively, while the emissions in Tianjin and Hebei would undergo minimal change. In Beijing, the main reason for the reductions was the closure of the thermal power plants and coal-fired units in the power sector under the BSPC, which caused a dramatic decline in coal consumption. It is estimated that by 2025, Beijing's power demand will be 35 million kW, in which nearly 75% will depend on external sources (Liu 2020). The main source of external transmission is from Shanxi and Inner Mongolia, which are still largely powered by coal (Jiang *et al* 2019a). Therefore, it may have negative effects of indirect emissions transmission on Shanxi and Inner Mongolia based on the generation structures used in the two provinces. In Hebei and Tianjin, although some thermal power units have been renovated or shut down, the thermal power output has increased since 2017 (TSB 2019), and coal consumption in the power sector is also increasing (GCMR 2019). The increasing demand due to its own industrial structures and economic development status is consistent with the analysis report on the mid-term evaluation and future prospect of power coal control during the 13th FYP period (NCEPU 2019), which predicts that the coal consumption in China's power sector will peak in 2020 and then plateau. Current ultra-low emissions from power plants only target general air pollutants, such as SO_2, but do not target CO_2. Therefore, CO_2 emissions in the power and heating sector in Tianjin and Hebei would not decrease significantly by 2020 and 2030 compared with the baseline scenarios. In addition, the residential combustion sector in Beijing and the sector of industrial combustion in Tianjin and Hebei also play important roles in CO_2 emissions. Their emissions account for 27.5%, 28.7%, and 28.9%, respectively, of the total emissions in 2015.

As is shown in figure 1, significant CO_2 emission reductions was projected in the residential combustion sector, indicating that implementing energy replacement from coal to gas and electricity can achieve significant reductions to both CO_2 and air pollutants emissions (figures S1–S3). Specifically, the reductions in the residential combustion sector will account for 39%, 73%, and 57% of the total CO_2 emissions reductions by 2020 for Beijing, Tianjin, and Hebei, respectively. Further, by 2030, it is projected

to accounts for 44%, 88%, and 43% for each region, respectively. In addition, the reductions in the power and heating plants of Beijing will account for 57% of the total reductions by 2020. And the reductions in the Industrial combustion sector for Tianjin and Hebei will account for 20% and 19% of the total reductions by 2020, respectively. Overall, the degrees of emission reduction potential vary in different sectors and regions.

Our results demonstrate that BSPC can reduce CO_2 emissions while reducing air pollutants. For controlling air pollutants (SO_2, NO_x, and $PM_{2.5}$), as shown in figures S1–S3 of the supporting information, reductions mainly occur due to the energy structure optimization and transformation (e.g. control coal consumption, coal to clean policy in residential combustion and thermal power plant sector), the transportation structure optimization and transformation (e.g. increasing new energy vehicles), and the industrial structure optimization and transformation (e.g. control of production capacity in high-pollution and high-emission industries). Therefore, the optimization and transformation of these major sectors has great impacts on CO_2 emission reductions.

3.2. Clean air co-effects on CO_2 mitigation

3.2.1. Evaluation by pollutants

The metric S_2 is applied to evaluate the co-effects of CO_2 emission reductions and other atmospheric pollutants reductions (listed in table 1) under policy scenarios of different regions (figure 3). The S_2 values range from 0.38 to 2.94 in Beijing, from 0.07 to 0.99 in Tianjin, and from 0.23 to 1.20 in Hebei and BTH. The values of S_2 for BTH are close to those of Hebei because Hebei dominates the total emissions of the BTH area.

