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RESEARCH ARTICLE

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Cost-benefit analysis of China's Action Plan for Air Pollution Prevention and Control

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Abstract China's rapid economic growth has caused severe air pollution and public health problems. Therefore, the Chinese government launched the Action Plan for Air Pollution Prevention and Control (hereinafter referred to as the "Air Plan") in 2013–2017 to improve air quality and safeguard public health. In this study, an analytical framework for a cost-benefit analysis applicable to China was constructed, and the costs and benefits of the implementation of the "Air Plan" in 30 cities and provinces in China from 2013 to 2017 were evaluated. Results show that the total cost of implementation of the "Air Plan" is 1.6511 trillion RMB. The benefits of air quality improvement were determined to be 2.4691 trillion RMB through the willingness-to-pay method to calculate the economic loss of premature deaths. The net benefit related to the implementation of the "Air Plan" was 818 billion RMB. The public health benefit of air quality improvement was 1.5 times the cost of the nationwide implementation of the "Air Plan". At the provincial level, net benefits that reach 279.3 billion RMB were the highest in Guangdong, whereas the benefit-cost ratio, where the benefit was 5.5 times the cost, was the highest in Fujian. Estimations in this study can serve as a reference for China in formulating similar environmental policies and implementing the "3-year Plan to Defend the Blue Sky". In addition, these estimations have practical significance for advancing the long-term effective mechanisms of the cost-benefit analysis of China's environmental policies.

Keywords Air Plan, cost-benefit analysis, health benefits, environmental policy

1 Introduction

As the world's second largest economy, China's rapid economic growth has led to the emission of many atmospheric pollutants (Chang et al., 2018), which have

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caused severe air pollution and public health problems (He et al., 2002; Guan et al., 2014). The rankings in the 2012 Asian Development Bank (ADB) report (Asian Development Bank, 2012) indicated that seven of the ten cities with the worst air quality are identified in China. Annual economic losses due to China's air pollution were estimated to account for approximately 1.2% of the nation's gross domestic product (GDP) based on disease cost. These losses also account for as much as 3.8% of the GDP based on the willingness-to-pay approach. In 2013, exposure to fine particulate matter ($PM_{2.5}$) air pollution in the environment resulted in 916000 premature deaths in China (Abubakar et al., 2015; GBD MAPS Working Group, 2016). Therefore, the Chinese government issued the Action Plan for Air Pollution Prevention and Control (hereinafter referred to as the "Air Plan") to improve air quality and safeguard public health (Zhao et al., 2018). The respirable particulate matter (PM_{10}) concentrations in cities at the prefecture-level or above nationwide are expected to reduce by more than 10% in comparison with the 2012 values. In addition, in the Beijing-Tianjin-Hebei, Yangtze River Delta (Shanghai, Jiangsu, Zhejiang, and Anhui), and Pearl River Delta (Guangdong) regions, the $PM_{2.5}$ concentrations were expected to reduce by approximately 25%, 20%, and 15%, respectively. To achieve these targets, the Chinese government has proposed 10 measures to optimize the structure and layout of industries, adjust energy structures and upgrade petrochemical products, and strengthen the comprehensive management of industrial pollution (Jin et al., 2016; Zheng et al., 2017).

The first phase of the "Air Plan" ended in 2017. Five years prior to which, the average PM_{10} concentration in 338 cities at the prefecture-level or above decreased by 22.7%. The average $PM_{2.5}$ concentrations in Beijing-Tianjin-Hebei, Yangtze River Delta, and the Pearl River Delta regions decreased by 39.6%, 34.3%, and 27.7%, correspondingly. The average $PM_{2.5}$ concentration in Beijing was 58 $\mu g/m^3$ (Ministry of Environmental Protection of PRC, 2017), thereby achieving the initially established environmental quality objectives. In consideration of the remarkable impacts of the "Air Plan", the Chinese government has released an ambitious second phase of the "Air Plan" (The State Council of PRC, 2018), with the objectives that, by 2020, the total sulfur dioxide and nitrogen oxide emissions will be 15% lower than that in 2015; the $PM_{2.5}$ concentration, which did not satisfy the initial target, in cities at the prefecture-level or above will be reduced by more than 18% in comparison with that in 2015; the ratio of days with excellent or good air quality in cities at the prefecture-level or above will reach 80%; the ratio of days with severe or very severe air pollution will be reduced by more than 25% in comparison with that in 2015.

Air pollution control is a complex and difficult task, which requires considerable capital input. During the implementation of the "Air Plan", the Chinese government and enterprises invested significant manpower, materials, and financial resources. The forecast for relevant research has indicated that the implementation of the "Air Plan" is estimated to cost 1.75 trillion RMB (Zhang et al., 2015). For a city with an area of only 16410 km^2, Beijing plans to spend 80 billion RMB to control air pollution. In 2017, Tianjin spent 15.629 billion RMB on the renovation of clean heating in 466600 households (He et al., 2019). Therefore, conducting a cost-benefit analysis provides a basis of reference for implementing the second phase of the "Air Plan" considering the total costs and benefits of environmental policies with large impacts (Zhu, 2017).

The cost-benefit analysis of environmental policies is a scientific judgment of the incurred costs and benefits on aspects, such as socioeconomic development and the ecological environment, following the formulation and implementation of these policies (Gauvin et al., 2010; Kronbak and Vestergaard, 2013). This analysis is widely used to assess various types of project proposals (Tol, 2001; Sáez and Requena, 2007). Since the 1970s, the occurrence of many environmental pollution incidents worldwide has prompted economists to seek additional effective approaches to assess the harms from changes in environmental quality and management efficiency. Cost-benefit analysis has been rapidly developed and applied (Olsthoorn et al., 1999; Liu et al., 2014). Comprehensive and systematic technical guidelines and workflow of cost-benefit analysis have been formulated in the United States (United States Environmental Protection Agency, 2010; 2011), the European Union, Japan, and other countries with various applications. For example, an environmental cost-benefit analysis was used by the US Environmental Protection Agency to evaluate the effectiveness of implementing the "Clean Air Act of 2002". The cost of its implementation was $30.9 billion; however, the benefit, which reached $118.9 billion, was approximately 4 times the cost (Arrow et al., 1996; Zhou, 2004). The European Union has also conducted a cost-benefit analysis of the "Council Directive 1999/31/EC on the Landfill of Waste" (Dong et al., 2011).

