frontiers in Environmental Science

ORIGINAL RESEARCH
published: 21 February 2022
doi: 10.3389/fenvs.2021.823536

Can Market-Based Environmental Regulation Promote Green Technology Innovation? Evidence from China

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To alleviate climate change and environmental issues, China has implemented many environmental regulation policies. This paper takes the SO_2 and carbon emission trading pilots (*SETP*, *CETP*) in China as the quasi-experiment and, under the difference-in-difference framework, studies whether the market-based environmental regulation (MER) policy promotes green technology innovation. The investigation is conducted employing patent data with the "IPC Green Inventory" on the panel data of China's 278 prefectural-level cities over the period 2003–2017. We found that 1) as for a single policy, *SETP* successfully promoted green technology innovation, but failed in *CETP*, which shows that not all MER policies can play a positive effect on green technology innovation. Meanwhile, *SETP* and *CETP* did not change the direction of technology innovation and had no impact on total technology innovation. 2) For the combination policy, *SETP* and *CETP* failed to jointly promote green technology innovation, and with the current MER policy in China, it is difficult to realize the policy combination effect. This result implies that repeated implementation of similar environmental policies failed to stimulate innovation. 3) Heterogeneity analysis shows that the promotion effect of *SETP* on green technology innovation, mainly in the eastern region, and the promotion effect on invention patents is more prominent than utility model patents, which shows that green technology has improved not only in quantity but also in quality. These findings provide empirical evidence and policy implication for the efficient implementation of environmental regulation.

Keywords: market-based environmental regulation, green technology innovation, SO2 emission trading pilot, carbon emission trading pilot, patents

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Edited by:
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Reviewed by:
Fanxin Meng, Beijing Normal University, China
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Jian Chai, Xidian University, China

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Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

Received: *27 November 2021*
Accepted: *29 December 2021*
Published: *21 February 2022*

Citation:
Qu F, Xu L and Chen Y (2022) Can Market-Based Environmental Regulation Promote Green Technology Innovation? Evidence from China. Front. Environ. Sci. 9:823536. doi: 10.3389/fenvs.2021.823536

INTRODUCTION

The potential contradiction between economic growth and environmental pollutants has threatened the development of human society. Through the environmental regulation (ER) policy to control the pollutants and promote technology innovation, to achieve the coordination between economic growth and environmental pollutants is the accordant goal for all over the world. This is because technological innovation is not only an essential driving force for economic growth but also a powerful weapon to compensate for environmental losses. Compared with the emission reduction effect of environmental policies, the emission reduction effect of technology innovation is easier to discuss (Cheng et al., 2020). In particular, green technology innovation plays a prominent role in economic green transformation and energy conservation and emission reduction. Therefore, whether ER policy can promote technology innovation and whether technology innovation can solve energy and environmental issues have always been the focus (Calel and Dechezleprêtre, 2016; Cai et al., 2020; Sun et al., 2021).

The Porter hypothesis is the representative research on ER policy and technology innovation (Porter and Linde, 1995). Although the Porter hypothesis is mainly aimed at enterprises, the endogenous economic growth theory shows that the technical change of an economic sector is determined by the technology innovation activities of all enterprises in this sector (Acemoglu et al., 2012; Aghion et al., 2016). Therefore, the Porter hypothesis can also be employed as a reference for the research at the macroeconomic level. It must be noted that there are many types of ER policies, which can be divided into command-and-control environmental regulation (CER), market-based environmental regulation (MER), voluntary environmental regulation (VER), and so on (Guo and Yuan, 2020). The primary objective of those ER policies is of course to control the pollutants, but from the economic perspective, it is crucial that they also provide incentives for technology innovation, since the new technologies may substantially reduce the cost of abatement (Jaffe et al., 2002). The impact of different types of ER policies on technology innovation belongs to the research category of the "general Porter hypothesis" (Jaffe and Palmer, 1997).

On the contrary, what types of technology innovation can a specific type of ER policy promote? This is the research on the "weak Porter hypothesis" (Jaffe and Palmer, 1997). Compared with general innovation, green technology innovation makes more prominent contributions to the environment and economic growth. It is vital to achieving "win-win" results in the economy and environment. Meanwhile, compared with the CER policy, countries around the world have advocated the adoption of MER policies to promote green technology innovation (Calel and Dechezleprêtre, 2016). Specifically, the effect of the "weak Porter hypothesis" produced by the CER policy has been proved to encourage specific innovation, especially green technology innovation (Lanoie et al., 2008; Ambec et al., 2013). The MER policy may affect green technology innovation in the following: Firstly, from the perspective of enterprises, MER policy increases the possibility of profits for enterprises, thus increasing R&D investment, which is conducive to green technology innovation (Ambec et al., 2013; Wang et al., 2019). Secondly, from a regional perspective, the agglomeration effect produced by the MER policy is conducive to technology diffusion, which is also beneficial to green technology innovation. Unfortunately, the cost of the MER policy is higher than that of the CER policy (Ambec et al., 2013), and the fact that environmental pollution always exists has not been changed (Zhang et al., 2017). Therefore, we have reason to doubt that the promotion effect of the MER policy on green technology innovation may not be effective in every country or region.

Does China implement the MER policy? Compared with the European Union emissions trading scheme (EU ETS), the SO_2 emission trading pilot (*SETP*) and carbon emission trading pilot (*CETP*) are considered as typical MER policies in China (Chang and Wang 2010; Zhang et al., 2019; Chen Z et al., 2021; Du et al., 2021; Peng et al., 2021; Meng et al., 2021). The *SETP* was issued by the Ministry of Ecology and Environment of PRC. In 2007, the pilot scope was expanded to cover 11 areas of Jiangsu, Tianjin, Zhejiang, Hubei, Chongqing, Hunan, Inner Mongolia, Hebei, Shaanxi, Henan, and Shanxi, and the variety of the subject matter of transaction was expanded from SO_2 to chemical oxygen demand (COD), nitrogen oxides (NOx), and so on. The scale of this policy is much larger than in 2002. Moreover, in 2011, the National Development and Reform Commission of PRC issued the "Notice on Carrying out the Emission Trading Pilot Work" to create a special carbon trading market. This is another MER policy that may affect green technology innovation in China (Munnings et al., 2016; Ouyang et al., 2020). It decided to carry out *CETP* in seven areas of Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen. The main purpose of the MER policy is to promote green technology innovation through marketization, to realize green economic growth. Therefore, the implementation of *SETP* and *CETP* provides an effective "quasi-experiment" for us to study the effect of the MER policy on green technology innovation. We discuss the impact of the MER policy on green technology innovation and provide theoretical and empirical suggestions for further deepening the establishment of environmental trading systems in developing countries and how the MER policy can promote green technology innovation effectively.

This paper is organized as follows: Literature review is presented in *Literature review*. *Methodology* shows the methodology. *Data* is the data description. *Empirical results* includes the empirical results, discussion, heterogeneity analysis, and robustness checks. Conclusions and implications for stakeholders are shown in *Conclusion and policy implications*.

