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Research article

Environmental and economic impact analysis of levying VOCs environmental protection tax in China

Ziwei Qian [a,b], Feng Long [b,c,*], Xianming Duan [a], Fenfen Bi [b], Xue Tian [b],
Zhankun Qi [a,b], Chazhong Ge [b]

[a] School of Management, Hangzhou Dianzi University, 310036, Hangzhou, China
[b] The Center for Environmental Tax, Chinese Academy of Environmental Planning, 100041, Beijing, China
[c] National Joint Research Center for Ecological Conservation and High Quality Development of the Yellow River Basin, 100012, Beijing, China

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ABSTRACT

China is one of the largest volatile organic compounds (VOCs) emitters worldwide. The emission levels of and harm caused by VOCs have attracted much attention. China has implemented multiple policies for VOCs prevention and control but lacks economic control measures for VOCs In this study, the input-output (IO) price model was used to simulate and analyze the emission reduction and economic effects resulting from the imposition of a VOCs environmental protection tax (EPT) in 31 provinces in China. The results show that, first, the collection of a VOCs-EPT can achieve not only VOCs emission reductions but also the synergistic emission reductions of other major pollutants. Second, the collection of a VOCs-EPT could have a negative impact on the macroeconomy, i.e., the greater the tax scope and the higher the tax rate are, the greater the negative economic impact. Third, differences in the level of economic development, the structure of pollution emissions and the stringency of tax policies among regions would cause the emission reduction effect and related negative economic impact to vary across regions. Finally, the collection of a VOCs-EPT could have heterogeneous impacts on various industries, as high-emission industries would suffer greater negative impacts. Therefore, each region should set tax rates that match its provincial economic and environmental development levels. Furthermore, a VOCs-EPT can be levied on key industries, and reasonable preferential tax policies can be formulated to reduce negative macroeconomic benefits.

1. Introduction

Volatile organic compounds (VOCs) are important precursors of secondary pollutants, such as ozone (O_3) and fine particulate matter ($PM_{2.5}$), and can cause atmospheric problems, such as haze and photochemical pollution [1–3]. In addition, VOCs pose a serious threat to human health by irritating the eyes, skin, and respiratory tract [4–6]. The sources of VOCs can be classified into natural and anthropogenic sources [7]. Natural sources are mainly from vegetation emissions [8], and anthropogenic sources are mainly from solvent use, vehicle emissions, combustion processes and industrial processes [9–13]. According to existing studies, in cities and industrial agglomerations, VOCs emissions from anthropogenic sources are much greater than those from natural sources [14–16]. For example, in 2014, the contribution rate of anthropogenic VOCs emissions in Los Angeles was 58.7 % [17]; in 2019, in the summer of

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[*] Corresponding author. Chinese Academy of Environmental Planning, Yard 15, Shixing St., Shijingshan District, 100041, Beijing, China.
E-mail address: longfeng@caep.org.cn (F. Long).

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Chengdu, the contribution rate of VOCs emissions from anthropogenic sources was 83 % [18]; and in 2019, the contribution rates of VOCs emissions from anthropogenic sources in Beijing and Shanghai were 82.5 % and 81.9 %, respectively [19]. In 2015, the global VOCs emissions from anthropogenic sources reached 120.5 Mt, of which VOCs emissions from anthropogenic sources in China were 32.4 Mt, ranking first globally [20]. Therefore, the effective control of VOCs emissions, especially their prevention and control from anthropogenic sources, is very important for reducing air pollution, improving air quality, and maintaining human health.

Economic measures can be adopted to effectively control VOCs emissions, as has been demonstrated by other countries and regions that have formulated VOCs control-oriented economic policies. For example, the United States has implemented a tiered VOCs penalty system based on emission permits, and Switzerland has established a VOCs positive list taxation system [21]. China has also carried out active exploration and practice in this area. In 2015, the *Pilot Measures for Volatile Organic Compounds Pollution Charges* (hereinafter referred to as the *Pilot Measures*) promulgated by the Ministry of Finance and other departments clarified that the VOCs pollution discharge fee could be collected on a pilot basis from the petrochemical industry and the packaging and printing industry [22]. However, due to the variety of VOCs, immature monitoring technology, and difficulty to determine emission factors, the conditions for fully levying VOCs-EPT are not yet available. The *Environmental Protection Tax Law of the People's Republic of China* implemented in 2018 does not completely follow the VOCs taxation system in the *Pilot Measures* [23]; instead, it taxes only some VOCs simple substances in a relatively narrow manner. Moreover, owing to the provisions of the *Environmental Protection Tax Law*, the tax basis for air pollutants is the converted pollution equivalent number, and taxes are levied on only the top three air pollutants with the highest pollution equivalent number at each discharge port. However, the pollution equivalent number of the VOCs simple substances is often not large enough to rank among the top three; as a result, overall VOCs emissions have not been effectively regulated. In recent years, the conditions for levying VOCs environmental protection tax have become increasingly mature in China. In 2021, the Ministry of Ecology and Environment issued the *Manual of Accounting Methods and Coefficients of Emissions from Emission Source Statistical Investigation*, which provides standardized methods and coefficients for the calculation of VOCs emissions. At the meantime, with the full coverage of the emission permit system, VOCs emission monitoring and related standards and specifications have also been rapidly developed. The *Opinions of the Central Committee of the Chinese Communist Party and the State Council on Fighting the Battle on Pollution Prevention and Control* in 2021 and the *Opinions of the Central Committee of the Chinese Communist Party and the State Council on Comprehensively Promoting the Building of a Beautiful China* in 2024 successively stated that VOCs should be included in the scope of EPT, which provide a policy basis for the maturity of tax conditions [24,25].