However, in China, the cost-benefit analyses of numerous major environmental policies or decisions have not attracted sufficient attention from policymakers (Luo et al., 2013; Gao et al., 2016; Zhou et al., 2019). The cost-benefit analysis of the formulation and implementation of environmental policies remains in the infancy stage (Liu et al., 2018). Existing research has focused on assessing the effects of comprehensive pollutant control (Wang et al., 2015; Zhang et al., 2018), the cost of the end-of-pipe treatment of individual pollutants (Fujii et al., 2013), the estimation of the benefits of direct pollution abatement (Jiang et al., 2013; Zheng et al., 2016) and environmental quality improvement (Wang et al., 2006;

Dong, 2011), and population health benefits (Chen et al., 2017; Huang et al., 2018). Systematic analyses of the overall cost and benefits of environmental policies remain lacking (Burch, 2014). China has considerably invested in the first phase of the “Air Plan”, and diminishing marginal effects gradually appear in the next phase of air pollution control because managing the atmospheric environment has become increasingly difficult (Pappin et al., 2016; 2015). Thus, through the cost-benefit analysis of the “Air Plan”, measures with relatively high marginal benefits may be identified (Liu et al., 2016). In the next phase of the “Air Plan”, additional economic measures to improve China’s environmental quality must be implemented (Peng, 2000; Wei et al., 2018).

In the present study, an analytical framework for cost-benefit analysis that is applicable to China was constructed. Then, a comprehensive assessment of the cost and benefits associated with the implementation of the “Air Plan” was conducted. Costs primarily refer to capital investments by society during the implementation of the “Air Plan”, while benefits refer to the monetized benefits of the avoided public health hazards due to estimated air quality improvement. Finally, the net benefits of the “Air Plan” were obtained. The assessed “Air Plan” primarily includes adjustments of the structure and layout of industries, clean use of energy, industrial pollution control, boiler retrofitting and control, nonpoint source pollution control, motor vehicle pollution control, and regulatory capacity building. The primary conclusions of this study can provide a reference for China’s formulation of similar environmental policies, such as the implementation of the “Blue Sky Plan”. These conclusions also have practical significance for advancing the long-term effective mechanisms of the cost-benefit analysis of China’s environmental policies.

2 Data and methods

2.1 Cost-benefit analysis framework for the “Air Plan”

The cost-benefit analysis of the implementation of the “Air Plan” primarily addressed the costs and benefits. This study used the annual average $PM_{2.5}$ concentration in each province and city, excluding the influences of meteorological factors (with 2013 as the base year). Costs included the costs related to the measures implemented in the seven aspects of the “Air Plan”, which consisted of inputs from the government, enterprises, and the public, considering the perspective of the society as a whole. The benefits included environmental improvement benefits (e.g., reduced emissions of major pollutants and improvements in environmental quality), health benefits, and other benefits (reductions in agricultural losses, building losses, and cleaning costs) of the implementation of the “Air Plan” (Fig. 1). Some investments in air pollution control are fixed

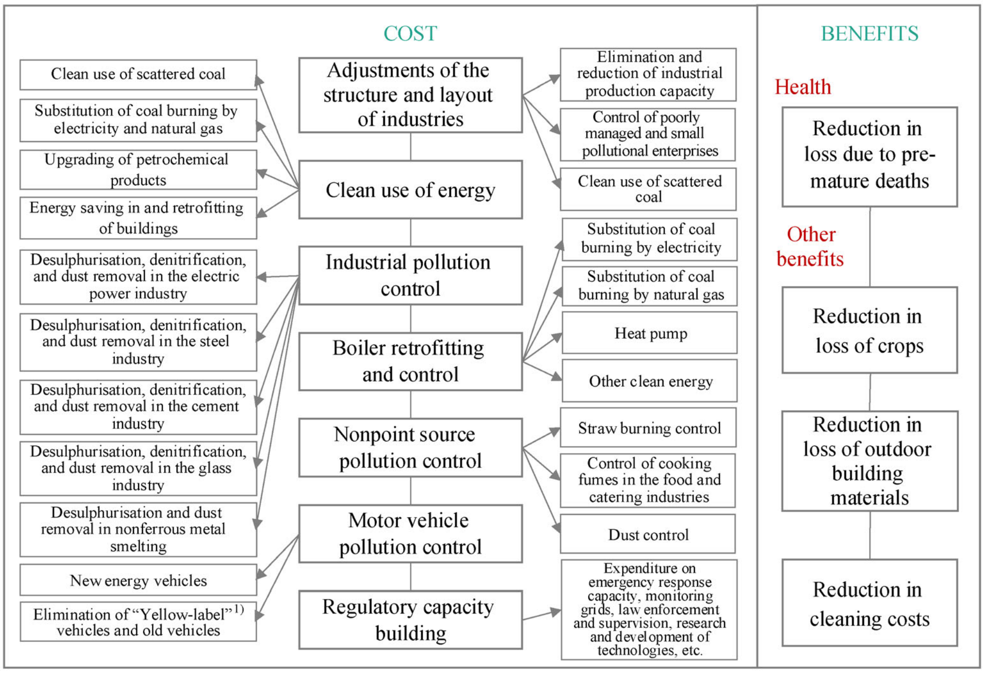

Fig. 1 Analytical framework for the cost-benefit analysis of the “Air Plan”.

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1) “Yellow-label” vehicles are gasoline vehicles whose pollutant emissions do not satisfy the “China I” emission standards; diesel vehicles whose pollutant emissions do not meet the “China III” emission standards; and motorcycles, tricycles, and low-speed trucks.

assets, and some benefits are long-term. When calculating costs and benefits, the depreciation of various fixed assets and discounting of benefits were also considered and specified in 2013–2017.

2.2 Methods of cost calculation

Policy measures implemented in the “Air Plan” are the target object of the cost-benefit analysis. Through organizing and combining policy measures related to the “Air Plan” implemented in 30 Chinese cities and provinces, seven main aspects were evaluated. These aspects are adjustments to the structure and layout of industries, clean use of energy, industrial pollution control, boiler retrofitting and control, nonpoint source pollution control, motor vehicle pollution control, and regulatory capacity building.

The costs of measures associated with the adjustments to the industrial structure primarily included government subsidies for eliminating outdated industrial capacity and reducing industrial overcapacity, investments in upgrading, and transforming poorly managed and small pollutional enterprises. The economic impacts of banning poorly managed and small pollutional enterprises were excluded from the costs.

The costs of clean use of energy primarily consisted of the clean use of scattered coal, the substitution of coal-burning with natural gas and electricity (referred to as “double substitution”), upgrading and transformed support of petrochemical products, and energy savings in buildings. The associated costs of the clean use of scattered coal included coal preparation, and the construction of coal preparation plants and clean coal blending centers. These costs were calculated through factor estimating method. The costs of the “double substitution” of coal-burning was calculated for households as a unit and predominantly included investments for heating equipment, construction costs of infrastructural facilities, and subsidies for annual operating costs. The costs of upgrading and transformed support of petrochemical products primarily included the increased costs associated with the upgrading of petrochemical products. The costs of energy savings in buildings was calculated on the basis of the area of existing buildings, where energy savings and retrofitting were implemented, and their unit cost.

