Energy Policy 127 (2019) 213–227

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Does China's air pollution abatement policy matter? An assessment of the Beijing-Tianjin-Hebei region based on a multi-regional CGE model

Na Li[a,b], Xiaoling Zhang[c,d], Minjun Shi[e,f,*], Geoffrey J.D. Hewings[g]

[a] School of Economics and Management, University of Chinese Academy of Sciences, No.80 Zhongguancun East Road, Beijing 100190, China
[b] Research Center on Fictitious Economy and Data Science, Chinese Academy of Sciences, No.80 Zhongguancun East Road, Beijing 100190, China
[c] Department of Public Policy, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China
[d] Shenzhen Research Institute, City University of Hong Kong, Shenzhen, China
[e] School of Public Affairs, Zhejiang University, No. 866 Yuhangtang Road, Hangzhou 310058, China
[f] School of Economics, Renmin University of China, No.59 Zhongguancun Street, Beijing 100872, China
[g] Regional Economics Applications Laboratory, University of Illinois, Urbana, IL 61801, USA

ARTICLE INFO

Keywords:
Air pollution abatement policy
$PM_{2.5}$ concentration
Cost effectiveness
Multi-regional CGE model
Beijing-Tianjin-Hebei area

ABSTRACT

This paper assesses the impact of China's air pollution abatement (APA) policies on both the economy and environment in the Beijing-Tianjin-Hebei (BTH) area, using a multi-regional energy-environment-economy computable general equilibrium (CGE) model incorporating the direct abatement expenditure of the proposed policies.

The results show that, over the entire BTH area, the policies could generate an average annual loss of 1.4% of Gross Regional Product growth in the Action Plan scenario and 2.3% in the Enhanced Action Plan scenario. Moreover, realizing the 2020 $PM_{2.5}$ BTH area concentration targets will not be possible in the Enhanced Action Plan scenario, even with a reduction in emissions of over 60% of sulfur dioxide, nitrogen oxide, and primary $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) and over 30% of VOC_S (volatile organic compounds). End-of-pipe control is identified as the most cost-effective policy for most pollutant emission reductions, and that more joint measures are needed in future to address end-of-pipe control and reductions from vehicles in Beijing and Hebei, and VOC mitigation in Hebei. Market-based policies and incentive measures also need to be enhanced, with local governments' expanding the development of environmentally friendly industry to upgrade industrial structure for economic growth.

1. Introduction

China stands at the crossroads of policy choice and assessment, having become one of the most air-polluted regions in the world and, as most developed countries experienced decades ago, paying a high resource and environmental price for its extensive economic development. Poor air quality killed an estimated 1.6 million people in China in 2013, accounting for 29% of the deaths caused by air pollution worldwide, of which ambient $PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) was a leading factor (Global Burden of Disease 2013).[1] Approximately 53% of the excess mortality in China due to $PM_{2.5}$ caused by coal consumption is experienced throughout the North China plain (Hove and Enoe, 2015), with each resident of northern China losing an average life expectancy of 5.5 years due to severe air pollution (Chen et al., 2013). The Beijing-Tianjin-Hebei (BTH) area, also in the North China plain - consisting of two municipalities (Beijing and Tianjin) and one province (Hebei) - suffers the worst air quality of all China. According to China's *Air Quality Report* in 74 Cities,[2] for example, of the 10 cities with the highest $PM_{2.5}$ concentration in March 2018, eight were located in the BTH area, with average $PM_{2.5}$ concentrations approximately 5.5–7.3 times higher than the World Health Organization (WHO) safety standards (15 $\mu g/m^3$), and the situation possibly worse in winter (Zhang and Cao, 2015).

To curb serious air pollution in the BTH area and improve public health, the Chinese government proposed its 2013 “Air Pollution

---

* Corresponding author at: School of Public Affairs, Zhejiang University, No. 866 Yuhangtang Road, Hangzhou 310058, China.
E-mail addresses: lina@ucas.ac.cn (N. Li), xiaoling.zhang@cityu.edu.hk (X. Zhang), mjshi@zju.edu.cn (M. Shi), hewings@illinois.edu (G.J.D. Hewings).

[1] http://www.healthdata.org/news-release/poor-air-quality-kills-55-million-worldwide-annually.

[2] http://www.mee.gov.cn/hjzl/dqhj/cskqzlzkyb/.

https://doi.org/10.1016/j.enpol.2018.12.019
Received 3 June 2018; Received in revised form 7 November 2018; Accepted 10 December 2018

Prevention and Control Action Plan (2013–2017)[3]" and 2016 "Enhanced measures of Air Pollution Prevention and Control in the BTH area (2016–2017)",[4] in which a series of policies and mitigation targets are specified. Local governments in this area also announced their own implementation details.[5] By 2017, compared to the 2012 level, $PM_{2.5}$ concentration in the BTH area needs to be reduced by 25% and $PM_{2.5}$ concentration should not exceed 60 $\mu g/m^3$ in Beijing and Tianjin and not more than 67 $\mu g/m^3$ in Hebei. By 2020, according to the "Ecological Environmental Plan for Coordinated Development of the BTH Area towards 2020[6]", $PM_{2.5}$ needs to be reduced by 40% in the BTH area compared to the 2013 level.

While clean air policies and regulations do matter for improving air quality, they can also bring along challenges to the social-economic system. On the one hand, as Upton (2016) asserts, local governments should curb air pollution at whatever cost since citizens' lives are invaluable. On the other, however, government intervention in the treatment of environmental pollution must consider its impact on the economy (Maloney and Yandle, 1984; Beckerman, 1992; Grossman and Krueger, 1995; Becker, 2005). The increase in air quality standards under command control policies always lead to increased costs for hitherto polluting sectors (Palmer et al., 1995; Greenstone, 2002; Chow, 1995; Rosenbaum, 2013), making policies tends to be delayed. Therefore, some form of compromise is clearly in need. Market-based methods, which can reduce direct government intervention (Haimes et al., 1977; Mendelsohn, 1980; Maloney and Yandle, 1984; Becker, 2005; Muller and Mendelsohn, 2009), can be used to achieve environmental improvement goals at a relatively low cost.

Therefore, in recognition of the futility of introducing policies that blindly compel companies to reduce emissions, it is vitally important to evaluate the impact of these different policies on both the economy and environment to provide an analytical base for policy improvements in the future (Pearce et al., 2006; Muller et al., 2011; Huo, 2016). In doing this, quantifying their costs and benefits involved is a particularly important consideration. Cost benefit analysis (CBA) has been used in ample research concerning the U.S. Clean Air Act and also studied in other countries (Freeman, 1982; U.S. EPA, 1997, 1999, 2011; Pearce et al., 2006; Revesz and Livermore, 2008; Winiwarter and Klimont, 2011). Estimating air quality improvement/emission reduction and economy-wide impact are two especially important aspects. In doing this, computable general equilibrium (CGE) models, specifying the optimal behaviors of economic agents as they interact across markets, and hybrid models based on CGE and bottom-up approaches, have been increasingly used. These analyze the effects of air pollution control on macroeconomic change and emission mitigation (Chen and He, 2014; Bollen, 2010; Rive, 2010; Vrontisi et al., 2016; Dong et al., 2015).

The impact of different air pollution mitigation measures have been analyzed in many studies, e.g., energy efficiency improvement and end-of-pipe control (Amman et al., 2008; Rive, 2010); environmental tax, energy, industrial structural adjustment, and changes in transportation mode (Bollen et al., 2010; Chen and He, 2014; Huang et al., 2012; He et al., 2016); and eliminating outdated production capacity and limiting the numbers of cars on the road (Gao et al., 2016; CAAC, 2015). Some studies have also assessed the health impact of air pollution control polices and health feedback for the whole economy (Matus et al., 2008, 2012; Nam et al., 2010). However, most do not account for the direct implementation costs of specific control measures. For the requirements of various air pollution abatement (APA) measures, the sectoral and domestic direct abatement expenditure on related abatement technologies or equipment are different, and increase the demand for the products of other industries. Unless these direct abatement costs are incorporated into the model, the evaluation of the interaction of the economic system and macroeconomic impact caused by the policies will probably be biased.

Many studies have focused on the environmental outcomes of air pollution control policies or targets in terms of $PM_{2.5}$. He et al. (2014) and Jiang et al. (2015), for example, examine the reduction of $PM_{2.5}$ and related pollutant emissions under the Air Pollution Prevention and Control Action Plan in the BTH and Pearl River Delta areas respectively; while Greenpeace (2014) simulate the required reductions in pollutant emissions to realize the 2022 target of 35 $\mu g/m^3$ of $PM_{2.5}$ concentration. However, only a few studies have assessed the economic impact of air pollution control policies on sectors, economic growth, fiscal deficit, and inflation (e.g., Ma and Li, 2014), as well as those combining economic with environmental impacts. Equally few studies have compared current $PM_{2.5}$ mitigation policies to find the most optimal and effective policies. The main reason appears to be the lack of a comprehensive framework from which to analyze the economic and environmental impacts involved.

There have also been rare studies of China's current specific APA policies, especially the enhanced measures – "Enhanced Measures of Air Pollution Prevention and Control in the BTH area (2016–2017)" – proposed in recent years in the BTH area. Moreover, although interregional economic differences and linkages within this area are also likely to have a significant effect on the outcomes of current APA policies, only a small number of studies have used a multi-regional framework involving both interregional economic differences and linkages in China.

As mentioned above, there has been little research into assessing the impact of APA policies, especially a basket of APA policies, involving 1) considering the direct expenditure/cost of emission reductions of each individual policy and the resulting influences on related sectors and the whole economy; 2) assessing simultaneously the economy and environmental effects as well as regional and sectoral effects; 3) incorporating interregional economic relations into assessment models to estimate the policy impact considering interregional interaction; 4) studying the economy-wide costs of different kinds of APA policies to identify the most effective types of measures.