The inclusion of VOCs in China's EPT requires scientific research and demonstration of the system design and implementation effectiveness. In recent years, studies in China and abroad have focused mainly on two aspects of a VOCs-EPT. First, in terms designing a VOCs-EPT system, a qualitative approach has been taken in most studies. Chen (2017) [26], Gao (2019) [27], Wang (2021) [28], Sun (2023) [29] and other scholars proposed that China should include VOCs in the EPT system at an appropriate time. Xu (2021) [30] suggested that VOCs taxation is helpful for China's energy transformation and urban environment optimization; China should abide by the principle of tax neutrality and optimize the design of VOCs tax incentives. Hu et al. (2018) [31] analyzed the problems and causes in the original verification of VOCs pollution discharge fee declarations and developed a more scientific verification system of VOCs-EPT declarations. Huang and Zhang (2020) [32] and Wen (2020) [33] recommended to continue the practice of the *Pilot Measures* and gradually expand the scope of VOCs taxation in the future. Second, in terms of predicting the implementation effectiveness of a VOCs-EPT, quantitative studies are mostly based on the computable general equilibrium (CGE) model. Liu (2011, 2013) [34] [35] established static and dynamic models to assess the economic and environmental benefits, respectively, of levying EPT on major VOCs-emitting sectors and reported that the collection of EPT clearly controlled VOCs emissions but had a negative impact on national economic development. Pan (2023) [36] studied the impact of Hebei Province's introduction of a VOCs-EPT under different tax rate scenarios and reached a conclusion similar to that of Liu; furthermore, Pan found that the VOCs-EPT policy had a synergistic effect on pollution and carbon reduction. Zhang (2023) [37] evaluated the synergistic emission reduction effect on major air pollutants from a regionally differentiated VOCs tax policy, estimated the corresponding environmental and health benefits and policy costs, and proposed that a regionally differentiated pricing policy could better promote environmental equity.

At present, articles on China's VOCs-EPT are mainly based on a single province or region; in-depth research covering all provinces in the country and targeting various industries is lacking. What kind of impact will the collection of a VOCs-EPT have on China's macroeconomy? What is the VOCs emissions reduction effect? What is the synergistic emission reduction effect on CO_2 and various pollutants (SO_2, NO_X, and $PM_{2.5}$)? What are the differences in effect of different industry coverages and tax rate standards? These questions need to be solved. Given the heterogeneity of VOCs emissions among different industries, the input-output (IO) model is highly suitable for measuring the impact of environmental policies [38]. In this paper, an IO model for assessing the impact of a VOCs-EPT was established. Different taxation scenarios were established for 31 provinces in China (including provinces, autonomous regions, and municipalities directly under the Central Government, but excluding the Macao Special Administrative Region, Hong Kong Special Administrative Region and Taiwan Province), the economic and environmental impacts of a VOCs-EPT on the whole country and individual provinces under different scenarios were simulated, and the heterogeneous impacts on industries were explored. The contribution of this paper is mainly reflected in the following aspects: the first one is in the terms of theoretical methods, the input-output model is used to comprehensively evaluate the implementation effect of this VOCs-EPT, which provides a new analytical tool for VOCs pollution control in China. The second one is in the terms of decision-making aspect, the multi-scenario setting by province is more practical. The specific measures and suggestions for improving the VOCs-EPT policy were proposed based on the simulation results, which provide some inspirations and references for the exploration of tax mechanisms in VOCs emission control area of China.

2. Research methods and data

2.1. Methods

The IO model contains two basic assumptions. One is the homogeneous sectoral assumption, i.e., each sector produces only a single product, and the products of the sector are irreplaceable; the other is the proportionality assumption, that is, the sectors consume intermediate inputs at a fixed proportion [39]. On the basis of the above assumptions, Leontief proposed an IO model that considers the economic impact from the perspective of the demand side [40]. In the early stage of taxation, government tax revenue could affect the value-added matrix; therefore, the supply-side IO model should be used to measure the impact of tax policy [38,41], that is, the Ghosh Input–Output model should be employed [42]. The Ghosh model starts from the column balance relationship in the IO table, and the column balance is used to represent the composition of each sector's products.

The z_{ij}^{rs} represents the intermediate input provided by sector j in province r to sector j in province s, v_j^s is the value-added vector of sector j in province s, x_j^s is the total input vector of sector j in province s, and the IO column balance relationship is constructed (Equation (1)):

$$\sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} v_j^s = x_j^s \tag{1}$$

Changes in the value added could cause changes in the price and output vectors. ΔV_s represents the added value vector, ΔP_s represents the price change vector, $(I-A)^{-1}$ is the Leontief inverse matrix, and Equation (2) is the IO price model:

$$\Delta P_s' = \Delta V_s'(I-A)^{-1} \tag{2}$$

Sectoral output (SO) is adjusted for price changes; therefore, the SO change can be calculated by assuming that the output change is proportional to the price change in each sector in the short term. The same assumption is also used to account for the changes in input and output in other studies [38,43]. The output change in sector j in province s (Δx_j^s) is obtained from the following equations:

$$\frac{x_j^{s*}}{x_j^s} = \frac{p_j^s}{p_j^{s*}} = \frac{p_j^s}{p_j^s\left(1+\Delta p_j^s\right)} = \frac{1}{1+\Delta p_j^s} \tag{3}$$

$$\Delta x_j^s = x_j^s - x_j^{s*} = x_j^s \frac{\Delta p_j^s}{1+\Delta p_j^s} \tag{4}$$

where x_j^s and x_j^{s*} represent the pretax and after-tax outputs of sector j in province s, respectively, and p_j^s and p_j^{s*} represent the pretax and after-tax prices of sector j in province s, respectively.

The total output vector of province s after the EPT is used as a column vector is X_s^*; the changes in gross domestic product (GDP) can be obtained as follows:

$$\Delta GDP = \mu * diag\ (\ A_v\ )\ * X_s^* \tag{5}$$

where $\mu = (1,1,1,\cdots,1)$, and $\mathrm{diag}(\mathrm{A}_v)$ is the diagonal matrix generated by the value-added coefficient vector.

Assuming that the consumption structure of residents remains unchanged, the total consumer price index (CPI^*) after the collection of a VOCs-EPT is:

$$CPI^* = \frac{(\Delta P_s)^T A_s^T (I-A) X_s^*}{1^T A_s^T (I-A) X_s^*} \tag{6}$$

where A_s^T represents the household consumption coefficient vector. According to the VOCs taxation scheme proposed in this paper, the CPI of each sector could show an upward trend due to the collection of EPT, resulting in a total CPI greater than 1.