LITERATURE REVIEW

There are many works of literature about whether environmental regulation can promote technology innovation. Early studies mainly used environmental intensity indicators to describe environmental regulation, including pollution control costs, amount of pollutant emission, environmental taxation, and R&D subsidies (Popp 2002; Hamamoto 2006; Carmen and Innes 2010; Acemoglu et al., 2012). These studies mostly prove that environmental policies can stimulate technology innovation from the theoretical. The Porter hypothesis is a representative study to explore the impact of environmental regulation policy on innovation. Through theory and case analysis, Porter and Linde (1995) finds that if the policy is designed properly, environmental regulation can produce a compensation effect by innovation, which can offset the cost increase brought by the implementation of environmental regulation. Although some studies describe the Porter hypothesis in more detail and believe that the impact of environmental regulation on technology innovation will be uncertain and dynamic because of location, industry, enterprise size, productivity, and other factors (Jaffe and Palmer 1997; Becker 2011; Broberg et al., 2013; Albrizio et al., 2017), the investigation of Porter hypothesis is mainly carried out from the microeconomics of manufacturers. Meanwhile, the theory of endogenous economic growth and the study of Acemoglu et al. (2012) implies an important assumption, that is, the technical change of a sector is determined by the technology innovation activities of all manufacturers in this sector. With the sustainable growth of green technology, non-green technology is not stagnant (Aghion et al., 2016). It has been mentioned whether the ER policy has made the directed technical change into the green trend. The above research has set the microeconomic foundation for exploring how ER affects technology innovation or technical change.

Consequently, recent studies pay more attention to the effectiveness of correlation between ER policy and green technology innovation, that is, to analyze the weak Porter hypothesis. Meanwhile, an increasing number of researches focus on the MER policy because the operation of the MER policy is to take the emission power or pollutant as the subject matter of the transaction and take the price index as the signal, to increase the cost of pollutant emission, and decrease the return relatively. When the marginal return is close to the marginal cost, manufacturers may select to stop production, transfer, or carry out green technology innovation, to limit the pollutant emissions in the area and achieve and transform the economic pattern. Selecting to stop production or transfer is equivalent to leaving the market, and if the above costs are too large, manufacturers will select green technology innovation immediately (Jaffe et al., 2002; Chen Z et al., 2021; Lv et al., 2021). This is the mechanism by which the MER policy can promote green technology innovation.

In addition, researchers have employed a variety of methods to explore the correlation between ER policy and technology innovation. Specifically, Jaffe and Palmer (1997) construct a simple econometric model based on mixed regression and fixed effect. Hamamoto (2006) constructed a panel model and found that ER policy promoted R&D investment and further stimulated productivity. Recently, based on the Panel Poisson fixed-effect model, Cai et al. (2020) believe that ER policy can stimulate the green technology innovation of Chinese polluting industries. Ouyang et al. (2020) found that environmental regulation will inhibit technological innovation in the short term, but this impact is positive in the long term. Their research employs a two-way fixed-effect panel data model. With the development of econometrics, researchers use the quasi-experiment to reflect the intensity of ER (Johnstone et al., 2010; Calel and Dechezleprêtre 2016), and most of them are based on the difference-in-difference (DID) and its derivative models to evaluate the policy effect of ER (Zhang et al., 2019; Peng et al., 2021). The DID model is a method based on quasi-experiment, which cannot only effectively avoid endogenous issues but also make policy variables visible. It has been widely recognized that DID method is employed to evaluate the policy effect.

An added problem is how to measure green technology innovation. It is conventional to measure the level of green technology innovation by measuring efficiency, productivity, and green investment (Lanoie et al., 2008; Broberg et al., 2013; Sun et al., 2020; Chen Y et al., 2021; Chen and Ma, 2021; Sun et al., 2021). However, the efficiency measurement method based on Data Envelopment Analysis (DEA) is suitable for green productivity, and there may be a deviation in the measurement of green technology innovation. Employing the patents to measure the technology innovation from a microeconomy perspective or technical change from a macroeconomy perspective has been commonly supported by some researchers (Popp 2002; Johnstone et al., 2010; Albino et al., 2014; Aghion et al., 2016). According to the "International Patent Classification (IPC) Green Inventory" issued by the World Intellectual Property Organization (WIPO)[1], the number of authorized patents in China is examined to reflect the level of current green technology innovation (Cai et al., 2020; Jiao et al., 2020; Chen Z et al., 2021; Xu et al., 2021; Wang et al., 2021). The IPC Green Inventory is based on the specific technical terms proposed by the United Nations Framework Convention on Climate Change (UNFCCC), and its purpose is to facilitate the retrieval of patent details related to environmentally sound technologies. Besides, invention and utility model patents are the categories of green technology innovation, and the value of invention patents is relatively high (Johnstone et al., 2010; Aghion et al., 2016). The heterogeneity caused by different types of patents is worth investigating.

In general, compared with the previous researches, the potential contributions of this paper on the study of environmental regulation and green technology innovation are as follows: First, we consider the impact of two typical MER policies (SO_2 emissions trading pilot and carbon emissions trading pilot) on green technology innovation and examines the effect of policy combination. Second, it is discussed whether the MER policy has altered the total technology innovation and directed technical change while promoting green technology innovation, that is, it investigates the empirical study of the weak Porter hypothesis in China's prefectural-level cities. Third, patents are employed to represent green technology innovation, and the potential heterogeneity of patent types (invention and utility model) is also within the scope of research.

METHODOLOGY

This paper employs the difference-in-difference (DID) and difference-in-difference-in-difference (DDD) methods for policy evaluation. SO_2 emission trading pilot (*SETP*) and carbon emission trading pilot (*CETP*) are typical MER policies in China, similar to the EU ETS. One of their connotations is to stimulate enterprise technology innovation through marketization, to realize the Porter effect (Ambec et al., 2013; Chen Z et al., 2021). To construct the policy variable of the MER policy and analyze the policy effect, we regard the areas covered by the pilot as the treatment group[2] and the non-pilot areas as the

[1]https://www.wipo.int/classifications/ipc/green-inventory/home.

[2]First, the treatment group of *SETP* comprises the prefectural-level cities of Jiangsu, Tianjin, Zhejiang, Hubei, Chongqing, Hunan, Inner Mongolia, Hebei, Shaanxi, Henan, and Shanxi. Second, the treatment group of *CETP* comprises the prefectural-level cities of Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen.

control group, and define the time after 2007 and 2011 as the treatment period of the corresponding policies[3] (Chen Z et al., 2021; Li and Du, 2021; Peng et al., 2021; Zhang et al., 2019).

Therefore, set the policy variable with the $SETP_{it} = treated_i \times period_{it}$ and $CETP_{jt} = treated_j \times period_{jt}$. Specifically, $treated_i$ and $treated_j$ are the treatment group dummy. If i belongs to the treatment group with the areas of *SETP*, $treated_i = 1$; otherwise $treated_i = 0$. If j belongs to the treatment group with the areas of *CETP*, $treated_j = 1$; otherwise $treated_j = 0$. The $period_{it}$ is the time dummy, if $t > 2007$ for the areas i of *SETP*, $period_{it} = 1$; otherwise, $period_{it} = 0$. The $period_{jt}$ is the time dummy, if $t > 2011$ for the areas i of *CETP*, $period_{jt} = 1$; otherwise, $period_{jt} = 0$.

