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The relationship between policy adjustment of SO_2 emissions charge standard and the growth of green total factor productivity—Evidence from China

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Evaluating the impact of environmental pollution charge system reform is necessary to help formulate a suitable policy to achieve a goal of emission control. The paper examines the relationship between policy adjustment of SO_2 emissions charge standard (PSC) and urban growth of green total factor productivity (GGTFP) using a natural experiment data of 280 cities in China. The results indicated that the improvement of SO_2 emissions charge standard can reduce emission and promote the GGTFP. Furthermore, it reveals an "N" relationship between the policy time period and the GGTFP, and an "Inverted-U" relationship between policy intensity and the GGTFP. The results imply that there is some policy room for policy makers to set a shadow price of pollution charge to maximize policy effect, and it is also important to consider the policy effect in the implementation time and intensity to maximize the policy effect and resource efficiency for the GGTFP and sustainable development.

KEYWORDS

SO_2 emissions charge standard, growth of green total factor productivity, time period effect of policy, intensity effect of policy, sustainable development

1 Introduction

The global average temperature in 2021 (from January to September) is about 1.09°C higher than that in 1850–1900 (*the 26th UN Climate Change Conference*). The United Kingdom declared that they will continue to work with all parties to increase climate action, build climate resilience and reduce carbon emissions (*the 26th UN Climate Change Conference, Glasgow, United Kingdom, November, 2021*). And China has also clearly put forward the goals of "carbon-peak" in 2030 and "carbon-neutralization" in 2060 for the climate change.

Limiting the discharge of pollutants, improving environmental quality and building a green modern country have become a long-term goal of China's sustainable development. On the road of sustainable development, China has made great stride to improve energy structure (*The ratio of coal in China's total energy consumption has been reduced to 59.0% in 2018 from 94.4% in 1953*) and to accelerate adoption of clean and low-carbon process (*the corresponding ratio of electric and other clean energy has increased from 1.8% to 14.3%*). However, China is still facing serious problem of air pollution (smoke discharge, waste-water, SO_2, PM2.5 and other emission) due to rapid development, energy consumption, and natural resource limitations (Fang et al., 2008; Ma et al., 2012; Wang et al., 2012; Li et al., 2011; Li et al., 2017; Zhang et al., 2016). The serious air pollution problem poses acute threat to public health and natural ecosystems (Streets and Waldhoff, 2000; Lu et al., 2010; Chung et al., 2011; Chen et al., 2012; Smith et al., 2011; Chen et al., 2012). The ratio of coal in China's total energy consumption has always remained the highest (*National Bureau of Statistics of China*), and coal is the dominant emitter of Sulfur Dioxide (SO_2), comprising 92% of total SO2 emissions (Su et al., 2011; Qian et al., 2020). Awan et al., 2022a and Awan et al., 2022b analysis the energy efficiency and CO_2 emission, as well as the impact of renewable energy, Internet use and foreign direct investment on carbon dioxide emissions. Qian et al., 2020 estimated the reduction potential of SO2 emissions from coal by 2050, and forecasted that SO_2 emissions will be reduced from 11.0 Mt in 2016 to 3.9–4.1 Mt in 2050 under four scenarios (NPS, CPS, RES, B2S), and the SO_2 emissions will be reduced by 62%–64% in 2050 compared to 2016, if the share of renewable energy in power generation is increased from 25% to 85%.

Scientists and scholars have pointed out that SO_2 emissions can be reduced by several measures, such as process treatment during and after combustion (Wang et al., 2017; Cheng and Zhang., 2018); adoption of SO_2 emissions control technologies for Flue-gas desulfurization (Streeter, 2016); the adoption of renewable energy (Awan et al., 2022a; Lu et al., 2010; Zhao et al., 2008; Arvesen and Hertwich, 2012; Nazari et al., 2010; Zhang et al., 2007; Xie et al., 2018); Subway expansion (Shen et al., 2016; Sun and Ouyang, 2014) and Intelligent Transportation Systems (ITS) (Chen Y. et al., 2017; Ahmad et al., 2017; Chen X. et al., 2017; Chen Z. et al., 2017; Ahmad et al., 2017), or carbon emissions trading policy (Zhang and Wang, 2021; Awan et al., 2022b). M Yang et al. (2018) have evaluated the impact of urban traffic investment on SO_2 emissions in China, and shown that urban traffic investment can reduce SO2 emissions significantly.

In recent years, the emission permit system as market policy instruments have gained increasing attention by policy makers and regulators (Boutabba et al., 2012), such as United States SO_2 trading program and carbon emission trading. Policy makers could plan their strategy to benefit from the dynamic behavioral response to the characteristics of the SO_2 trading market by exploiting the long-term relationship between SO_2 permit price, scrubbing costs, industrial production, and weather conditions (Boutabba et al., 2012; Burtraw, 1996; Ellerman and Montero, 1998; Carlson et al., 2000), as well as the relationship between electricity demand, regulation, technologies and SO_2 permit price (Schennach, 2000). In addition, the financial institutions (Godby et al., 1997; Mestelman et al., 1999; Cason and Gangadharan, 2006), public regulations, and other state laws (Winebrake et al., 1995; Fullerton et al., 1997; Arimura, 2002; Sotkiewicz and Holt, 2005) are also relevant factors to determine the SO_2 market price.

There exists a variety of regulations and market mechanisms on reducing SO_2 emissions, hence it is important to analyze and evaluate the effect of these environmental policy measures and methods. Zhao and Qiao, 2022 used a convex quantile regression method to evaluate shadow prices of CO_2, SO_2, and NOx produced by United States coal power plants from 2010 to 2017. Mekaroonreung and Johnson (2012) estimated the shadow prices of SO_2 and NOx for United States coal power plants by a convex nonparametric least squares approach. Kanada et al. (2013) identified the effect of regional disparity and cost-effective SO_2 pollution control through the use of the GAINS-China model (used for different SO2 emissions scenarios) in five mega-cities in China. The results from their study demonstrated a potential for large SO_2 reduction, as well as a great disparity in SO_2 reduction across regions. Other researchers conducted the estimation by using Data Envelopment Analysis (Zková, 2011; Charnes et al., 1978) or other similar methods (Färe et al., 1993; Coggins and Swinton, 1996; Boyd et al., 1996; Färe et al., 2005); other studies include technical efficiency, shadow price of carbon dioxide emissions, and substitutability for energy (Lee and Zhang, 2012); technical efficiency, shadow price and substitutability of Chinese industrial SO2 emissions (Xie et al., 2015; Li et al., 2015); environmental efficiency, productivity, and shadow price of carbon dioxide emissions (Deng and Du, 2020); and productivity change of United States coal power plants (Yaisawarng and Klein, 1994; Tyteca, 1997).

According to the above literature, it can be seen that limiting the discharge of pollutants (specially for SO_2 emissions from coal) is important for environmental quality, climate change and sustainable development. And some scholars have analyzed the SO_2 emissions from the perspective of energy structure, reduction potential, emission control, technical efficiency, emission trading, shadow prices of SO_2, and etc. (Awan et al., 2022a; Xie et al., 2018; Zhang and Wang, 2021; Awan et al., 2022b; Zhao and Qiao, 2022; Deng and Du, 2020; Qian et al., 2020; Tiwari et al., 2022). However, there are fewer articles to analysis the influence of policy and system on the SO_2 emissions in China. Besides, evaluating the effect of policy on the SO_2 emissions is necessary to help formulate a suitable policy to achieve a goal of emission control, and a comprehensive evaluation of the impact of policy will provide reference for the future policy making.

