frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 10 January 2023
DOI 10.3389/fenrg.2022.895539

How the carbon emissions trading system affects green total factor productivity? A quasi-natural experiment from 281 Chinese cities

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SPECIALTY SECTION
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

RECEIVED 14 March 2022
ACCEPTED 30 September 2022
PUBLISHED 10 January 2023

CITATION
Shao W, Yang K and Jin Z (2023), How the carbon emissions trading system affects green total factor productivity? A quasi-natural experiment from 281 Chinese cities.
Front. Energy Res. 10:895539.
doi: 10.3389/fenrg.2022.895539

China's emissions trading system is often cited as a model for developing countries using market-based means to solve pollution problems, but few have objectively assessed the solution from a productivity perspective. Therefore, in this study, the green total factor productivity (GTFP) of 281 prefecture-level cities was calculated by using the DEA–Malmquist method, and the policy effects were evaluated by setting up quasi-natural experiments. The results show that the carbon emissions trading system has a positive contribution to GTFP; when facing a more compatible carbon trading system, enterprises will choose two paths: innovation compensation and industrial upgrading to improve GTFP, so as to get rid of the cost constraints caused by carbon emission control; the policy effect of the carbon emissions trading system varies significantly in different regions. In the economically developed eastern region, the effect of policy implementation is relatively significant, while the effect of policy implementation in the western region is not significant. Further analysis shows that as a market-based environmental policy, the incentive effect of the carbon trading system relies on a perfect market system. This study provides empirical evidence and policy enlightenment for developing countries to build and improve the emissions trading system.

KEYWORDS
carbon emissions trading system (ETS), green total factor productivity (GTFP), quasi-natural experiments, difference-in-difference (DID), innovation compensation effect, industrial upgrading effect

1 Introduction

For a long time, economists have insisted that the solution to greenhouse gas emissions should rely on the market mechanism. Therefore, in the regulations on the administration of carbon trading and relevant government statements, the carbon emissions trading system (hereinafter referred to as the CETS) is described as "an important policy tool for implementing the national carbon peak and carbon neutralization vision." According to the data released by China's Ministry of Ecology and Environment, by June 2021, China's carbon market had a total transaction volume of 4.833 million tons, covering more than 20 industries such as power generation and petrochemicals. It is preliminarily estimated that the emission reduction elasticity of the CETS is more than 15% (Zhang et al., 2020). However, as an important institutional innovation of economic reform, emission reduction is not the sole purpose of the CETS, and its ultimate policy orientation is to achieve "low emissions, high efficiency, and sustainable development." Existing research does not provide an answer for the following questions: when are carbon emission rights involved in production as a capital factor? Can both energy conservation and emission reduction and economic growth be achieved? Benefiting from the acceptability and compatibility of the CETS, what path will enterprises choose to achieve "green sustainable development" in the real sense?

Green total factor productivity (GTFP) refers to the comprehensive productivity of each factor considering the environmental cost. Since resources and environment are included in the evaluation index, the coordination and sustainability of regional economic development can be comprehensively evaluated (Feng et al., 2021). Dong et al. (2019) believes that the improvement of GTFP includes two objectives: economic growth and environmental protection. However, for enterprises pursuing profit maximization, the pursuit of a higher GTFP level means that enterprises need to bear additional environmental protection costs. Notably, in the competitive environment, this is not in line with the core interests of enterprises. Therefore, in reality, enterprises often lack the initiative to improve GTFP, and they must rely on appropriate external constraints to motivate enterprises to take the initiative to bear this externality cost. In relevant studies, economists place their hopes on the emission trading system. They believe that the CETS with the market mechanism as the core has typical incentive compatibility characteristics, and a properly designed CETS can provide compensation for enterprise externalities in the form of property rights and prices, so as to achieve the purpose of correcting the enterprise behavior without damaging the production enthusiasm (Hass and Dales, 1969; Montagnoli and De Vries, 2010; Wu and Wang, 2022).

Why is the CETS widely supported by economists? It is because the CETS has a higher ability to achieve desirable goals than command-based environmental regulation. Regulatory policies convert external environmental resources into endogenous costs. Therefore, under the constraints of environmental costs, enterprises may have no excess profit space for technological improvement (Montgomery, 1972; Cook, 1986), so they can only avoid further punishment by either reducing production or stopping production. Therefore, if environmental control is relaxed in the later stage, the emission level of enterprises will rebound immediately. In order to solve this contradiction, Hass and Dales (1969) combined the property right mechanism with the transaction mechanism and put forward the related concepts of the emission trading system. The introduction of the market mechanism turns the uncertainty risk brought by carbon emission control into price shock, providing a buffer zone for enterprises to adjust production and investment decisions, thus producing a stronger ability to achieve desired goals. Under the role of this mechanism, enterprises are more active in technological improvement and solving negative externalities, which not only encourages enterprises to carry out innovation but also forces enterprises to carry out transformation and upgradation so as to obtain relative competitive advantages in the carbon market, namely, the so-called "Porter effect" (Porter and Van der Linde, 1995).This is the core mechanism for the CETS to exhibit its policy effects, which has also been proven in the studies by Karp and Zhang (2005), Cui et al. (2018), and Wang et al. (2020).

At present, the international economic situation is in a turbulent stage of development, and the contradiction between environmental protection and economic development is becoming increasingly prominent (Bekun, 2022; Mujtaba et al., 2022). The new development goals will place greater demands on emerging markets, but so far, increasingly severe environmental problems still plague social planners (Bekun and Alola, 2022; Bekun et al., 2022). As the largest developing country in the world, the introduction of the CETS is an important attempt made by China to balance environmental protection and economic development. Evidently, if we only pay attention to the emission reduction mechanism of the carbon trading system and ignore other economic effects, we cannot fully describe the policy value of the CETS for the transformation of production mode and high-quality economic development. It means that new evidence must be provided to accurately evaluate the significance of the CETS for China's economic development.