Pollution control of key industries primarily targeted the air pollution of key industries identified in the “Air Plan”, including electric power, steel, cement, nonferrous metal, and plate glass industries. The cost calculation process primarily considered the estimated annual average investments and operating costs of newly constructed desulfurization, denitrification, and dust removal facilities (excluding ultra-low emission retrofitting) and the annual average investments and operating costs of the ultra-low emission retrofitting of coal-fired generating units in the electric power industry. The thermal power industry is used as an example.

$$INT_{\mathrm{f}} = NCAP \times C_{\mathrm{in}} \times Y_{\mathrm{o}} \times Y_{\mathrm{d}}, \tag{1}$$

$$COP_{\mathrm{df}} = GCAP_{\mathrm{df}} \times P_{\mathrm{df}}, \tag{2}$$

$$COP_{\mathrm{ul}} = GCAP_{\mathrm{ul}} \times P_{\mathrm{ul}}, \tag{3}$$

where INT_{f} is the estimated annual average investments of newly constructed desulfurization, denitrification, and dust removal facilities, and the ultra-low emission retrofitting of coal-fired generating units in the electric power industry; $NCAP$ is the capacity of new facilities (in 10000 kW); C_{in} is the unit capacity investment cost (in RMB/kW); Y_{o} is the operation period of facilities (in year); Y_{d} is the depreciation period of facilities (in year). COP_{df} is the operating costs of newly constructed desulfurization, denitrification, and dust removal facilities; $GCAP_{\mathrm{df}}$ is the unit-generating capacity of newly constructed facilities (in 10 GWh); P_{df} is electricity price subsidy (in RMB/10 MWh). COP_{ul} is the operating costs of newly constructed ultra-low emission retrofitting of coal-fired generating units; $GCAP_{\mathrm{ul}}$ is the unit generating capacity of newly constructed coal-fired generating units with ultra-low emission retrofitting (in 10 GWh); P_{ul} is the electricity price subsidy, which is 1.5 cent RMB/MWh, of coal-fired generating units with ultra-low emission retrofitting (in RMB/10 MWh).

Boiler retrofitting and control primarily included the measures of eliminating and retrofitting small coal-fired boilers. The primary targeted objects involved industrial, commercial, and residential (community) boilers generating less than 10 tons of steam per hour. The four main methods for retrofitting small coal-fired boilers are elimination, the substitution of coal-burning by electricity or natural gas, substitution by clean energy, and heating supply by heat pumps. The primary cost was the investment expenditure of boiler heating equipment; it is calculated on the basis of the tons of steam per hour generated by boilers.

Measures of motor vehicle pollution control primarily included the elimination of “Yellow-label” and old vehicles and the promotion of new clean energy vehicles. The primary cost of eliminating “Yellow-label” and old vehicles was the loss of the residual value of the vehicles (substituted by the cost of subsidies), and the cost of promoting clean energy vehicles primarily included the cost of subsidies for the promotion. For the replacement of “Yellow-label” and old vehicles with new clean energy vehicles, the pollutant emissions were approximately 10–25 times that of the “China V” or “China VI” emission standards; the cost of air pollution control associated with the promotion of new clean energy vehicles is 1/20 of the subsidies for promoting new clean energy vehicles (Zhou et al., 2019).

Nonpoint source air pollution control primarily included measures to control dust, cooking fumes from the food and catering industries, and straw burning. Specifically, dust refers to construction, road, and slag dust. The actual costs of nonpoint source air pollution control mainly consisted of government subsidies, the installation costs of government-controlled facilities, investments in enterprise facilities, and daily control, operation, and maintenance costs.

Capacity building of environmental regulation and technological support primarily involved the capacity of air pollution prevention and emergency responses, the establishment of an atmospheric environment monitoring grid system, the establishment of a law enforcement and supervision system (including environmental supervision and inspection), and technological research and development (National Key Research and Development Program of China in Atmospheric Sciences). Considering that the cost of each measure was difficult to calculate, the cost of capacity building was empirically selected to be 1.5% of the total expenditure of the "Air Plan". These data originated from the self-examination reports of the implementation of the "Air Plan" in 30 Chinese cities and provinces in 2017. These reports were submitted by the local authorities to the Ministry of Ecology and Environment. Tibet was excluded from the analysis given the significant data loss in that region.

2.3 Methods of health benefit calculation

The health benefits of air quality improvement were calculated by accounting for the reduction in losses due to air pollution across time. That is, the health benefits of air quality improvement in a particular year are equivalent to the health loss due to air quality in the previous year minus the health loss due to air quality in the current year. A positive difference indicates the positive benefits of environmental improvements that result from air pollution control. A negative difference indicates that air pollution control does not result in positive benefits of environmental improvement. A total of 338 regions, in which human health benefits from air pollution, were considered of cities at the prefecture-level or above, and $PM_{2.5}$ (concentration value after excluding the influences of meteorological factors) was primarily used as the air pollution variable for the human health impact assessment.

(1) Health loss due to air pollution

The economic loss of air pollution health hazards EC_a consists of three components, namely, economic loss due to premature deaths of all causes given air pollution (EC_{a1}); economic benefits due to reduced hospitalizations of patients with respiratory and cardiovascular diseases due to air pollution, number of days off work and the associated economic loss (EC_{a2}); and new cases of chronic bronchitis because of air pollution and the associated economic loss (EC_{a3}). EC_{a1} is calculated using the number of premature deaths from cardiovascular and respiratory diseases caused by air pollution (Chen et al., 2013; Ma et al., 2016a; 2016b). The values were calculated through the willingness-to-pay method. EC_{a2} was computed through the cost-of-illness method. The sum of hospitalization and time-off-work costs were also calculated. EC_{a3} was evaluated through the disability-adjusted life year (DALY) method as the economic loss.

$$EC_a = EC_{a1} + EC_{a2} + EC_{a3}, \tag{4}$$

$$EC_{a1} = P_{ed} \cdot PW_{mu}, \tag{5}$$

$$EC_{a2} = P_{eh}(C_h + WD \cdot C_{wd}), \tag{6}$$

$$EC_{a3} = \gamma \cdot P_{eb} \cdot HC_{mu}, \tag{7}$$

where P_{ed} is the number of premature deaths of all causes given the current levels of air pollution (in 10000); PW_{mu} is the willingness-to-pay to reduce the risk of premature deaths caused by air pollution (OECD, 2012); P_{eh} is the number of increased hospitalizations and number of days off work due to related diseases caused by the current air pollution (in 10000); C_h is the hospitalization cost of patients, including direct hospitalization cost and indirect hospitalization cost, such as transportation and nutrition (in RMB per patient visit), the data for which were from the *China Health Statistics Yearbook*; WD is the number of days off work caused by diseases (in RMB per person per day); C_{wd} is the cost of days off work caused by diseases (in RMB per day); γ is the coefficient of the loss in ability caused by chronic bronchitis (0.4); P_{eb} is the number of new cases of chronic bronchitis caused by air pollution (in 10000); and HC_{mu} is the average per capita human capital (in 10000 RMB per person). The calculation of coefficient was based on our previous researches (Chen et al., 2013; Ma et al., 2016a; 2016b).