DID Model

The DID model quantitatively evaluates the impact of the policy by comparing the changes between the treatment group and the control group before and after the policy intervention. Besides, it is necessary to consider the area fixed effects, year fixed effects, and supplement control variables to further decline the endogenous issue. The DID models are as follows:

$$\ln GTI_{it} = \alpha + \beta_1 period_{it} + \beta_2 treated_i + \beta_3 SETP_{it} + \sum X_{it} + \gamma_i + \mu_t + \varepsilon_{it} \tag{1}$$

$$\ln GTI_{jt} = \alpha + \beta_1 period_{jt} + \beta_2 treated_j + \beta_3 CETP_{jt} + \sum X_{jt} + \lambda_j + \mu_t + \varepsilon_{jt} \tag{2}$$

where all non-dummy variables are in logarithmic form to eliminate heteroscedasticity. Subscripts *i,j* indicate the area of the city, and t indicates the time of year. GTI is the dependent variable, which represents the level of green technology innovation of city *i,j* in year *t*. $SETP_{it}$ and $CETP_{jt}$ are the policy variables and shown at the top of *Methodology*. μ is the year fixed effect, which controls the common trend of green technology innovation at the national level. γ and λ are the area fixed effect that controls the time-invariant features in a city. X shows the prefectural-level city's time-varying control variables, which may also have an impact on green technology innovation. It includes economic development (*GDP*), urbanization rate (*URB*), government administration (*GOV*), foreign direct investment (*FDI*), research and development investment (*RD*), command-and-control environmental regulation (*CER*), and financial development (*FD*). The source and measurement of all variables are described in the section *Data*.

Combined Effects Model

In general, *SETP* and *CETP* are quota management for some specific pollutant emissions and trade these quotas in a market-based way, so *SETP* and *CETP* are the same types of policy tools. Therefore, we can believe that one of the purposes of implementing *SETP* and *CETP* at parallel is to hope that *CETP* can form a supplement to *SETP*, to produce a policy combination effect and jointly promote green technology innovation. Under the difference-in-difference-in-difference (DDD) framework, to examine the effect of policy combination is conducive to finding the causality on different MER policies. The DDD model is as follows:

$$\begin{aligned} \ln GTI_{ijt} = \alpha &+ \beta_1 SETP_{it} + \beta_2 CETP_{jt} \\ &+ \beta_3 SETP_{it} \times CETP_{jt} \\ &+ \sum X_{ijt} + \gamma_i + \lambda_j + \mu_t + \varepsilon_{ijt} \end{aligned} \tag{3}$$

$SETP \times CETP$ is an interactive item of the policy with "SO_2 emissions trading pilot" and "carbon emissions trading pilot," which represents the effect of policy combination. Because *SETP* or *CETP* is a policy variable obtained by multiplying two dummy variables and still belongs to dummy variables, $SETP \times CETP$ can be regarded as a triple difference. Consequently, β_3 in **Eq. 3** is the target of our research, and its magnitude and significance measure the effect of policy combination on green technology innovation. X, γ, λ, and μ are the same as the *DID Model*.

DATA

This paper employs the annual panel data onto 278 prefectural-level cities in China as the research sample over the period of 2003–2017. Due to the lack of detail, all prefectural-level cities in the areas of Tibet, Hong Kong, Macao, and Taiwan are not included. Economic data come from the China City Statistical Yearbook, and the patent data come from China National Intellectual Property Administration (CNIPA)[4]. Economic data and patent data are matched by the details on address with text processing. To avoid faults, we also used the zip code for matching.

Note that 1) after a technology innovation occurs, if this innovation has the potential value, it will often immediately apply for patent protection to obtain the monopoly benefits from this technology (Popp, 2002). This is an important reason for employing the number of authorized patents as the representative of green technology innovation. 2) Patent data generally take 2–3 years from submission to authorization (Johnstone et al., 2010; Cai et al., 2020). Thus, the period of research sample is stopped in 2017, because the delay of patent data is considered. 3) After 2017, China's carbon emission trading will not be piloted in different areas but will adopt a unified national trading market. The trading center is located in Shanghai and the registration center is located in Wuhan.

Green Technology Innovation

The level of green technology innovation (*GTI*) is measured by patent authorization stocks according to the IPC Green Inventory in China[5] (Chen Z et al., 2021; Du et al., 2021; Zhang et al., 2021).

[3]The policy of *SETP* was implemented in 2007, and the policy of *CETP* was implemented in 2011.

[4]In 2018, the abbreviation of the English on China National Intellectual Property Administration has changed from "SIPO" to "CNIPA".

[5]https://www.wipo.int/classifications/ipc/green-inventory/.

The IPC Green Inventory is divided into seven topics: alternative energy production, transportation, energy conservation, waste management, agriculture/forestry, administrative regulatory or design aspects, and nuclear power generation. Since the detail of the patent contains the title, date, inventor, type, and address, it lets us match the patent data with the economic data of the prefectural-level cities in China.

In addition, we also constructed two other dependent variables to notice the impact of the MER policy on the total technology innovation (*TI*) and green direction of technology innovation (*GDTI*). *GDTI* is represented by the proportion of authorized patents according to the IPC Green Inventory in an area to all of the authorized patents (Aghion et al., 2016). *TI* is represented by the authorized number of all patents in the prefectural-level cities.

Control Variables

Other essential factors affecting green technology innovation at the prefectural-level cities need to be controlled. The choice of control variables is reflected in the relevant research (Blackman 2010; Cai et al., 2020; Chen Z et al., 2021; Tang et al., 2020; Li and Du 2021; Xu et al., 2021), as follows: 1) Economic development (*GDP*): GDP per capita indicates the level of economic development; 2) Urbanization rate (*URB*): The ratio of urban population to the non-urban population in an area; 3) Government administration (*GOV*): The high level of government regulation, the great impact of MER policies on green technology innovation. Therefore, this paper uses the proportion of local government fiscal expenditure to GDP to represent government administration. 4) Foreign direct investment (*FDI*): Technology spillover also impacts green technology innovation (Jiao et al., 2020). This paper uses the amount of foreign direct investment in each area to control the impact of technology spillover. 5) Research and development investment (*RD*): This article uses the per capita fiscal expenditure on science and technology in each area as the proxy variable of R&D investment (Zhang et al., 2019). 6) Financial development (*FD*): The financial development in an area with a high level, then financial constraints are relatively low, and companies have more abundant funds to carry out the green technology innovation (Lv et al., 2021). This paper uses the average loan balance of financial institutions at the end of the year to indicate financial development. 7) Command-and-control environmental regulation (*CER*): Consistent with Zhao et al. (2015) and Tang et al. (2020), we control the impact of the *CER* policy on green technology innovation.