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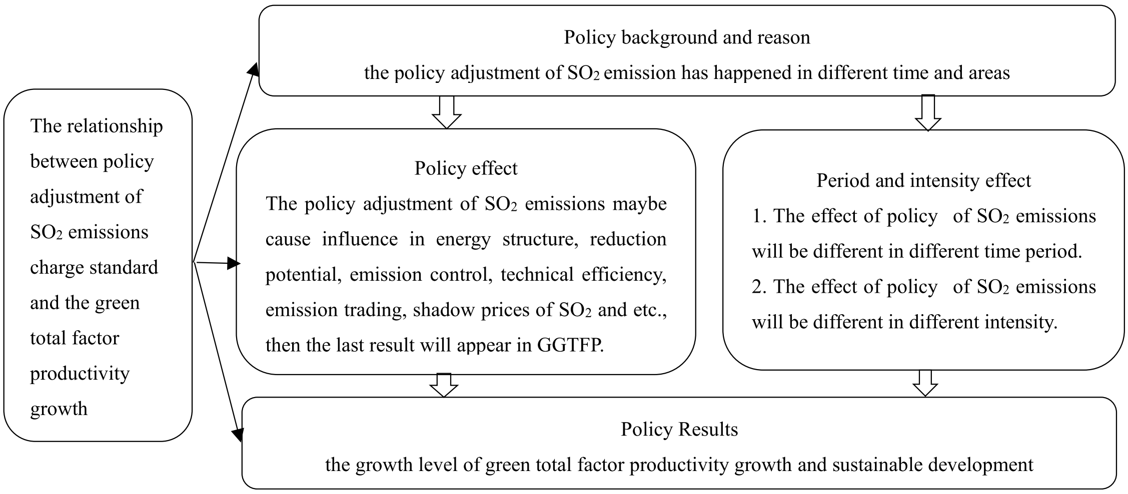

FIGURE 1
Analysis ideas for the relationship between policy adjustment of SO_2 emissions charge standard (PSC) and the growth of green total factor productivity (GGTFP).

Therefore, we choose an important environmental reform event (*Environmental pollution charge system reform*) to explore the policy effect of SO_2 emissions charge standard adjustment in China, as well as the relationship between policy adjustment of SO_2 emissions charge standard and environmental resource efficiency (Huang et al., 2022; Wang et al., 2020; Awan et al., 2022b; Liu and Luo, 2022), which is a relatively less studied research area, in addition, it also analyzed the policy effect of SO_2 emissions in different time period and in different intensity. Figure 1 is the analysis ideas for the relationship between policy adjustment of SO2 emissions charge standard (PSC) and the growth of green total factor productivity (GGTFP).

The rest of the paper is organized as follows. Section 2 describes the policy background of SO_2 emissions charge standard adjustment. Section 3 introduces the methodology and describes the data. Section 4 shows and discusses the results. Section 5 presents the conclusions and recommendations.

2 Policy backgroud

Pledging to achieve the 2030 vision (environmental issues are handled in an inclusive, sustainable and coherent manner through integrated policy and effective norms and institutions at all levels of governance), UNEP is committed to help countries to implement the environmental dimension of the 2030 Agenda, and will work to ensure that national and sector-based laws, standards, policies and plans on chemicals, waste management and air quality are fully grounded in the best-available science and technology (*MEDIUM TERM STRATEGY 2018–2021, Published by United Nations Environment Programme (UNEP), May 2016*).

In cooperation with the UNEP 2030, China sets a long-term goal of building a green and eco-friendly country, and has applied *the policy of saving resources and protecting the environment* to be a national policy mandate. The energy consumption per unit of GDP (a binding index) has been written into the national economic and social development plans consecutively from the 11th 5-year plan to 13th 5-year plan. In addition, Chinese government has also issued some planning and other special documents, such as *"the strategic action plan for energy development (2014–2020)", "the revolutionary strategy for energy production and consumption (2016–2030)", "the action plan for energy technology revolution and innovation (2016–2030)", and "the 13th 5-year plan for renewable energy development"*.

To achieve the dual target of energy conservation and emission reduction, and to induce the enterprises to reduce pollutant emissions and protect the ecological environment, the government has issued the relevant policy notifications such as "*adjusting the collection standard of sewage charges*" over time. In particular, the *"Administrative measures for collection standards of sewage charges"* [*(2003) No.31*] was promulgated on 28 February 2003 and took effect on 1 July 2003. It clarified the collection standard and set the calculation method of waste gas discharge fee, according to the type and quantity of pollutants discharged by the polluter. Specifically, the standard of SO_2 emissions charge was set at 0.6 yuan per

TABLE 1 The adjustment of SO_2 emissions charge standards in different provinces of China. (The unit of data in Table 1: yuan/pollution equivalent, *0.63 yuan/kg = 0.60 yuan/pollution equivalent*).

Province	Standard before adjustment	Cost adjustment time	Standard after adjustment	Province	Standard before adjustment	Cost adjustment time	Standard after adjustment
Anhui	0.60	2008.1.1	0.8	Heilongjiang	0.60	2012.7.1	1.20
	2009.1.1	1.0	Beijing	0.60	2014.1.1	9.50	
	2010.1.1	1.20	Ningxia	0.60	2014.3.1	1.20	
	2015.7.1	1.20	Zhejiang	0.60	2014.4.1	1.20	
Jiangsu	0.60	2007.1.1	1.20	Fujian	0.60	2015.1.1	1.20
	2016.1.1	3.60	Chongqing	0.60	2015.2.1	1.20	
	2018.1.1	4.8	Shanxi	0.60	2015.6.1	1.20	
Hebei	0.60	2008.7.1	0.96	Hunan	0.60	2015.6.30	1.20
	2009.7.1	1.20	Sichuan	0.60	2015.7.1	1.20	
	2015.1.1	2.4	Hubei	0.60	2015.7.1	1.20	
	2017.1.1	4.8	Shanxi	0.60	2015.6.1	1.20	
	2020.1.1	6.0	Jilin	0.60	2015.7.1	1.20	
Shandong	0.60	2008.7.1	1.20	Henan	0.60	2015.7.1	1.20
	2015.10.1	3.0	Gansu	0.60	2015.7.1	1.20	
	2017.1.1	6.0	Qinghai	0.60	2015.7.1	1.20	
Inner Mongolia	0.60	2008.7.10	0.90	Hainan	0.60	2015.7.1	1.20
	2009.1.1	1.20	Shaanxi	0.60	2015.7.1	1.20	
Guangxi	0.60	2009.1.1	0.90	Jiangxi	0.60	2015.10.26	1.20
	2010.1.1	1.20	Guizhou	0.60	2016.1.1	1.20	
	2015.7.1	1.20	Liaoning	0.60	2010.8.1	1.20	
Shanghai	0.60	2009.1.1	1.20			2015.7.1	1.20
	2018.1.1	6.65	Yunnan	0.60	2009.1.1	0.90	
	2019.1.1	7.60			2010.1.1	1.20	
Guangdong	0.60	2010.4.1		1.20		2015.7.1	1.20
	2016.1.1	1.20	Tianjin	0.60	2010.12.20	1.20	
Xinjiang	0.60	2012.8.1		1.20		2014.7.1	6.00
	2015.7.1	1.20					

pollution equivalent from 1 July 2005. Hence, we choose 2006 as the starting point of the data for analysis. A decade later, the policy of SO_2 emissions charge standard was changed into an environmental protection tax, and *"Environmental protection tax law of the People's Republic of China"* took effect from 1 January 2018. Hence, we choose 2017 as the ending point of the data for this study. Based on the document of *"Notice on adjusting the collection standard of sewage charges"* [(*2014*) *No. 2008*], different cities began to adjust the standard of the SO_2 emissions charge during the period of 2006–2017. Since the cities were affected by policies in different time and areas, it constituted a natural experiment to analyze the impact of environmental charge system reform on urban environment and resource efficiency. Specifically, the analysis involved how the standard adjustment of the SO_2 emissions charge affected the enterprise production process and then affected the GGTFP. The adjustment of SO_2 emissions charge standards in different provinces of China is described in Table 1, with the implementation time point and corresponding specific implementation standards indicated.

Data sources: The data of Table 1 are from official websites of provincial governments, such as *The provincial development and Reform Commission, The provincial finance department (Finance Bureau), The Provincial Ecological Environment Department (Provincial Environmental Protection Department), The provincial Price Bureau, the tax bureau, The provincial economic and Trade Commission, and The general office of the provincial government.* The data are collected and complied by authors.

3 Methodology and data

Since the policy adjustment of SO_2 emission has happened in different time and areas, it offered the natural experimental evidence to analyze the impact of policy reform on

TABLE 2 The description and measurement of control variables.