The objective of this study is to completely describe the policy mechanism of the CETS acting on the two objective functions of economic growth and environmental protection through a more reasonable index design and method setting, so as to provide an effective reference basis for developing countries to improve the market incentive environmental regulation system and promote green economic transformation. First, referring to the practices of Caves et al. (1982) and Chung et al. (1997), the expected output (economic growth) and unexpected output (pollution emissions) are included in the same index system. The "Green total factor productivity" of each prefecture-level city is calculated by using the DEA–Malmquist index, and the policy effect of the CETS is comprehensively evaluated from this perspective. Second, the quasi-natural experiment is set against the background of China's carbon trading pilot program in 2013. Combined with the intermediary effect model, it depicts the mechanism's role in innovation compensation and industrial upgradation in policy effects, which is different from the results of Li et al. (2013) and Cui et al. (2018). Finally, by setting up the regulation effect model, this article studies the role of the market system in the trading system and improves the whole mechanism analysis chain.

From the perspective of research objects and basic issues, the research studies of Feng et al. (2021), Huang and Chen (2022), and other scholars are better in line with this study. Among them, Feng et al. (2021) mainly analyzed the effectiveness of SO_2 ETS introduced in 2007 from the perspective of regional differences. Huang and Chen (2022) explored the spatial characteristics of CETS policy effects using the spatial model and the mediation model. Unfortunately, the research of these scholars was evidently more inclined to quantitative analysis and did not further explain the deep-seated reasons for the effect of the emission trading system on GTFP from the level of the economic mechanism. It also does not answer the key proposition of how developing countries should improve CET, which leads to the lack of reliable academic reference at the level of public policy. Therefore, on the basis of the aforementioned literatures, this study makes the following marginal contributions: first, based on the new database, the GTFP of each prefecture-level city in China is re-calculated, and from this perspective, the general law of the CETS acting on economic growth and environmental protection is measured. Second, on the basis of the aforementioned quantitative analysis, the policy mechanism of CET is analyzed from multiple perspectives, the economic mechanism of CET acting on GTFP is explained, the general law and characteristics of the evolution between the two are summarized, and the deficiencies of Feng et al. (2021) and other scholars in mechanism analysis are complemented. Third, by introducing marketization index, this study further discusses the regulatory effect of institutional environment and market mechanism construction on CET and improves the relevant analysis framework. Fourth, combined with the current economic and social situation of China, this study puts forward policy suggestions on how to construct and optimize CET in many developing countries and answers the key question of how to improve the market-motivated environmental regulation system in emerging markets.

The remainder of this article is organized as follows: Section 2 presents the literature review; Section 3 discusses the mechanism analysis and research hypothesis; Section 4 presents the model specification and variables' description; Section 5 describes the empirical analysis; Section 6 describes the robustness test; Section 7 presents the analysis of regional heterogeneity of policy effect; Section 8 discusses the promotion and demonstration of policy compatibility; Section 9 presents the conclusion and policy enlightenment; and Section 10 discusses the research prospect.

2 Literature

GTFP is the contribution of various factors to economic growth when considering environmental costs, that is, environmental variables are included on the basis of the traditional total factor productivity index. Because this index comprehensively considers economic benefits and environmental effects, GTFP can evaluate the quality of economic growth of a region more effectively and objectively than that of the traditional total factor productivity index (Wang et al., 2021); therefore, it is widely used to evaluate the final effect of environmental policies (Rodríguez et al., 2018; Xia and Xu, 2020). So, what are the main factors that affect GTFP? Several studies have shown that in addition to endogenous factors, such as investment (Zhang et al., 2016) and industrial structure (Eiadat et al., 2008), the change of GTFP is also significantly related to environmental policies, but different types of policies will have different impacts on GTFP. In general, administrative environmental regulation can stimulate technological innovation, expand productivity, reduce pollution control costs, and promote the improvement of GTFP (Fan et al., 2022). However, strict environmental regulations will lead to additional pollution control costs, which will have a negative impact on normal business activities (Li et al., 2021). However, as a market-based environmental regulation policy, the biggest advantage of the CETS lies in its ability to achieve its desired goals and lower policy implementation costs. So, will this significantly differ from the traditional administrative mandatory environmental regulation policy and help to improve the green total factor production rate?

The theory of the carbon emissions trading system can be traced back to Coase (1960). He believes that if the definition of property rights is clear, the problem of negative externalities will be solved through the trading behavior between subjects. Inspired by this proposition, scholars such as Hass and Dales (1969) proposed a tradable emission trading system. In the framework of emission right trading proposed by Hass and Dales (1969), it is suggested that enterprises should be allowed to trade with given emission rights, that is, enterprises should intervene in external non-economic behaviors by means of the property rights mechanism and trading mechanism. Stavins (1995), Rogge et al. (2011), and other scholars have shown that a properly designed emissions trading system will guide enterprises to continuously improve their production process through market signals, and finally find a new equilibrium point of marginal revenue and marginal cost to promote the equalization of marginal emission reduction costs in the whole market. Therefore, in studies by Montgomery (1972), Karp and Zhang (2005), Bayer and Aklin (2020), Yu et al. (2021), Zhang and Wang (2021), Tian et al. (2022), and other studies, CETS is described as a successful case. Using various analytical tools, scholars have measured the effect of the CETS on agricultural productivity (Hua et al., 2022), spatial spillover effect (Wu and Wang, 2022), and pollution reduction performance (Yan et al., 2020). The policy effect of CET is verified together.

However, this does not mean that there is no controversy over the CETS. The studies of Cason et al. (2003), Hoffmann (2007), and Zachmann and Von Hirschhausen (2008) have expressed concern about the "market-based instruments." They believe that the implementation of the CETS will seriously limit the profit space, and the short-term behavior of "quantity for quality" of enterprises will curb the long-term development, so as to curb the GTFP (Yi et al., 2019). Some scholars have found that environmental regulation pilot policies drain the government's technology expenditure to a certain extent, thereby inhibiting the improvement of GTFP by verifying similar environmental regulation policies (Fan et al., 2021). Particularly, when a variety of environmental regulation tools are used at the same time, it will distort the normal business behavior of enterprises, and this distortion effect is not short-term, but will show a heterogeneous trend under the changes of economic conditions. It is also possible that the imperfect market system of developing countries may lead to serious problems of "endogenous law enforcement" and "selective law enforcement," which has also become a key consideration in the promotion of the CETS in various countries.