The measurement method of the *CER* is according to Levinson (1996), Tang et al. (2020), and Ouyang et al. (2020). This paper considers the emissions of industrial sulfur dioxide (SO_2), industrial dust (*YC*), and industrial wastewater (*WW*) in various areas. First, the above pollutant emission of each area is standardized. The method of linear standardization is as follows:

$$DE^{s}_{ijt} = \frac{DE_{ijt} - \min\left(DE_{jt}\right)}{\max\left(DE_{jt}\right) - \min\left(DE_{jt}\right)} \tag{4}$$

TABLE 1 | Descriptive statistics of variables

Variable	Obs	Average	Std. Dev.	Min	Max
lnGTI	3,987	3.352	1.828	0	9.400
lnTI	4,156	5.766	1.840	0	11.430
lnGDTI	3,984	−2.551	0.454	−5.112	−0.511
Invention	3,104	2.093	1.706	0	8.626
Utility model	3,956	3.196	1.781	0	8.783
SETP	4,160	0.285	0.451	0	1
CETP	4,160	0.059	0.235	0	1
lnCER	3,950	−1.481	1.746	−11.080	1.408
lnURB	4,157	−3.485	0.926	−7.663	0.774
lnGOV	4,151	−1.900	0.579	−4.176	1.799
lnFDI	3,939	−6.341	1.397	−14.848	−0.965
lnRD	4,149	−3.901	1.310	−10.323	−0.234
lnFD	4,140	9.486	1.407	4.838	14.303
lnGDP	4,109	10.438	0.794	2.791	15.675

All variables are logarithmic (except the dummy variables).

where, DE_{ijt} is the actual unit emission of pollutants in area i, pollutant j, and period t. $j \in (1, 2, 3)$ shows the type of pollutant emission, which belongs to SO_2, *YC*, and *WW* respectively. $\max(DE_{jt})$ and $\min(DE_{jt})$ indicate the maximum and minimum values of pollutants j in all areas during the period t. DE^{s}_{ijt} is the standardized pollutant emission.

Second, set the adjustment coefficients of pollutant emissions in various areas. This is because the size of pollution emissions in various areas is different, and the emission intensity of various pollutants is also different. Therefore, we set the adjustment coefficients as weights, the method is as follows:

$$W_{jt} = DE_{ijt} / \overline{DE_{ij}} \tag{5}$$

$\overline{DE_{ij}}$ is the average level of emission per unit of area i and pollutant j in the research period. Third, the *CER* in area i at period t can be calculated as:

$$CER_{it} = (1/3)\sum_{j=1}^{3} W_{jt} \times DE^{s}_{ijt} \tag{6}$$

Descriptive statistics

According to the description in **Table 1**, some stylized facts can be found: 1) Not all areas have carried out the technology innovation, or green technology innovation because the Min of *lnTI* or *lnGTI* is 0. 2) From the perspective of patents, the proportion of authorized green patents in all authorized patents is less than 10% on average. The green bias of technical change is not sufficient. 3) The control variables show the great gap in the economic and social development in various areas of China.

EMPIRICAL RESULTS

In this section, based on the DID method, we first investigate whether the SO_2 emission trading pilot (*SETP*) and carbon emission trading pilot (*CETP*) promote green technology innovation. Second, whether *SETP* and *CETP* can jointly promote green technology innovation is discussed. Third, we

TABLE 2 | Estimation results of the DID model (*SETP*)

Variables	*lnGTI*			*lnTI*	*lnGDTI*
	(1)	(2)	(3)	(4)	(5)
SETP	0.085** (2.31)	0.095** (2.54)	0.091** (2.40)	0.028 (1.00)	0.027 (0.95)
Period	3.045*** (67.10)	3.047*** (56.27)	2.765*** (12.09)	2.655*** (16.02)	0.301* (1.78)
treated	1.335*** (6.97)	1.325*** (6.92)	1.235*** (5.88)	1.522*** (9.83)	0.342** (2.13)
lnCER	No	Yes	Yes	Yes	Yes
Control variables	No	No	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes
Cons	0.096 (0.66)	0.095 (0.66)	−0.404 (−0.73)	2.540*** (7.91)	2.299*** (7.01)
Obs	3,987	3,781	3,557	3,730	3,596
Adj R^2	0.9285	0.9269	0.9269	0.9546	0.3154

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

TABLE 3 | Estimation results of the DID model (*CETP*)

Variables	*lnGTI*			*lnTI*	*lnGDTI*
	(1)	(2)	(3)	(4)	(5)
CETP	0.010 (0.22)	0.020 (0.42)	0.003 (0.07)	−0.026 (−0.69)	0.007 (0.18)
period	3.077*** (70.91)	3.079*** (58.38)	2.767*** (12.07)	2.661*** (16.03)	0.299* (1.76)
treated	1.396*** (7.32)	1.389*** (7.28)	1.305*** (6.24)	1.551*** (10.06)	0.324** (2.03)
lnCER	No	Yes	Yes	Yes	Yes
Control variables	No	No	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes
Cons	0.068 (0.47)	0.066 (0.46)	−0.393 (−0.71)	2.538*** (7.90)	2.300*** (7.02)
Obs	3,987	3,781	3,557	3,730	3,596
Adj R^2	0.9284	0.9268	0.9269	0.9546	0.3152

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

also analyze the heterogeneity caused by different regions and different patent types. Finally, we conduct robustness tests to ensure the effectiveness of the empirical results.

Estimation Results of the DID Model

The empirical results of *SETP* are shown in **Table 2**. For *lnGTI* in Column 1, the coefficient of *SETP* is significantly positive at the 5% level. The results prove that the MER policy such as the SO_2 emission trading pilot can promote green technology innovation through current marketization. In Column 2, we control the impact of CER policy, and the coefficient of *SETP* is still significantly positive. Similar results remain after more control variables are introduced into Column 3. However, the empirical result in Columns 4 and 5 are disappointing, because the *SETP* policy does not make the direction of technical change into the green trend and does not stimulate total technology innovation (for *lnGDTI and lnTI*, the coefficients of *SETP* are not significant). The above empirical results indicate that although SO_2 emission trading pilots can effectively promote green technology innovation. We found evidence that the weak Porter hypothesis exists at the prefectural-level cities in China because environmental regulation only promotes the innovation of some specific technologies, not all.

The empirical results of *CETP* are shown in **Table 3**. It is not difficult to find that the promoting effect of *CETP* on technology innovation is hard to recognize in the sample period (for *lnGTI*, the estimated coefficient is not significant). Furthermore, the empirical results of *lnTI* and *lnGDTI* also support that the promotion effect of *CETP* on technology innovation does not exist. The *CETP* policy does not realize the weak Porter hypothesis. This result is similar to the findings of Chen Z et al. (2021) and Zhang et al. (2019). At present, the policy effect of *CETP* is mainly to reduce carbon emissions by inhibiting output, rather than green technical innovation.

We discuss the potential reasons for the success of the *SETP* policy in promoting green technology innovation and the failure of the *CETP* policy. The Porter hypothesis holds that the causality between environmental regulation policy and technology innovation is affected by the two effects of "compliance cost" and "innovation compensation" (Jaffe and Palmer, 1997; Ambec et al., 2013). Firstly, assuming that the compliance costs of *SETP* and *CETP* are consistent, the failure of the *CETP* policy can be attributed to its less innovative compensation effect than that of *SETP* policy. In reality, the difficulty of technology innovation for carbon emission reduction is greater than that for the treatment of general pollutants such as sulfur dioxide. Secondly, assuming that the innovation compensation of *SETP* and *CETP* is consistent, the success of the *SETP* policy can be attributed to its less compliance cost effect than the *CETP* policy. In reality, the *CETP* policy takes place after *SETP* policy, which covers a wider

TABLE 4 | Estimation results of the combined effects model

Variables	*lnGTI*		
	(1)	(2)	(3)
SETP	0.085** (2.27)	0.096** (2.52)	0.093** (2.41)
CETP	0.014 (0.24)	0.025 (0.41)	0.009 (0.14)
SETP×CETP	–0.005 (–0.06)	–0.010 (–0.10)	–0.028 (–0.29)
lnCER	No	Yes	Yes
Control variables	No	No	Yes
Year fixed effects	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes
Cons	0.097 (0.67)	0.097 (0.67)	–0.488 (–0.86)
Obs	3,987	3,781	3,557
Adj R^2	0.9285	0.9268	0.9269

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

range and involves more enterprises. The cost of some enterprises participating in carbon emission trading is relatively high.