Variable name	Variable name and meaning
Industry	The ratio of urban tertiary industry output value to secondary industry output value
ln_ Expenditure	Ln of Expenditure on science and technology of the region (/Ten thousand yuan)
ln_ Density	Ln of Urban population density (person/km^2)
ln _Road	Ln of Residential road area (m^2/person)
ln_ GDP	Ln of Urban per capita GDP (/yuan)
ln_ FDI	Ln of foreign direct investment (/Ten thousand yuan)

environment and resource efficiency. Therefore, using panel data of 280 cities in China from 2006 to 2017 and difference-in-differences (DID) model (Jia et al., 2021; Zhang and Wang, 2021), we examine the policy adjustment effect of SO_2 emissions charge standard on the GGTFP (Huang et al., 2022; Wang et al., 2020; Liu and Luo, 2022). The estimation model is set as follows:

$$GGTFP_{it} = \beta_0 + \beta_1 PSC_{it} + \beta_z Z_{it} + u_i + \pi_t + \varepsilon_{it} \tag{1}$$

Where cities are indexed by i (i = 1,2,3 . . . , N.) and time periods are indexed by t (t = 1,2,3 . . . , T.). The dependent variable, $GGTFP_{it}$ is the growth rate of green total factor productivity of city i in period t, indicating the change of resource allocation efficiency (Huang et al., 2022; Wang et al., 2020; Lee and Lee, 2022; Zhang, JX et al., 2021; Fang et al., 2021; Pei L and Zhengmao L, 2022; Liu and Luo, 2022); PSC_{it} is the core explanatory variable, representing the policy adjustment effect of SO_2 emissions charge standard of city i in period t, such that if city i adjusts the standard of the SO_2 emissions charge in a certain t year for the first time, then the $PSC_{it} = 1$ in year t and later years, otherwise $PSC_{it} = 0$. If the policy becomes effective before July 1st, the current year will be included in the policy implementation year; if the policy occurs after July 1st, the current year will not be included, and the next year and subsequent years will be included in the policy implementation years. Z_{it} is a vector of control variables, which are shown in Table 2. u_i , π_t , ε_{it} represented the unobserved city random effect, time random effect and the i. i.d disturbance term, respectively. And the Hausmann test analysis indicated that the individual fixed effect model is more suitable than random effect model for panel estimation here.

This paper uses the method of SBM directional distance function and Luenberger function (Pei L and Zhengmao L, 2022; Fare et al., 1994; Fare et al., 2007; Fare and Grosskopf, 2010; Caves et al., 1982.) to measure and calculate the green total factor productivity of 280 cities from 2006 to 2017 in China. It is a factor input-output production function model commonly used to measure the growth of green total factor productivity (Lee and Lee, 2022; Zhang, JX et al., 2021; Fang et al., 2021; Pei L and Zhengmao L, 2022), which is essentially designed to capture the changes in resource efficiency (Huang et al., 2022; Wang et al., 2020). The method is as follows.

In the model, it is assumed that city K uses N kinds of elements as inputs X, X = $(x_1, x_2, x_3, \cdots x_N) \in R_N^+$, and produces M kinds of "good" outputs Y, Y = $(y_1, y_2, y_3, \cdots y_M) \in R_N^+$, as well as I types of "bad" outputs B, B = $(b_1, b_2, b_3, \cdots b_I) \in R_N^+$. The input and output set of city K are $(x^{t,k}, y^{t,k}, b^{t,k})$, when the corresponding production possibility set meets the basic assumptions. The DEA data envelopment method is used to set the model as follows:

$$P^t(x^t) = (y^t, b^t): \left\{ \begin{array}{l} \sum_{k=1}^{K} z_k^t y_{km}^t \geq y_{ki}^{t'}, \forall m \\ \sum_{k=1}^{K} z_k^t x_{kn}^t \geq x_{ki}^{t'}, \forall n \\ \sum_{k=1}^{K} z_k^t b_{ki}^t \geq b_{ki}^{t'}, \forall i \\ \sum_{k=1}^{K} z_k^t = 1, \; z_k^t \geq 0, \forall k \end{array} \right\} \tag{2}$$

where z_k^t represents the weight of each cross-sectional observation of the model. If $\sum_{k=1}^{K} z_k^t = 1$ and $z_k^t \geq 0$, this means that the production technology is variable return to scale (VRS). If $z_k^t \geq 0$, this means constant return to scale (CRS). This paper assumes VRS in the production process.

In this paper, the global SBM directional distance function and the Luenberger productivity index model (Pei L and Zhengmao L, 2022; Yang et al., 2019) is used; the specific method is as follows:

$$S_V^G\left(x^{t,k}, y^{t,k}, b^{t,k}, g^x, g^y, g^b\right) = max_{s^x s^y s^b} \frac{\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{g_n^x} + \frac{1}{M+I}\left(\sum_{m=1}^{M}\frac{s_m^y}{g_m^y} + \sum_{i=1}^{I}\frac{s_i^b}{g_i^b}\right)}{2} \tag{3}$$

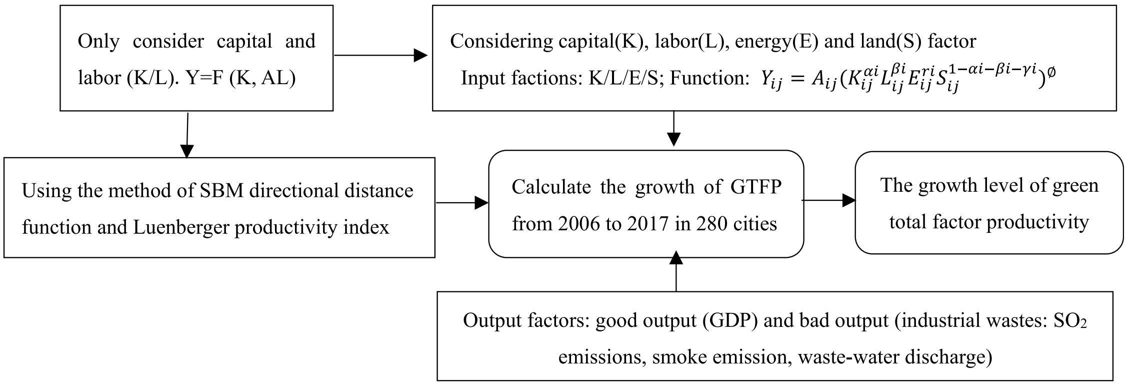

FIGURE 2
Measure method for the growth level of green total factor productivity.

$$\text{s.t.}\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{kn}^t, \forall n;\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{km}^t, \forall m$$

$$s.t.\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t - s_i^b = b_{ki}^t, \forall i$$

$$s.t.\sum_{k=1}^{K} z_k^t = 1,\ z_k^t \geq 0, \forall k;\ s_n^x \geq 0, \forall n;\ s_m^y \geq 0, \forall m; s_i^b \geq 0, \forall i$$

$$GGTFP_t^{t+1} = \frac{1}{2}\{[S_C^t(x^t, y^t, b^t: g) - S_C^t(x^{t+1}, y^{t+1}, b^{t+1}: g)] + [S_C^{t+1}(x^t, y^t, b^t: g) - S_C^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}: g)]\} \tag{4}$$

In the above, $x^{t,k}$, $y^{t,k}$, and $b^{t,k}$, respectively, represent the input of resource elements, "good" output and "bad" output of city K in T period. Then, g^x, g^y, and g^b, respectively, represent the direction vectors of input reduction, "good" output increase, and "bad" output decrease. Finally, s_n^x, s_m^y, and s_i^b, respectively, represent the slack vectors of input, "good" output and "bad" output; that is, the quantities of excessive input, insufficient "good" output and excessive "bad" output. If s_n^x, s_m^y, s_i^b are all positive, this means that the actual input s_n^x is greater than the boundary input, the actual good output s_m^y is less than the boundary output, and the actual bad output s_i^b is greater than the boundary output (Wang et al., 2010; Yang et al., 2015; Yang et al., 2019). Figure 2 is the measure method for the growth level of green total factor productivity growth.