This paper aims to assess the impact of China's current APA policies in the BTH area by 2020 to fill these gaps and contribute to the literature. Using a multi-regional economy-energy-environmental CGE model combining both interregional economic differences and linkages, the study incorporates the likely abatement expenditure/costs resulting from potential policies together with the consequential increase in demands for the products of other industries. It also assesses both the economy and environment, the regional and sectoral impacts of these policies, and the economy-wide costs of different kinds of policies. Attention is therefore directed to three major questions: (1) How significant will be the likely impact of these policies on different regional economic growth within the BTH area? (2) How much can pollutant emissions be reduced by these policies and can the proposed $PM_{2.5}$ concentration targets be achieved? and (3) What policies are the most cost-effective and how should these be modified in the future?

2. Methodology and data

2.1. The dynamic multi-regional energy-environment-economy CGE model

The dynamic multi-regional energy-environment-economy CGE model used here is built on the basic structure developed by Lofgren et al. (2002), and the energy (including electricity) and emission

---

[3] http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm.

[4] http://huanbao.bjx.com.cn/news/20160707/749105.shtml.

[5] http://www.mee.gov.cn/gkml/hbb/bwj/201309/W020130918412886411956.pdf http://www.mee.gov.cn/home/ztbd/rdzl/dqst/mbzrs/201401/P020140127516560167960.pdf.

[6] http://huanbao.bjx.com.cn/news/20160104/697490.shtml.

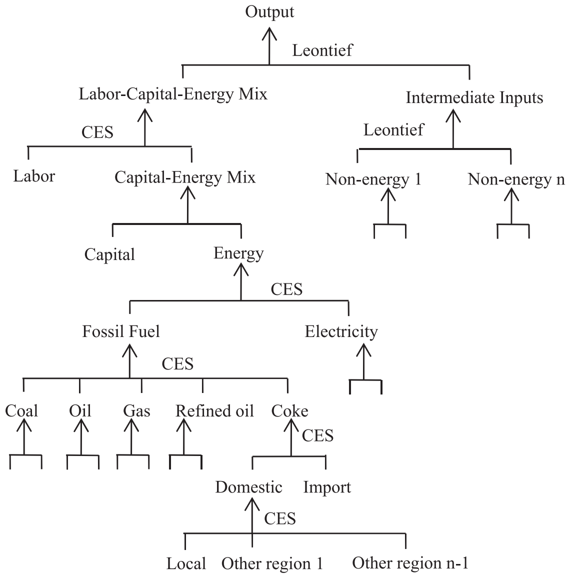


Fig. 1. Basic production structure in the CGE model.

modules developed by Wu and Xuan (2002) and Paltsev et al. (2005). It is developed in two aspects: 1) the economic linkages across regions, including interregional commodity trade, labor, and capital allocation mechanisms is added Li et al. (2015); and 2) the direct abatement costs of polices are incorporated into the model (see Section 2.2).

This model covers 4 regions (Beijing, Tianjin, Hebei, and the rest of China), 17 sectors (see Appendix Tables A.1), 3 production factors (labor, capital, and energy) and 4 emission sources (primary $PM_{2.5}$ and the three precursors of $PM_{2.5}$: sulfur dioxide (SO_2), nitrogen oxide (NO_X) and volatile organic compounds (VOC_S). The economic agents in the model optimize their objective functions (profit for enterprises, and utility for households and governments) and decide separately the supply/demand of/for production factors and other goods.

Production is described by a multi-level nested structure, since the elasticity of substitution varies between different inputs (Fig. 1). Intermediate commodities are entered into the model with a Leontief structure to reflect the assumption of no substitution between different intermediate commodities, as well as between the intermediate commodities' bundle and factors' bundle (comprising a labor bundle and a capital-energy bundle). The non-substitution Leontief structure is used because the parameters are fixed in the short run, as the substitution between them is assumed very weak. Energy is embedded into the model with a multi-level nested structure: an electricity bundle, and a fossil fuel bundle (comprising coal, crude oil, natural gas, refined oil, and coke). A constant elasticity of substitution (CES) function is adopted to describe the substitution relationship between these energy inputs. It should be noted that coal, natural gas, and crude oil are raw materials or intermediate inputs (not production factors) for coking and coal-fired power generation, natural gas power generation, and refined petroleum and oil-fired power generation, respectively. The raw materials are difficult to substitute with other intermediate inputs and production factors. Hence, the Leontief structure is used to describe the relationship between them and other inputs. In the electricity sector, electric power generation is divided into two types: renewable power and thermal power (including coal-fired, oil-fired, and natural gas power generation). These two types of power are assumed perfectly substitutable. Technological improvements, including total factor productivity (TFP) growth and autonomous energy efficiency improvements (AEEI) are explicitly represented in the production functions. Emissions are estimated in two ways. Energy emissions are obtained by multiplying each type of fossil fuel consumption by its emission factor, while emissions from industrial processes are calculated by multiplying each sector's output by its emissions per unit of output.

Household income is used for tax payments, consumption, and saving, while government income is expended on transfer payments, subsidies, consumption, and saving. Household and government consumption are co-determined by income and consumption preferences and described by an extended linear expenditure system (ELES) and a Cobb-Douglas function respectively. The demand of commodities for investment is expressed by a Leontief function. The Armington assumption (Armington, 1969) is used to distinguish between domestic goods and imported (exported) goods. The demand for imports (or exports) is determined by domestic sales and the relative price of domestic sales to international sales.

The optimal behaviors of all the economic agents (producers, households, government, importers, exporters, etc.) are specified according to each region's characteristics that reflect regional economic differences.

This model also specifies the economic linkages across regions, including interregional commodity trade, labor, and capital allocation mechanisms, which can facilitate the assessment of policy impacts considering interregional interaction. For commodity trade across regions, goods produced from different regions are presumed to be imperfectly substitutable, using a CES function to describe this characteristic. Labor is imperfectly mobile across regions. Given the national employment population, labor forces in different regions are determined by the national average wage and a regional wage distortion factor. Capital is mobile across regions according to the relative ratio of investment returns and capital price. The tax rates levied by governments are exogenous, whereas government savings are endogenous. In addition, the exchange rate is exogenous, while the international trade surplus is endogenous. Finally, total national investment is driven by total national savings from households, governments, enterprises, and abroad.

The model is recursively dynamic and the simulation period is from 2007 to 2020. Regional economic growth over time is realized via capital accumulation, labor growth, and technological improvement. The accumulation of capital over time in each sector accrues by adding net investment to the capital stock in each time period. The national labor force changes exogenously, assuming a constant proportion of effective labor force to total population and fixed regional wage distortion parameters over the simulation period (assuming wage differences between regions do not change in a short time), and regional labor forces change accordingly. TFP growth and AEEI that reflect technology improvements are set to be exogenous in each time period (see Section 2.3).

2.2. Modeling abatement costs

Current APA policies are divided into four major categories: structural adjustment, end-of-pipe control, reduction from vehicles, and VOC mitigation. *Structural adjustment* involves energy and industrial structural adjustment, including coal reduction, production capacity reduction, increasing gas supply, as well as the switch, upgrade, or shut down of industrial boilers and kilns. *End-of-pipe control* includes the desulfurization, denitration, and upgrading dust collectors in coal-fired power and heating plants, desulfurization and upgrading dust collectors in coal-fired industrial boilers and the steel and cement industries, low-nitrogen transformation in gas-fired boilers, ultra-low emission transformation in coal-fired generating units, and environmental control and transformation in the steel industry. *Reduction from vehicles* includes eliminating yellow-sticker and old vehicles, improving fuel quality, raising emission standards, and promoting the use of new energy vehicles. *VOC mitigation* measures include controlling VOC emissions from key industries, vapor recovery, and promoting environmentally friendly paints and solvents.

The commonly used method to incorporate abatement costs in a CGE framework is to impose an exogenous constraint on emissions to generate a shadow cost or to introduce a tax on the production cost of the emitting agents that would cause economic agents to reduce emission levels. An alternative formulation would be the explicit incorporation of the emissions and marginal (or total) abatement costs in the model (Vrontisi et al., 2016). In this model, we combine and apply these two approaches according to the categories of current APA policies.

For the measures of end-of-pipe control, reduction from vehicles, and VOC mitigation, and specific structural adjustment-switch, upgrade, or shut down of industrial boilers and kilns, we use the second approach to incorporate their abatement expenditure (or investment) and direct reduction of pollutant emissions into the model.

Following Vrontisi et al. (2016), the abatement expenditure per sector due to these measures is added as a necessary intermediate input to the unit cost of production, which does not create additional capital stock in the economy. The abatement expenditure of firms and households creates a sector product demand that mainly comprises the manufacture of machinery and electronics, the construction and chemical industry, providing abatement equipment, technologies, or other inputs. Therefore, abatement expenditure can have a different impact on different sectors.

For the measures of reducing coal consumption and certain sectors’ outputs, we use the first approach, in which a shadow cost (or an implicit tax) is designed to meet the exogenous constraint of associated levels of coal consumption or outputs. In this way, pollutant emissions can be reduced by the substitution of fuels or energy for other production factors that can reduce energy-related emissions, and by a fall in production due to the increased cost of production.

2.3. Input and output of the model

The *input* of the CGE model comprises the input for the basic model and the input for scenarios. The former includes information of the current economic system and energy-environmental situation, specifically including the interregional input-output table for China, energy consumption and emissions data (emission inventory), and such other information as tax, payment, flow of funds, investment and population.