Estimation Results of the Combined Effects Model

In this subsection, we will further consider the effect of policy combination with "SO_2 emission trading pilot" and "carbon emission trading pilot" based on **Eq. 3**, because the latter is another MER policy. The results are shown in **Table 4**.

The coefficients of interaction item (*SETP* × *CETP*) are not significant in Columns 1–3, which indicates that "SO_2 emission trading pilot" and "carbon emission trading pilot" cannot promote green technology innovation together. The effect of policy combination does not exist. However, the coefficient of *SETP* is still significantly positive, indicating that the promoting role of the SO_2 emission trading pilot on green technology innovation is not affected by carbon emission trading pilot. At present, not all of the MER policies can promote green technology innovation in China. The reason may be that the scheme of carbon emission trading pilot is not robust, the market activity is low, and it is hard to stimulate the power of innovation of relevant enterprises, which leads to the weakness of green technology innovation in the area of prefectural-level cities.

Heterogeneity Analysis

The heterogeneity analysis of this paper includes two categories. First, whether there are differences between *SETP* and *CETP* in the impact of the eastern, central, and western regions; second, how *SETP* and *CETP* affect different types of patents (Invention and Utility model patents). **Table 5** reports the results for the heterogeneity analysis opening on cities in different regions. **Table 6** reports the results of the heterogeneity analysis of different types of patents. Our strategy of heterogeneity analysis draws on the research of Chen Z et al. (2021).

Columns 1–3 of **Table 5** show the empirical results of regional heterogeneity of *SETP* policy, and Columns 4–6, for *CETP* policy. The impact of *SETP* on green technology innovation shows heterogeneity between the eastern regions and other regions. Specifically, the estimation coefficient of *SETP* in the eastern region is significantly positive, but it is not significant in the central and western regions. Meanwhile, comparing the empirical results in **Tables 2**, **5**, the incentive effect of green technology innovation in the eastern region is higher than the national average (0.332 > 0.091). Fundamentally, the innovation vitality of the eastern region is relatively high, the amount of enterprises in cities is also higher than that in the central and western regions, and the eastern region is more prone to green technology innovation. The impact of the *CETP* policy on green technology innovation in each region is still not significant, and even the estimated coefficient is negative in the eastern and central regions. To some extent, the *CETP* policy even inhibits green technology innovation in the eastern and central regions.

Further, we divide green technology patents into invention and utility model patents. Both of the invention and utility model patents, the *SETP* policy has played a promoting effect to them, as shown in Columns 1 and 2. Meanwhile, the promoting effect of invention patents is greater than utility model patents (0.144 > 0.090), which reveals the simultaneous increase in the quantity and quality of green technology innovation.

TABLE 5 | Heterogeneity analysis of different regions

Variables	*lnGTI*					
	Eastern Regions	Central Regions	Western Regions	Eastern Regions	Central Regions	Western Regions
	(1)	(2)	(3)	(4)	(5)	(6)
SETP	0.332*** (6.20)	0.035 (0.58)	0.034 (0.28)	—	—	—
CETP	—	—	—	–0.013 (–0.22)	–0.091 (–1.02)	0.040 (0.13)
lnCER	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Cons	–3.211*** (–3.93)	1.134 (1.30)	–2.101 (–0.66)	–3.104*** (–3.74)	1.261 (1.44)	–2.246 (–0.71)
Obs	1,359	1,609	758	1,359	1,609	758
Adj R^2	0.9449	0.8903	0.9103	0.9432	0.8903	0.9103

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

TABLE 6 | Heterogeneity analysis of different types of green innovation patents

Variables	*Invention patents*	*Utility model patents*	*Invention patents*	*Utility model patents*
	(1)	(2)	(3)	(4)
SETP	0.144** (2.51)	0.090** (2.28)	—	—
CETP	—	—	0.059 (0.85)	0.029 (0.57)
lnCER	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes
Cons	0.549 (0.68)	−0.193 (−0.34)	0.547 (0.68)	−0.180 (−0.31)
Obs	2,758	3,533	2,758	3,533
Adj R^2	0.8758	0.9176	0.8755	0.9174

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

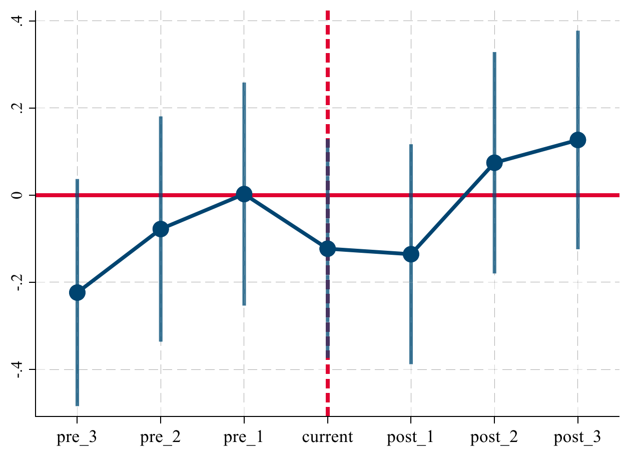

FIGURE 1 | The results of the common trend test.

Robustness Checks

This paper employs four types of robustness checks to ensure the reliability and validity of the empirical results: common trend test, dynamic effect test, placebo test, and policy uniqueness test. Since the *CETP* policy failed to promote green technology innovation, that is, this policy had no impact on the dependent variable, the robustness check for *CETP* was not implemented.

Common Trend Test

Employing the DID method for policy evaluation needs to conform to the hypothesis of the common trend, that is, to avoid the issue that the difference between the treatment group and the control group may be driven by the difference in the time trends of patenting. Therefore, we conducted a common trend test on *SETP* policy as follows:

$$\begin{aligned}\ln GTI_{it} = \alpha + \beta_1 (treated_i \times period_{i,t-3}) \\ +\beta_2 (treated_i \times period_{i,t-2}) + \beta_3 (treated_i \times period_{i,t-1}) \\ + \beta_4 (treated_i \times period_{i,t-0}) + \beta_5 (treated_i \times period_{i,t+1}) \\ + \beta_6 (treated_i \times period_{i,t+2}) + \beta_7 (treated_i \times period_{i,t+3}) \\ + \sum X_{it} + \gamma_i + \mu_t + \varepsilon_{it}\end{aligned} \tag{7}$$

Specifically, $t = 2007$, the interaction item $treated \times period$ takes a value of 1 if the city is included in the pilot areas and pilot time for the *SETP* policy; otherwise, it is 0. We plotted the estimated coefficients under the 95% confidence interval. Of course, we still controlled CER, area fixed effects, and year fixed effects, as shown in **Figure 1**.

It is not difficult to find that before the implementation of the *SETP* policy, all confidence intervals cover 0, indicating that there is no systematic difference in trend between the treatment group and the control group. After the implementation of the *SETP* policy, green technology innovation has gradually improved except for the first year. **Figure 1** proves the effectiveness of the empirical results of this paper to a certain extent.