The provincial VOCs-EPT revenue (F_s) can be calculated via Equation (7), where t_s represents the VOCs tax rate in province s and C_j^s is the direct emission amount of VOCs in sector j in province s. According to the *Pilot Measures*, the VOCs pollution equivalent value is 0.95 kg, that is, $b = 0.95$.

$$F_s = \frac{t_s C_j^s}{b} \tag{7}$$

First, the VOCs direct emission intensity (E_j^s) of sector j in province s is defined as

$$E_j^s = \frac{C_j^s}{x_j^s} \tag{8}$$

Then, the amount of VOCs reduction in sector j in province s (ΔC_j^s) can be obtained via the following equation:

$$\Delta C_j^s = E_j^s \Delta x_j^s \tag{9}$$

According to existing studies, CO_2 and air pollutant emissions have the characteristics of the same root, same origin and same process. Fossil energy consumption, industrial production, transportation and residential life are the main sources of environmental pollutants and greenhouse gas emissions [44,45]. The emission intensity of CO_2 and other major pollutants (E_n^s) and emission reduction (ΔC_n^s) can be obtained via the following equations.

$$E_n^s = \frac{C_n^s}{x^s} \tag{10}$$

$$\Delta C_n^s = E_n^s \Delta x^s \tag{11}$$

where $n = 1, 2, 3, 4$ represent CO_2, SO_2, NO_X, and $PM_{2.5}$, respectively.

2.2. Sectoral division

According to statistics, more than 50 % of China's industrial boilers are used in major industrial sectors, including textile industry (19.5 %), the energy industry (17.5 %), building materials (13.0 %), the construction industry (12.5 %), the chemical industry (9.5 %), the metallurgical industry (8.0 %), and transportation (7.0 %) [46]. In terms of the energy industry, coal consumption is the highest at 60.4 %, followed by oil and gas at 25.8 % and primary electricity and other energy at 13.8 % [47]. Based on the above criteria, the VOCs emissions inventory from industrial boilers in the original Multi-resolution Emission Inventory for China (MEIC) was apportioned using the percentage of each industry as the weight to obtain a new MEIC inventory.

In order to establish the emission inventory required for the simulation of the VOCs taxation policy, a sectoral cross-reference table was established between 42 sectors of the IO model and sectors in the new MEIC inventory. Referring to the sectoral division methods of Liu et al. (2010) [48], Liu (2020) [49] and Qi (2022) [50], and in conjunction with the National Economic Industry Classification (NEIC) standard, the original 42 sectors in the IO table were reclassified into 11 sectors (Table 1). The sector of agriculture, forestry and fisheries products and services was not included in this paper because the two sectors in the MEIC, fertilizer application and animal husbandry, have zero VOCs emissions.

Table 1
Sectoral integration.

Serial Number	Name of the sector after integration	MEIC Sector	Corresponding number in the original IO table
C1	Agricultural, forestry and fishery products and services	Fertilizer application, animal husbandry	1
C2	Fossil energy processing and mining industry	Energy industry	2, 3
C3	Light industry	Light and textile industry, printing and dyeing	6, 7, 8, 9, 10
C4	Petrochemical industry	Coking, petrochemical and chemical industries, industrial coatings, architectural coatings	11, 12
C5	Nonmetallic mineral products	Cement and building materials	13
C6	Metal smelting and products	Iron and steel and metallurgical industry	14, 15
C7	Other manufacturing industries	Other industrial sectors	4, 5, 16, 17, 18, 19, 20, 21, 22, 23, 26
C8	Production and supply of electricity, heat and gas	Electric power, heat power and energy industry	24, 25
C9	Building	Construction industry	27
C10	Transportation	Oil and gas storage and transportation, gasoline vehicles, diesel vehicles, motorcycles, nonroad mobile sources, transportation	29
C11	Tertiary industry	Civil source	28, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42

2.3. Scenario setting

According to China's current EPT law, flat tax rates within a certain range are used for air pollution tax items, with the tax rate being 1.2 to 12 RMB per pollution equivalent. Each region sets the applicable tax rate within the tax range according to its actual local situation. In terms of the scope of taxation, due to the need to gradually expand the scope of control in the future, scenarios involving industrial sector levies and all sector levies were established. The industrial sectors did not include mobile road sources or civil sources in the MEIC. In terms of tax rate setting, three levels of tax rates, high, medium and low, were established (Table 2). The low tax rate scenario is the EPT rate of air pollutants in each province in 2023, while the medium and high tax rate scenarios gradually increase the tax rate according to the environmental carrying capacity, pollutant emission status and the economic, social and ecological

Table 2
VOCs-EPT rate setting.

Tax rate (RMB/equivalent)	Low (L)	Medium (M)	High (H)
Beijing	12	12	12
Tianjin	10	10	10
Hebei	4.8	6	9.6
Shanxi	1.8	3.6	6
Inner Mongolia	2.4	3.6	6
Liaoning	1.2	3.6	6
Jilin	1.2	3.6	6
Heilongjiang	1.2	3.6	6
Shanghai	1.2	7.6	10
Jiangsu	6	8.4	10
Zhejiang	1.2	6	10
Anhui	1.2	3.6	6
Fujian	1.2	6	8
Jiangxi	1.2	3.6	6
Shandong	1.2	6	8
Henan	4.8	6	8
Hubei	1.2	3.6	6
Hunan	2.4	3.6	6
Guangdong	1.8	6	10
Guangxi	1.8	3.6	6
Hainan	2.4	3.6	6
Chongqing	3.5	6	8
Sichuan	3.9	6	8
Guizhou	2.4	3.6	6
Yunnan	2.8	3.6	6
Tibet	1.2	3.6	6
Shaanxi	1.2	3.6	6
Gansu	1.2	3.6	6
Qinghai	1.2	3.6	6
Ningxia	1.2	3.6	6
Xinjiang	1.2	3.6	6

Note: Due to the regional differentiation of the tax standards in Jiangsu Province, for the convenience of calculation, the intermediate tax rate was chosen as the basic tax rate, i.e., 6 RMB/pollution equivalent.