The inputs are different for different scenarios. The CGE analysis compares policy scenarios with a baseline scenario to assess the impact of APA polices by the change in key variables. The baseline scenario describes how the economy could develop towards 2020, which involves assumptions of the main drivers of economic growth, such as population change and technical improvement, and the influences of already adopted policies. These parameters are inputs for baseline scenarios as well as for policy scenarios, for they do not change in all scenarios. The additional inputs for policy scenarios are the change in variables related to APA policies, which include abatement expenditure, emission factor, and the outputs of certain sectors.

The *output* of the CGE model comprises Gross Regional Product (GRP) by region, output by sector by region, emission reduction by pollutant by policy by region, economy-wide cost by policy by region, and such other results as energy consumption and sector price.

The CGE simulation results can provide the emission reduction rates from local production. In addition to locally produced emissions, regional transport from surrounding area also influences the $PM_{2.5}$ concentrations of a specific area. To include the interregional emission transfer effect, based on CGE simulation results, the emission reduction rates with spatial transfer effect (ER_T) can be calculated as

Table 1
Contribution of interregional emission transfer in the BTH area (%).
Source: Xue et al. (2014).

Regional source	Beijing	Tianjin	Hebei
Beijing	63	5	5
Tianjin	4	58	5
Hebei	24	26	64
Shanxi, Inner Mongolia, Shandong, Henan, etc.	9	11	26
Total interregional emission transfer	37	42	36
Total	100	100	100

$$ER_T = ER_{loca} * (1 - \alpha) + ER_{surr} * \alpha \tag{1}$$

where ER_{loca} and ER_{surr} denote the local and average emission reduction rates respectively of surrounding area, while α denotes the contribution ratio of interregional emission transfer, retrieved from Xue et al. (2014) and presented in Table 1. It is assumed that the interregional transfer pattern of $PM_{2.5}$ precursors share the same pattern as the interregional transfer pattern of $PM_{2.5}$ itself. The ER_{surr} of the BTH area is estimated using Hebei's individual pollutant's emission reduction rate multiplied by the ratio of the $PM_{2.5}$ concentration reduction targets in the BTH surrounding area and Hebei. The average $PM_{2.5}$ concentration reduction target in the BTH surrounding area is assumed 15%.[7]

2.4. Data

The basic dataset of the model is Shi and Zhang's (2012) 2007interregional input-output table of 55 sectors of China's 30 regions. These are merged into 4 regions and 17 sectors according to the National Economic Industries (GB/T4754-2011) classification system. Customs, tax, international balance of payment, flow of funds, and fixed assets investment are obtained from the China Statistical Yearbook (NBSC, 2008a), Finance Yearbook of China (FYCCC, 2008), and China Customs Statistics Yearbook (NEPRC, 2008). The parameters for the substitution elasticities of production factors are taken from Wu and Xuan (2002) and Li et al. (2015). The values for the substitution elasticities between regional commodities are set to be two times those between import and domestic commodities. The latter is taken from the GTAP (Global Trade Analysis Project) 9 Database.[8]

Because thermal power and renewable power are not separated in the input-output table, the electric sector needs to be split according to these two power ratios in different regions in the China Energy Statistical Year Book (NBSC, 2008b). Their power generation costs are obtained from the IEA (2005, 2007) and Paltsev et al. (2005). The energy consumption data are from the Energy Balance Sheet in the China Energy Statistical Year Book (NBSC, 2008b), and the emissions

---

[7] No policy simulation and emission inventory is established for the BTH surrounding area of Shanxi, inner Mongolia, Shandong and Henan provinces, etc. Therefore, no information is directly provided of the average emission reduction rate of this surrounding area as a whole. It is estimated by using Hebei's individual pollutant emission reduction rate multiplied by the ratio of the $PM_{2.5}$ concentration reduction targets in the BTH surrounding area and Hebei. In the Air Pollution Prevention and Control Action Plan, the $PM_{2.5}$ concentration reduction target in Hebei, Shanxi, inner Mongolia, and Shandong provinces is set separately at 25%, 20%, 20%, and 10%, while no quantitative target specified for Henan province. Therefore, we choose 15% as the average $PM_{2.5}$ concentration reduction target for the whole BTH surrounding area.

[8] https://www.gtap.agecon.purdue.edu/databases/default.asp.

Table 2
Scenario settings.

Scenarios	Description
Baseline scenario	During 2013–2020, GRP grows and energy intensities reduce (in all regions), based on the local governments' goals in the "12th Five-year plans" (2010–2015) and "13th Five-year plans" (2016–2020) respectively.
Action Plan (AP) scenario	From 2013, the "Air Pollution Prevention and Control Action Plan" and its detailed rules are implemented in the BTH area. After 2017, they continue to be implemented until 2020.
Enhanced Action Plan (EAP) scenario	Based on the AP scenario, from 2016, the "Enhanced measures of Air Pollution Prevention and Control in the BTH area" are carried out until 2020.

Table 3
Regional economic impact of APA policies (%).

% change from baseline			GRP	Income	Cons	Inve	Exports	Imports	Net outflows
2017	AP scenario	BTH	−4.8	−2.54	−2.9	−0.21	−5.2	2.6	−594.4
		Beijing	−4.6	−3.50	−3.6	−0.11	1.6	5.4	−9.7
		Tianjin	−4.1	−3.39	−3.2	−0.16	−4.1	4.4	−9.1
		Hebei	−5.1	−2.57	−2.2	−0.29	−22.9	−11.1	−127.5
		ROC	−0.1	0.41	−0.3	0.01	0.4	4.0	594.4
	EAP scenario	BTH	−8.4	−4.58	−5.0	−0.36	−6.4	2.4	−554.5
		Beijing	−9.7	−6.46	−6.2	−0.19	1.4	6.1	−32.9
		Tianjin	−6.9	−5.85	−5.0	−0.26	−4.6	4.0	−13.0
		Hebei	−8.5	−3.83	−3.9	−0.51	−28.1	−12.7	−205.5
		ROC	0.1	0.45	−0.1	0.00	0.5	4.1	554.5
2020	AP scenario	BTH	−10.2	−5.92	−5.0	−0.49	−8.8	15.8	−856.3
		Beijing	−9.8	−4.85	−3.7	−0.16	3.1	19.5	−42.2
		Tianjin	−6.7	−6.28	−4.9	−0.22	−10.0	21.7	−22.8
		Hebei	−11.7	−7.26	−6.2	−0.84	−34.1	−8.7	−155.5
		ROC	−0.3	0.65	−0.2	0.01	0.7	13.7	856.3
	EAP scenario	BTH	−16.0	−8.45	−6.9	−0.68	−11.5	17.7	−780.1
		Beijing	−18.2	−7.87	−6.4	−0.27	4.4	23.2	−73.8
		Tianjin	−11.1	−8.43	−6.7	−0.29	−13.9	22.7	−40.3
		Hebei	−17.0	−9.57	−7.4	−1.00	−45.6	−8.7	−252.7
		ROC	0.0	0.79	0.3	0.02	0.9	14.4	780.1

Note: BTH represents the whole BTH area. Cons and Inve denote consumption and investment respectively.Net outflows denotes the exports to other domestic regions minus imports from other domestic regions.

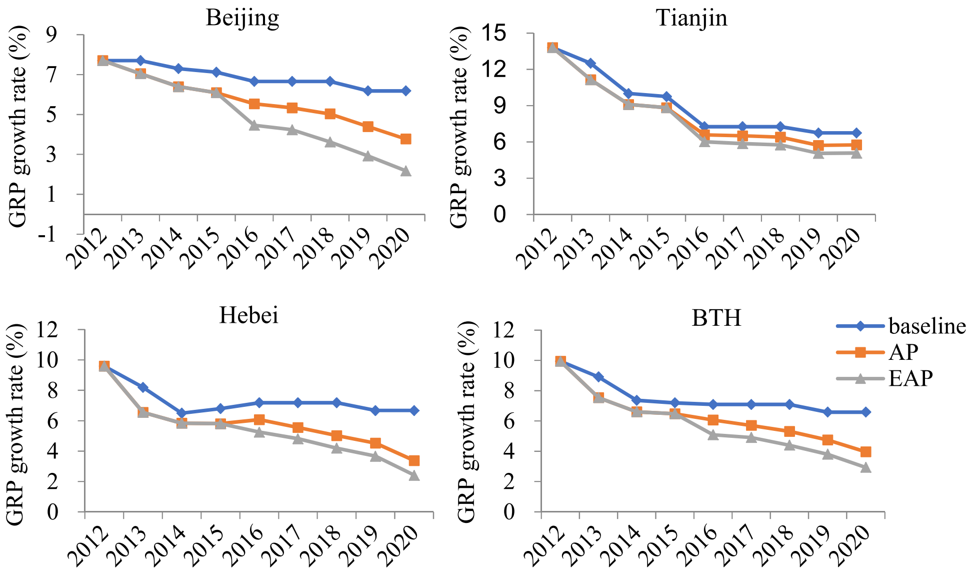


Fig. 2. GRP growth rates (%) in different scenarios.

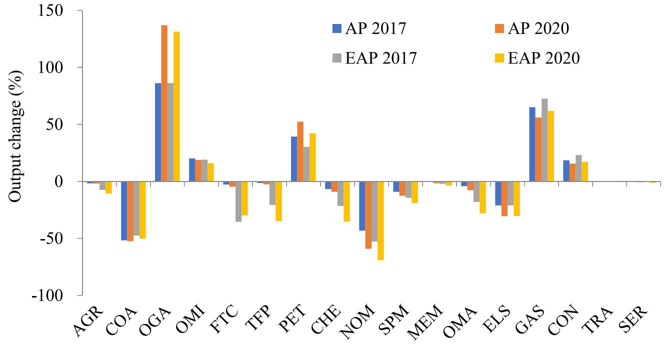


Fig. 3. Sectoral output changes in the AP and EAP scenarios compared to baseline scenarios.

data are from Tsinghua University's MEIC[9] (multi-resolution emission inventory for China). The data for the direct reduction and abatement expenditure of policies are calculated based on statistical data, policy plans, and research by CAAC (2015) and He et al. (2014) (Appendix Tables A.2–A.4).