Dynamic Effect Test

Although the *SETP* policy can promote green technical innovation, its impact may be delayed in time. Consequently, the promoting effect of *SETP* on green technology innovation may gradually appear over time, that is, it is necessary to test whether the *SETP* policy has a dynamic effect. Specifically, the dummy variable $period_{it}$ in $treated_i \times period_{it}$ is replaced by another nine annual dummy variables. Suppose that the annual dummy variable is $yrdum_{it}$ $(t = 2008, \ldots, 2017)$, when $t = 2008$, the $yrdum_{i,2008}$ takes 1, otherwise 0, and so on. Thus, the following model is employed to the dynamic effect test:

$$\ln GTI_{it} = \alpha + \sum_{j=1}^{9} \beta_j yrdum_{it} \times treated_i + \sum X_{it} + \gamma_i + \mu_t + \varepsilon_{it} \tag{8}$$

where the coefficient β measures the persistent impact of SO_2 emission trading pilot on green technology innovation after j years of implementation, that is, the dynamic effect.

As shown in **Table 7**, the coefficients in all interaction items are positive most of the time, and there is no alternation of positive and negative, which indicates that the promotion effect of *SETP* policy on green technology innovation is consistent. Note that the coefficient $t = 2008$ is not statistically significant, which means the impact of *SETP* on green technology innovation is not immediate. Moreover, even if the coefficient is statistically significant, the occurrence that orders them is discontinuous. In Column (1), the impact of the *SETP* on green technology innovation disappeared $t = 2013$ and did not reappear until

TABLE 7 | Heterogeneity analysis of the dynamic effect of *SETP*

Variables	*lnGTI*	*Invention patents*	*Utility model patents*	*lnGTI (Eastern Regions)*
	(1)	(2)	(3)	(4)
$yrdum_{2008} \times treated$	−0.005 (−0.07)	−0.096 (−0.94)	−0.029 (−0.41)	0.037 (0.39)
$yrdum_{2009} \times treated$	0.167** (2.42)	0.149 (1.49)	0.179** (2.49)	0.243** (2.52)
$yrdum_{2010} \times treated$	0.219*** (3.21)	0.159 (1.57)	0.193*** (2.72)	0.239** (2.49)
$yrdum_{2011} \times treated$	0.077 (1.14)	0.174* (1.83)	0.092 (1.30)	0.239** (2.50)
$yrdum_{2012} \times treated$	0.117* (1.72)	0.204** (2.18)	0.101 (1.42)	0.388*** (3.97)
$yrdum_{2013} \times treated$	0.178** (2.45)	0.285*** (2.91)	0.168** (2.23)	0.403*** (3.81)
$yrdum_{2014} \times treated$	0.074 (1.08)	0.165* (1.81)	0.062 (0.88)	0.464*** (4.76)
$yrdum_{2015} \times treated$	0.084 (1.22)	0.174* (1.93)	0.086 (1.21)	0.546*** (5.63)
$yrdum_{2016} \times treated$	0.136 (1.64)	0.277** (2.56)	0.138 (1.59)	0.485*** (4.52)
$yrdum_{2017} \times treated$	0.394** (2.18)	0.267*** (2.69)	0.404** (2.16)	0.633*** (5.95)
lnCER	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes
Cons	−0.419 (−0.76)	0.490 (0.61)	−0.211 (−0.37)	−3.331*** (−4.12)
Obs	3,557	2,758	3,533	1,359
Adj R^2	0.9270	0.8762	0.9177	0.9465

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities.*

TABLE 8 | Estimation results of placebo test.

Variables	*lnGTI*		*Invention patents*		*Utility model patents*	
	(1)	(2)	(3)	(4)	(5)	(6)
$period_{2004} \times treated$	0.080 (1.17)	—	0.212 (0.98)	—	0.114 (1.61)	—
$period_{2005} \times treated$	—	0.118 (1.48)	—	0.246 (1.20)	—	0.104 (1.56)
lnCER	Yes	Yes	Yes	Yes	Yes	Yes
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Cons	0.370 (0.85)	0.377 (0.87)	0.614 (0.75)	0.607 (0.74)	−0.231 (−0.39)	−0.234 (−0.40)
Obs	3,598	3,598	2,758	2,758	3,533	3,533
Adj R^2	0.9269	0.9271	0.8756	0.8760	0.9175	0.9177

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities. The coefficient of control variables is not shown.*

$t = 2017$. Similar empirical results are shown in Columns (2) and (3), but the difference is that invention patents are affected longer than utility model patents. These empirical results indicate that the promoting role of the *SETP* policy on green technology innovation has the hysteresis effect and volatility effect. The reasons may be due to the policy shock caused by the implementation of the carbon emission trading pilot in 2011, which maintains that the *SETP* policy will be affected by other environmental policies and temporarily invalid. Finally, in the eastern region (Column 4), the impact of *SETP* on green technology innovation lags only 1 year, which is continuous.

Placebo Test

The randomness of the policy intervention is necessary, and the control group will not be affected by the policy intervention. Consequently, to further exclude the difference in green technical innovation between the pilot and non-pilot areas due to other multiple factors, we conduct a placebo test by the move back the time of policy implementation of the *SETP* policy 2 and 3 years (Set the $period_t$ and $t \geq 2005$, $t \geq 2004$). The result of the placebo test is shown in **Table 8**.

Although the coefficients of interaction terms $period_{2004} \times treated$ and $period_{2005} \times treated$ in Columns 1, 2, 5, and 6 are positive, they are not significant, indicating that the policy implementation of SO_2 emission trading pilot in the year 2004 or 2005 will not affect green technology innovation. However, in Columns 3 and 4 the coefficients of interaction terms are significantly positive. The invention patent in green technology innovation is also affected by other factors. For the main dependent variable, the placebo test proves that the expansion of SO_2 emission trading pilot in the year 2007 is a decisive policy factor affecting green technology innovation from the perspective of time counterfactual.

Policy Uniqueness Test

Before 2007, China has also issued other policies similar to the SO_2 emission trading pilot, but they are not the type of MER policies. The direct aim of these policies is to reduce pollutants,

TABLE 9 | Estimation results of policy uniqueness test.

Variables	*lnGTI*			*Invention patents*	*Utility model patents*
	(1)	(2)	(3)	(4)	(5)
SETP	0.138* (1.89)	0.134* (1.83)	0.138* (1.88)	0.175** (2.25)	0.037 (0.54)
TEC	−0.018 (−0.28)	−0.005 (−0.07)	−0.010 (−0.15)	−0.027 (−0.24)	−0.122 (−1.24)
lnCER	No	Yes	Yes	Yes	Yes
Control variables	No	No	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes
Cons	0.107 (0.74)	0.107 (0.74)	0.380 (0.88)	0.639 (0.78)	−0.225 (−0.38)
Obs	3,987	3,781	3,598	2,758	3,533
Adj R^2	0.9286	0.9269	0.9271	0.8757	0.9177

, **, * represent significance at the 10%, 5%, and 1% levels. T statistics in parentheses. Area fixed effects are clustered to prefectural-level cities. The coefficient of control variables is not shown.*

such as the plan of total emission control for major pollutants issued in 2006. Meanwhile, this plan is not only used to reduce pollutants but also may indirectly encourage green technology innovation. Specifically, this plan is connected with the achievements of local governments, which makes all areas begin to pay attention to pollution control and emission reduction. This plan occurs before the policy of the SO_2 emission trading pilot, so we need to construct a new policy variable, Total Emission Control (*TEC*), to put a brake on the estimation error caused by other policies. The plan of total emission control for major pollutants is carried out nationwide, and there is no particular treatment group or control group. However, as pollution control is connected with the achievements of local governments, the impact of this plan on non-pilot areas may be more prominent. Consequently, we set $TEC_{it} = treated_i \times period_t$, if $t > 2006$, $period = 1$, otherwise $period = 0$, *treated* is the same as **Eq. 1**. The results are shown in **Table 9**.