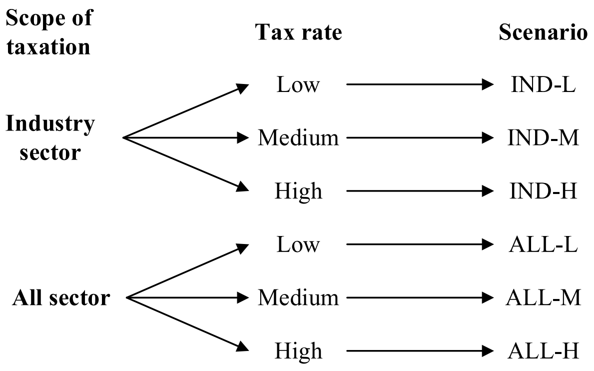

Fig. 1. Scenario setting of a VOCs-EPT.

development goals, but the maximum will not exceed 12 RMB per pollution equivalent. In summary, two collection scopes and three tax rates were set, i.e., a total of six scenarios (IND-L, IND-M, IND-H, ALL-L, ALL-M, ALL-H), as shown in Fig. 1.

2.4. *Data source and description*

In this study, the most recent multi-regional IO table in the Carbon Emission Accounts and Datasets (CEADs), which includes the IO data of 42 sectors in 31 provinces in 2017, was selected for analysis [51]. The emission data for VOCs, CO_2 and other major pollutants were obtained from the air pollutant emission inventory provided by the MEIC (http://meicmodel.org.cn/). The MEIC emission inventory covers more than 700 anthropogenic emission sources in mainland China and includes emissions of 8 major air pollutants (primary $PM_{2.5}$, NOx, SO_2, NH_3, BC, OC, PM_{10}, and NMVOCs) and CO_2 emissions. The 2020 NMVOCs and pollutant emission inventory for mainland China provided by MEIC v1.4 and the 2020 carbon emission inventory for mainland China provided by MEIC v2.0 were used in this study [52,53].

3. Results and discussion

3.1. *Revenue of VOCs tax*

The total emission of VOCs in 2020 given by the MEIC inventory was 25.6443 million tons. After the mobile road sources and civil sources are removed, 17.5235 million tons of industrial source emissions remain. The VOCs-EPT revenue calculated according to each scenario shows that the national VOCs-EPT revenue in 2020 ranges from 48.697 to 210.627 billion RMB. Under the same tax rate and different tax scopes, the tax revenue of the all sectors is 50 % greater than the tax revenue of the industrial sectors, as shown in Fig. 2. In 2020, China's actual total EPT revenue was 20.706 billion RMB, of which the total revenue from the air pollutant EPT was 18.436 billion RMB [54], accounting for 89.0 % of the total national EPT revenue. Therefore, the collection of a VOCs-EPT according to the scenario set in this paper could increase China's EPT revenue by 135.2 %–917.2 %.

The five regions with the highest emission of VOCs in 2020 are Shandong, Guangdong, Zhejiang, Jiangsu, and Hebei. However, under the current tax rate scenario, i.e., the low tax rate scenarios (IND-L, ALL-L), Beijing, Hebei, Jiangsu, Henan and Sichuan have high levels of VOCs-EPT revenues, while Zhejiang, Guangdong, and Shandong have medium levels of VOCs-EPT revenues. This situation occurred because according to the current EPT policy, the tax rate does not match the pollution emissions and environmental quality [55]. With the differentiated tax rates, under the scenarios of the medium tax rate and the high tax rate (IND-M, IND-H, ALL-M, ALL-H), the VOCs-EPT revenues in Jiangsu, Shandong, Guangdong, Zhejiang, and Hebei are increased, which is more in line with their levels of economic and social development. The negative environmental externalities can be internalized well through the collection of an EPT, which prompts economically developed but heavily polluting cities or enterprises to bear more environmental protection responsibility.

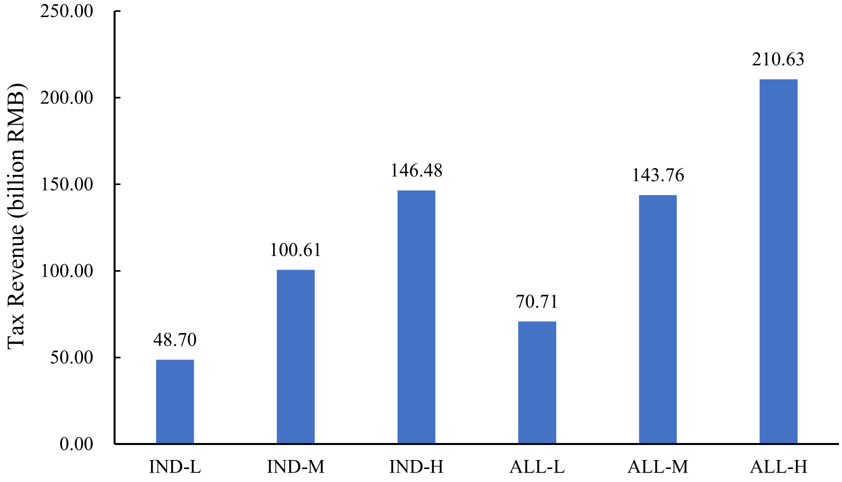

Fig. 2. VOCs tax revenue under the different scenarios.