High values of S_2 indicate high synergies due to the co-effects of implementing the BSPC. Our results show that NO_x has the highest co-effects with CO_2 in Beijing, Tianjin, Hebei, and BTH in each of the policy scenarios because of the higher reduction potential of CO_2 per unit of NO_x emission reductions. This finding is consistent with the results from Feng *et al* (2018), which indicated that a co-effect for CO_2 control exists when NO_x emission control measures are implemented and identified that the energy efficiency technologies have significant co-effects on reducing NO_x and CO_2 emission levels simultaneously in China's cement industry with the Integrated MARKAL-EFOM System (TIMES) model. In our study, the values of S_2 for NO_x in Beijing are significantly higher than those of Tianjin and Hebei, which indicates a stronger co-effect on the CO_2 emission reductions due to application of NO_x control measures in Beijing. Higher S_2 value of NO_x in Beijing means higher reduction potential of CO_2 emissions while reducing per unit of NO_x emission.
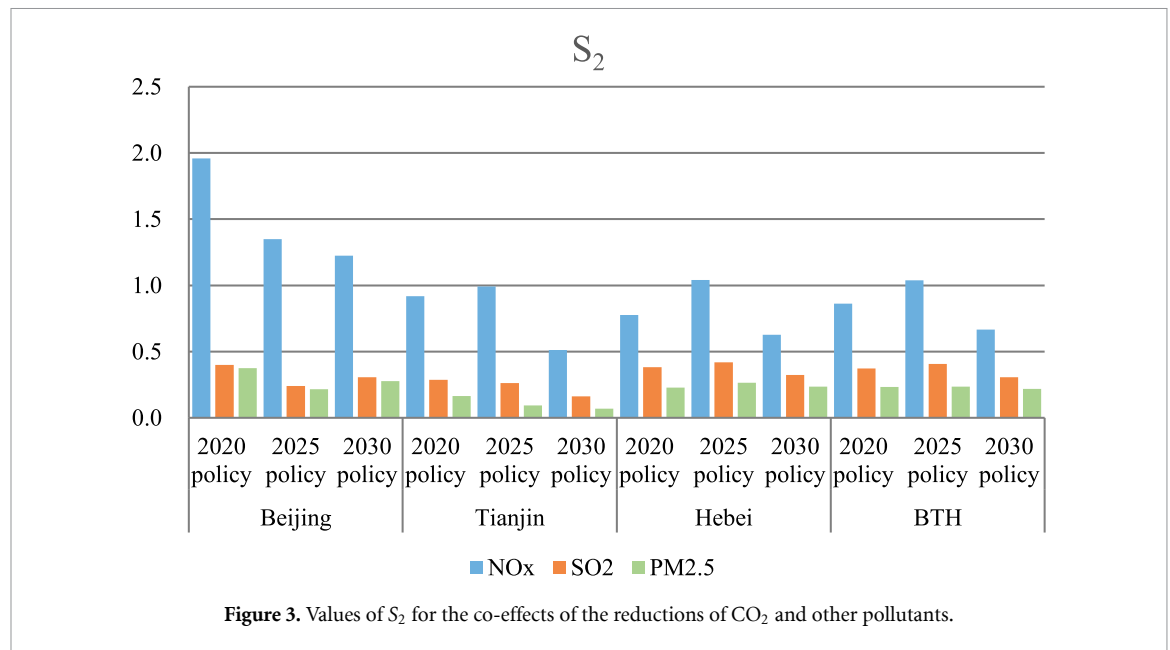
Figure 3. Values of S_2 for the co-effects of the reductions of CO_2 and other pollutants.

Table 2. Co-effects of the reductions of CO_2 and other pollutants emissions in main sectors with S_2.

Regions	Key sectors	2020-Policy			2025-Policy			2030-Policy		
		NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$	SO_2
Beijing	Power and heating plants	**1.74**	**2.12**	**2.32**	**1.75**	**2.14**	**2.25**	**1.73**	**1.71**	**2.27**
	Residential combustion	0.41	0.16	0.19	0.54	0.17	0.22	0.59	0.20	0.30
	Industrial combustion	1.09	—	1.22	0.52	—	**8.45**	0.12	—	1.37
	Light duty vehicles	0.82	—	—	0.99	—	—	1.09	—	—
Tianjin	Power and heating plants	−0.26	−0.21	−0.10	−0.52	−0.31	−0.41	−0.52	−0.31	−0.38
	Residential combustion	**14.11**	**3.02**	**2.07**	13.56	2.73	2.56	13.56	2.73	2.56
	Industrial combustion	0.71	0.09	0.42	0.06	0.00	0.03	0.06	0.00	0.03
	Light duty vehicles	0.31	—	—	0.71	—	—	0.71	—	—
Hebei	Power and heating plants	−0.29	−0.01	−0.18	−0.35	−0.02	−0.10	−4.09	−0.23	−0.69
	Residential combustion	0.75	0.38	0.57	0.67	0.29	0.46	0.66	0.29	0.37
	Industrial combustion	**8.57**	0.34	**2.31**	8.23	0.33	2.14	7.59	0.30	0.48
	Light duty vehicles	0.75	**1.92**	1.10	1.61	**3.39**	1.07	2.06	**0.51**	0.99
	Heavy duty vehicles-diesel	0.85	1.03	1.50	0.80	1.79	1.69	0.77	0.15	**1.89**

Note: Bold values represent the maximum S_2 of each key sector in the corresponding pollutant and indicates stronger synergetic effects.

3.2.2. Evaluation by key sectors

Higher S_2 values of NO_x in Beijing compared with Tianjin and Hebei are mainly attributed to Beijing's implementation of policies that substantially decrease the coal consumption in power and heating and residential sectors. By 2020, the two sectors will account for 38.6% and 54% of Beijing's total reduction in NO_x, and 57% and 39% of Beijing's total CO_2 reductions, respectively. In addition, for NO_x reductions, the two sectors will totally account for 39% and 29% of total NO_x reductions by 2020 for Tianjin and Hebei, respectively. For SO_2 reductions, the two sectors will totally account for 70% and 94% of total SO_2 reductions by 2020 for Tianjin and Hebei, respectively. Table 2 presents the CO_2 co-effects evaluated by S_2 in major sectors. The values in bold represent the maximum S_2 of each key sector in the corresponding pollutant, which indicates stronger synergetic effects.