(2) Health benefits of air quality improvement

Health benefits of air quality improvement were calculated as the reduced economic loss due to premature deaths of all causes due to air quality improvement, that is,

$$BEC_a = EC_a^{2017} - EC_a^{2013}, \tag{8}$$

where EC_a^{2017} and EC_a^{2013} are the health losses caused by pollution levels in 2017 and 2013, respectively.

(3) Other benefits

In addition to improving human health, air quality improvement can benefit crops, outdoor building materials, and cleanliness. Other benefits of air quality improvement primarily involved reductions in agricultural losses, outdoor building material losses, and cleaning costs. The deterioration of air quality results in crop yield reduction.

Its economic value can be measured through the market value method. Acid rain and SO_2 further aggravate the damage of outdoor building materials. The loss represents the years of material life reduction under pollution conditions; it can be calculated in economic value. The cleaning costs are mainly for the cleaning of public facilities, such as vehicles and buildings, caused by air pollution and the increase in labor costs. The coefficients and methods of other benefits were based on our previous researches (Chen et al., 2013; Ma et al., 2016a; 2016b). The data are mainly obtained from the *China Statistical Yearbook*, the *China Health and Family Planning Statistical Yearbook*, the *China Rural Statistical Yearbook*, and the corresponding statistical yearbooks by provinces.

3 Results

3.1 Total costs of the “Air Plan”

During the 5-year implementation period of the “Air Plan”, expenditures on air pollution controls (1.6511 trillion RMB) in China were primarily from the government and enterprises. The costs were 53.6 billion RMB in 2013, 310.3 billion RMB in 2014, 336.1 billion RMB in 2015, 402.0 billion RMB in 2016, and 549.0 billion RMB in 2017 (Fig. 2a). In terms of the different measures (Fig. 2b), the costs for industry structure and layout adjustments, the clean use of energy, industrial pollution controls, boiler retrofitting and controls, nonpoint source pollution controls, motor vehicle pollution controls, and capacity building of regulation and technological support were 51.5, 584.0, 657.6, 68.9, 74.7, 189.9, and 24.6 billion RMB, correspondingly (5-year cumulative value). Among the measures, the costs of industrial pollution controls and the clean use of energy exceeded 500 billion RMB, which account for 40% and 35% of the total costs, respectively. In terms of the costs of implementing the clean use of energy and adjustment measures, the cost of upgrading and transformed support of petrochemical products was the highest. The cost amounts to 309.2 billion RMB or 52.9% of the total costs. The costs of implementing the clean use of scattered coal and the “double substitution” of coal-burning were 24.1% and 16.4% of the total expenditures, respectively. The costs of motor vehicle pollution controls ranked third among the seven measures. This cost accounts for 12% of the total expenditures. Motor vehicle pollution controls only included the elimination of old vehicles and the promotion of new clean energy vehicles. The cost of eliminating “Yellow-label” and old vehicles was 169.6 billion RMB. This cost accounts for 89.3% of the total motor vehicle pollution control costs, whereas the cost of promoting new clean energy vehicles accounts for 10.7%.

Thirty cities and provinces have large differences in their expenditures due to various resource endowments, geographical conditions, economic foundations, and pollution structures. For example, Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta are the key areas of the “Air Plan”; thus, they have relatively large investments. Among the 30 cities and provinces (Fig. 3), expenditures were high in Shandong, Hebei, Shanxi, Jiangsu, Henan, and Guangdong, which amount to 140.3, 135.7, 120.8, 117.0, 106.2, and 101.6 billion RMB, respectively. The costs of implementing the “Air Plan” in these six provinces have all exceeded 100.0 billion RMB. Among the cities and provinces, the $PM_{2.5}$ concentration levels in Shandong, Hebei, Shanxi, Henan, and Shaanxi in 2017 exceeded 56 $\mu g/m^3$, which have experienced the most severe pollution. The $PM_{2.5}$ concentration levels were lower in the economically developed regions of Jiangsu, Guangdong, and Zhejiang than in the five aforementioned provinces. Simultaneously, in the areas with good air quality, such as Hainan, Qinghai, Ningxia, Yunnan, and Gansu, the air pollution problems were not prominent. Moreover, their industries were under development, the remaining atmospheric environment capacity was high, and the investment in air pollution control was relatively small. The two provinces with the optimal air quality were Qinghai and Hainan, where the cost of implementing the “Air Plan” was the lowest of approximately 6.0 billion RMB. The implementation costs of approximately 20.0–25.0 billion RMB in provinces with improved air quality, including Guangxi, Chongqing, Ningxia, Jilin, Yunnan, and Gansu, were low. The implementation costs in the remaining cities and provinces ranged from 30.0 to 60.0 billion RMB.

The costs of different measures varied between cities and provinces (Table 1). The difference in measures was mainly due to the variation in the pollution structure of 30 cities and provinces. In Northern China, heating is necessary during winter. Therefore, additional investment is made in the “double substitution” and the clean use of scattered coal. Industrial pollution control costs in areas with high industrialization processes, such as Jiangsu, Zhejiang, and Guangdong, are relatively high. In areas where urbanization is high but the industry is limited, such as Beijing and Sichuan, the investment in motor vehicle pollution control and upgrading and transformed support of petrochemical products are relatively high.

In terms of the absolute cost, the cost of adjusting the structure and layout of industries was the highest in Hebei (18.1 billion RMB); the cost of industrial pollution controls was the highest in Shandong (75.6 billion RMB); the cost of the clean use of energy and adjustments was the highest in Shanxi (72.1 billion RMB); the costs of boiler pollution controls were the highest in Tianjin and Hebei (13.3 and 12.6 billion RMB, respectively); the costs of nonpoint source air pollution controls were the highest in Jiangsu and Hebei (9.9 and 9.2 billion RMB, correspondingly); and the costs of motor vehicle pollution controls were the highest in Shandong and Guangdong (19.5 and 19.3 billion RMB, respectively).