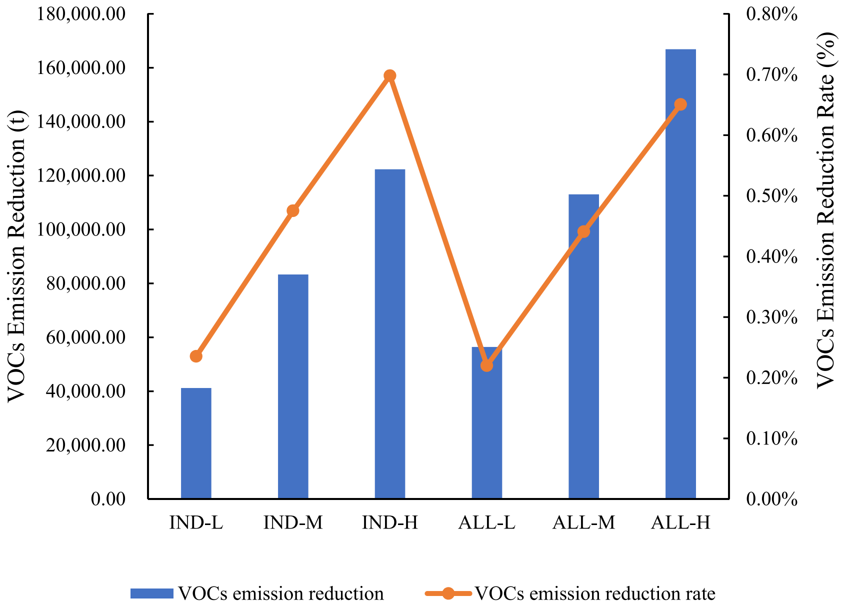

Fig. 3. National VOCs emission reduction and emission reduction rate under the different scenarios.

3.2. Effect on VOCs emission

Both the tax range and tax rate affect the emission reduction effect on VOCs to varying degrees. Under the all sector scenarios, the national VOCs emissions decrease by 56428.29–166847.01 tons, with emission reduction rates ranging from 0.22 % to 0.65 %. Under the industry sector scenarios, the emission reductions range from 41233.13 to 122314.79 tons, with emission reduction rates ranging from 0.24 % to 0.70 %. Fig. 3 shows that for the six scenarios, the emission reduction follows the order of ALL-H > IND-H > ALL-M > IND-M > ALL-L > IND-L, and the emission reduction rate follows the order of IND-H > ALL-H > IND-M > ALL-M > IND-L > ALL-L. Under the same tax rate with different taxation scopes, the VOCs emission reduction is greater when the tax is levied on the all sectors; furthermore, it is greater when the tax is levied on industrial sectors. All sectors levy cover more emission sources, thus increasing the potential and area for emission reductions. In contrast, the industrial sectors are the main emission sources of VOCs, accounting for nearly 70 % of the total national VOCs emissions, so the collection of EPT from the industrial sectors alone is more targeted.

The VOCs emission reduction rate reflects the effectiveness of VOCs pollution prevention and control in each region. Different regions have different VOCs emission structures; thus, VOCs emission reduction rates are different under different scenarios, as shown in Fig. 4 In the all sector scenarios, the emission reduction rates of Beijing, Tianjin, Sichuan and Yunnan are relatively high. In the industrial sector scenarios, the emission reduction rates of Beijing, Tianjin, Chongqing and Sichuan are relatively high under the low and medium tax rates; and the emission reduction rates of Beijing, Tianjin, Shanxi, Inner Mongolia and Yunnan are relatively high under the high tax rate. The efficiency of VOCs emission reduction is affected by the level of economic development, industrial structure, tax policy, etc.; therefore, reasonable emission reduction goals and measures should be formulated based on the actual situation.

3.3. Impacts on the emissions of CO_2 and other pollutants

CO_2 and air pollutant emissions have the same root, same source, and same process. The collection of a VOCs-EPT could promote technological innovation or product substitution in polluting enterprises and increase the proportion of clean energy use; such efforts could create synergistic emission reduction benefits for CO_2 and other air pollutants, as shown in Fig. 5. Overall, as the stringency of the policy increases, the emission reduction efficiency of CO_2 and other pollutants gradually increases, and the emission reduction rate of VOCs under any scenario is much greater than that of CO_2 and other atmospheric pollutants, reflecting the effectiveness and pertinence of a VOCs-EPT policy. From the perspective of a single pollutant, the emission reduction efficiency of each pollutant under different scenarios is different due to the different emission characteristics of CO_2 and other pollutants. When levies are placed on industrial sectors, the order of emission reduction rates from high to low is VOCs > SO_2 >$PM_{2.5}$>CO_2 >NO_X; when levies are placed on the all sectors, the order of emission reduction rates from high to low is VOCs > NO_X > SO_2 >$PM_{2.5}$>CO_2. Vehicular transportation structures are one of the main emission sources of NO_X [56]. According to the MEIC emission inventory, the NO_X emissions of the