The doubts about the CETS continue, as Rodrik (2008) said, in any system that operates in a suboptimal form. To judge whether an institutional system is worth promoting should not only consider its possible distortion but also consider whether its economic consequences meet the external constraints of the real environment. The biggest advantage of the CETS lies in its cost transfer and price incentive mechanism (Webster et al., 2010; Zhu et al., 2018; Arimura and Abe, 2021; Boroumand et al., 2022; Ma et al., 2022). The CETS enables quotas to have property rights and flow properties, and economic subjects with "environmental protection" advantages will gain a relatively advantageous position in the market, so that they can transfer the "compliance costs" brought by environmental regulations to disadvantaged enterprises by quota trading and obtain additional economic returns (polluter pays). In order to get rid of this quota constraint, the relatively weak party will also improve its situation by continuous adjustment, forming the so-called "forced" effect on the whole. In addition, with the establishment of the "carbon market," the original environmental constraints will be transformed into a dynamic market signal, making decision makers more sensitive to the pressure on environmental costs. Under the guidance of the "carbon price," enterprises have more sufficient motivation to adjust production and technology strategies, so as to drive the overall "Pareto improvement." This role of promoting energy innovation and market stability through financial means has also been confirmed in many scholars' studies (Kaiser and Welters, 2019; Naqvi et al., 2021; Taghizadeh-Hesary et al., 2021; Umar et al., 2021; Karim et al., 2022). The advantages of these financial instruments and the promotion of corporate social responsibility awareness (Ielasi et al., 2018; Ferrat et al., 2021; Lobato et al., 2021; Dorfleitner and Grebler, 2022), which can well match China's current development goals and become an important replacement and supplement of command-based environmental regulation policies (Ji et al., 2021).

There are many literatures on the evaluation of the CETS's economic effect, mainly focusing on energy saving and emission reduction (Xuan et al., 2020; Tian et al., 2022), industrial structure upgrading (Hu et al., 2020; Tang et al., 2021), enterprise competitiveness (Zhang and Wang, 2021; Sun et al., 2022), technology innovation (Zhu et al., 2019; Li et al., 2022), energy transformation (Yu et al., 2022), and promotion of foreign direct investment (Liu et al., 2020); these scholars confirmed the positive role of the CETS using different indicator systems. However, the problem is that although the aforementioned indicator system can also meet the requirements of policy evaluation, has the overall operation quality of economy has changed after the implementation of CETS? Through what path does it work? The aforementioned literature evidently does not give the desired answer. Although some scholars have discussed the relationship between the CETS and productivity or environmental indicators based on the non-linear relationship theory (Shi and Li, 2020), the conclusion still fails to reflect the economic effect and environmental effect at the same time (Huang and Chen, 2022). Therefore, based on the quasi-natural experimental method, this study calculates GTFP at the prefecture level by introducing productivity and environmental index evaluation indicators and discusses the impact of the CETS on economic development in China using the intermediary effect model. In addition, considering the particularity of China as a developing country, this study discusses the effect of institutional environment construction on the CETS by introducing market-oriented indexes. It is hoped that the rigorous empirical analysis process will provide empirical evidence and policy enlightenment for developing countries to construct and improve the emission trading system.

3 Mechanism analysis and research hypothesis

The Chinese government has been trying to balance the two objective functions of economic development and environmental protection using institutional design. The suggestions given by economists mainly include three categories: command control, information disclosure, and market incentive (Hass and Dales, 1969; Porter and Van der Linde, 1995; Li and Shen, 2008; Acemoglu et al., 2012). However, limited by the economic environment, the first two tools were mainly selected in the early stage. For example, around 1992, China closed down and rectified a large number of small coal mines, thermal power, and steel smelting enterprises with high energy consumption and high emission at one time and took the initiative to invite international organizations such as the American Natural Resources Conservation Association (NRDC) to carry out collaborative supervision and information disclosure on China's carbon emissions. However, these systems did not play a significant role under the policy guidance of "expanding domestic demand" and "incremental investment." On the contrary, strict command-based regulation and information disclosure increased the burden on enterprises. Therefore, there are increasing disputes about the impact of environmental regulation on economic growth. With the establishment of the European Union and the United States carbon trading market, the Chinese government also began to conceive and demonstrate the feasibility of introducing the carbon emission trading system and officially carried out the pilot work from 2011 to 2013[1]. However, considering the acceptability of the market, in the preliminary plan, the first batch of pilot projects was mainly concentrated in economically developed areas such as Beijing, Tianjin, and Shanghai and was planned to be promoted nationwide after 2017. By the end of 2020, the China's carbon market had nearly 3,000 active players, covering eight industries including power generation, petrochemical, and chemical, with an average transaction value of 600 million yuan per month.