The results of S_2 show that the power and heating sector has a major synergistic role in reducing

CO_2 in Beijing, which mainly due to the closure of the thermal power plants and coal-fired units in the power sector. And whether the additional external sources of electricity that Beijing traded with Inner Mongolia and Shanxi would cause their additional increase in CO_2 emissions depends on the generation structures of the electricity in the two provinces. However, the sector of residential combustion presents the highest co-effect on reducing CO_2 in Tianjin. For Hebei, the industrial combustion sector has the major synergies. The discussion in section 3.2.1 indicates that NO_x and CO_2 have high synergetic effects and therefore as a major emitter of NO_x, the transport sector may play a role in the co-effects in the BTH region. However, the data suggest otherwise. For example, in Beijing, although the NO_x emissions from the transportation sector is substantial (figure S2), the CO_2 emission reductions from the transportation sector is minimal, which yields small values of S_2.

It is worth noting that the co-benefits to both SO_2 and CO_2 from changes in power sector in Beijing is potential large, as indicated by the relatively large S_2 value in the power and heating sector. It indicates a higher reduction potential of CO_2 emissions while reducing per unit of SO_2 emission in the power and heating sector of Beijing, representing high synergies. However, for Tianjin and Hebei, it is the sector of residential combustion and industrial combustion that presents high co-effects, respectively. This is mainly due to the different intensity of policies implemented by each region under the BSPC, resulting in different reduction potential of air pollutants in different sectors and regions. The results show that under the BSPC, different sectors would have different reduction potentials (He *et al* 2018). Our results show agreement with the conclusions reached by Akimoto *et al* (2010), who showed that power sectors have high emission reduction potentials of CO_2, and the conclusions reached by Lu *et al* (2019), who showed that the industry and residential sectors will significantly produce large amounts of CO_2 reductions due to the implementation of the APPCAP. In addition, these studies are in agreement with the research results of China's CDM projects, which indicates that the coal-to-gas conversion policy in the industry enables high CO_2 reduction synergies (Nathan and Kristin 2010, Qie *et al* 2011).

4. Conclusion and policy implications

Our study demonstrates that BSPC can reduce CO_2 emissions while reducing air pollutants. These synergic results can further increase the overall benefits of the BSPC and reduce the costs for mitigating CO_2 in future. The BSPC can reduce CO_2 emissions by 20.7 Mt, 6.8 Mt, and 80.2 Mt by 2020 compared with the 2020 baseline scenario and reduce CO_2 emissions by 37.8 Mt, 4.85 Mt, and 69.9 Mt by 2030 compared to the 2030 baseline scenario in Beijing, Tianjin, and Hebei, respectively. In the BTH region, the relatively stable CO_2 emissions remained since 2015 after implementing the BSPC, suggesting that the CO_2 emission in the BTH region peaked in 2015. Therefore, it is reasonable to conclude that the relatively stable CO_2 emissions in the BTH region contribute to the peak of CO_2 emissions being achieved before 2030 in China and the CO_2 emissions from the BTH region have positive effects on controlling China's total CO_2 emissions.

Major sectors have great impacts on decreasing both air pollutants (SO_2, NO_x, and $PM_{2.5}$) and CO_2 emissions, which includes the structure optimization of energy and industry. Significant CO_2 emission reductions were observed in the residential combustion sector in each of the BTH region. Fully implementing these control policies for residential combustion were projected to reduce CO_2 emissions by 8.1 Mt, 6.4 Mt, and 46 Mt by 2020 and reduce CO_2

emissions by 15.7 Mt, 7.15 Mt, and 30.3 Mt by 2030 in Beijing, Tianjin, and Hebei, respectively. Significant CO_2 emission reductions were also presented in the power and heating sector in Beijing which is due to the closure of the thermal power plants and coal-fired units in the power sector under the BSPC.

The results of S_2 show that NO_x reduction in the BSPC has the highest co-effect with CO_2 in Beijing, Tianjin, Hebei, and BTH. The power and heating sector has a major synergistic role in reducing CO_2 in Beijing. The residential combustion presents the highest co-effects on CO_2 in Tianjin. For Hebei, the industrial combustion sector has the major synergies.

Our conclusions indicate the implementation of the BSPC, specifically the control measures in the power and heating, residential combustion, and industrial combustion sectors for Beijing, Tianjin, and Hebei, respectively, have high synergies and can simultaneously reduce CO_2 and other atmospheric emissions.

Data availability statements

All data that support the findings of this study are included within the article (and any supplementary files).

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