We can find that the promoting effect of SO_2 emission trading pilot on green technology innovation is gradually shown after 2007, and not in 2006. It can be considered that the policy effect of the SO_2 emission trading pilot is unique in 2007.

CONCLUSION AND POLICY IMPLICATIONS

Under the goals of "carbon peaking and carbon neutrality," green technology innovation is an important way to coordinate economy and environment. Different from the integrated market such as EU ETS, China has established the pilot trading markets for different pollutants. Can these markets based on MER policies jointly promote green technology innovation? We need to reflect on the effectiveness of policies and explore more details of the policy effect. Consequently, the methods of DID and DDD are employed in this paper to explore the impact of MER policies (SO_2 emission trading pilot, carbon emission trading pilot) on green technology innovation, and whether the combination of different MER policies can realize the purpose of promoting green technology innovation together. According to China's IPC Green Inventory, the amount of authorized patents is employed as the proxy for green technology innovation. The economic data and patent data are matched by address and zip code to complete the empirical analysis.

Our empirical results indicate that the MER policy has a very diversified influence on the development of green technology innovation in the area of the prefectural-level city. Firstly, the SO_2 emission trading pilot can promote green technology innovation, while the carbon emission trading pilot has failed to play a similar role. This empirical result shows that not all MER policies can achieve the weak Porter hypothesis. Secondly, the superposition of the SO_2 emission trading pilot and carbon emission trading pilot does not realize the policy combination effect, which shows that the same type of MER policy does not achieve the role of jointly promoting green technology innovation in China. Thirdly, the heterogeneity analysis shows that the impact of SO_2 emission trading pilot on invention patents is more prominent than utility model patents. Therefore, we can find that green technology innovation has not only increased in quantity but also quality. Fourthly, the dynamic effect test believes that the impact of SO_2 emission trading pilot on green technology innovation does not take effect immediately, but there are features of hysteresis and volatility. This suggests that the stability of the MER policy needs to be improved.

The above conclusion provides implications to stakeholders as follows: 1) If the goal of the CER policy is to reduce pollutants, then the goal of the MER policy can promote green technology innovation while saving the environment, thereby completely transforming the pattern of economic development. Therefore, the MER policy can be used as a supplement to the CER policy to further promote green technology innovation. 2) Establishing different projects of emission trading pilot for different pollutants is difficult to repeatedly stimulate green technology innovation. Therefore, establishing a national unified emission trading market and managing it according to industry categories may be another choice. 3) The implementation of the MER policy cannot be limited to the emission trading pilot, and the expansion of policy types is imperative. Although the "SO_2 emission trading pilot" and "carbon emission trading pilot" failed to jointly promote green technology innovation, the role of the carbon emission trading pilot in restricting emissions still exists. From the perspective of green technology innovation, a similar type of emission trading pilot should be more refined than more expansive.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: China National Intellectual Property Administration; China urban statistical yearbook.

AUTHOR CONTRIBUTIONS

FQ: conceptualization; methodology; data curation; writing-original draft; writing-reviewing and editing. LX: supervision; funding acquisition; writing–reviewing and editing. YC: supervision; methodology; funding acquisition; writing-reviewing and editing.

FUNDING

This work was financially supported by the National Natural Science Foundation of China (71971175, 71673250, 72174180).

ACKNOWLEDGMENTS

The authors would like to thank the anonymous referee for reading the paper carefully and giving several constructive suggestions.

REFERENCES

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The Environment and Directed Technical Change. *Am. Econ. Rev.* 102, 131–166. doi:10.1257/aer.102.1.131

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., and Van Reenen, J. (2016). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. *J. Polit. Economy* 124, 1–51. doi:10.1086/684581

Albino, V., Ardito, L., Dangelico, R. M., and Messeni Petruzzelli, A. (2014). Understanding the Development Trends of Low-Carbon Energy Technologies: A Patent Analysis. *Appl. Energ.* 135, 836–854. doi:10.1016/j.apenergy.2014.08.012

Albrizio, S., Kozluk, T., and Zipperer, V. (2017). Environmental Policies and Productivity Growth: Evidence Across Industries and Firms. *J. Environ. Econ. Manage.* 81, 209–226. doi:10.1016/j.jeem.2016.06.002

Ambec, S., Cohen, M. A., Elgie, S., and Lanoie, P. (2013). The porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Rev. Environ. Econ. Pol.* 7, 2–22. doi:10.1093/reep/res016

Becker, R. A. (2011). Local Environmental Regulation and Plant-Level Productivity. *Ecol. Econ.* 70, 2516–2522. doi:10.1016/j.ecolecon.2011.08.019

Blackman, A. (2010). Alternative Pollution Control Policies in Developing Countries. *Rev. Environ. Econ. Pol.* 4, 234–253. doi:10.1093/reep/req005

Broberg, T., Marklund, P.-O., Samakovlis, E., and Hammar, H. (2013). Testing the Porter Hypothesis: The Effects of Environmental Investments on Efficiency in Swedish Industry. *J. Prod. Anal.* 40, 43–56. doi:10.1007/s11123-012-0335-6

Cai, X., Zhu, B., Zhang, H., Li, L., and Xie, M. (2020). Can Direct Environmental Regulation Promote Green Technology Innovation in Heavily Polluting Industries? Evidence from Chinese Listed Companies. *Sci. Total Environ.* 746, 140810. doi:10.1016/j.scitotenv.2020.140810

Calel, R., and Dechezleprêtre, A. (2016). Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Rev. Econ. Stat.* 98, 173–191. doi:10.1162/REST_a_00470

Carrión-Flores, C. E., and Innes, R. (2010). Environmental Innovation and Environmental Performance. *J. Environ. Econ. Manage.* 59, 27–42. doi:10.1016/j.jeem.2009.05.003

Chang, Y.-C., and Wang, N. (2010). Environmental Regulations and Emissions Trading in China. *Energy Policy* 38, 3356–3364. doi:10.1016/j.enpol.2010.02.006

Chen, Y., and Ma, Y. (2021). Does green Investment Improve Energy Firm Performance? *Energy Policy* 153, 112252. doi:10.1016/j.enpol.2021.112252

Chen, Y., Chen, M., and Li, T. (2021). China's CO2 Emissions Reduction Potential: A Novel Inverse DEA Model with Frontier Changes and Comparable Value. *Energ. Strategy Rev.* 38, 100762. doi:10.1016/j.esr.2021.100762

Chen, Z., Zhang, X., and Chen, F. (2021). Do carbon Emission Trading Schemes Stimulate green Innovation in Enterprises? Evidence from China. *Technol. Forecast. Soc. Change* 168, 120744. doi:10.1016/j.techfore.2021.120744