To calculate the growth of green total factor productivity, we need to consider the "input factor" of production function and the "good output and bad output". In this paper, the "input factor" covers four factors of production (capital, labor, energy, land), and the "output factor" includes "the good output" (urban GDP (/yuan)) and "the bad output" (industrial wastes: SO_2 emissions, smoke emission, waste-water discharge) (Liu and Luo, 2022). The specific indicators are as follows: 1) Capital investment is represented by fixed assets investment in the city (Ten thousand yuan); 2) Labor is represented by the number of unit employees at the end of the year (Ten thousand people) in the city; 3) Energy input is represented by the main energy consumption in the city, which includes the urban liquefied petroleum gas (LPG) (t), natural gas (m^3), and electricity consumption (kwh). We calculate the heat generated from energy consumption according to the conversion coefficient to obtain the heat data (kJ). The conversion coefficient: LPG (50,179 kJ/kg, 1t = 1,000 kg), and Natural gas (32,238–38931 kJ/m^3). The average value of natural gas is 35,584.5 kJ/m^3, electricity consumption (3600kj/kwh). The energy conversion coefficient table is in *China energy statistical yearbook 2018*; 4) the investment of land resources elements is measured by urban construction area (km^2).

The policy adjustment variable of SO_2 emissions charge standard is the core explanatory variable, the policy coefficient β_1 reflects the impact of policy adjustment of SO_2 emissions charge standard (PSC) on the GGTFP. By construction, if the coefficient $\beta_1 > 0$, the improvement of pollution charge standard is conducive to boosting the GGTFP; if the coefficient $\beta_1 < 0$, the improvement of pollution charge standard is not conducive to increasing the GGTFP. The control variables and their specification are shown in Table 2. The summary statistics of explanatory and control variables are shown in Table 3.

Figure 3 displays the kernel density distribution of GGTFP in experiment group and control group. The GGTFP_psc1 stands for the kernel density estimation of GGTFP in experiment group (The cities that the policy of SO_2 emissions charge standard had been adjusted, then PCS = 1); the GGTFP_psc0 stands for the kernel density estimation of control group (cities that the policy of SO_2 emissions charge standard had not been adjusted, then

TABLE 3 Summary statistics of explanatory and control variables.

Sstats	GGTFP	Industry	Ln_expenditure	Ln_ density	Ln _road	Ln_ GDP	Ln_ Fdi
Mean	0.0158	0.9882	9.6327	6.4664	2.2455	12.4726	9.0695
Observation	3,360	3,360	3,360	3,360	3,360	3,360	3,360
Max	0.7607	3.5280	13.8716	8.3733	3.5942	13.6348	13.715
Min	−0.6764	0.1563	5.6937	3.6579	0.2390	11.0650	3.4965
Var	0.0399	0.3210	2.3057	0.8555	0.3436	0.2576	3.7573
Cv	12.6001	0.5733	0.1576	0.1430	0.2610	0.4006	0.2137

Note: To avoid the unduly influence of outliers, the data are processed by winsor2.

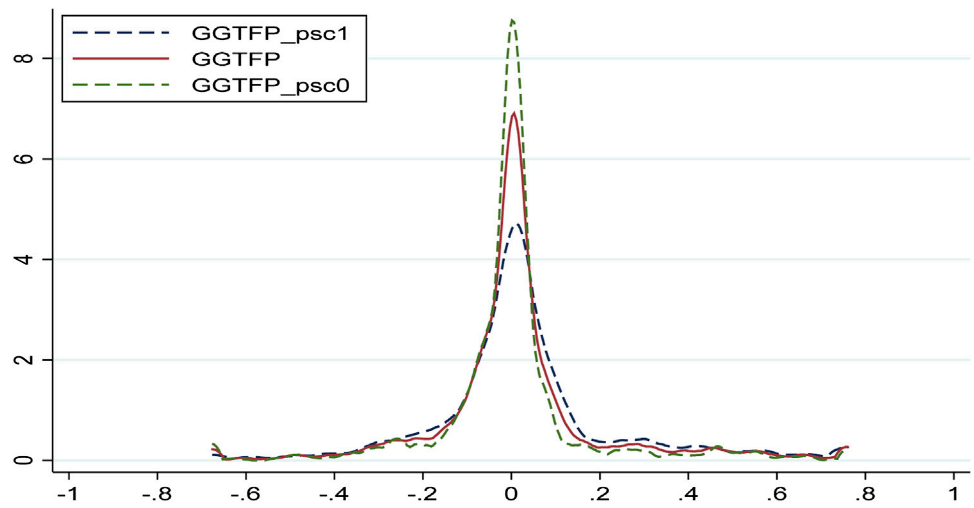

FIGURE 3
The kernel density distribution of GGTFP in experiment group and control group.

PSC = 0), and the GGTFP stands for the kernel density estimation of total sample cities. It appears that the skewness of GGTFP_psc1 is in the right of GGTFP and GGTFP_psc0, and the Kurtosis of GGTFP_psc0 is lower than other two curves. This suggests that the average level of GGTFP in experiment group is higher than control group due to the policy adjustment of SO_2 emissions charge standard, but the degree of concentration around mean value of curve is higher in control group.

4 Empirical results

Table 4 shows the impact of policy adjustment of SO_2 emissions charge standard on GGTFP. Eqs (1–3) in Table 4 are the baseline results without control variables, and Eq (4) in Table 4 are the results that include control variables. The result of Eq (6) in Table 4 showed that the policy adjustment of SO_2 emissions charge standard has significant effects on the GGTFP. Specifically, the coefficient of PSC in Eq (4) is 0.0356 and significant at 1% level, and the corresponding coefficients in other columns also show similar influence. Thus it can be concluded that the improvement of SO_2 emissions charge standard can reduced SO_2 emissions (emission from the oil, coal, or other energy), and increased the GGTFP of the city.

The lag period coefficient of PSC in Eqs (5–6) in Table 4 is significant at 1% level (PSC_1 = 0.0428; PSC_2 = 0.0489, respectively). The lag period policy coefficient can be regarded as reflecting the time delayed impact of SO_2 emissions charge standard adjustment on the GGTFP. It indicated that the environmental pollution charge may appear to have a positive long-time effect on the GGTFP. The possible theoretical mechanism and reasons for the results are as follows: The increase of SO_2 emissions charge standard raise the pollution

TABLE 4 The impact of environmental charge system reform on the GGTFP.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PSC	0.0404***	0.0195	0.0327***	0.0356***			0.0183	0.0315***	0.0259*
	(5.74)	(1.64)	(3.27)	(3.83)			(1.46)	(2.82)	(1.92)
PSC_1		0.0322***			0.0428***		0.0318**		0.0116
		(2.69)			(4.35)		(2.56)		(0.74)
PSC_2			0.0404***			0.0489***		0.0412***	0.0359***
			(3.89)			(4.55)		(3.72)	(2.71)
Control variables	NO	NO	NO	YES	YES	YES	YES	YES	YES
Time fixed effect	NO	NO	NO	NO	NO	NO	NO	NO	NO
Individual Fixed effect	YES	YES	YES	YES	YES	YES	YES	YES	YES
Constant	−0.0038	−0.0070	−0.0162**	−0.0624	0.0843	0.0471	0.1459	0.2306	0.2416
	(−0.84)	(−1.33)	(−2.56)	(−0.31)	(0.39)	(0.19)	(0.66)	(0.91)	(0.95)
Observations	3,360	3,080	2,800	3,360	3,080	2,800	3,080	2,800	2,800
R-squared	0.011	0.014	0.019	0.015	0.019	0.023	0.020	0.026	0.026
Number of dmu	280	280	280	280	280	280	280	280	280

Note: The Hausmann test found that the individual fixed effect model is suitable. t-statistics in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The PSC_1 and the PSC_2 represent the lag periods of policy variable. The results of control variables are not listed to save space.