China's CETS is endowed with multiple expectations to promote energy conservation and emission reduction, strengthen green and sustainable development, and promote environmental and ecological governance. Then, what role does the establishment of the CETS play in the transformation of China's social production mode? The existing research is mainly from the perspective of "production function transformation" and "profit rediscovery." From the perspective of production function transformation, environmental regulation transforms the original exogenous environmental resources into the fixed cost of the enterprise (Aghion et al., 2016), which has an impact on its original production function and breaks the original market equilibrium state. Although it has played a role in environmental protection in the short term, it has caused high costs in the later stage of enterprises, and the opposition between environmental regulation and enterprise production began. In the scenario of the CETS, environmental resources are regarded as a property right that can carry out initial resource allocation, allowing social subjects to trade the allocated environmental resource rights to replace and make up for the "compliance cost." Under the dual effects of the property right mechanism and transaction mechanism, each manufacturer gradually approaches its lowest cost point and reaches a new equilibrium when the marginal emission reduction cost is equal (Montgomery, 1972). The market state after rebalancing has undergone qualitative changes. The traditional production mode has been completely broken under the impact of exogenous policies. Under the new market equilibrium state, the production function of enterprises has changed, and carbon emission rights have been added to product production as a new factor of production. Under the impact of flexible cost, all subjects will carry out optimal social production under the constraint of carbon cost through continuous technological adjustment (Pareto improvement). Therefore, the CETS is also considered as the emission control policy with "lowest social cost" (Hass and Dales, 1969; Löschel et al., 2019). Tang et al. (2021) found that the CETS could promote emission reduction without sacrificing productivity, and Pan et al. (2022) found that the CETS could improve productivity.

From the perspective of profit rediscovery, the advantages of the CETS are more evident. Apart from the traditional environmental regulation policies, the emission trading system mainly relies on the price mechanism to control pollutants. In the mechanism design of carbon emission rights, the quota of enterprises is in the same position as technology and capital in the production function. Under the price discovery function of the carbon market, exogenous environmental rights and interests have value attribute and monetary attribute. Therefore, enterprises with more emission quotas have an absolute competitive advantage in the market and are motivated to expand economic returns and stabilize market position by further investment strategy adjustment, which has been verified in the study of Calel and Dechezleprêtre (2016). At the same time, because the carbon price is endogenous, in the supply–demand game of the carbon market, the disadvantaged enterprises bear most of the environmental costs, thus forming a forcing effect similar to Porter hypothesis (Porter and Van der Linde, 1995), forcing the disadvantaged enterprises to adopt strategies to change the mode of production, so as to get rid of the constraints of emission rights on the production and operation of enterprises. In conclusion, the unique cost mechanism and price mechanism of the CETS will encourage enterprises to make more emission reduction without damaging their production enthusiasm, which will be directly reflected in the change of GTFP. Accordingly, the first hypothesis of this study is put forward:

H1: The establishment of the CETS has a positive marginal contribution to the improvement of GTFP.

If the CETS can effectively improve green total factor productivity, how does it achieve this effect? A deep understanding of the policy mechanism of the CETS acting on the two objective functions of economic growth and environmental protection will improve the market incentive for developing countries. It provides an effective reference for the regulatory system and accelerates the green transformation of the economy. Porter and Van der Linde (1995) believe that appropriate environmental regulation policies can promote social productivity. The research works by scholars such as Karp and Zhang (2005) and Cui et al. (2018) believe that this

1 Notice of the General Office of the National Development and Reform Commission on The Pilot Work of Carbon Emission Right Trading, Climate [2011] No. 2601, Development, and Reform Office of China, hereinafter referred to as the Pilot Notice.

hypothesis is still applicable in the context of the emission trading system. In the mechanism analysis of "Porter hypothesis," existing studies mainly attribute the transmission path to two channels, one is innovation compensation and the other is industrial upgrading. According to the research of Karp and Zhang (2005), Cui et al. (2018), and Ma et al. (2022), the unique price mechanism and quota mechanism of the CETS will amplify the competitive effect of the carbon market. As the enterprises face the rise of CETS' price, they will have strong motivation to invest in R&D, patents, and other cost-reducing activities to gain competitive advantages.

In the traditional market competition, the purpose of enterprises carrying out production is mainly to obtain a higher market share and maximize profits in the current period. However, in the scenario of the carbon emissions trading system, commodity production is no longer the only profit source of enterprises. The "balance" of carbon emission rights obtained through technological improvement may produce higher economic returns. Therefore, the form and scope of competition have also changed fundamentally. Enterprises with technology first mover advantage will gradually occupy a favorable competitive position under the role of the trading mechanism, so as to transfer the carbon emission cost to other operators, and other followers will also carry out innovation activities under the guidance of price to avoid further widening of the gap (innovation compensation). Therefore, as the carbon trading market game forms a virtuous circle, the economic motivation of innovation activities will be further amplified, resulting in Pareto improvement in the overall sense. This point has been verified in the studies of Cui et al. (2018). According to their measurement results, the promoting effect of the CETS on technological innovation is about 5%–10%, while Zhang et al. (2021) believe that this effect will be directly reflected in the improvement of GTFP. Under the action of this mechanism, the production level of the whole society will be effectively improved. In conclusion, the following hypothesis is put forward:

H2: The establishment of the CETS will have an incentive effect and reverse force effect on the technological research and development of enterprises and will then bring about the improvement of GTFP.

Judging from scholars' observations of China's CETS, industrial upgrading may be another channel for the emission trading system to promote the improvement of the social production efficiency. Affected by historical factors such as international industrial transfer, China's economic development is very dependent on heavy industry and manufacturing. However, in the face of rigid carbon emission control, energy-intensive and asset-heavy enterprises such as power generation and smelting are very difficult to carry out technological research and development. Compensation effects cannot completely offset the opportunity cost of regulation. In addition, technological innovation has the characteristics of intertemporal benefits (Arrow, 1962). Therefore, many enterprises can only transfer their factories to other regions to maintain production, but they will not invest all its funds in technology research and development. However, the CETS mechanism gives liquidity to environmental rights and interests, and heavy polluting enterprises have certain quota advantages when determining the initial quota, according to the historical emission method. However, this advantage does not mean that the pressure on enterprises to reduce emission reduction is reduced. On the contrary, with the gradual tightening of the total amount constraint function of the carbon market, the marginal emission reduction cost of high energy consuming enterprises will gradually increase. The difference is that the "one size fits all" mandatory regulation does not provide enterprises with time to adjust production decisions, while the emission trading system provides enterprises with a longer adjustment period and profit support. Therefore, the "horizontal avoidance effect" in the context of administrative regulation will be transformed into vertical industrial upgrading in the context of emission rights. On the whole, production factors will change from non-green production industries with low productivity to green industries with high productivity under the action of the trading mechanism. The most intuitive embodiment of the aforementioned utility is the increase in the proportion of the tertiary industry (industrial structure optimization) (Du et al., 2021). This industrial upgrading effect and efficiency improvement effect caused by the change of environmental policy have also been supported by corresponding experience in Europe and other countries (Zang et al., 2020). Based on the aforementioned analysis, another hypothesis of this study is put forward:

H3: The incentive effect of the CETS will guide enterprises to upgrade from the traditional industry to the tertiary industry with more environmental protection and higher efficiency, thus bringing about the improvement of GTFP.