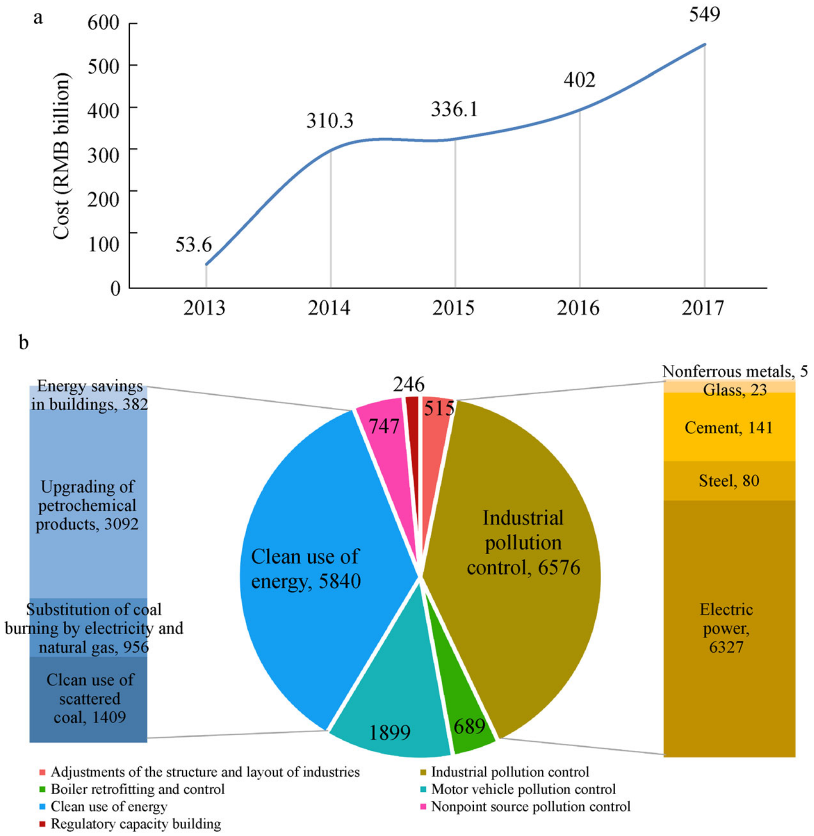

Fig. 2 Costs of the “Air Plan” in China from 2013 to 2017: (a) Costs of the “Air Plan” by year; (b) Costs of the “Air Plan” by measures (in 100 million RMB).

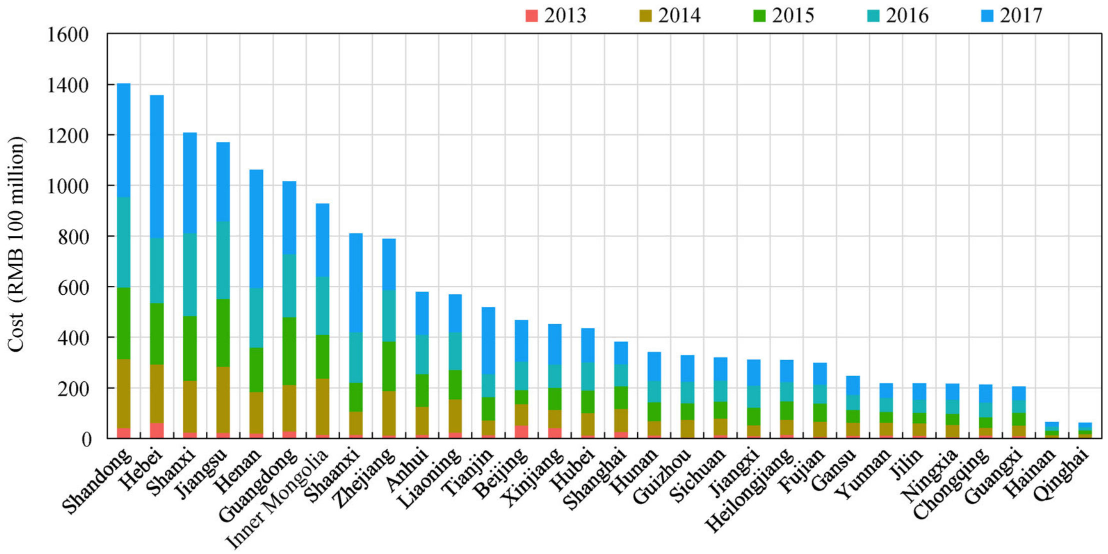

Fig. 3 Costs of the “Air Plan” in 30 cities and provinces by year.

In terms of relative cost, industrial pollution controls and the clean use of energy and adjustments were the more costly measures in Beijing, Tianjin, and Sichuan than in the other cities and provinces, for these three have relatively small industries. In the two major coal-producing provinces, namely, Shanxi and Shaanxi, the cost of the clean use of energy and adjustments constituted more than 59% of the total expenditures. The cost of the clean use of

Table 1 Costs of seven measures in the 30 cities and provinces in China during the 5-year implementation period of the “Air Plan” (in RMB 100 million)

Province/City	Adjustments of the structure and layout of industries	Industrial pollution control	Clean use of energy	Boiler retrofitting and control	Nonpoint source pollution control	Motor vehicle pollution control	Regulatory capacity building
Beijing	4	6	282	12	37	121	7
Tianjin	32	87	167	133	30	62	8
Hebei	181	405	424	126	92	109	20
Shanxi	18	372	721	19	13	48	18
Inner Mongolia	5	525	323	11	12	38	14
Liaoning	24	201	207	34	14	81	8
Jilin	2	74	74	7	9	47	3
Heilongjiang	2	102	130	7	13	51	5
Shanghai	0	101	187	21	15	51	6
Jiangsu	11	649	229	67	99	98	17
Zhejiang	4	405	204	44	23	96	12
Anhui	6	349	105	13	19	79	9
Fujian	5	159	78	4	10	38	4
Jiangxi	3	128	114	2	18	42	5
Shandong	59	756	292	61	19	195	21
Henan	40	428	417	16	40	106	16
Hubei	10	167	151	22	21	58	6
Hunan	4	118	120	10	32	54	5
Guangdong	3	399	325	7	74	193	15
Guangxi	5	66	77	3	17	34	3
Hainan	1	27	21	1	3	11	1
Chongqing	4	55	90	2	36	22	3
Sichuan	11	55	152	4	30	65	5
Guizhou	12	147	128	1	11	26	5
Yunnan	6	36	111	0	20	43	3
Shaanxi	6	237	479	23	12	42	12
Gansu	3	109	71	25	6	30	4
Qinghai	0	19	22	7	4	9	1
Ningxia	2	161	33	2	4	12	3
Xinjiang	50	233	108	5	12	38	7

energy and adjustments in Beijing constituted 60% of the total expenditures due to petrochemical product upgrades and the “double substitution” of coal burning. The cost of industrial pollution controls in Inner Mongolia, Jiangsu, Anhui, Shandong, and Ningxia constituted more than 53% of the total expenditures and approximately 74% in Ningxia. Among the industrial pollution control expenses, ultra-low emission retrofitting constituted the largest proportion. In Ningxia, the pollution from thermal power enterprises was the focus of air pollution prevention and controls, where the completion rate of ultra-low emission retrofitting of coal-fired generating units was 75.3%, because thermal power enterprises currently comprise the largest proportion of air pollutant emissions.