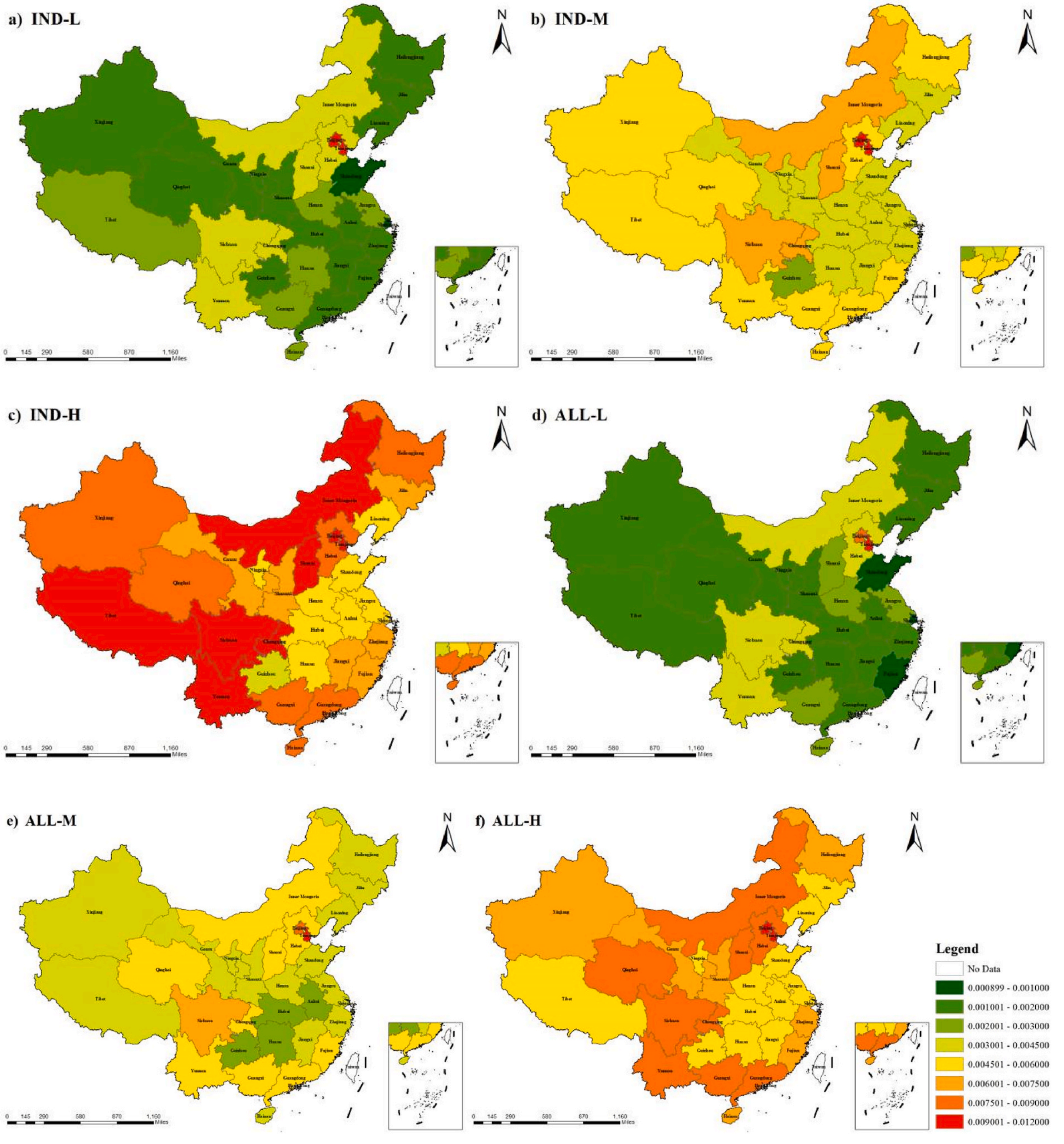

Fig. 4. VOCs emission reduction rate in each province under the different scenarios.

transportation industry account for 35.0 % of the total annual emissions in 2020. Therefore, when a VOCs-EPT is levied on the all sector, the emission reduction effect of NO_X is more significant. The main source of CO_2 emissions is energy activities, and the reduction in CO_2 emissions mainly depends on the adjustment of the energy structure and the improvement in energy use efficiency [57]. The emission of air pollutants mainly comes from industrial processes. In addition to adjusting the energy structure, improving the process flow and adopting pollution control technologies are necessary. Therefore, the effect of collecting a VOCs-EPT on synergistic emission reductions in CO_2 is relatively weak.

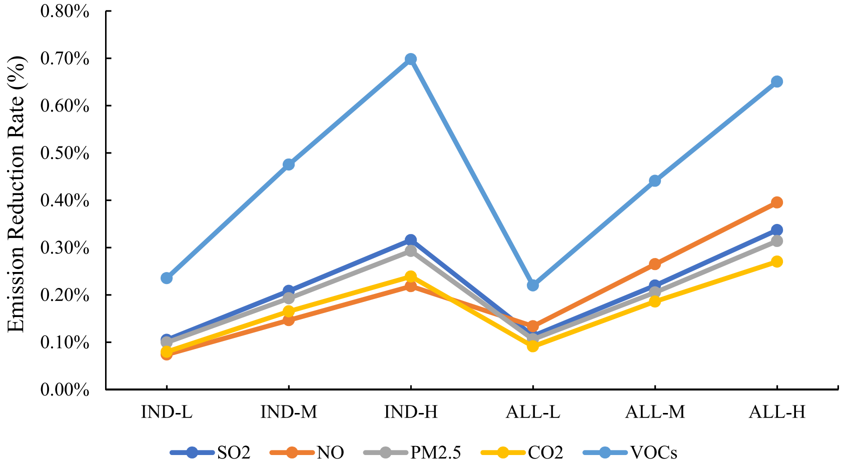

Fig. 5. National emission reduction rates of CO_2 and other air pollutants under the different scenarios.

Table 3
National macroeconomic impact in 2020 under the different scenarios.

Scenario	GDP		Resident consumption	Government consumption	CPI	Export
	Decrease/100 million RMB	Descend rate				
IND-L	−444.91	−0.0439 %	−0.0581 %	−0.0017 %	0.0506 %	−0.1171 %
IND-M	−908.51	−0.0897 %	−0.1131 %	0.0019 %	0.1018 %	−0.2651 %
IND-H	−1322.23	−0.1306 %	−0.1658 %	0.0058 %	0.1474 %	−0.3818 %
ALL-L	−682.31	−0.0674 %	−0.0871 %	−0.0507 %	0.0757 %	−0.1386 %
ALL-M	−1372.29	−0.1355 %	−0.1684 %	−0.0886 %	0.1506 %	−0.3130 %
ALL-H	−2011.85	−0.1987 %	−0.2480 %	−0.1296 %	0.2203 %	−0.4514 %

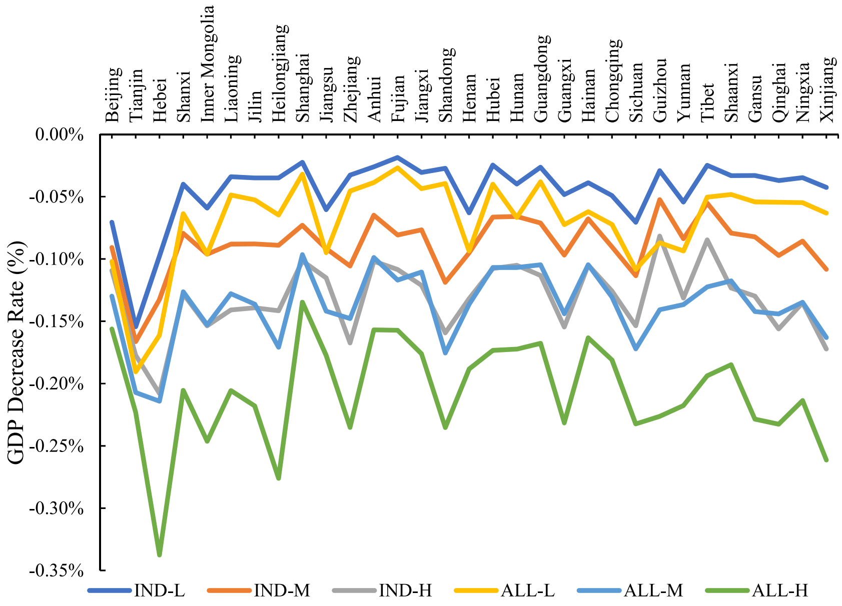

Fig. 6. Decrease rate of the GDP in each province under the different scenarios.