4 Model specification and variables description

To test the aforementioned three hypotheses, we first need to solve two key problems: one is to build a measurement index, which can measure environmental protection and productivity at the same time, and the other is to build a quasi-natural experiment.

The first question is that the existing research usually adopts the method of the double-index system for verification, that is, the productivity index is combined with an environmental assessment index (Ren et al., 2019 , Shi and Li, 2020).

Although this method has certain rationality, this classification test method cannot describe the sum of the two effects, so there is room for improvement in the explanatory power of the model. In recent years, in order to study the resource and environmental costs of economic growth, some scholars have included resource and environmental factors into productivity measurement in traditional TFP analysis and considered the input–output efficiency of energy consumption and pollutant emission. The improved index is called green total factor productivity (GTFP) (Li et al., 2013; Chen and Golley, 2014). Therefore, referring to the methods of Li et al. (2013) and Shen et al. (2017), this study measures the indicator (green total factor productivity, referred to as GTFP) after the modification of negative externalities (greenhouse gas emissions) using DEA–Malmquist index, which includes both desired output (economic growth) and undesired output (pollution emission). Therefore, it is more appropriate to evaluate the performance of environmental policy (Feng et al., 2021; Huang and Chen, 2022).

The estimation methods of GTFP can be divided into the parameter stochastic frontier method and data envelopment analysis (DEA) method. The stochastic frontier function method can only identify one decision unit (DMU) as the most effective decision unit in the frontier, but it will underestimate the efficiency level of the overall sample. DEA is a non-parametric test method proposed by Charnes et al. (1978) on the basis of efficiency analysis. There are two types of DEA models, namely, the CCR model and BBC model. The CCR model is based on the assumption of constant return to scale (CRS) and has limitations. Although the BBC model is based on variable return to scale, the BBC model can only statically compare the level of GTFP at the same time node and cannot measure dynamic changes and future development trends. Therefore, this study adopts the DEA method and Malmquist index method at the same time to measure GTFP from static and dynamic perspectives, which not only considers the absolute efficiency of each decision-making unit on the cross-section but also takes into account the changes of time series on the vertical section, that is, the DEA–Malmquist method solves the problem of separation between static and dynamic analysis of the two methods and can better evaluate the efficiency index. The calculation of this index mainly uses five groups of data: labor input, capital input, energy input, actual GDP, and emissions. The data sources are the China Urban Statistical Yearbook and the China Energy Statistical Yearbook. The CO_2 emission data come from China Emission Accounts and Datasets (CEADs); refer Supplementary Appendix S1 for the specific calculation model and calculation process[2].

The second question is that in order to accurately assess the net effect of the policy, a quasi-natural experimental framework needs to be constructed, and a dual-difference model (DID) needs to be used to analyze the effectiveness of the policy. The double difference method can accurately evaluate the policy effect, mainly by observing the changes of a variable before and after the implementation of the policy to estimate the net effect after the implementation of the policy, and it can effectively avoid the impact of endogenous problems and regional heterogeneity on the research object. It is a simple and easy way to understand the method of policy evaluation. According to the relevant government documents, there are seven provinces and cities in the first batch of CETS pilot projects in China, namely, Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen. This study takes the panel data covering 281 prefecture-level cities in China from 2009 to 2017 as the research sample. From the distribution of the pilot sites, the pilot projects are mainly the first-tier cities with developed economy and heavy industrial enterprises, which cover the east, middle, and west of China, meeting the requirements of the quasi-natural experiment for the control group (treat). Other cities not listed as pilot cities are used as the treatment group. In the identification of pilot cities, this study is consistent with Cui et al. (2018) and Wang et al. (2020). However, in the sample statistics, this study excludes some provinces with serious data deficiency (data from Hong Kong, Macao, and Taiwan are temporarily unavailable), so the final sample selected and adopted is 281 municipal units. There are 37 in the control group and 244 in the treatment group, with a ratio of 1:6.59.

Another element of building a quasi-natural experimental framework is the policy time point (time). According to the time of policy announcement, it seems that the time point should be set to 2011, but the problem is that the policy effectiveness of the carbon trading system is mainly the market mechanism and default punishment mechanism. Even if it is the first listed Shenzhen carbon exchange in China, its earliest trading time can only be traced back to June 2013. Therefore, 2011–2012 is only the demonstration and preparation stage of the carbon emissions trading system. Setting the time point as 2011 will overestimate the policy effect of carbon trading, which has also been verified in detail by Cui et al. (2018). Therefore, taking 2013 as the pilot time point, this study sets the time virtual variable, that is, 0 before 2013 and 1 after the implementation of the policy, that is, in 2013 and after. In terms of time window, considering that the carbon trading system will be expanded from pilot provinces and cities to the whole country after 2017, the interval will be locked during 2009–2017.

Based on the panel data of 281 prefecture-level cities, the benchmark DID measurement model in this article is set as follows:

$$\mathrm{GTFP_{it}} = \beta_0 + \beta_1 Treat_{\mathrm{i}} \times Time_t + \beta_2 X_{it} + \varepsilon_{it} \quad (1)$$

where $\mathrm{GTFP_{it}}$ represents the GTFP located in prefecture-level city i in t; $Time_t$ is the time point variable of the policy, reflecting

2 Reference Supplementary Appendix S1 for a specific calculation model and calculation process, and see Table 1 for final calculation results

TABLE 1 Main variable description statistics.