The data for the employed population and GRP growth are set based on the historical records for 2007–2012 and the growth trends for 2013–2020. The AEEIs are set according to the AIM (Asia-Pacific Integrated Model) provided by the Energy Research Institute (ERI) of China, and the "Medium- and Long-term Energy Conservation Plan" (www.ndrc.gov.cn). The TFPs are calibrated according to GRP growth, which are set in a baseline scenario based on the historical records for 2007–2012 and the local government economic growth goals in the "12th Five-year plans" for 2013–2015 and "13th Five-year plans" for 2016–2020.[10]

3. Scenarios

Three scenarios are designed in this research: the Baseline, Action Plan, and Enhanced Action Plan scenarios. The *Baseline* scenario is a simulation of economic development towards 2020 considering certain economic growth and energy intensity reduction without additional air pollution mitigation policies. The *Action Plan* (AP) and *Enhanced Action Plan* (EAP) scenarios are policy scenarios in which Air Pollution Prevention and the Control Action Plan and Enhanced measures are carried out. The setting of these scenarios are detailed in Table 2. The specific AP and EAP policies are shown in Appendix Tables A.2 and A.3 respectively.

4. Results and discussion

4.1. Economic impact of APA policies

Table 3 presents the regional economic impact of APA policies compared to the baseline scenario. The BTH GRP decreases by 4.8% and 10.2% for 2017 and 2020 respectively in the AP scenario. With the implementation of the enhanced policies, the magnitude of the abatement policy shock increases further and the BTH GRP has an overall decrease of 8.4% and 16% by 2017 and 2020 respectively in the EAP scenario. The simulated BTH GRP growth rates by 2020 are described in Fig. 2. The decline in GRP growth rates in Beijing and Hebei are larger than Tianjin due to the policies' focus in the former regions being higher than the latter region. The average annual loss of GRP growth rates during 2013–2020 in Beijing, Tianjin, Hebei, and BTH are 1.4%, 0.9%, 1.7%, and 1.4% respectively in the AP scenario, and 2.6%, 1.6%, 2.5%, and 2.3% respectively in the EAP scenario. By 2020, the GRP growth rates in different BTH regions will be around 3.4–5.8% in the AP scenario and 2.2–5.1% in the EAP scenario respectively, while they will be 6.2–6.7% in the baseline scenario.

The decreases in GRP in the AP and EAP scenarios may be traced to a deterioration of international and interregional trade balance and a decline in household consumption (Table 3). In particular, there is a large increase in Beijing and Tianjin imports, a large decrease in Hebei exports, and a significant fall in net outflows (exports to other domestic regions minus imports from other domestic regions) for all BTH. This is due to the higher production costs and prices of the goods produced by the abating sectors and a (comparatively) lower price of the goods produced by international and other domestic producers compared to the baseline. Household consumption declines because of the increased prices of goods and services and the loss of disposable income to satisfy the required abatement expenditure caused by substituting coal for gas or electricity. The rest of China (ROC) impact on the GRP is small and even better by 2020, with net outflows increasing because of ROC not implementing APA policies.

The impact varies significantly across different sectors according to their air pollution emissions, energy use structure, abatement requirement, and cost. As Fig. 3 illustrates, many sector outputs decline as the APA policies are implemented. The most negatively affected sectors are coal mining, manufacture of non-metallic mineral products, electricity and steam supply, chemical industry, smelting, and metal pressing. In the EAP scenario, for example, the output reductions in these sectors are around 19–69% by 2020. Most of these are energy-intensive or emission-intensive (except coal mining) and have a higher abatement cost to reduce coal use and increase other cleaner energy use by buying abatement equipment or technology, resulting in significant output reductions in these sectors. Reduction in coal demand leads to a substantial decrease in coal mining output. In addition, in the EAP scenario, the outputs in the manufacture of food, textile and leather, timber, furniture and paper and other manufacture sectors drop significantly because of the strengthened policies for more polluting sectors. On the other hand, there are also some "better-off" sectors. The increase in the outputs of oil and natural gas extraction, gas supply, petroleum processing and coking, is generated by the policy requirement to increase the gas supply and decrease coal consumption, and the substitution of coal by other energy inputs. The outputs of other mining and quarrying and construction increase mainly because of less shock on themselves and obtaining released capital and labor resources from the sectors with a decrease in production. There are few changes in the outputs of the service and transportation sectors. Industrial structure will upgrade to some degree because of the decline of the outputs of many energy-intensive and emission-intensive sectors caused by these policies.

The impact of these policies on the economy is the price to pay for reducing air pollution and is so big that it may become the largest of all environment policies ever been adopted in China; it also demonstrates the Chinese government's strong determination to upgrade economic structure to control air pollution.

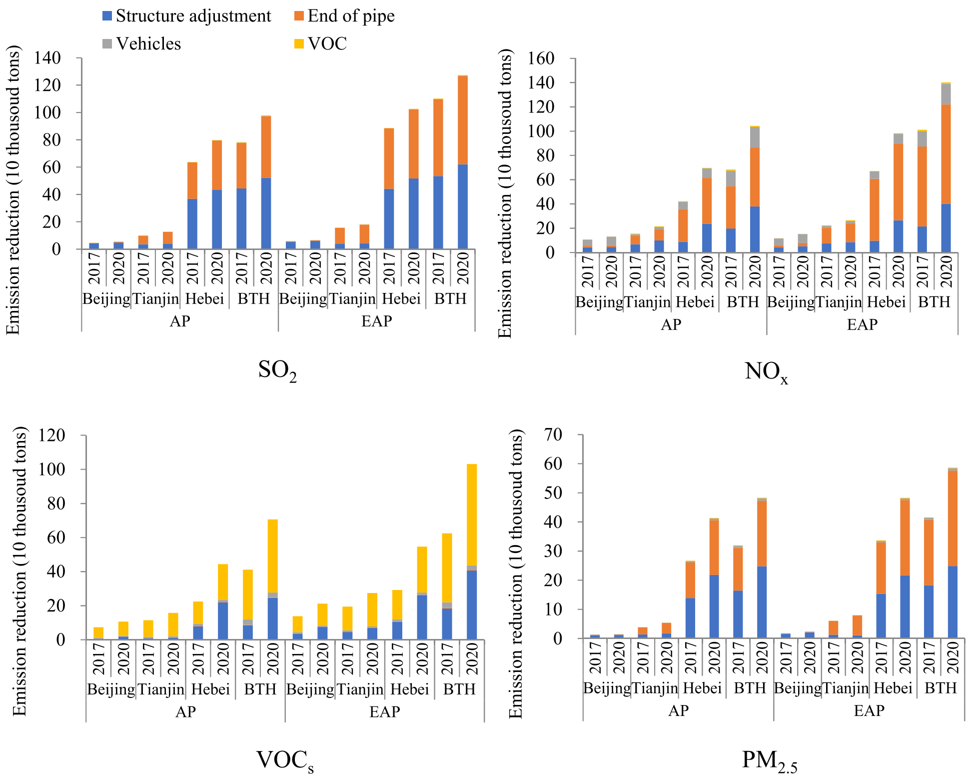
4.2. Emission reduction impact of APA policies

Fig. 4 shows the significant emission reductions caused by APA policies. The BTH SO_2, NO_X, VOC_S, and primary $PM_{2.5}$ emissions by 2020 can be reduced by 978, 1044, 706, and 483 thousand tons respectively in the AP scenario, which corresponds to a decrease of 54.7%, 42.7%, 20.9%, and 44.8% respectively compared to the baseline level. These emissions decrease by 1273, 1401, 1032, and 586 thousand tons respectively in the EAP scenario, with a fall of 68.8%, 54.4%, 36%, and 53.7% respectively compared to the baseline scenario. The policies in the AP scenario focus more on reducing coal consumption – the main

---

[9] www.meicmodel.org.

[10] Generally, the economic growth rates used in the baseline scenario should be ones not affected by the policies studied. Therefore, instead of real economic growth rates, local government economic growth goals that are set before the implementation of air pollution abatement policies are chosen in the baseline scenario.



SO_2

NO_x

VOC_s

$PM_{2.5}$

Fig. 4. SO_2, NO_X, VOC_S, and primary $PM_{2.5}$ emission reductions compared to baseline scenarios.

Table 4
Reduction rates of pollutant emissions and their reduction targets to realize $PM_{2.5}$ concentration targets compared to the 2012 level (%).