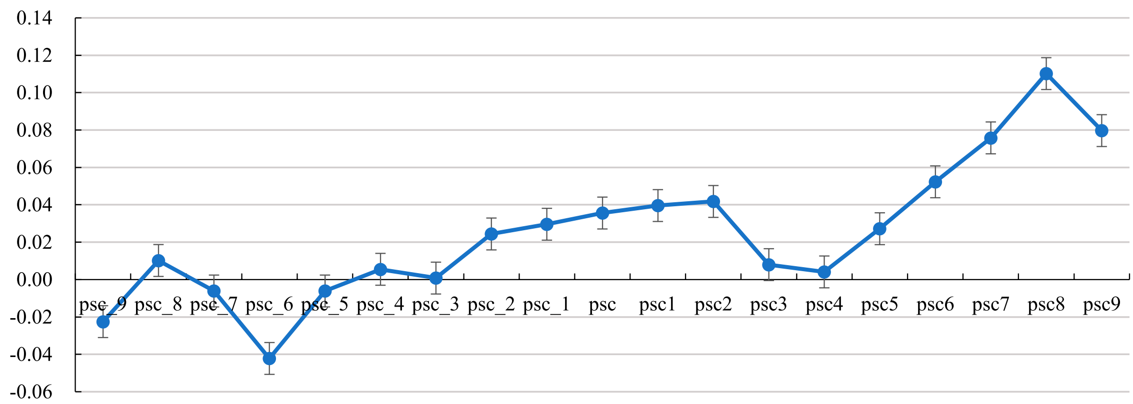

FIGURE 4
The estimated coefficients in Parallel trend test.

emission cost and production cost for enterprises, prompting the enterprises to carry out industrial restructuring, technological innovation, and production facility transformations in order to reduce the emission cost of SO_2. These actions and strategies taken by enterprises lead to improvement of the environmental and economic efficiency, and the increase in the GGTFP.

5 Robustness test

As mentioned above, the paper analyses the policy effect using the DID method, which requires that the change trend of the treatment group to be consistent with that of the control group. Here we conduct the parallel trend test to check the validity of this research methodology. The parallel trend test involves advancing the policy implementation year by 1 year (psc_1), 2 years (psc_2), 3 years (psc_3), etc. And delaying its implementation year by 1 year (psc1), 2 years (psc2) and 3 years (psc3), etc. Specifically, here we add 9 advance years (from psc_1 to psc_9) and 9 delay years (from psc1 to psc9) into the estimation equation to investigate the policy effect before and after the implementation year. The counterfactual results based on Eq (4) in Table 4 are presented in Figure 4.

Figure 4 shows that the change trend of the test group was consistent with the control group before the year of policy

TABLE 5 The results of propensity score matching.

psmatch2: Treatment assignment	psmatch2: Common support		Total
	Off support	On support	
Untreated	84	1,638	1722
Treated	14	1,624	1,638
Total	98	3,262	3,360

TABLE 6 The results of propensity score matching estimation.

Variable	Sample	Treated	Controls	Difference	S.E	T-stat
GGTFP	Unmatched	0.0304	0.0020	0.0284	0.0068	4.13
	ATT	0.0318	−0.0054	0.0373	0.0141	2.64
	ATU	0.0017	−0.0218	−0.0236	——	——
	ATE	——	——	0.0067	——	——

implementation from psc_1 to psc_9, and the estimated coefficients of PSC fluctuate around the ordinate 0. This indicates that there is no significant difference or systematic error between the test group and the control group before implementation of the policy. Hence, the equilibrium trend condition is satisfied, the test group exhibits parallel trend with the control group. But in the later years following policy implementation, the estimated coefficients have a significant upward trend, indicating that the policy can promote the GGTFP.

The core idea of Propensity Score Matching estimation (*PSM*) is to identify a group of cities that didn't implement the policy (*SO_2 emissions charge standard had not been adjusted*) but have same propensity score with cities that implement the policy (*SO_2 emissions charge standard had been adjusted*). Because the two group share similar characteristics (*the characteristics of control variables in* Table 1) except the policy implementation, the difference on the GGTFP between the two groups can be interpreted as the effect of the policy implementation.

The methodology of propensity score matching (Zhang Y J and Wang W,2021; Heckman et al., 1999) is set as follows:

$$GGTFP = D{*}GGTFP_1 + (1 - D){*}GGTFP_0$$

$P_{(X)} = probit\,[D = 1\,|X\,] = E[D|\,X\,] = \varphi(X)$; $\varphi(X)$ is for iidATT = E [$GGTFP_1 - GGTFP_0\,|D = 1]$ $= \{\,E[GGTFP_1 - GGTFP_0\,|D = 1\,, P_{(X)}]\}$ = E $\{\,E[GGTFP_1|D = 1, P_{(X)}] - E[GGTFP_0|D = 0, P_{(X)}]\,\}$ As shown above, if PSC = 1, then $GGTFP = GGTFP_1$; if PSC = 0, then. $GGTFP = GGTFP_0$

And if PSC = 1, then D = 1; if PSC = 0, then D = 0.

Using PSM method and the nearest neighbors matching method, each observation value in test group cities (*The policy of SO_2 emissions charge standard had been adjusted*) (D = PSC = 1) was matched with the observation value with similar propensity score in the control group cities (*The policy of SO_2 emissions charge standard had not been adjusted*) (D = PSC = 0). $P_{(X)}$ (*Propensity score*) is the conditional probability of accepting intervention under given conditions, as well as the probability of the policy adjustment of SO_2 emissions charge standard. The result of propensity score matching was shown in Table 5, and the estimation results of propensity score matching are shown in Table 6.

The estimation results of propensity score matching in Table 6 indicated that the coefficient difference of policy effect between treated and control group on ATT is 0.0373 (*t = 2.64, The results are significant*), which is similar to the results in Eq (4) from Table 4 (where *the coefficient of PSC is 0.0356*). Table 7 is a repeated test (500 iteration) of the PSM results, which converged to the same results on ATT as before.

All of the above results support and reinforce reliability of results, that is, the policy adjustment of SO_2 emissions charge standard can effectively promote the GGTFP. In order to check the reliability for the PSM method, we also use the method of bias-corrected matching estimator, the results are similar to PSM method, so it is reliable.

6 The time period effect of policy

To explore the nonlinear relation between the time period of policy implementation and the GGTFP, we modify the initial

TABLE 7 Using self _help method to get standard error in propensity score matching/repeat 500 times.

	Observed coef	Bootstrap std. Err	Z	$p > \|Z\|$	Normal-based [95% conf. Interval]	
r (ATT)	0.0373	0.0171	2.18	0.029	0.0037	0.0709
r (ATU)	−0.0236	0.0128	−1.84	0.066	−0.0487	0.0015
r (ATE)	0.0067	0.0115	0.58	0.559	−0.0158	0.0293

TABLE 8 The time period effect of policy adjustment of SO2 emissions charge standard.

	(1)	(2)	(3)
psc_time	0.0103***	0.0077*	0.0380***
	(5.68)	(1.84)	(4.89)
psc_time2		0.0003	−0.0092***
		(0.71)	(−4.37)
psc_time3			0.0007***
			(4.61)
Control variables	YES	YES	YES
Time fixed effect	NO	NO	NO
Individual Fixed effect	YES	YES	YES
Observations	3,360	3,360	3,360
R-squared	0.021	0.021	0.028
Number of dmu	280	280	280

Note: The psc_time2 and psc_time3 represent the square and cubic terms of psc_time respectively.

TABLE 9 The intensity effect of SO_2 emissions charge.

	(1)	(2)	(3)
psc_charge	0.0213***	0.0667***	0.0614**
	(3.75)	(4.32)	(2.42)
psc_charge2		−0.0068***	−0.0049
		(−3.16)	(−0.65)
psc_charge3			−0.0002
			(−0.26)
Control variables	YES	YES	YES
Time fixed effect	NO	NO	NO
Individual Fixed effect	YES	YES	YES
Observations	3,360	3,360	3,360
R-squared	0.015	0.018	0.018
Number of dmu	280	280	280

estimation equation (Eq (1) in 3.1 model specification). The revised estimation equation is set as follows:

$$GGTFP_{it} = \beta_0 + \beta_1 PSC\_time_{it} + \beta_2 PSC\_time2_{it} + \beta_3 PSC\_time3_{it} + \beta_z Z_{it} + u_i + \pi_t + \varepsilon_{it} \quad (5)$$

And psc_time2 = psc_time*psc_time (square term);

And psc_time3 = psc_time*psc_time*psc_time (cubic term);

The psc_time stands for the time period effect of SO_2 emissions charge standard adjustment on urban GGTFP. For example, if the value of psc_time is 1, it stands for the first year of policy implementation, and if the value of psc_time is 2, it stands for the second year of policy implementation, and etc. And the psc_time2 and psc_time3 represent the square and cubic term of psc_time respectively. The other variables are same as Eq (1) in 3.1 model specification.