Variable	Observation	Mean	Standard error	Min	Max
GTFP	2,529	1.2865	0.4579	0.2706	2.329
Treat	2,529	0.1317	0.3382	0	1
Time	2,529	0.07315	0.2604	0	1
Lnpgdp	2,529	8.7891	0.5996	6.7631	13.8228
Lnpmidu	2,529	5.7349	0.8938	1.7169	7.8461
Lnenergy	2,529	6.9822	0.8260	4.0635	9.4266
Lndensity	2,529	5.7349	0.8938	1.7169	7.8461
LnFDI	2,529	10.0584	1.7534	2.7726	14.9413
Lnfd	2,529	10.0154	0.7824	6.9385	13.5342
Lnie	2,529	1339.521	1869.893	20.26	41,389.12
Industry	2,529	44.086	11.337	9.76	80.56
Patent	2,529	594.76	2,229.9	1	46,060

the time effect of the policy; and the $Treat_i$ is the grouped variable reflecting the original productivity gap between the control group and the treatment group. The $Treat_{\mathrm{i}} \times Time_t$ interaction term is the core explanatory variable in this article, and its coefficient β_1 represents the net effect of the policy, where X_{it} represents a set of control variables, and $\varepsilon_{\mathrm{it}}$ is the random disturbance term.

In the experimental design of this article, the influence of other factors on pilot selection and productivity (endogeneity) needs to be taken into account, so it needs to be controlled in the form of increasing control variables. These control variables mainly include 1) city size factor. Lndensity (population density) is obtained by dividing the population of prefecture-level cities by the area of administrative regions, and the city size is measured together with Lnpmidu (urban population). The data source is the China Urban Statistical Yearbook. 2) Lnpgdp (GDP per capita), per capita GDP level represents the level of economic development and is the ratio of GDP to total population in the current year, which must be controlled in prefecture-level city panel analysis. 3) Lnenergy (total energy consumption) measures the level of urban energy consumption, which can affect GTFP by affecting the resource utilization rate and production scale expansion. This study uses the energy consumption data of Shi and Li (2020), which is measured by combining with night light data simulation. 4) LnFDI (foreign direct investment), which measures the capital vitality and openness of prefecture-level cities. 5) LnFD (fiscal expenditure): the higher the level of fiscal expenditure, the higher the level of government intervention. When the market fails, the government can intervene to ensure the realization of economic and environmental goals. This article adopts the total amount of general fiscal expenditure of prefecture-level cities to measure. 6) Lnie (number of industrial enterprises), industrial enterprises are the main source of carbon emissions. On the one hand, their scale can integrate resources and reduce production costs; on the other hand, the increase of the number of industrial enterprises also increases environmental pollution, which will affect GTFP, and the intermediary variables, industry (proportion of the tertiary industry) and patent (number of patents), used in the mechanism test part reflect the industrial structure and innovation level of prefecture-level cities. This data source is also the China Urban Statistical Yearbook.

5 Results and discussion

5.1 Data description

The final statistical description is shown in Table 1.

For the problem of statistical caliber deviation or data deviation that may occur in processing, this article adopts the method of large-scale sampling and comparison, and compares it with the China Urban Statistical Yearbook and the Statistical Bulletins of various cities many times. If there were inconsistent data between the two, the more authoritative China Urban Statistical Yearbook prevailed.

At the same time, in order to show the common spillover effect of GTFP in each prefecture-level city, this study refers to the Pesaran's CD test proposed by Pesaran (2004) and thus puts forward the statistic as follows:

$$\mathrm{CD} = \sqrt{\frac{2}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \sqrt{T_{ij}\hat{\rho}_{ij}} \right. \tag{2}$$

According to this statistic, the cross-sectional dependence test is carried out, and Pesaran's CD test is used to obtain the test results under the fixed effects model and random effects model. If the residual of the econometrics model still shows cross-sectional dependence after controlling the main influencing factors, it can be considered that there is a spatial interaction and linear relationship between GTFP, and the results are shown in Table 2:

TABLE 2 Estimated value and significance level of Pesaran's CD test.

Method	Fixed effect		Random effect	
	Estimated value of statistics	*p*-value	Estimated value of statistics	*p*-value
Pesaran CD test	96.227	0.0000	94.517	0.0000

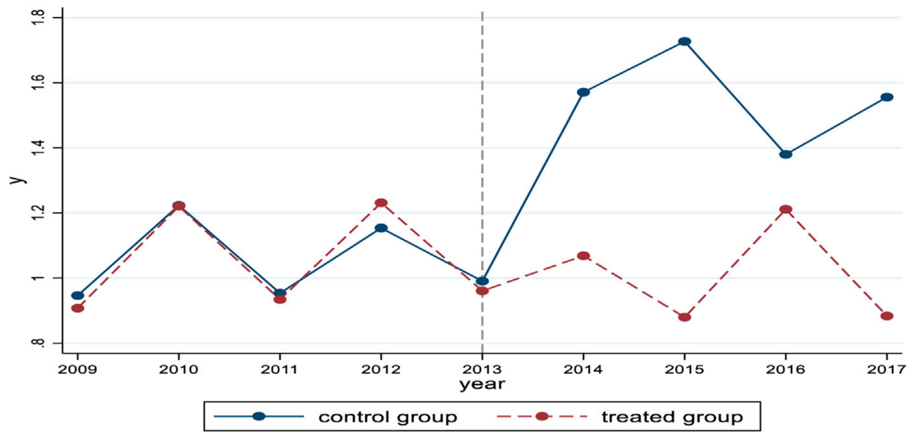

FIGURE 1
Parallel trend test.

The cross-sectional dependence test results are shown in Table 2. There may be correlation between each cross section, which may cause empirical error. In order to deal with cross-sectional-related problems, this study chose to correct the standard error in the empirical analysis to alleviate the error caused by cross-sectional correlation, namely, "panel correction standard error" (PCSE).