With(out) spatial transfer effect	Year	Emissions	AP scenario				EAP scenario				Targets
			Beijing	Tianjin	Hebei	BTH	Beijing	Tianjin	Hebei	BTH	
Without spatial transfer effect	2017	SO_2	42.1	42.4	43.5	43.3	51.9	63.8	58.3	58.6	40
		NO_X	39.7	41.1	24.7	28.6	42.5	56.7	35.6	39.3	40
		$PM_{2.5}$	30.6	36.2	28.6	29.5	36.2	54.6	35.8	37.8	35
		VOC_S	16.4	16.6	6.7	10.1	34.8	36.8	11.4	20	30
	2020	SO_2	50.9	53.3	55.2	54.7	60.3	73.7	68.7	68.8	64
		NO_X	49.9	57	38.9	42.7	56.7	68.4	51.3	54.3	64
		$PM_{2.5}$	37.8	49.1	44.8	44.8	48.3	70.3	52	53.7	56
		VOC_S	23.9	23.9	19.3	20.9	53.4	53	26.7	36	48
With spatial transfer effect	2017	SO_2	41.0	40.9	38.9	39.2	52.4	58.6	52.2	53.0	40
		NO_X	33.9	33.9	23.7	26.2	39.5	46.6	33.3	35.9	40
		$PM_{2.5}$	29.1	31.8	26.1	26.9	35.5	45.1	33.0	34.4	35
		VOC_S	13.0	12.6	7.0	9.0	26.7	26.8	12.7	17.6	30
	2020	SO_2	50.4	51.5	49.1	49.5	61.1	68.2	61.4	62.3	64
		NO_X	45.2	48.2	36.3	39.0	53.5	59.2	47.1	48.7	64
		$PM_{2.5}$	38.9	45.0	40.0	40.5	48.5	60.1	47.3	48.7	56
		VOC_S	21.7	21.3	17.8	19.1	43.6	42.1	26.6	32.2	48

Note: the reduction target data in the last column of 2017 refers to He et al.'s (2014) research based on an air quality model to realize the targets proposed in the "the Air Pollution Prevention and Control Action Plan (2013–2017)". Based on this, the 2020 data are calculated according to the concentration reduction target of 40% in 2020 proposed in "the Ecological Environmental Plan for Coordinated Development of Beijing-Tianjin-Hebei Area".

source of SO_2 emissions – so these policies generate a greater reduction in SO_2 emissions. Under the EAP scenario, with more policies focusing on VOC_S emission abatement, VOC_S emissions can be reduced by an additional 15.1% compared to the AP scenario, which is higher than the additional reduction rate of other emissions. However, the overall reduction rate of VOC_S emissions is still less than other emission reductions.

The mitigation contributions differ between different regions and policies (Fig. 4). Within the emissions reduction of SO_2 and primary $PM_{2.5}$, the contributions of structural adjustment and end-of-pipe control measures account for an equal amount in Hebei and the BTH entire, whereas there is a greater contribution from structural adjustment in Beijing and more contribution from end-of-pipe control in Tianjin. As for NO_X, the reduction from vehicles contributes over 50% of the overall reduction of NO_X emissions in Beijing because the transportation sector is the largest emission source - accounting for 38% of its total NO_X emissions in 2012. By contrast, Tianjin and Hebei are more dependent on structural adjustment and end-of-pipe control measures to reduce NO_X emissions because their electricity and steam supply sector is the largest emission source in these regions. The VOC_S emission mitigation is the main contributor to the reduction of VOC_S emissions, but other policy measures (especially structural adjustment

Table 5

Average economy-wide costs of different policies per ton of reduced emissions (CNY 10,000).

Region	Policy	AP scenario				EAP scenario			
		SO_2	NO_X	VOC_S	$PM_{2.5}$	SO_2	NO_X	VOC_S	$PM_{2.5}$
Beijing	Total	355.8	145.7	179.8	1266.1	538.2	232.4	167.3	1489.6
	Struct adjust	378.7	413.8	331.0	1511.4	567.3	666.3	453.7	1652.2
	End of pipe	0.2	0.1	368.3	1.3	40.7	7.2	511.4	217.4
	Vehicles		8.1	88.2	288.2		9.7	106.4	344.8
	VOC			2.0				1.3	
Tianjin	Total	99.6	58.4	80.2	231.9	115.6	78.7	76.5	261.7
	Struct adjust	286.0	116.1	1021.1	655.0	452.2	232.0	285.4	1792.0
	End of pipe	7.2	6.5	867.3	16.9	4.8	4.2	875.9	9.6
	Vehicles		11.2	26.6	407.8		11.4	27.0	411.8
	VOC			2.4				1.8	
Hebei	Total	77.2	88.3	138.8	148.8	87.3	91.2	163.9	185.7
	Struct adjust	133.7	244.5	264.5	264.7	165.8	323.4	327.9	394.7
	End of pipe	6.9	6.7	1016.6	13.4	5.4	4.3	1012.4	10.5
	Vehicles		7.2	44.3	100.4		7.2	44.2	99.9
	VOC			3.1				2.4	
BTH	Total	95.3	89.3	131.9	192.9	114.6	104.2	141.4	249.0
	Struct adjust	168.1	230.9	356.0	353.0	225.0	348.1	344.1	561.5
	End of pipe	6.9	6.4	993.0	13.9	5.5	4.4	934.6	10.9
	Vehicles		8.0	49.7	164.6		8.7	54.3	179.3
	VOC			2.6				2.0	

Note: ‘Struct adjust’ denotes Structural adjustment.

Table 6

Effect of changes in parameter values on the change in GRP and emissions in the 2020 EAP scenario (%).

Changes in parameter values	Regions	Change in GRP	Change in emissions			
			SO_2	NO_X	VOC_S	$PM_{2.5}$
TFP growth increase by 20%	Beijing	2.82	0.07	1.04	1.02	0.03
	Tianjin	2.38	0.39	1.16	1.67	0.31
	Hebei	1.88	0.30	0.37	1.34	0.49
	BTH	2.19	0.30	0.52	1.35	0.43
TFP growth decrease by 20%	Beijing	− 3.43	− 0.37	− 0.89	− 1.04	− 0.09
	Tianjin	− 2.80	− 0.47	− 0.75	− 1.34	− 1.11
	Hebei	− 1.91	− 0.46	− 1.07	− 1.56	− 0.78
	BTH	− 2.43	− 0.45	− 1.02	− 1.44	− 0.75
AEEI increase by 20%	Beijing	0.06	− 0.62	− 0.80	− 1.01	− 0.98
	Tianjin	0.18	− 0.58	− 0.61	− 1.70	− 0.82
	Hebei	0.38	− 0.07	− 0.40	− 0.85	− 0.91
	BTH	0.29	− 0.20	− 0.52	− 0.93	− 0.78
AEEI decrease by 20%	Beijing	− 0.32	0.55	0.61	1.29	1.67
	Tianjin	− 0.22	0.70	0.62	1.36	0.17
	Hebei	− 0.57	0.11	0.49	0.65	1.03
	BTH	− 0.44	0.22	0.58	0.88	1.05
Substitution elasticities increase by 20%	Beijing	0.01	0.21	0.27	0.34	0.33
	Tianjin	0.04	0.19	0.20	0.57	0.27
	Hebei	0.08	0.02	0.13	0.28	0.30
	BTH	0.06	0.07	0.17	0.31	0.26
Substitution elasticities decrease by 20%	Beijing	− 0.06	− 0.18	− 0.20	− 0.43	− 0.56
	Tianjin	− 0.04	− 0.23	− 0.21	− 0.45	− 0.06
	Hebei	− 0.11	− 0.04	− 0.16	− 0.22	− 0.34
	BTH	− 0.09	− 0.07	− 0.19	− 0.29	− 0.35

and reduction from vehicles) also provide additional abatement benefits through reduced energy use and production of emission-intensive sectors.

Can these emission reductions realize the government's $PM_{2.5}$ concentration targets? He et al.’s (2014) simulation of an air quality model[11] shows that, if the targets proposed in the “the Air Pollution Prevention and Control Action Plan (2013–2017)” of a reduction of 25% of BTH $PM_{2.5}$ concentration compared to the 2012 level and not more than 60 μg/m^3 by 2017 in Beijing can be realized, SO_2, NO_X, VOC_S, and primary $PM_{2.5}$ need to be reduced by 40%, 40%, 30%, and 35% respectively by 2017. According to this, if the $PM_{2.5}$ concentration reduction target of 40% by 2020 proposed in “the Ecological Environmental Plan for Coordinated Development of BTH Area” can be realized, it can be estimated that SO_2, NO_X, VOC_S, and primary $PM_{2.5}$ need to be reduced by 64%, 64%, 48%, and 56% respectively by 2020. Comparing the reduction rates of pollutant emissions caused by the policies (considering only local emissions reduction and not emission spatial transfer) and their reduction targets (as shown in Table 4), indicates that under the AP scenario, only the 2017 SO_2 BTH emissions reduction target can be realized, while the primary 2017$PM_{2.5}$ BTH emissions reduction target can be further realized under the EAP scenario. The reduction rates of NO_X and VOC_S emissions in Hebei are much lower, even in the EAP scenario, which means the entire BTH reduction targets of NO_X and VOC_S emissions cannot be reached. In 2020, under the AP scenario, none of the 2020 BTH four emissions reduction targets can be realized, and only the 2020 BTH SO_2 emissions reduction target the can be reached under the EAP scenario because of the insufficient reduction in NO_X, VOC_S, and primary $PM_{2.5}$ emissions in Hebei, and NO_X and primary $PM_{2.5}$ emissions in Beijing.

Most of the emission reduction rates *with* a spatial transfer effect are much lower than those *without* spatial transfer effect (as shown in Table 4). In 2017, only the BTH SO_2 emission reduction target the can be realized under the EAP scenario, while in 2020, none of the reduction targets of four BTH emissions can be realized even in the EAP scenario. Therefore, considering the interregional emission transfer effect, it is harder for BTH to reach its related reduction targets if the reduction rates in surrounding area are small. However, the interregional emission transfer effect does not change the structure of BTH's

---

[11] This is called CMAQ (Community Multiscale Air Quality), a powerful computational tool used for air quality management, developed by EPA (US Environmental Protection Agency). The CMAQ modeling system links meteorological models, emissions models, and an air chemistry-transport model, allowing users to use it for predicting the fate and transport of multiple air pollutants (including ozone, particulate matter, and a variety of air toxics) and for generating air quality estimates for communities, states, and regions.

emission reductions. Hebei's emission reduction rate is still the lowest and Tianjin's is still the highest.