The results in Table 8 indicated that the policy adjustment of SO_2 emissions charge standard had significant time period effect on the GGTFP, with the estimated coefficients significant at 1% level to confirm the presence of the nonlinear relationship. As shown by the coefficients of cubic function (0.0380, −0.0092, 0.0007) in Eq (3) of Table 8, the short-term policy effect on total factor productivity growth is positive, the intermediate effect turns negative, and the effect at last turns positive again. In other word, there was an "N" relationship between the policy time period and the GGTFP.

The plausible theoretical mechanism and reasons of the "N" relationship between the time period of policy implementation and the GGTFP could be as follows. In the initial year of the policy adjustment of SO_2 emissions charge standard, due to the higher emission cost and penalty from SO_2 emissions, enterprises actively carry out industrial restructuring, and production facilities transformation, which will effectively improve the growth level of green total factor productivity. But in the later stage, the enthusiasm and motivation for enterprise to enhance green production is reduced due to the decline of policy restraint ability, causing a slow decline on green total factor productivity. At last stage, under the pressure of enterprise survival, the enterprises will ultimately have to improve the environmental and economic efficiency to meet the social new requirements, thus forming an "N" relationship.

7 The intensity effect of policy

We investigated a possible nonlinear relation between the intensity of SO_2 emissions charge and the GGTFP. The estimation equation is set as follows:

$$GGTFP_{it} = \beta_0 + \beta_1 PSC\_charge_{it} + \beta_2 PSC\_charge2_{it} + \beta_3 PSC\_charge3_{it} + \beta_z Z_{it} + u_i + \pi_t + \varepsilon_{it} \quad (6)$$

And psc_charge2 = psc_charge*psc_charge;

And psc_charge3 = psc_charge*psc_charge*psc_charge.

The psc_charge stands for the intensity effect of SO_2 emissions charge, i.e. if the SO_2 emissions charge standard before adjustment in Table 1 is 0.60, then psc_charge = 0.60.; if the standard after adjustment in Table 1 is 1.20, then psc_charge = 1.20, using the difference of the emission charge standard to show the intensity effect. And the psc_charge2 and psc_charge3 represent the square and cubic terms of psc_charge respectively. The others variables are same as in Eq (1) on Table 9.

The result of Eq (3) on Table 9 showed that the intensity effect of SO_2 emissions charge has significant effects on the growth of green total factor productivity, and there is a nonlinear square term relationship between them, but psc_charge3 is not significant. According to the coefficients of square function (psc_charge = 0.0667, psc_charge2 = −0.0068) in Eq (2) on Table 9, the short-term effect between the intensity of SO_2 emissions charge and total factor productivity growth is positive, but the long-term effect is negative, so there may be an "Inverted-U″ relationship between the intensity effect and the GGTFP.

Initially, when facing a hike of SO_2 emissions charge, enterprises are pushed and motivated to carry out industrial restructuring, production facilities transformation, and technological innovation, which may enhance the GGTFP. But if the level and intensity of SO_2 emissions charge continue to rise, it will make current operation not profitable or firms was experiencing diminishing returns due to the increase of cost in production, causing the reduction of production efficiency, which will lead to an "Inverted-U″ relationship between emission charge intensity and productivity growth (a positive prime effect firstly, negative effect in later period).

8 Conclusion and policy implication

This paper uses the panel data of 280 cities in China from 2006 to 2017, and the DID model to examine the relationship between the policy adjustment of SO_2 emissions charge standard and the GGTFP, and it also examined the time period effect of policy implementation, and the intensity effect of SO_2 emissions charge on the GGTFP. The findings are as follows:

(1) The improvement of SO_2 emissions charge standard has significant effects on the GGTFP. It indicated that the improvement of SO_2 emissions charge standard can reduce SO_2 emissions in production process, and it can induce the enterprises to embrace and act on the concept of green development in production process, resulting in the growth of green total factor productivity. (2) There appears to be an "N" relationship between the policy time period of policy implementation and the GGTFP. That is, the policy adjustment of SO_2 emissions charge standard firstly has a positive effect on the growth of total factor productivity, negative effect in a later time, and eventually exhibits a positive effect again. (3) There also appears to be an "Inverted-U″ relationship between the policy intensity of SO2 emissions charge standard and green total factor productivity growth. That is, the policy intensity has a positive effect on productivity growth in a short-term but negative effect in a long-term.

Based on the above findings, some policy implications and recommendations are as follows:

Firstly, the evidence showed that the environmental pollution charge reform is conducive to resource efficiency and the GGTFP, which implies that there is room for market-oriented policy measure for policy makers to adopt for the development of high-quality economic and environmental protection. Instead of imposing outright restrictions by laws and regulations, policy maker can formulate a pricing strategy (such as an optional shadow price of pollution charge) to elicit behavioral response by enterprises for desirable environmental outcome, which may be more effective in market than direct government action.

Secondly, the policy time period and policy intensity are necessary factors to be considered in policy implementation and effect evaluation. The "N" relationship pattern in the time and "Inverted-U″ relationship in the intensity informed us that there was a best policy time or policy intensity choose to make full use of the policy effect, and the policy of pollution emission charge should be timely adjusted according to the effect in different time stage or in a different policy intensity.

Thirdly, with great regional differences, governments should adopt suitable and differentiated pollution emission charge measures in different area to maximize the policy effect and the GGTFP level according to the characteristics of enterprises at different stages of development. Besides, it is advised to consider their specific local economic situation and industry structure in different cities to set the differentiated emission charge standard, which will ensure the process successfully for environmental protection and sustainable development.

Recommendations for future study is that we need to more focus on the policy change of pollution emission charge, emission trading, shadow prices of SO_2 emission and so on in the background of carbon peak and carbon neutralization, and we also need to analysis the influence of these policy on the low-carbon and environmental-friendly production, the transformation of industrial structure, eco-economic efficiency, climate change, and the high-quality development in the future from different perspective, so as to set a more suitable policy pattern and policy intensity by the regional and temporal differences. The limitation of our study is that it only pays attention to the urban level from the macro perspectives, and it lacks the analysis of micro enterprises, because the enterprises of different industries or sizes may show different reactions when the external environment policy come to change.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, PL, SW; Methodology, PL, SW; Validation, PL, W-CH, ZC, SW, TR; Data management and analysis, PL, SW; Writing-original draft preparation, PL, SW; Writing-editing and revision, PL, W-CH

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahmad, F., Mahmud, S. A., and Yousaf, F. Z. (2017). Shortest processing time scheduling to reduce traffic congestion in dense urban areas. *IEEE Trans. Syst. Man. Cybern. Syst.* 5 (47), 838–855. doi:10.1109/TSMC.2016.2521838

Arimura, T. H. (2002). An empirical study of the SO 2 allowance market: effects of PUC regulations. *J. Environ. Econ. Manag.* 44, 271–289. doi:10.1006/jeem.2001.1202

Arvesen, A., and Hertwich, E. G. (2012). Corrigendum: environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. *Environ. Res. Lett.* 7. doi:10.1088/1748-9326/7/3/039501

Awan, A., Abbasi, K. R., Rej, S., Bandyopadhyay, A., and Lv, K. (2022a). The impact of renewable energy, internet use and foreign direct investment on carbon dioxide emissions: A method of moments quantile analysis. *Renew. Energy* 189 (8), 454–466. doi:10.1016/j.renene.2022.03.017

Awan, A., Kocoglu, M., Banday, T. P., and Tarazkar, M. H. (2022b). Revisiting global energy efficiency and CO2 emission nexus: fresh evidence from the panel quantile regression model. *Environ. Sci. Pollut. Res.* 29 (31), 47502–47515. doi:10.1007/s11356-022-19101-5

Boutabba, M. A., Beaumais, O., and Lardic, S. (2012). Permit price dynamics in the U.S. SO 2 trading program: A cointegration approach. *Energy Econ.* 34, 714–722. doi:10.1016/j.eneco.2011.04.004

Boyd, G., Molburg, J., and Prince, R. (1996). Alternative methods of marginal abatement cost estimation: non-parametric distance function. *Proc. USAEE/IAEE 17th Conf.*, 86–95.