5.2 Parallel trend test

The parallel trend test is an important hypothetical premise of the DID model, which requires to ensure that the treatment group and the control group have the same development trend before the experiment, so as to better illustrate that the policy impact is the only motivation for their behavioral changes. Therefore, this article refers to the event analysis method commonly adopted by Jacobson et al. (1993) for testing. As can be seen from Figure 1, there was no significant difference in the fluctuation between the control group and the treatment group before 2013, but after 2013, there was a notable external impact, causing the control group to begin floating significantly, and the gap between the two became more and more evident over time. In conclusion, it can be assumed that it has passed the strict parallel trend test.

5.3 Principal regression result

In this article, the OLS–DID (least square method) method is used for regression analysis of model (1), and the regression results are shown in Table 3. It can be seen that regardless of the test method, the net effect coefficient β_1 of the policy most concerned in this article is positive, and the coefficient has reached more than 1% at the significance level. The original hypothesis is that no correlation can be rejected.

Based on Table 3, it can be assumed that hypothesis H1 "the establishment of the CETS has a positive marginal contribution to the improvement of GTFP" is valid. In the economic sense, the establishment of the CETS has transformed exogenous emission constraints into endogenous prices and has the liquidity attribute. Environmental rights and interests begin to join the enterprise profit function in the form of production factors. The difference between the social cost and private cost caused by carbon emission will be gradually transferred to high pollution and high energy consuming enterprises in the form of the factor cost, forming a "backward force" on these enterprises. If they still do not change their production decision and adhere to low-efficiency production mode, they will completely lose their competitive advantage in the subsequent price game. Therefore, for enterprises, this price shock and cost shock are

TABLE 3 DID baseline regression results (PCSE).

Variable	(1)	(2)
Treat×Time	0.2702***	0.1863***
	(3.98)	(3.85)
Lnpgdp		0.1372***
		(4.59)
Lnpmidu		0.0513***
		(3.52)
Lnenergy		−0.1170***
		(−5.24)
Lndensity		0.0006
		(0.07)
LnFDI		−0.2943***
		(−2.81)
Lnfd		0.1036***
		(2.93)
Lnie		−0.0001**
		(−2.23)
_cons	1.2667***	−0.1256
	(23.81)	(−0.26)
Control variables	No	Yes
Observations	2,529	2,529
R-squared	0.024	0.062

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

TABLE 4 Innovating the transmission mechanism of the compensation effect (PCSE).

Variable	Patent	GTFP	GTFP
	(1)	(2)	(3)
Treat×Time	0.2832*	0.1863***	0.1599***
	(1.89)	(3.85)	(3.89)
Patent	—		0.0126*
			(1.68)
Lnpgdp	0.9239***	0.1372***	0.1256***
	(10.51)	(4.59)	(4.59)
Lnpmidu	0.5352***	0.0513***	0.0446***
	(14.82)	(3.52)	(2.80)
Lnenergy	−0.3949***	−0.1170***	−0.1121***
	(−6.39)	(−5.24)	(−5.00)
Lndensity	0.05484***	0.0006	−0.0001
	(3.35)	(0.07)	(−0.01)
LnFDI	0.0130	−0.2943***	−0.0296***
	(0.28)	(−2.81)	(−2.81)
Lnfd	0.7523***	0.1036***	0.0941***
	(7.34)	(2.93)	(3.00)
Lnie	0.0001*	−0.0001**	−0.0001**
	(1.67)	(−2.23)	(−2.32)
_cons	−12.0437***	−0.1256	0.0255
	(−9.91)	(−0.26)	(0.06)
Observations	2,529	2,529	2,529
R-squared	0.369	0.062	0.067

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

more sensitive than external direct constraints, and with the intensification of competition, the signal effect of "carbon price" on production regulation will become increasingly significant. This is also similar to the conclusions of Karp and Zhang (2005), Lange (2012), Zhang and Wang (2021), Ma et al. (2022), and Tian et al. (2022).

5.4 Mechanism analysis validation: Innovation compensation effect

Porter and Van der Linde (1995) believe that designing appropriate environmental regulations can create maximum innovation opportunities for enterprises and encourage enterprises to actively make up for environmental costs by innovation. Existing studies believe that this technology R&D based on solving externalities plays a key role in improving the social production efficiency (Ren et al., 2019). As an incentive environmental policy, the innovation incentive effect of the CETS has been confirmed, but whether its intermediary effect on GTFP is significant or not still needs a new chain of evidence. Therefore, this article introduces the city's patent authorization (patent) in the current year as the proxy variable of innovation compensation and constructs an intermediary effect model based on the basis of the DID panel benchmark model to test the intermediary effect of the innovation compensation effect. The mediation model based on panel data is set as follows:

$$\mathrm{Patent}_{\mathrm{it}} = \alpha_0 + \alpha_1 Treat_i \times Time_t + \alpha_2 X_{it} + \varepsilon_{it} \quad (3)$$

$$\mathrm{GTFP}_{\mathrm{it}} = \beta_0 + \beta_1 Treat_{\mathrm{i}} \times Time_t + \beta_2 X_{it} + \varepsilon_{it} \quad (4)$$

$$\mathrm{GTFP}_{\mathrm{it}} = \gamma_0 + \gamma_1 \mathrm{Patent}_{\mathrm{it}} + \gamma_2 Treat_{\mathrm{i}} \times Time_t + \gamma_3 X_{it} + \varepsilon_{it} \quad (5)$$

where α_1 in model (3) represents the impact coefficient of CETS policy on the innovation compensation effect; β_1 in model (3) represents the impact coefficient of CETS policy on GTFP; γ_1 in model (4) represents the impact coefficient of the innovation compensation effect on GTFP; and γ_2 represents the direct impact coefficient of CETS policy on GTFP. From the concatenation models (3)–(5), we can observe the intermediary role of innovation compensation from a mathematical point of view. From the statistical results (Table 4), the incentive effect (α_1) of the pilot policy on innovation compensation is significantly positive at the level of 1%, which is consistent with the conclusions of Cui et al. (2018). After the innovation compensation effect and pilot variables are all included in the regression (model 5), the coefficients of γ_1 and γ_2 are significantly positive, indicating that the intermediary effect of innovation compensation is notable.