4.3. The economy-wide cost of different kinds of emission reduction policies

The cost of different kinds of emission reduction policies analyzed in this section is the economy-wide cost. This includes both direct expenditure cost in abatement industries and the resulting indirect economic cost for other industries and households. For the costs of different policies for various emission reduction to be comparable, the average economy-wide costs of the unit-reduced emissions of different policies are calculated in Table 5.

Cost-effective policies are defined here as those with lower economy-wide cost of unit emission reduction. For each pollutant (except VOC_S), the structural adjustment policy's average economy-wide cost per ton of reduced emissions is much higher than the end-of-pipe control policy in both policy scenarios; hence, the current structural adjustment policy is *not* cost-effective. Although the end-of-pipe control policy involves the increased investment expenditure of abatement sectors, it also increases direct demand for the products of some industries (including machinery and electronics manufacture, and construction), with the resulting indirect demand for the products of other industries leading to a relatively small final economy-wide cost of abatement. End-of-pipe control is therefore a more preferable, cost-effective policy; a structural adjustment policy – especially involving a substantial reduction in the manufacture of non-metallic mineral products, and smelting and pressing metals – has a very high direct and indirect cost, while indirect demand/benefit for other sectors is rare, resulting in higher average economy-wide costs.

The policy of reduction of emissions from vehicles is also relatively cost-effective for NO_X emission mitigation; the average economy-wide costs for this reduction in all regions are a little higher than end-of-pipe control but much lower than structural adjustment in both policy scenarios. Therefore, more measures of end-of-pipe control and reduction from vehicles could be adopted in the future to reduce emissions to realize the $PM_{2.5}$ concentration targets. For VOC_S emission reduction, the policy of VOC emission mitigation is the most cost-effective (although other policies can reduce VOC_S emissions to some extent) and its average economy-wide cost is very low, which offers a greater possibility of reducing VOC_S emissions in the future.

5. Sensitivity analysis

Three key parameters/assumptions are manipulated to test the sensitivity of the simulation results. First, is a higher and a lower (± 20%) TFP growth change in the EAP scenario, the policy scenario with largest shock, since GRP growth is an important driver of energy consumption and pollutant emissions. Second, since energy efficiency improvements contribute substantially to reducing pollutant emissions, a higher and a lower change (± 20%) in energy efficiency (AEEIs) is also considered. Finally, the substitution elasticities between capital and energy and among fossil fuels are varied (± 20%) as their empirical estimates vary substantially.

Table 6 displays the effect of changes in key assumptions on GRP and pollutant emissions in the 2020 EAP scenario. Unsurprisingly, the TFP growths change has a significant effect on GRP and consequently impacts pollutant emissions. The change in AEEIs also has an influence on pollutant emissions, but the impact on GRP is smaller from AEEIs than from TFP growth. The elasticities of substitution between capital and energy and between fossil fuels have a smaller impact on GRP and pollutant emissions. The sensitivity results further indicate that these key parameter changes only alter the GRP and pollutant emissions a little in the EAP scenario, suggesting the simulation results in Section 4 are relatively robust.

6. Conclusions and policy implications

This study assesses the impact of China's current APA policies on both the regional economy and environment in the BTH area by 2020, using a multi-regional energy-environment-economy CGE model incorporating the direct abatement expenditure of the policies. A sensitivity analysis indicates the results to be reasonably robust.

The simulation results demonstrate that the current APA policies in the BTH area could generate a large negative influence on economic growth, with an average annual GRP growth loss of 1.4% in the AP scenario and 2.3% in the EAP scenario in the entire BTH area. The decline in Beijing and Hebei's GRP growth rates are larger than Tianjin. There are also obvious decreases in the production of energy- and emission-intensive sectors, which are offset to some extent by industrial structural transformation and upgrading. These policies illustrate the commitment of Chinese government to change the economic development mode in a way that will reduce air pollution.

It is inevitable that the current APA policies play an important role in environmental improvement in the BTH area, with a reduction of more than 50% and 60% in 2017 and 2020 respectively in SO_2, NO_X, and primary $PM_{2.5}$ emissions, and a fall of more than 20% and 30% in 2017 and 2020 in VOC_S emissions respectively in the EAP scenario. However, there is still a gap between the reduced emissions and the requirements for the related $PM_{2.5}$ concentration targets proposed by the government in this area. Considering the interregional emission transfer effect, the gap will be even larger if the reduction rates in the BTH surrounding area are small. The $PM_{2.5}$ concentration reduction of BTH is mainly dependent on the reduction in local emissions. According to the simulation results, in order to realize the $PM_{2.5}$ concentration targets and improve air quality, VOC_S emission mitigation needs to be enhanced, especially in Hebei. In addition, more determination and policies are needed to reduce NO_X and primary $PM_{2.5}$ emissions in Hebei and Beijing.

Within the four types of the APA policies in the BTH area, end-of-pipe control is the most cost-effective for the reduction of most pollutant emissions. The policies of reduction from vehicles and VOC emission mitigation are cost-effective for NO_X and VOC_S emissions respectively. The current proposed structural adjustment policy contributes significantly to a reduction of all of four emissions but with a high cost. Hence, if APA policies could be better designed and more targeted, it would be helpful for APA but at a smaller future social price.

Some implications for policy-making and industry development can be identified from the analysis. *First*, stronger policies are needed, as current APA strategies are insufficiently effective for meeting related $PM_{2.5}$ concentration targets. According to the results of the emission reduction and economy-wide cost of policies, more measures that address end-of-pipe control and reductions from vehicles for NO_X and primary $PM_{2.5}$ emissions in Beijing and Hebei, and more measures of VOC mitigation for VOCs emissions in Hebei should be adopted in the future to reduce $PM_{2.5}$ concentration. In addition, joint prevention and control in inner BTH and its surrounding area is also needed to reduce the negative effect of interregional emission transfer.

Second, such command and control approaches as mandatory output reduction should not be implemented for a long period as the high economy-wide cost of industrial structural adjustment may harm corporate emission reduction initiatives. Considering the great contribution of structural adjustment to reducing emissions, the incentives to accelerate structural adjustment therefore need to be increased. According to many experiences that have occurred in the developed countries, the early introduction of such market-based approaches as environmental tax or emission trading could be beneficial because they can realize industrial and energy structure improvement at a low cost. This means that air pollution reduction actions and enterprises-led emission reduction behaviors should play a leading role in the future, while direct intervention by the government should be gradually reduced. On the other hand, enterprises should strengthen their emission reduction actions through effective policy guidance and incentives. In addition, subsidies and rewards need to be increased for abating sectors and households. For example, end-of-pipe control measures require sectors to buy abating equipment, and the policy of reduction from vehicles encourages households to eliminate older vehicles or buy new clean-energy vehicles; at present, however, these are relatively expensive and current subsidies are relatively low. Therefore, the government needs to increase subsidies to reduce the financial burden on industries and households. More rewards can be offered for private enterprises as incentives to improve energy efficiency as well as technological innovation to increase abatement potential. In terms of energy structure adjustment, in order to reduce the economy-wide cost of policies and make it easier to substitute cleaner energy for coal, the government could guide reasonable energy prices and make gas and renewable energy more economical and competitive than coal. One of the most important roles of the government in the future emission reduction of air pollution could be to design an institutional framework for subsidies and incentives, play a reasonable guiding role, and avoid false emission reduction behaviors that may result from policy loopholes, and thus truly encourage incentives to reduce emissions. Finally, it is also necessary to expand the development of environmentally friendly industry. The cost of upgrading the economic structure generated by the APA policies is very large, while the negative policy impact on service and other environmentally friendly industry sectors is very small. Thus, the development of environmentally friendly industries with little or zero emission and/or high added value needs to be accelerated to upgrade industrial structure and encourage economic growth to compensate for the economic loss of air pollution abatement.

A limitation of this study is that the health impact of APA policies is not assessed. Nevertheless, the analysis can provide important inputs for the evaluation of the impact on health. For further research, it will be important to link health damage and air pollution, and to evaluate the health impact of APA policies to make it possible to incorporate health feedback costs and benefits into the economy to assess the comprehensive effect of APA policies using CBA analysis.

Acknowledgment

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (No. 71673262; 71673232), the key project of the National Social Science Foundation of China (No. 15ZDC006) and the foundation of University of Chinese Academy of Sciences (UCAS) for cooperative projects between UCAS and Institutions of Chinese Academy of Sciences.

Appendix A

See Tables A.1–A.5.

Table A.1
Division of sectors.

Codes		Sectors
1	AGR	Agriculture
2	COA	Coal mining
3	OGA	Oil and natural gas extraction
4	OMI	Other mining and quarrying
5	FTC	Food and textile, clothes industry
6	TFP	Timber, furniture and paper manufacturing
7	PET	Petroleum processing and coking
8	CHE	Chemical industry
9	NOM	Non-metallic mineral products manufacturing
10	SPM	Smelting, pressing of metals
11	MEM	Machinery and electronics manufacturing
12	OMA	Other manufacturing
13	ELS	Electricity and steam supply
14	GAS	Gas supply
15	CON	Construction
16	TRA	Transportation
17	SER	Services

Table A.2

Policies of the Action Plan and related direct reduction.