Burtraw, D. (1996). The SO_2EMISSIONS trading program: COST savings without allowance trades. *Contemp. Econ. Policy* 14, 79–94. doi:10.1111/j.1465-7287.1996.tb00615.x

Carlson, C. P., Burtraw, D., Cropper, M., and Palmer, K. (2000). SO2 control by electric utilities: what are the gains from trade. *J. Political Econ.* 108, 1292–1326. doi:10.1086/317681

Cason, T. N., and Gangadharan, L. (2006). Emissions variability in tradable permit markets with imperfect enforcement and banking. *J. Econ. Behav. Organ.* 61, 199–216. doi:10.1016/j.jebo.2005.02.007

Caves, D. W., Christensen, L. R., and Diewert, W. E. (1982). Multilateral comparisons of output, input, and productivity using superlative index numbers. *Econ. J.* 92 (365), 73–86. doi:10.2307/2232257

Charnes, A., Cooper, W. W., and Rhodes, E. (1978). Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* 2, 429–444. doi:10.1016/0377-2217(78)90138-8

Chen, R., Huang, W., Wong, C.-M., Wang, Z., Quoc Thach, T., Chen, B., et al. (2012). Short-term exposure to sulfur dioxide and daily mortality in 17 Chinese cities: The China air pollution and health effects study (CAPES). *Environ. Res.* 118, 101–106. doi:10.1016/j.envres.2012.07.003

Chen, X., Shao, S., Tian, Z., Xie, Z., and Yin, P. (2017). Impacts of air pollution and its spatial spillover effect on public health based on China's big data sample. *J. Clean. Prod.* 14, 915–925. doi:10.1016/j.jclepro.2016.02.119

Chen, Z., Li, L., and Liu, J. (2017). The emissions reduction effect and technical progress effect of environmental regulation policy tools. *J. Clean. Prod.* 149, 191–205. doi:10.1016/j.jclepro.2017.02.105

Cheng, G., and Zhang, C. (2018). Desulfurization and denitrification technologies of coal-fired flue gas. *Pol. J. Environ. Stud.* 27, 481–489. doi:10.15244/pjoes/75959

Chung, K. F., Zhang, J., and Zhong, N. (2011). Outdoor air pollution and respiratory health in Asia. *Respirology* 16 (7), 1023–1026. doi:10.1111/j.1440-1843.2011.02034.x

Coggins, J. S., and Swinton, J. R. (1996). The price of pollution: a dual approach to valuing SO2 allowances. *J. Environ. Econ. Manag.* 30, 58–72. doi:10.1006/jeem.1996.0005

Deng, X., and Du, L. (2020). Estimating the environmental efficiency, productivity, and shadow price of carbon dioxide emissions for the belt and road initiative countries. *J. Clean. Prod.* 277 (3), 123808. doi:10.1016/j.jclepro.2020.123808

Ellerman, A. D., and Montero, J. P. (1998). The declining trend in sulfur dioxide emissions: Implications for allowance prices. *J. Environ. Econ. Manag.* 36, 26–45. doi:10.1006/jeem.1998.1033

Fang, L., Hu, R., Mao, H., and Chen, S. (2021). How crop insurance influences agricultural green total factor productivity: Evidence from Chinese farmers. *J. Clean. Prod.* 321 (7), 128977. doi:10.1016/j.jclepro.2021.128977

Fang, Y. P., Zeng, Y., and Li, S. M. (2008). Technological influences and abatement strategies for industrial sulphur dioxide in China. *Int. J. Sustain. Dev. World Ecol.* 15, 122–131. doi:10.1080/13504500809469777

Fare, R., and Grosskopf, S. (2010). Directional distance functions and slacks-based measures of efficiency: Some clarifications. *Eur. J. Operational Res.* 206 (3), 702. doi:10.1016/j.ejor.2010.02.033

Fare, R., Grosskopf, S., and Norris, M. (1994). Productivity growth, technical progress, and efficiency change in industrialized countries. *Am. Econ. Rev.* 84 (5), 1040–1044.

Fare, R., Grosskopf, S., and Pasurka, C. A. (2007). Environmental production functions and environmental directional distance functions. *Energy* 32 (7), 1055–1066. doi:10.1016/j.energy.2006.09.005

Färe, R., Grosskopf, S., Lovell, C. A. K., and Yaisawarng, S. (1993). Derivation of shadow prices for undesirable outputs: a distance function approach. *Rev. Econ. Stat.* 75, 374–380. doi:10.2307/2109448

Färe, R., Grosskopf, S., Noh, D. W., and Weber, W. (2005). Characteristics of a polluting technology: theory and practice. *J. Econom.* 126, 469–492. doi:10.1016/j.jeconom.2004.05.010

Fullerton, D., McDermott, S. P., and Caulkins, J. P. (1997). Sulfur dioxide compliance of a regulated utility. *J. Environ. Econ. Manag.* 34, 32–53. doi:10.1006/jeem.1997.1004

Godby, R., Mestelman, S., Muller, R. A., and Welland, J. D. (1997). Emissions trading with shares and coupons when control over discharges is uncertain. *J. Environ. Econ. Manag.* 32, 359–381. doi:10.1006/jeem.1997.0977

Heckman, J. J., Lalonde, R. J., and Smith, J. A. (1999). The economics and econometrics of active labor market programs. *Handb. Labor Econ.* 3 (1), 1865–2097. doi:10.1016/s1573-4463(99)03012-6

Huang, Xiuquan, Feng, Chao, Qin, Jiahong, Wang, Xi, and Zhang, Tao (2022). Measuring China's agricultural green total factor productivity and its drivers during 1998–2019. *Sci. Total Environ.* 829 (10), 154477. doi:10.1016/j.scitotenv.2022.154477

Jia, R., Shao, S., and Yang, L. (2021). High-speed rail and CO2 emissions in urban China: A spatial difference-in-differences approach. *Energy Econ.* 99, 105271. doi:10.1016/j.eneco.2021.105271

Kanada, M., Dong, L., Fujita, T., Fujii, M., Inoue, T., Hirano, Y., et al. (2013). Regional disparity and cost-effective SO2 pollution control in China: A case study in 5 mega-cities. *Energy Policy* 61, 1322–1331. doi:10.1016/j.enpol.2013.05.105

Lee, C. C., and Lee, C. C. (2022). How does green finance affect green total factor productivity? Evidence from China. *Energy Econ.* 107, 105863. doi:10.1016/j.eneco.2022.105863

Lee, M., and Zhang, N. (2012). Technical efficiency, shadow price of carbon dioxide emissions, and substitutability for energy in the Chinese manufacturing industries. *Energy Econ.* 34 (5), 1492–1497. doi:10.1016/j.eneco.2012.06.023

Li, C., McLinden, C., Fioletov, V., Krotkov, N., Carn, S., Joiner, J., et al. (2017). India is overtaking China as the world's largest emitter of anthropogenic sulfur dioxide. *Sci. Rep.* 7, 14304–14307. doi:10.1038/s41598-017-14639-8

Li, L., Tan, Z., Wang, J., Xu, J., Cai, C., and Hou, Y. (2011). Energy conservation and emission reduction policies for the electric power industry in China. *Energy Policy* 39, 3669–3679. doi:10.1016/j.enpol.2011.03.073

Li, X., Wu, X., and Zhang, F. (2015). A method for analyzing pollution control policies: Application to SO2 emissions in China. *Energy Econ.* 49, 451–459. doi:10.1016/j.eneco.2015.03.015

Liu, P., and Luo, Z. (2022). A measurement and analysis of the growth of urban green total factor productivity——based on the perspective of energy and land elements. *Front. Environ. Sci.* 10, 838748. doi:10.3389/fenvs.2022.838748

Lu, Z., Streets, D. G., Zhang, Q., Wang, S., Carmichael, G. R., Cheng, Y. F., et al. (2010). Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000. *Atmos. Chem. Phys.* 10, 6311–6331. doi:10.5194/acp-10-6311-2010

Ma, S., Wen, Z., and Chen, J. (2012). Scenario analysis of sulfur dioxide emissions reduction potential in China's iron and steel industry. *J. Industrial Ecol.* 16, 506–517. doi:10.1111/j.1530-9290.2011.00418.x

Mekaroonreung, M., and Johnson, A. L. (2012). Estimating the shadow prices of SO2 and NOx for U.S. coal power plants: A convex nonparametric least squares approach. *Energy Econ.* 34 (3), 723–732. doi:10.1016/j.eneco.2012.01.002

Mestelman, S., Moir, R., and Muller, R. A. (1999). "A laboratory test of a Canadian proposal for an emissions trading program," in *Research in experimental economics*. Editors C. Holt and R. M. Isaac, 7, 45–92.