Cheng, S., Fan, W., Chen, J., Meng, F., Liu, G., Song, M., et al. (2020). The Impact of Fiscal Decentralization on CO2 Emissions in China. *Energy* 192, 116685. doi:10.1016/j.energy.2019.116685

Du, G., Yu, M., Sun, C., and Han, Z. (2021). Green Innovation Effect of Emission Trading Policy on Pilot Areas and Neighboring Areas: An Analysis Based on the Spatial Econometric Model. *Energy Policy* 156, 112431. doi:10.1016/j.enpol.2021.112431

Guo, R., and Yuan, Y. (2020). Different Types of Environmental Regulations and Heterogeneous Influence on Energy Efficiency in the Industrial Sector: Evidence from Chinese Provincial Data. *Energy Policy* 145, 111747. doi:10.1016/j.enpol.2020.111747

Hamamoto, M. (2006). Environmental Regulation and the Productivity of Japanese Manufacturing Industries. *Resource Energ. Econ.* 28, 299–312. doi:10.1016/j.reseneeco.2005.11.001

Jaffe, A. B., and Palmer, K. (1997). Environmental Regulation and Innovation: A Panel Data Study. *Rev. Econ. Stat.* 79, 610–619. doi:10.1162/003465397557196

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2002). Environmental Policy and Technological Change. *Environ. Resour. Econ.* 22, 41–70. doi:10.1023/A:1015519401088

Jiao, J., Chen, C., and Bai, Y. (2020). Is green Technology Vertical Spillovers More Significant in Mitigating Carbon Intensity? Evidence from Chinese Industries. *J. Clean. Prod.* 257, 120354. doi:10.1016/j.jclepro.2020.120354

Johnstone, N., Haščič, I., and Popp, D. (2010). Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. *Environ. Resource Econ.* 45, 133–155. doi:10.1007/s10640-009-9309-1

Lanoie, P., Patry, M., and Lajeunesse, R. (2008). Environmental Regulation and Productivity: Testing the Porter Hypothesis. *J. Prod. Anal.* 30, 121–128. doi:10.1007/s11123-008-0108-4

Levinson, A. (1996). Environmental Regulations and Manufacturers' Location Choices: Evidence from the Census of Manufactures. *J. Public Econ.* 62, 153–178. doi:10.1016/0047-2727(96)01572-1

Li, J., and Du, Y. (2021). Spatial Effect of Environmental Regulation on green Innovation Efficiency: Evidence from Prefectural-Level Cities in China. *J. Clean. Prod.* 286, 125032. doi:10.1016/j.jclepro.2020.125032

Lv, C., Shao, C., and Lee, C.-C. (2021). Green Technology Innovation and Financial Development: Do Environmental Regulation and Innovation Output Matter? *Energ. Econ.* 98, 105237. doi:10.1016/j.eneco.2021.105237

Meng, F., Chen, S., Cheng, S., Chen, B., Li, Z., Wang, F., et al. (2021). Analysis of Subnational CO2 Mitigation Policy Pressure in the Residential Sector in China. *J. Clean. Prod.* 293, 126203. doi:10.1016/j.jclepro.2021.126203

Munnings, C., Morgenstern, R. D., Wang, Z., and Liu, X. (2016). Assessing the Design of Three Carbon Trading Pilot Programs in China. *Energy Policy* 96, 688–699. doi:10.1016/j.enpol.2016.06.015

Ouyang, X., Li, Q., and Du, K. (2020). How Does Environmental Regulation Promote Technological Innovations in the Industrial Sector? Evidence from Chinese Provincial Panel Data. *Energy Policy* 139, 111310. doi:10.1016/j.enpol.2020.111310

Peng, J., Xie, R., Ma, C., and Fu, Y. (2021). Market-Based Environmental Regulation and Total Factor Productivity: Evidence from Chinese Enterprises. *Econ. Model.* 95, 394–407. doi:10.1016/j.econmod.2020.03.006

Popp, D. (2002). Induced Innovation and Energy Prices. *Am. Econ. Rev.* 92, 160–180. doi:10.1257/000282802760015658

Porter, M. E., and Linde, C. v. d. (1995). Toward a New Conception of the Environment-Competitiveness Relationship. *J. Econ. Perspect.* 9, 97–118. doi:10.1257/jep.9.4.97

Sun, H., Kporsu, A. K., Taghizadeh-Hesary, F., and Edziah, B. K. (2020). Estimating Environmental Efficiency and Convergence: 1980 to 2016. *Energy* 208, 118224. doi:10.1016/j.energy.2020.118224

Sun, H., Edziah, B. K., Kporsu, A. K., Sarkodie, S. A., and Taghizadeh-Hesary, F. (2021). Energy Efficiency: The Role of Technological Innovation and Knowledge Spillover. *Technol. Forecast. Soc. Change* 167, 120659. doi:10.1016/j.techfore.2021.120659

Tang, M., Li, X., Zhang, Y., Wu, Y., and Wu, B. (2020). From Command-And-Control to Market-Based Environmental Policies: Optimal Transition Timing and China's Heterogeneous Environmental Effectiveness. *Econ. Model.* 90, 1–10. doi:10.1016/j.econmod.2020.04.021

Wang, Y., Sun, X., and Guo, X. (2019). Environmental Regulation and green Productivity Growth: Empirical Evidence on the Porter Hypothesis from OECD Industrial Sectors. *Energy Policy* 132, 611–619. doi:10.1016/j.enpol.2019.06.016

Wang, H., Cui, H., and Zhao, Q. (2021). Effect of green Technology Innovation on green Total Factor Productivity in China: Evidence from Spatial Durbin Model Analysis. *J. Clean. Prod.* 288, 125624. doi:10.1016/j.jclepro.2020.125624

Xu, L., Fan, M., Yang, L., and Shao, S. (2021). Heterogeneous Green Innovations and Carbon Emission Performance: Evidence at China's City Level. *Energ. Econ.* 99, 105269. doi:10.1016/j.eneco.2021.105269

Zhang, H., Duan, M., and Deng, Z. (2019). Have China's Pilot Emissions Trading Schemes Promoted Carbon Emission Reductions?- the Evidence from Industrial Sub-Sectors at the Provincial Level. *J. Clean. Prod.* 234, 912–924. doi:10.1016/j.jclepro.2019.06.247

Zhang, J., Ouyang, Y., Ballesteros-Pérez, P., Li, H., Philbin, S. P., Li, Z., et al. (2021). Understanding the Impact of Environmental Regulations on Green Technology Innovation Efficiency in the Construction Industry. *Sustain. Cities Soc.* 65, 102647. doi:10.1016/j.scs.2020.102647

Zhang, Y. J., Peng, Y. L., Ma, C. Q., and Shen, B., (2017). Can Environmental Innovation Facilitate Carbon Emissions Reduction? Evidence From China. *Energy Policy* 100, 18–28. doi:10.1016/j.enpol.2016.10.005

Zhao, X., Yin, H., and Zhao, Y. (2015). Impact of Environmental Regulations on the Efficiency and CO2 Emissions of Power Plants in China. *Appl. Energ.* 149, 238–247. doi:10.1016/j.apenergy.2015.03.112

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.