Policy		Sector	Energy/prod-uct/ emission	Reduction amount (10 kt)			Reduction rate (%)		
				Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Energy and industrial structural adjustment	Coal reduction	Electricity and steam supply	Coal	900	678	680	71.6	18.0	6.1
		Industry (except electricity and steam)	Coal	200	296	2966	47.2	16.5	19.1
		residential	Coal	200	27	354	34.0	14.0	17.3
	Production capacity reduction	Non-metallic mineral products manufacturing-cement	Cement	515	108	3195	58.9	13.8	24.9
		Smelting, metals/steel pressing	Steel		424	1749		20.0	9.7
	Increasing gas supply	Industry	Gas	84[a]	93[a]	162[a]	171.4 [a]	547.1[a]	648.0[a]
		Residential	Gas	25.75[a]	5[a]	67 [a]	67.3[a]	71.4[a]	87.0[a]
End-of-pipe control	Desulfurization in coal-fired power plants	Electricity and steam supply	SO_2	0	3.02	13.73	0.0	24.8	37.4
	Denitration in coal-fired power and heating plants		NO_X	0.89	4.93	22.5	10.8	22.9	30.3
	Upgrade dust collectors in power sector		$PM_{2.5}$	0	0.45	1.3	0.0	23.2	24.6
	Desulfurization in industrial boilers	Industry	SO_2	0.65	5.07	7.01	26.8	73.2	11.1
	Upgrade dust collectors in industrial boilers		$PM_{2.5}$	0.02	0.38	2.05	52.9	68.8 s	32.8
	Desulfurization in sinter plants (industrial process)	Smelting, metal/steel pressing	SO_2	0	1.24	10.25	0.0	29.0	28.8
	Upgrade dust collectors in steel industry (industrial process)		$PM_{2.5}$	0	1.17	6.23	0.0	29.6	22.5
	Denitration in cement industry (industrial process)	Non-metallic mineral products manufacturing-cement	NO_X	0.26	0.16	3.61	17.4	12.8	24.0
	Upgrade dust collectors in industrial kilns (industrial process)		$PM_{2.5}$	0.59	0.31	3.17	30.5	28.0	22.9
Reductions from vehicles	Eliminate yellow-sticker vehicles, improve fuel quality, increase emission standard, and promote new energy vehicles	Transportation	NO_X	5.24	1.4	5.14	41.2	18.5	8.2
			VOC_S	2.58	1.69	6.29	82.4	72.3	46.9
			$PM_{2.5}$	0.23	0.07	0.53	42.8	17.4	13.7
VOC reduction	Control VOC emissions from key industries (industrial process)	Petroleum processing and coking, and chemical industry	VOC_S	0.8	2.27	0.85	10.0	13.0	3.0
	Vapor recovery (industrial process)	Petroleum processing and coking	VOC_S	4.53	3.63	3.39	80.0	64.3	36.2
	Promote environment-friendly paints and solvents	Related industries[b]	VOC_S	2.53	1.7	3.63	13.3	14.2	7.3

Source and note: estimated according to Air Pollution Prevention and Control Action Plan and its implementation details, MEIC database, He et al. (2014), and China Energy Statistical Year Book 2013. For structure adjustment, the Air Pollution Prevention and Control Action Plan and its implementation details often specify the target reduction amount of a sector's energy consumption or production. For example, the industry sector in Beijing needs to cut 2000 thousand tons of coal consumption while that of Tianjin should decrease 4240 thousand tons of cement production. Reduction targets are not given explicitly for a few sectors, and their reduction amounts are retrieved from the related quantitative results of these policies (He et al., 2014) or estimated based on this research. These reduction targets are taken as an exogenous restriction in the CGE model. For specific measures belonging to end-of-pipe control, reduction from vehicles and VOC mitigation, such as desulfurization and denitration in coal-fired power plants, and related direct emission reduction can be deduced based on the emission reduction amount or rate of each specific technology or measure. He et al.'s (2014) research of provides the parameters of a specific technology or measure and related emission reduction using an emission inventory. Based on this research, the emission inventory (MEIC database) and China Energy Statistical Year Book, the direct reduction amount or rate of emissions of all these policies are estimated. These emission reductions are taken to change related emission factors instead of being as exogenous restriction in the CGE model. [a]For gas, the data is the increased amount (100 million m^3) or rate. [b]Related industries include timber, furniture and paper manufacturing, chemical industry, non-metallic mineral products manufacturing, machinery and electronics manufacturing, and other manufacturing.

Table A.3
Enhanced measures of Air Pollution Prevention and Control in the BTH area (2016–2017) and related direct reduction.

Policies		Sectors	Energy/product/emission	Reduction amount (10 kt)			Reduction rates (%)		
				Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Energy and industrial structural adjustment	Substitution of bulk coal for cleaner energies	Residential	Coal	240	127	254	40.75	65.80	12.40
	Industrial boilers and kilns switch, upgrade or shut down	Industry	Coal	143			33.73		
	Shut down and eliminate polluting plants	Related polluting industries[a]	Related products				15.00	10.00	10.00
	Stop production in certain time period	Non-metallic mineral products manufacturing	Non-metallic mineral products				10.00	10.00	10.00
		Petroleum processing and coking	Steel				10.00	10.00	10.00
End-of-pipe control	Low-nitrogen transformation in gas-fired boilers	Industry	NO_X	1			18.94		
	Ultra-low emission transformation in coal-fired generating units	Electricity and steam supply	SO_2		6.47	19.51		53.15	53.15
			NO_X		8.18	28.20		37.95	37.95
			$PM_{2.5}$		1.07	2.91		55.1	55.1
	Environment control and transformation in steel industry	Smelting, pressing of metals-steel	SO_2		0.25	2.05		5.79	5.77
			$PM_{2.5}$		0.23	1.25		5.93	9.00
Reductions from vehicles	Eliminate old vehicles	Transportation	NO_X	0.10			0.82		
			VOC_S	0.05			1.65		
			$PM_{2.5}$	0.00			0.86		
VOC reduction	Control VOC emissions from key industries(industrial process)	Petroleum processing and coking, Chemical industry	VOC_S	1.86	5.29	1.98	23.30	30.22	7.07
	Promote environment-friendly paints and solvents	Related industries[b]	VOC_S	1.69		1.82	8.88		3.63

Source: estimated according to Enhanced measures of Air Pollution Prevention and Control in Beijing-Tianjin-Hebei area (2016–2017) and the Table above. [a]Related polluting industries includes Food and textile, clothes industry, Timber, furniture and paper manufacturing, Petroleum processing and coking, Chemical industry, Non-metallic mineral products manufacturing, Smelting, pressing of metals, Other manufacturing. [b]Please see the note ‘b’ of the Table.

Table A.4
Direct abatement expenditure of the Action Plan and Enhanced measures (CNY 100 million).

Policies			Sectors	Beijing	Tianjin	Hebei
The Action Plan	Structural adjustment	Coal-fired boilers and units switch to gas, upgrade or shut down	Industry	123.81	95.24	380.95
	End-of-pipe control	Desulfurization, denitration and upgrading dust collectors in coal-fired power and heating plants	Electricity and steam supply	3.21	102.22	447.24
		Desulfurization and upgrading dust collectors in coal-fired industrial boilers	Industry	9.46	33.04	102.02
		Desulfurization and upgrading dust collectors in steel industry (industrial process)	Smelting, pressing of metals-steel		10.29	74.40
		Denitration and upgrading dust collectors in cement industry (industrial process)	Non-metallic mineral products manufacturing-cement	0.13	0.08	1.43
	Reductions from vehicles	Eliminate yellow-sticker vehicles, improve fuel quality, increase emission standard, and promote new energy vehicles	Transportation	154.36	41.24	151.42
	VOC reduction	Control VOC emissions from key industries (industrial process)	Petroleum processing and coking, and chemical industry	6.23	17.67	6.62
		Vapor recovery (industrial process)	Petroleum processing and coking	20.42	16.36	15.28
Enhanced Measures	Structural adjustment	Industrial boilers and kilns switch, upgrade or shut down	Industry	88.52		
	End-of-pipe control	Low-nitrogen transformation in gas-fired boilers	Industry	17.96		
		Ultra-low emission transformation in coal-fired generating units	Electricity and steam supply		23.35	93.40
		Environment control and transformation in steel industry	Smelting, metal/steel pressing		2.06	14.88
	Reductions from vehicles	Eliminate old vehicles	Transportation	30.87		
	VOC reduction	Control VOC emissions from key industries (industrial process)	The petroleum processing and coking, and chemical industries	1.04	8.08	1.06

Source: estimated according to the Air Pollution Prevention and Control Action Plan and its implementation details, Enhanced measures of Air Pollution Prevention and Control in the BTH area (2016–2017), CAAC (2015) and He et al. (2014).

Table A.5
Main abbreviations in this paper.

Abbreviations	Unabbreviated Term
AEEI	Autonomous energy efficiency improvements
AIM	Asia-Pacific Integrated Model
AP	Action Plan
APA	Air pollution abatement
BTH	Beijing-Tianjin-Hebei
CBA	Cost benefit analysis
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CMAQ	Community Multiscale Air Quality
EAP	Enhanced Action Plan
ELES	Extended linear expenditure system
GRP	Gross regional product
GTAP	Global Trade Analysis Project
MEIC	Multi-resolution emission inventory for China
NO_X	Nitrogen oxide
$PM_{2.5}$	Particulate matter with an aerodynamic diameter less than 2.5 μm
ROC	Rest of China
SO_2	Sulfur dioxide
TFP	Total factor productivity
VOC/VOC_S	Volatile organic compound(s)

References

Amman, M., Kejun, J., Jiming, H., Wang, S., Xing, Z., Wei, W., Xiang, D.Y., Hong, L., Jia, X., Chuying, Z., Bertok, I., Borken, J., Cofala, J., Heyes, C., Höglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schöpp, W., Toth, G., Wagner, F., Winiwarter, W., 2008. GAINS-Asia: Scenarios for Cost-effective Control of Air Pollution and Greenhouse Gases in China. IIASA, Laxenburg, Austria. 〈http://pure.iiasa.ac.at/8670〉.

Armington, P.S., 1969. A theory of demand for products distinguished by place of production. Staff Pap. Mar. 1 (16), 159–178.