3.4. *Impact on the economy*

The introduction of a VOCs-EPT could have a negative impact on the national economy (Table 3) . Fig. 6 lists the changes in each macroeconomic indicator after a VOCs tax is imposed. When the industrial sector is levied, the national GDP in 2020 is expected to decrease by 44.491–132.223 billion RMB, which is equivalent to a decrease of 0.044 %–0.131 % in the national GDP growth rate in 2020. The national GDP is expected to decrease by 68.231–201.185 billion RMB when an all sector levy is imposed, which is equivalent to a decrease of 0.067 %–0.199 % in the national GDP growth rate in 2020. The wider the collection scope and the higher the tax rate are, the greater the negative impact on GDP. This is similar to the process by which a carbon tax affects the economy [58–60]. From the perspective of producers, a VOCs-EPT increases the tax burden on enterprises, thereby increasing the production costs; the export costs and product prices also increase accordingly. From the perspective of consumers, a VOCs-EPT could increase product prices, reduce consumer surplus, and affect consumer demand. This negative economic impact can also be reflected in household consumption, government consumption, the CPI and exports, among which household consumption and exports decrease to varying degrees. The CPI is expected to increase by 0.051 %–0.220 %. After the tax is applied, enterprises could transfer the tax cost to product costs, resulting in an increase in product prices, which could directly or indirectly increase the CPI. In addition, government consumption is affected by government tax revenue, output level and price factors [36,61]. Under the IND-M and IND-H scenarios, the positive factor of government tax revenue plays a leading role and thus increases government consumption; under the IND-L, ALL-L, ALL-M and ALL-H scenarios, negative factors, such as declining output and rising product prices, play a dominant role and thus decrease government consumption.

Due to the differences in the level of economic development, the status of pollution emissions and the stringency of the EPT policy in different regions, the economic impacts of collecting a VOCs-EPT in different regions also differ, as shown in Fig. 6. Under the IND-L and ALL-L scenarios, the provinces with the highest GDP decrease rates are Beijing, Tianjin, Hebei, Henan and Sichuan. However, under the other four scenarios, different combinations of provinces have the highest GDP decrease rates. Under the IND-M scenario, the provinces with the highest GDP decrease rates are Tianjin, Hebei, Shandong, Sichuan and Xinjiang; under the IND-H scenario, the provinces with the highest GDP decrease rates are Tianjin, Hebei, Zhejiang, Shandong and Xinjiang; under the ALL-M scenario, the provinces with the highest GDP decrease rates are Tianjin, Hebei, Heilongjiang, Shandong, and Sichuan; and under the ALL-H scenario, the provinces with the highest GDP decrease rates are Hebei, Inner Mongolia, Heilongjiang, Shandong and Xinjiang.

3.5. Impact on the industry

From an industry perspective, the petrochemical industry and the transportation industry are the key industries for VOCs emissions [62,63]. In 2020, the VOCs emissions of the petrochemical and transportation industries accounted for 45.3 % and 18.3 % of the total emissions, respectively, making them the top two industries in terms of VOCs emissions. When levies are imposed on the all sectors, the emission reductions from the petrochemical and transportation industries account for approximately 85.5 % of the total emission reductions; when levies are applied to industrial sectors, the emission reductions from the petrochemical industry account for approximately 89.5 % of the total emission reductions. Fig. 7 shows that the output reduction rates and emission reduction rates of each sector under different taxation scenarios. The emission reduction rates of the petrochemical industry range from 0.31 % to 0.96 %, and the emission reduction rates of transportation range from 0.08 % to 0.65 %. The proportion of emissions reductions in the petrochemical industry surges after the tax rate increases, and the proportion of emissions reductions in the transportation industry surges after the tax range is expanded, indicating that these industries have great potential for VOCs emission reductions.

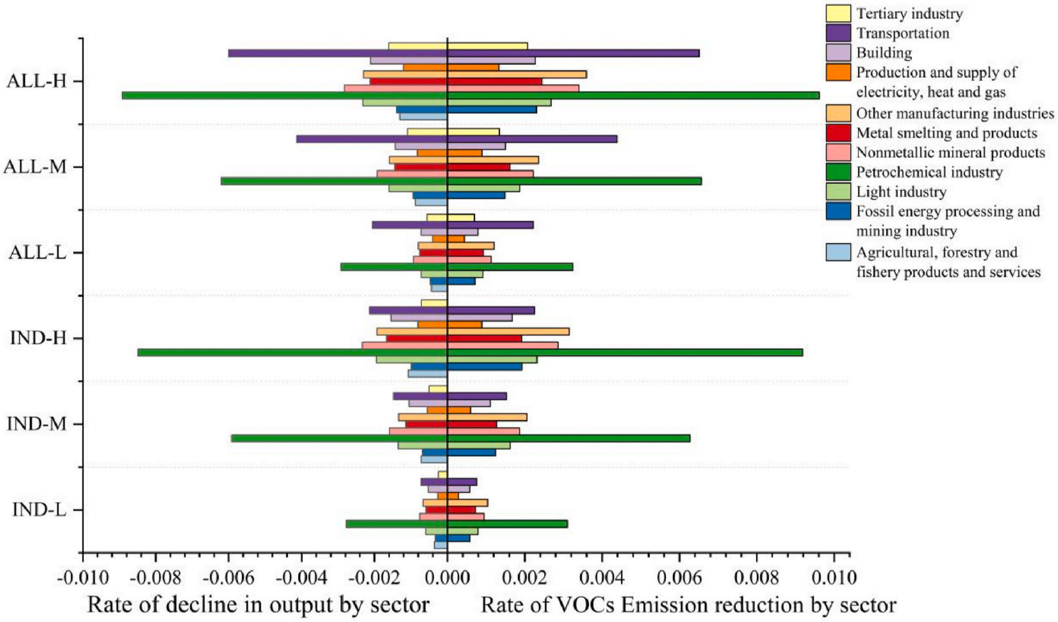

Fig. 7. Output reduction rate and emission reduction rate of each sector under the different scenarios.