3.2 Health benefits of the “Air Plan”

The implementation of the “Air Plan” substantially improved China’s air quality. The national annual average $PM_{2.5}$ decreased from 57 μg/m^3 in 2013 to 45 μg/m^3 in 2017. The total number of premature deaths caused by air pollution in China was 2.085 million in 2013–2017. The number of reduced premature deaths following the implementation of the “Air Plan” was 97000, which accounts for 4% of all premature deaths. The total number of hospitalizations was 7.263 million, and the number of reduced hospitalizations was 1.83 million, which accounts for 25.2% of the total. Through the willingness-to-pay method, public health benefits of air quality improvement were assessed to be 2.4691 trillion RMB, which was 1.5 times the total expenditures. In addition to improving human health, air quality improvement can benefit crops, outdoor building materials, and cleanliness. In 2013–2017, other benefits from air quality improvement amounted to 43.64 billion RMB. These benefits consisted of reductions in agricultural losses, outdoor building material losses, and cleaning costs, which amounted to 15.6, 17.28, and 10.76 billion RMB, correspondingly.

The gap between benefits across cities and provinces is a comprehensive reflection of differences in concentration, population, and economic development. Figure 4 illustrates the air quality improvement and its benefits in 30 Chinese cities and provinces during the 5-year implementation period of the "Air Plan". In accordance with the $PM_{2.5}$ concentration decline rate in 2013–2017, the order from high to low is presented as follows (Fig. 4a): Shanghai had the highest $PM_{2.5}$ concentration decline rate, which reached 58%; Qinghai ranked second at 50%; Tianjin, Fujian, Chongqing, and Zhejiang reached more than 40%; and the other provinces reached more than 30%. At the provincial level, in 2013–2017, the benefits of air quality improvement were the highest in Guangdong, Jiangsu, Shandong, Hebei, and Zhejiang (all amounted to more than 200 billion RMB); and the benefits of air quality improvement in Shanghai, Fujian, and Sichuan were greater than 100 billion RMB. Superior benefits were predominantly concentrated in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions, which were the key regions of the "Air Plan". The benefits of air quality improvement in Ningxia, Shanxi, Inner Mongolia, Heilongjiang, and Shaanxi were negative, thereby indicating that air quality did not improve and environmental degradation intensified. Specifically, the negative impacts were primarily due to the negative net benefits of agricultural losses in Inner Mongolia and negative net health benefits in other provinces. The benefits were predominantly expressed as health benefits because the total percentage of other benefits was small and less than 5%. In terms of other benefits, the benefits of reduced agricultural loss due to air quality improvement were the greatest in Hebei, Inner Mongolia, and Shandong. The reduced loss in outdoor building materials was the highest in the Yangtze River Delta and Pearl River Delta regions. The benefits of reduced cleaning costs were the greatest in Shandong, Zhejiang, and Guangdong.

3.3 Net benefits of China's "Air Plan"

The net benefits of the "Air Plan" are equivalent to the total benefits minus total costs. The net benefit in China was 818.0 billion RMB; thus, the socioeconomic benefits were far greater than the costs. The 30 cities and provinces were ranked in accordance with the net benefits from high to low (Fig. 5). Guangdong had the greatest net benefits with 279.3 billion RMB, which significantly exceeded that of the other cities and provinces. The net benefits in the Yangtze River Delta region were 155.3 billion RMB in Shanghai (ranked second), 150.9 billion RMB in Jiangsu (third), and 122.8 billion RMB in Zhejiang (fifth). The net benefit in Fujian was 127.0 billion RMB, which ranked fourth among all cities and provinces. The net benefits were positive in Shandong, Hebei, Sichuan, Chongqing, Hunan, Hubei, Tianjin, Yunnan, Qinghai, Guizhou, Guangxi, Beijing, and Hainan, thereby demonstrating that the benefits were greater than the costs. This finding also indicated that the total benefits of air quality improvement, including health benefits, due to the implementation of the "Air Plan" were higher than the total costs of implementation of various measures. The net benefits were negative in Jilin, Gansu, Anhui, Jiangxi, Ningxia, Liaoning, Xinjiang, Heilongjiang, Henan, Inner Mongolia, Shaanxi, and Shanxi. This finding implied that the total benefits of air quality improvement, including health benefits, due to the implementation of the "Air Plan" are lower than the total costs of implementation of various measures. Economically developed regions have positive net benefits, whereas economically underdeveloped regions have negative net benefits. For example, the net benefits in the three provinces in Northeastern China were negative because the economically developed regions invested additional capital on improving environmental quality, and the absolute amount and returns were great.

The benefit-cost ratio of the "Air Plan" was obtained by dividing the total benefits by the total costs (Fig. 5). China's benefit-cost ratio was 1.49, thus indicating that the socioeconomic benefits generated exceeded the costs by approximately 50%. The benefit-cost ratio was the highest in Fujian (5.52), followed by Shanghai, Chongqing, Qinghai, Guangdong, and Sichuan. The values in these cities and provinces were greater than 3. This finding indicated that the benefits of the implementation of the "Air Plan" exceeded the costs by 300%, thereby confirming the remarkable impacts of the "Air Plan". The benefit-cost ratio was lowest in Heilongjiang (-0.27) and was also below zero in Shaanxi, Ningxia, Shanxi, and Inner Mongolia. The negative values indicated that the expenditures did not improve the environment and even worsened air quality.