Becker, R.A., 2005. Air pollution abatement costs under the Clean Air Act: evidence from the PACE survey. J. Environ. Econ. Manag. 50, 144–169.

Beckerman, W., 1992. Economic growth and the environment: whose growth? Whose environment? World Dev. 20, 481–496.

Bollen, J., van der Zwaan, B., Hers, S., 2010. An integrated assessment of climate change, air pollution, and energy security policy. Energy Policy 38, 4021–4030.

CAAC (Clean Air Alliance of China), 2015. Investment Demand and Impacts of Air Pollution Prevention and Control Action Plan in China (2013–2017) (in Chinese). CAAC Policy Report. 〈http://www.cleanairchina.org/product/7466.html〉.

Chen, S.M., He, Y.L., 2014. Welfare loss of China's air pollution: how to make personal vehicle transportation policy. China Econ. Rev. 31, 106–118.

Chen, Y.Y., Ebenstein, A., Greenstone, M., Li, H.B., 2013. Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. PNAS 110, 12936–12941.

Chow, J.C., 1995. Measurement methods to determine compliance with ambient air quality standards for suspended particles. J. Air Waste Manag. Assoc. 45, 320–382.

Dong, H.J., Dai, H.C., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., Fujii, M., Masui, T., 2015. Pursuing air pollutant co-benefits of CO_2 mitigation in China: a provincial leveled analysis. Appl. Energy 144, 165–174.

Freeman, A.M., 1982. Air and Water Pollution Control: A Benefit-Cost Assessment. J. Wiley, New York.

FYCCC (Finance Yearbook of China Compilation Committee), 2008. Finance Yearbook of China 2008 (in Chinese). China Finance Magazine Press, Beijing.

Gao, J.L., Yuan, Z.W., Liu, X.W., Xia, X.M., Huang, X.J., Dong, Z.F., 2016. Improving air pollution control policy in China-a perspective based on cost–benefit analysis. Sci. Total Environ. 543, 307–314.

Greenstone, M., 2002. The impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 clean air act amendments and the census of manufactures. J. Political Econ. 110, 1175–1219.

Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110, 353–377.

Haimes, Y.Y., Nainis, W.S., Goldstone, S., 1977. Cost-sharing approach for air quality control implementation A case study. J. Environ. Econ. Manag. 4, 219–238.

He, K., Zhang, Q., Hong, C.P., Xie, H.X., Ba, I.Y., Du, J., Zhao, L.J., Cai, J.J., Lin, Y., Zhou, R., 2014. Can Beijing, Tianjin and Hebei Achieve Their $PM_{2.5}$ Targets by 2017? Assessment of the potential for air quality improvements in the Beijing-Tianjin-Hebei region under China’s new air pollution action plan. Beijing-Tianjin-Hebei AQM Policy Report Series. 〈http://www.cleanairchina.org/file/loadFile/73.html〉.

He, K., Zhang, Q., Tong, D., Jang, K.J., Xie, H.X., Wang, L.S., 2016. How to realize air quality standard compliance in Beijing-Tianjin-Hebei area- based on a study of $PM_{2.5}$ standard compliance scenario (in Chinese). 〈http://www.cleanairchina.org/product/7532.html〉.

Hove, A., Enoe, M., 2015. Climate change, air quality and the economy: integrating policy for China’s economic and environmental prosperity (in Chinese). 〈http://www.paulsoninstitute.org/wp-content/uploads/2015/07/Climate-Change-Air-Quality-and-the-Economy-Chinese-version-2015July10.pdf〉.

Huang, J., Deng, F.R., Wu, S.W., Guo, X.B., 2012. Comparisons of personal exposure to $PM_{2.5}$ and CO by different commuting modes in Beijing, China. Sci. Total Environ. 425, 52–59.

Huo, P.F., 2016. The Research of American Air Pollution Regulation Mechanism Transformation During 1970s to 1990s (in Chinese). Hebei Normal University.

IEA (International Energy Agency), 2005. Projected costs of generation electricity. 〈http://dx.doi.org/10.1787/9789264008274-en〉.

IEA (International Energy Agency), 2007. World Energy Outlook 2007.

Jiang, X.J., Hong, C.P., Zheng, Y.X., Zheng, B., Guan, D.B., Gouldson, A., Zhang, Q., He, K.B., 2015. To what extent can China's near-term air pollution control policy protect air quality and human health? A case study of the Pearl River Delta region. Environ. Res. Lett. 10, 104006.

Li, N., Shi, M.J., Shang, Z.Y., Yuan, Y.N., 2015. Impacts of total energy consumption control and energy quota allocation on China's regional economy based on a 30-region computable general equilibrium analysis. Chin. Geogr. Sci. 25, 657–671. https://doi.org/10.1007/s11769-015-0739-0.

Lofgren, H., Harris, R., Robinson, S., 2002. A Standard Computable General Equilibrium Model in GAMS. IFPRI. 〈http://www.ifpri.org/publication/standard-computable-general-equilibrium-cge-model-gams-0〉.

Ma, J., Li, Z.G., 2014. Economic Policy of $PM_{2.5}$ Mitigation. China Economy Press, Beijing.

Maloney, M.T., Yandle, B., 1984. Estimation of the cost of air-pollution-control regulation. J. Environ. Econ. Manag. 11, 244–263.

Matus, K., Nam, K.M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Glob. Environ. Change 22, 55–66.

Matus, K., Yang, T., Paltsev, S., Reilly, J., Nam, K.M., 2008. Toward integrated assessment of environmental change: air pollution health effects in the USA. Clim. Change 88, 59–92.

Mendelsohn, R., 1980. An economic analysis of air pollution from coal-fired power plants. J. Environ. Econ. Manag. 7, 30–43.

Muller, N.Z., Mendelsohn, R., 2009. Efficient pollution regulation: getting the prices right. Am. Econ. Rev. 99, 1714–1739.

Muller, N.Z., Mendelsohn, R., Nordhaus, W., 2011. Environmental accounting for pollution in the United States economy. Am. Econ. Rev. 101, 1649–1675.

Nam, K.M., Selin, N.E., Reilly, J.M., Paltsev, S., 2010. Measuring welfare loss caused by air pollution in Europe: a CGE analysis. Energy Policy 38, 5059–5071.

NBSC (National Bureau of Statistics of China), 2008a. China Statistical Yearbook 2008 (in Chinese). China Statistics Press, Beijing.

NBSC (National Bureau of Statistics of China), 2008b. China Energy Statistical Yearbook 2008 (in Chinese). China Statistics Press, Beijing.

NEPRC (National Emblem of the People's Republic of China), 2008. China Customs Statistics Yearbook 2008 (in Chinese). China Customs Press, Beijing.

Palmer, K., Oates, W.E., Portney, P.R., 1995. Tightening environmental standards: the benefit-cost or the no-cost paradigm? J. Econ. Perspect. 9, 119–132.

Paltsev, S., Reilly, J.M., Jacoby, H.D., et al., 2005. The MIT emissions prediction and policy analysis (EPPA) model: version 4. MIT Jt. Program Report. Ser. 125. 〈http://globalchange.mit.edu/publication/14578〉.

Pearce, D.W., Atkinson, G., Mourato, S., 2006. Cost-Benefit Analysis and the Environment: Recent Developments. OECD publishing, Pairs.

Revesz, R.L., Livermore, M.A., 2008. Retaking Rationality: How Cost-Benefit Analysis Can Better Protect The Environment and Our Health. Oxford University Press, Oxford.

Rive, N., 2010. Climate policy in Western Europe and avoided costs of air pollution control. Econ. Model. 27, 103–115.

Rosenbaum, W.A., 2013. Environmental Politics and Policy. Cq Press, Washington, D.C.

Shi, M.J., Zhang, Z.Y., 2012. The Construction of China Interregional Input Output Model 2007 (in Chinese). Research Centre on Fictitious Economy & Data Science, Chinese Academy of Sciences.

U.S. EPA (Environmental Protection Agency), 1997. Benefits and costs of the clean air act, 1970 to 1990. US Environmental Protection Agency Report. 〈https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1970-1990-retrospective-study〉.

U.S. EPA (Environmental Protection Agency), 1999. The benefits and costs of the clean air act 1990 to 2010. US Environmental Protection Agency Report. 〈https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-second-prospective-study〉.

U.S. EPA (Environmental Protection Agency), 2011. The Benefits and Costs of the Clean Air Act from 1990 to 2020: Final Report-Rev. A. US Environmental Protection Agency Report. 〈https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf〉.

Upton, S., 2016. The real cost of the air pollution (in Chinese). China Policy Rev. 9, 50–51.

Vrontisi, Z., Abrell, J., Neuwahl, F., Saveyn, B., Wagner, F., 2016. Economic impacts of EU clean air policies assessed in a CGE framework. Environ. Sci. Policy 55, 54–64.

Winiwarter, W., Klimont, Z., 2011. The role of N-gases (N_2O, NOx, NH_3) in cost-effective strategies to reduce greenhouse gas emissions and air pollution in Europe. Curr. Opin. Environ. Sustain. 3, 438–445.

Wu, Y.J., Xuan, X.W., 2002. Economic Theory of Environmental Tax and Analysis of Their Application in China (in Chinese). Economic Science Press, Beijing.

Xue, W.B., Fu, F., Wang, J.N., Tang, G.Q., Lei, Y., Yang, J.T., Wang, Y.S., 2014. Numerical study on the characteristics of regional transport of $PM_{2.5}$ in China (in Chinese). Environ. Sci. 34, 1361–1368.

Zhang, Y.L., Cao, F., 2015. Fine particulate matter ($PM_{2.5}$) in China at a city level. Sci. Rep. 5, 14884.