The VOCs tax could cause cross-industry flows of production factors, such as capital and labor; production factors could flow from industries with high VOCs emissions to industries with low VOCs emissions, thus having a heterogeneous impact on industrial output. Fig. 7 shows that under any scenario, the rate of decrease in the output of the petrochemical industry is much greater than that of other industries, indicating that the collection of a VOCs-EPT has the greatest negative impact on the petrochemical industry. After a VOCs-EPT is imposed on the all sector, the output reduction rate of the transportation industry increases significantly, with the output reduction rate second only to that of the petrochemical industry, indicating that the scope of the tax levy has a greater impact on the transportation industry.

4. Conclusion and suggestions

4.1. Conclusions

In this study, the IO price model and the multi-regional IO model were employed; differentiated tax policies that accounted for both the scope of taxation and tax rates were formulated for 31 provinces; the effects of a VOCs-EPT on VOCs emission reductions and the synergistic emission reductions of CO_2 and other major air pollutants were predicted; and the economic impacts on each province and each industry were measured. The following conclusions were obtained:

The collection of VOCs-EPT can promote the VOCs emission reductions and has a synergistic emission reduction effect on CO_2 and other major air pollutants. The simulation results reveal that the VOCs emission reductions range from 41105.78 to 166466.31 tons. For the industrial sector levy and all sector levy scenarios, the VOCs emission reduction rates are only 0.22 % and 0.23 %, respectively, when the tax rate is low; with the gradual increase in the tax rate, the VOCs emission reduction rate and tax revenue increase by nearly 100 % and 50 %, respectively. The tax rate has a great impact on the effectiveness of a VOCs-EPT policy.

The collection of a VOCs-EPT has certain negative effects on China's macroeconomy. The simulation results show that the collection of a VOCs-EPT could cause the growth rate of China's GDP to decrease by 0.044 %–0.199 %, and household consumption could decrease by 0.058 %–0.248 %. The price indices of all sectors increase to varying degrees, with the CPI increasing by 0.051 %–0.220 %. However, the collection of a VOCs-EPT could increase government revenue by 48.697 billion RMB to 210.627 billion RMB.

The impact of collecting a VOCs-EPT varies regionally. Due to the differences in the economic development level, industrial structure, and pollution emission status of the provinces, the emission reduction effects and the degree of economic downturn in the provinces are different under different scenarios. Following an increase in tax rates with the same tax range, economic growth in Zhejiang, Shandong, and Xinjiang decreases at the fastest rate; following an expansion of the tax range for the same tax rate, economic growth in Heilongjiang and Xinjiang decreases at the fastest rate.

The impacts of collecting a VOCs-EPT on industries varies by industry. The VOCs emissions clearly exhibit industrial characteristics. The petrochemical industry and the transportation industry have the highest VOCs emissions, accounting for 63.5 % of the total annual VOCs emissions. These two industries are the most affected by a VOCs-EPT. In terms of the emission reduction effect, the VOCs emission reductions of the two industries account for 85–90 % of the total emission reduction, indicating that the two industries have the highest emission reduction potential. In terms of economic effects, the total output of the petrochemical industry decreases by 0.278 %–0.892 %, and the total output of the transportation industry decreases by 0.073 %–0.600 %, causing these two industries to suffer the most from negative economic impacts.

4.2. Suggestions

A VOCs-EPT rate should be reasonable. All regions should make full use of the authority provided by the tax law to determine and adjust tax rates; formulate applicable tax rates according to the characteristics of regional VOCs emissions, the level of economic development, and the carrying capacity of the environment; better realize the unification of economic and environmental benefits; and promote the prevention and control of VOCs pollution. In general, regions with high levels of VOCs emissions, high levels of economic development, and low environmental carrying capacity can set higher tax rates to increase the motivation and pressure on industries for emission reductions; regions with low levels of VOCs emissions, low levels of economic development, and high environmental carrying capacity can initially set lower tax rates and then gradually increase the tax rate to reduce the economic burden and support development.

A VOCs-EPT could be levied on key emitting industries in stages. The collection of VOCs-EPT has differentiated impacts on each industry; the key emitting industries should have the greatest emission reduction effect, the greatest negative impact on output, and the greatest tax pressure. VOCs taxation should be imposed first on industries with large baseline emissions and high emission reduction potential, such as the petrochemical industry. Subsequently, the scope of VOCs taxation on industries can be gradually expanded according to the need for VOCs control.

Simultaneously, a preferential VOCs-EPT policy should be promoted. For example, tax reductions and exemptions could be given to enterprises with low emission concentrations or those that actively use VOCs control technologies and equipment. This approach can guide enterprises in reducing VOC emissions and implementing green innovations while increasing the use of tax incentives as an economic instrument.

The capacity of VOCs monitoring and supervision should be strengthened. The VOCs monitoring technology, system and network should be improved, and comprehensive rectification that combines source reduction, process control and end-of-process control should be carried out. These actions can help achieve refined management and control. The support system for enterprise monitoring and declaration should be improved; the monitoring specifications and emission factors for VOCs pollutants should be developed and improved; the building of enterprise VOCs emission monitoring requirements and capacity should be strengthened; and the development of VOCs control technology and the service industry should be encouraged.

Data availability statement

The datasets used during the current study are available in the MEIC repository, http://meicmodel.org.cn/

CRediT authorship contribution statement

Ziwei Qian: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Feng Long:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Xianming Duan:** Supervision, Conceptualization. **Fenfen Bi:** Validation, Methodology. **Xue Tian:** Formal analysis, Data curation. **Zhankun Qi:** Data curation. **Chazhong Ge:** Project administration.

Declaration of competing interest

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

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