125.6 billion RMB was required for each 1 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration for the implementation of the "Air Plan". The annual trend revealed that, in 2013–2017, the control costs for each 1 $\mu g/m^3$ decrease in the $PM_{2.5}$ concentration were 142.2, 87.6, 212.1, and 114.3 billion RMB, respectively. For the key regions, the costs for each 1 $\mu g/m^3$ decrease in the $PM_{2.5}$ concentration were 20.1 billion RMB in Beijing-Tianjin-Hebei and adjacent provinces, 7.9 billion RMB in the Yangtze River Delta, and 7.2 billion RMB in the Pearl River Delta. The control costs

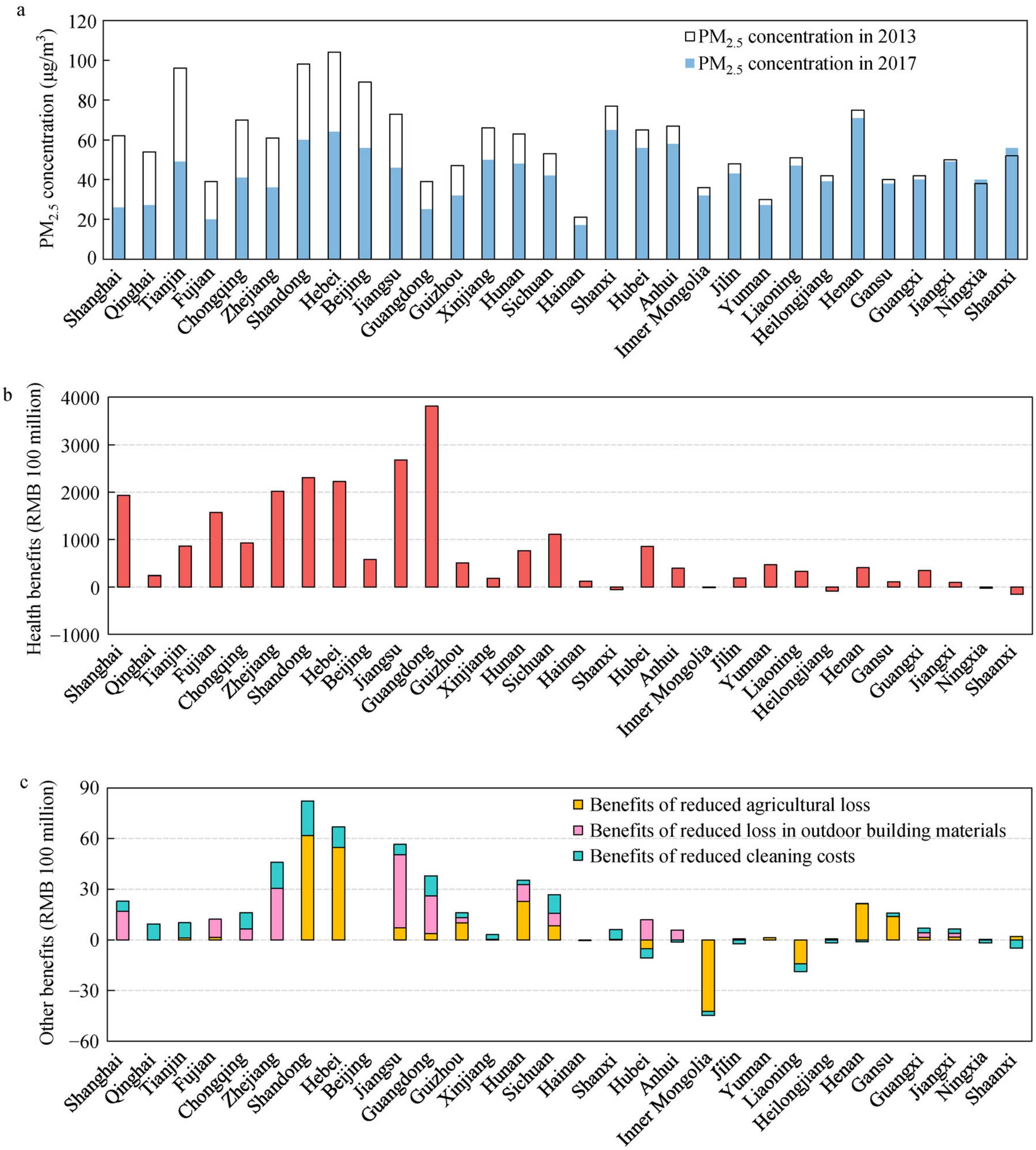

Fig. 4 Air quality improvement and its benefits in 30 Chinese cities and provinces during the 5-year implementation period of the “Air Plan”: (a) Air quality improvement due to the “Air Plan”; (b) Health benefits of the “Air Plan”; (c) Other benefits of the “Air Plan”.

for each 1 μg/m^3 decrease in the PM$_{2.5}$ concentration and total costs in the three key regions were correlated with the extent of decrease in the PM$_{2.5}$ concentration. The PM$_{2.5}$ concentration decreased by 29 μg/m^3 with a total cost of 581.0 billion RMB in Beijing-Tianjin-Hebei and adjacent provinces, and the PM$_{2.5}$ concentration decreased by 29 μg/m^3 with a total cost of 228.2 billion RMB in the Yangtze River Delta region. The lowest total cost in the Pearl River Delta region (98.8 billion RMB) resulted in the smallest reduction in the PM$_{2.5}$ concentration (14 μg/m^3).

3.4 Limitations

Coefficient selection and assessment ranges of costs and benefits have several limitations given data availability and other reasons; these limitations may be addressed in future studies. First, in calculating costs, the use and growth of capital independent of the “Air Plan” policy and other factors, such as the increase in cost due to technological advances, industrial structure adjustments, and economic growth, must be determined. Second, several methodological uncertainties are inherent in the coefficients and data.

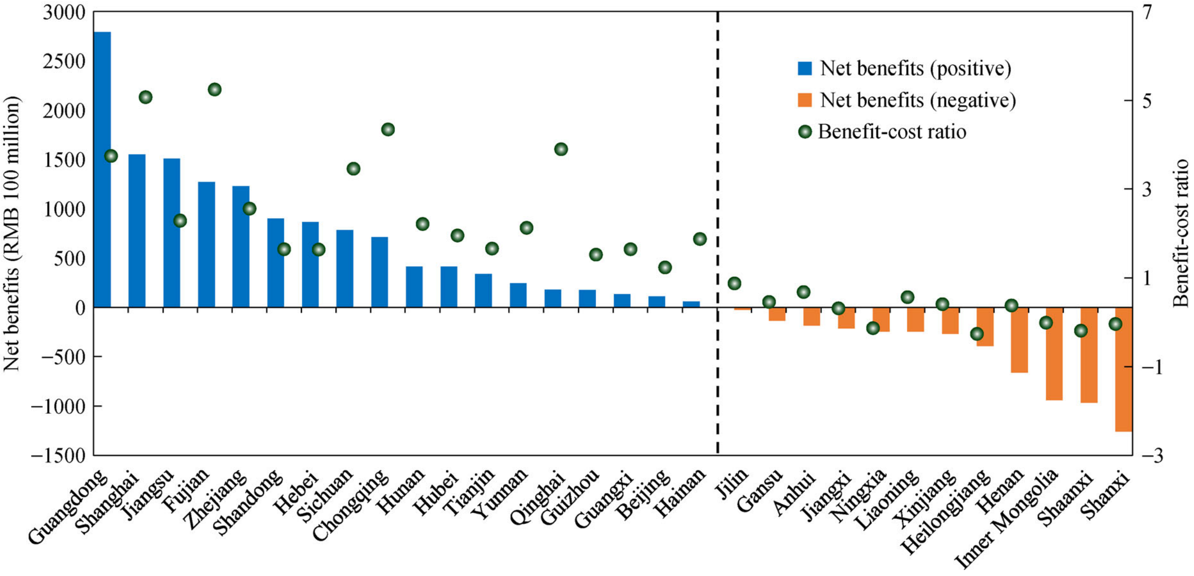

Fig. 5 Net benefits and benefit-cost ratio in 30 cities and provinces during the five-year implementation period of the "Air Plan".