Nazari, S., Shahhoseini, O., Davari, S., Paydar, R., and Delavar-Moghadam, Z. (2010). Experimental determination and analysis of CO2, SO_2 and NOx emission factors in Iran's thermal power plants. *Energy* 35, 2992–2998. doi:10.1016/j.energy.2010.03.035

Qian, Y., Scherer, L., Tukker, A., and Behrens, P. (2020). China's potential SO2 emissions from coal by 2050. *Energy Policy* 147, 111856. doi:10.1016/j.enpol.2020.111856

Schennach, S. M. (2000). The economics of pollution permit banking in the context of title IV of the 1990 clean air act amendments. *J. Environ. Econ. Manag.* 40, 189–210. doi:10.1006/jeem.1999.1122

Shen, Q., Chen, P., and Pan, H. (2016). Factors affecting car ownership and mode choice in rail transit-supported suburbs of a large Chinese city. *Transp. Res. Part A Policy Pract.* 94, 31–44. doi:10.1016/j.tra.2016.08.027

Smith, S. J., Aardenne, J. V., Klimont, Z., Andres, R. J., Volke, A., and Delgado Arias, S. (2011). Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmos. Chem. Phys.* 10 (6), 1101–1116. doi:10.5194/acp-11-1101-2011

Sotkiewicz, P. M., and Holt, L. (2005). Public utility commission regulation and cost-effectiveness of title IV: Lessons for CAIR. *Electr. J.* 18, 68–80. doi:10.1016/j.tej.2005.08.003

Streeter, J. L. (2016). Adoption of SO 2 emission control technologies - an application of survival analysis. *Energy Policy* 90, 16–23. doi:10.1016/j.enpol.2015.11.035

Streets, D. G., and Waldhoff, S. T. (2000). Present and future emissions of air pollutants in China:. *Atmos. Environ.* 34 (3), 363–374. doi:10.1016/S1352-2310(99)00167-3

Su, S., Li, B., Cui, S., and Tao, S. (2011). Sulfur dioxide emissions from combustion in China: from 1990 to 2007. *Environ. Sci. Technol.* 45, 8403–8410. doi:10.1021/es201656f

Sun, C. W., Ouyang, X. L., Cai, H., Luo, Z., and Li, A. (2014). Household pathway selection of energy consumption during urbanization process in China. *Energy Convers. Manag.* 84, 295–304. doi:10.1016/j.enconman.2014.04.038

Tiwari, A. K., Kocoglu, M., Banday, U. J., and Awan, A. (2022). Hydropower, human capital, urbanization and ecological footprints nexus in China and Brazil: evidence from quantile ARDL. *Environ. Sci. Pollut. Res. Int.* doi:10.1007/s11356-022-20320-z

Tyteca, D. (1997). Linear programming models for the measurement of environmental performance of firms — Concepts and empirical results. *J. Product. Anal.* 8, 183–197. doi:10.1023/a:1013296909029

Wang, B., Wu, Y. R., and Yan, P. F. (2010). Regional environmental efficiency and green TFP growth in China. *Econ. Res.* 5, 95–109.

Wang, F., Liu, B., and Zhang, B. (2017). Embodied environmental damage in interregional trade: a MRIO-based assessment within China. *J. Clean. Prod.* 140, 1236–1246. doi:10.1016/j.jclepro.2016.10.036

Wang, J., Lei, Y., Yang, J., and Yan, G. (2012). China's air pollution control calls for sustainable strategy for the use of coal. *Environ. Sci. Technol.* 46, 4263–4264. doi:10.1021/es301226n

Wang, Ke-Liang, Pang, Su-Qin, Ding, Li-Li, and Zhuang, Miao (2020). Combining the biennial Malmquist–Luenberger index and panel quantile regression to analyze the green total factor productivity of the industrial sector in China. *Sci. Total Environ.* 739, 140280. doi:10.1016/j.scitotenv.2020.140280

Winebrake, J. J., Farrell, A. E., and Bernstein, M. A. (1995). The clean air act's sulfur dioxide emissions market: estimating the costs of regulatory and legislative intervention. *Resour. Energy Econ.* 17, 239–260. doi:10.1016/0928-7655(95)00006-j

Xie, H., Shen, M., and Wei, C. (2015). Technical efficiency, shadow price and substitutability of Chinese industrial SO2 emissions: a parametric approach. *J. Clean. Prod.* 112 (2), 1386–1394. doi:10.1016/j.jclepro.2015.04.122

Xie, Y., Dai, H., and Dong, H. (2018). Impacts of SO_2 taxations and renewable energy development on CO_2, NOx and SO2 emissions in Jing-Jin-Ji region. *J. Clean. Prod.* 171, 1386–1395. doi:10.1016/j.jclepro.2017.10.057

Yaisawarng, S., and Klein, J. D. (1994). The effects of sulfur dioxide controls on productivity change in the U.S. electric power industry. *Rev. Econ. Stat.* 76, 447–460. doi:10.2307/2109970

Yang, M., Ma, T., and Sun, C. (2018). Evaluating the impact of urban traffic investment on SO2 emissions in China cities. *Energy Policy* 113, 20–27. doi:10.1016/j.enpol.2017.10.039

Yang, X., Li, X. P., and Zhou, D. C. (2015). Research on the difference and convergence of carbon productivity in China's manufacturing industry. *Res. Quant. Econ. Technol. Econ.* 12, 3–20. doi:10.13653/j.cnki.jqte.2015.12.001

Yang, X., Li, X., and Zhong, C. (2019). Research on the evolution trend and influencing factors of industrial biased technological progress in China. *Res. Quant. Econ.* 4, 101–119. doi:10.13653/j.cnki.jqte.2019.04.006

Zhang, J., Lu, G., Skitmore, M., and Ballesteros-Perez, P. (2021). A critical review of the current research mainstreams and the influencing factors of green total factor productivity. *Environ. Sci. Pollut. Res.* 28 (27), 35392–35405. doi:10.1007/s11356-021-14467-4

Zhang, P., Jia, G., and Wang, G. (2007). Contribution to emission reduction of CO_2 and SO_2 by household biogas construction in rural China. *Renew. Sustain. Energy Rev.* 11, 1903–1912. doi:10.1016/j.rser.2005.11.009

Zhang, Y. J., Hao, J. F., and Song, J. (2016). The CO_2 emission efficiency, reduction potential and spatial clustering in China's industry: evidence from the regional level *Appl. Energy* 174, 213–223. doi:10.1016/j.apenergy.2016.04.109

Zhang, Y. J., and Wang, W. (2021). How does China's carbon emissions trading (CET) policy affect the investment of CET-covered enterprises? *Energy Econ.* 98, 105224. doi:10.1016/j.eneco.2021.105224

Zhao, S., and Qiao, G. (2022). The shadow prices of CO2, SO2 and NOx for U.S. coal power industry 2010–2017: a convex quantile regression method. *J. Product. Anal.* 57 (3), 243–253. doi:10.1007/s11123-022-00629-0

Zhao, Y., Wang, S., Duan, L., Lei, Y., Cao, P., and Hao, J. (2008). Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction. *Atmos. Environ. X.* 42, 8442–8452. doi:10.1016/j.atmosenv.2008.08.021

Zková, P. (2011). The overall efficiency of the dynamic DEA models. *Cent. Eur. J. Oper. Res.* 2021 (1030), 495–506. doi:10.1007/s10100-021-00777-y