For cost calculation, the data are mainly obtained from self-examination reports submitted by the cities and provinces. The coefficients are mainly obtained from the survey and empirical data. The cost of most measures is calculated through the factor estimation method. However, the price of petrochemical products, the calculated investment unit of the electric power industry, and other coefficients used are national-level coefficients, which do not incorporate their differences between cities and provinces. The next step is to select differentiated coefficients to well reflect the dissimilarities between cities and provinces. Finally, the assessment range of the benefits of the "Air Plan" is limited. The benefits generated by the "Air Plan" include health benefits and social benefits, such as increases in regulatory capacity and people's happiness. For example, following the implementation of the "Air Plan", the regulatory capacity of the atmospheric environment in China was significantly enhanced. Prior to 2012, no routine monitoring stations exist for $PM_{2.5}$ in China, and all 1436 nationally controlled monitoring stations have the ability to monitor six indicators, including $PM_{2.5}$. However, such benefits are often difficult to quantify. For health benefits, the uncertainty of the research results is primarily from the following aspects. First, we only used the average annual concentration of $PM_{2.5}$ when estimating the average exposure index of the population, whereas the long- and short-term time variability of the $PM_{2.5}$ concentration was disregarded. Second, existing epidemiological evidence cannot easily estimate the independent effects of different pollutants. $PM_{2.5}$ was selected as the evaluation index of air pollution, whereas O_3, SO_2, NO_2, and other pollutants were ignored, thereby underestimating the health benefits. Third, different value assessment methods can be used to evaluate the premature death caused by air pollution, thus leading to the uncertainty in health benefits assessment. In future studies, further detailed research must be developed to address the problems associated with these limitations and enhance the scientific value and precision of subsequent studies.

4 Discussions and conclusions

A cost-benefit analysis was used to evaluate the costs and benefits of the implementation of the "Air Plan" in 2013–2017. The results revealed that the total cost of implementing the "Air Plan" in 2013–2017 is 1.65 trillion RMB. The benefit of air quality improvement was 2.47 trillion RMB through the willingness-to-pay method for calculating the economic loss of premature deaths. For the entire country, the public health benefits of air quality improvement were 1.5 times the cost of the nationwide implementation of the "Air Plan". This finding indicated that the socioeconomic benefits generated exceeded the costs, thereby highlighting the environmental and economic benefits of implementing the "Air Plan", that is, economical and feasible.

Industrial pollution controls contributed the most to the reduction in atmospheric pollutant emissions. Implementing measures aimed at the clean use of energy-generated environmental and health benefits and enhanced people's quality of life. During the 5-year implementation period of the "Air Plan", the emissions of the major air pollutants in China decreased significantly. By 2017, the national emissions of SO_2, NO_x, and $PM_{2.5}$ decreased by 14.93 (59%), 5.61 (20%), and 4.08 (29%) million tons, correspondingly. The results of the cost calculation of seven measures indicated that the pollution controls of the major industries are the most costly measures. The pollution controls constituted 39.8% of the total costs. During the implementation of the "Air Plan", the reduction in industrial emissions was a major component of the overall reduction in emissions. The reduction in $PM_{2.5}$ emissions was primarily associated with reductions in the industrial sector. Industrial boilers, steel, cement, and glass industries contributed to 43% of the reduction in the national emissions. The clean use of energy was the second most costly measure among the seven measures. In terms of the adjustment of the energy structure, the Chinese government has proposed supplying clean heating alternatives in the country's northern region. This measure is important for fundamentally addressing large pollutant emissions from scattered coal during winter. Solving this problem can enhance people's quality of life. A switch from coal-burning to using natural gas and electricity would alter and optimize the energy structure of the entire region. With the advancement of the "Air Plan" policy, pollutant emissions will be reduced, and environmental quality will be improved. Moreover, a relatively healthy economy will continue to develop, and the people's quality of life and sense of achievement will be enhanced.

The achievement of air quality objectives is a long-term and difficult mission, and air quality improvement becomes increasingly difficult with the strengthening and advancement of air quality control measures. In terms of advancing the industrial, energy, and transportation structures, certain regions remain dependent on developing traditional industries, where the structural problems of pollution remain prominent. For example, adjusting the transportation structure is a difficult task, and significant opportunities for enhancing rail freight volume are present. In the future, pursuing efforts to advance environmental control and quality improvements will become increasingly difficult and complex. In terms of air quality, the amount of major pollutant emissions remains great, and the level of pollution remains high. Certain regions have a high frequency of smog occurrence during winter (Zhao et al., 2018). In 2017, the primary chemical constituents of $PM_{2.5}$ pollution in key regions evolved. For example, although the various components of $PM_{2.5}$ in Beijing-Tianjin-Hebei and adjacent areas have decreased to different degrees, the primary source of pollutants during winter has changed from industrial coal-burning to domestic emissions. The absolute and relative concentrations of nitrates have significantly exceeded those of sulfates, thereby becoming an important secondary inorganic component. In addition, the O_3 concentration levels have increased, and the prevention and control of nitrogen oxides and volatile organic compounds have become increasingly urgent. The Report on the Completion of Environmental Conditions and Environmental Protection Targets in 2018 by the State Council of PRC states that "the marginal effect of environmental governance is declining" (Li, 2019). Given that the diminishing marginal effects of air pollution prevention and control gradually emerge, a process remains to be developed for structural optimization and adjustments, and continuously improving air quality will be increasingly difficult. For example, the coal-burning in thermal power plants has been initially solved, but the pollution of coal-fired boilers, industrial coal, and residential coal have not been solved. The government can coordinate thermal power plants easily because of the particularity of this industry. However, the wide and scattered characteristics of scattered coal combustion have remained a weak part of air pollution control in China, thereby affecting the quality of winter atmospheric environment in Northern China. In addition, motor vehicle pollution and small-scale industrial clusters in townships and towns in these areas, such as Beijing-Tianjin-Hebei, are difficult to control because controlling them requires additional manpower, material resources, or financial resources.

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