In combination with the economic significance of variables, the stimulation of innovation compensation utility mainly depends on the following paths. Under the traditional carbon emission constraints, the competition among enterprises is mainly reflected in the competition for market share. Therefore, the purpose of technology research and development is mainly to make up for the loss of production reduction caused by regulation and ensure the original profit advantage. The unique quota mechanism of the CETS enables enterprises with low emissions to have additional sources of profits, and the original market competition has greatly changed in scope and form. Relying only on the production of products with low carbon emissions may damage the profits of enterprises, which cannot meet the demand of producers for profit maximization. Therefore, reducing carbon emissions through technological improvement has become a new way for enterprises to pursue profits in the new form. Therefore, in this sense, the "compensation" effect of the innovation of the trading system can also be understood as the profit compensation of the original enterprises under the new competitive situation, and this compensation effect is not one-way, it will form a cycle with the market game, so as to realize the overall Pareto improvement, that is, hypothesis H2, "the establishment of the CETS will have an incentive effect and reverse force effect on the technological research and development of enterprises and will then bring about the improvement of GTFP," is established.

5.5 Mechanism analysis verification: Industrial upgrading effect

In addition to the "innovation compensation effect," the total amount restriction mechanism and trading mechanism of the carbon emissions trading system will also promote enterprises to implement a diversification strategy and change their economic structure (Du et al., 2021). The most significant features of this process are the adjustment of the regional industrial structure, the gradual reduction of the high-polluting secondary industry with large carbon emissions, and the increasing tertiary industry with low emission constraints, high returns, and low barriers, which are finally reflected in the improvement of the whole GTFP. In order to verify the aforementioned transmission mechanism, this study introduced "the proportion of the added value of the tertiary industry in total GDP" as the index of industrial structure optimization (industry), and constructed the following mediating effect model based on panel data:

$$\text{Industry}_{\text{it}} = \alpha_0 + \alpha_1 Treat_{\text{i}} \times Time_t + \alpha_2 X_{it} + \varepsilon_{it} \quad (6)$$

$$\text{GTFP}_{\text{it}} = \beta_0 + \beta_1 Treat_{\text{i}} \times Time_t + \beta_4 X_{it} + \varepsilon_{it} \quad (7)$$

TABLE 5 Transmission mechanism of industrial upgrading (PCSE).

Variable	Industry (1)	GTFP (2)	GTFP (3)
Treat×Time	0.2036***	0.1863***	0.1680***
	(3.39)	(3.85)	(3.49)
Industry	—	—	0.0897***
			(4.48)
Lnpgdp	0.1178***	0.1372***	0.1266***
	(4.20)	(4.59)	(4.48)
Lnpmidu	0.0527***	0.0513***	0.0466***
	(5.70)	(3.52)	(3.17)
Lnenergy	−0.0329***	−0.1170***	−0.1141***
	(−2.83)	(−5.24)	(−5.18)
Lndensity	0.0123*	0.0006	−0.0005
	(1.73)	(0.07)	(−0.05)
LnFDI	0.0059	−0.2943***	−0.0301***
	(0.63)	(−2.81)	(−2.91)
Lnfd	−0.0425	0.1036***	0.1074***
	(−1.23)	(2.93)	(3.21)
Lnie	−0.0001**	−0.0001**	−0.0001**
	(−2.05)	(−2.23)	(−2.19)
_cons	0.2280	−0.1256	−0.1431
	(0.44)	(−0.26)	(−0.79)
Observations	2,529	2,529	2,529
R-squared	0.026	0.062	0.078

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

$$\text{GTFP}_{\text{it}} = \gamma_0 + \gamma_1 \text{Industry}_{\text{it}} + \gamma_2 Treat_{\text{i}} \times Time_t + \gamma_3 X_{it} + \varepsilon_{it} \quad (8)$$

where α_1 in the model represents the impact coefficient of CETS policy on industrial structure optimization; β_1 represents the impact coefficient of CETS policy on GTFP; γ_1 represents the impact coefficient of industrial structure optimization on GTFP; and γ_2 represents the direct impact coefficient of CETS policy on GTFP. The regression results are shown in Table 5 later. Similarly, after controlling the year fixed effect and regional fixed effect, the pilot policy is significantly positive at the level of 5% for the optimization of the industrial structure, which proves the positive role of the carbon emissions trading system in the optimization of the industrial structure. In addition, from the numerical point of view and from the point that the core coefficient γ_2 is less than coefficient β_1, it is indicated that the optimization of the industrial structure does play an intermediary role. Therefore, hypothesis H3, "the incentive effect of the CETS will guide enterprises to upgrade from the traditional industry to the tertiary industry with more environmental protection and higher efficiency, thus bringing about the improvement of GTFP," is established.

Comparing the estimated results in Table 4, it can also be seen that in the process of carbon trading system playing an incentive effect, the intermediary role of innovation compensation and industrial upgrading is basically similar in statistics, but their economic mechanisms are completely different. Innovation compensation mainly depends on profit rediscovery, while industrial upgrading is more reflected in cost. In the scenario of the CETS, due to the existence of the price mechanism and trading mechanism, all the external costs of commodity production will eventually be borne by equity buyers, resulting in a competitive disadvantage. Therefore, there are two most effective ways for enterprises to change the current situation. One is technological innovation, that is, reducing their own emissions using technological improvement, and the other is industrial upgrading, that is, transforming from the heavy pollution industry to the service industry and other industries. In reality, the latter is more difficult to operate and requires higher costs, but it can fundamentally reverse the passive situation of enterprises, exchanging production profits for emission rights. Therefore, many enterprises still choose this approach, such as steel in Henan Province abandoning the foundry industry for an ecological park and steel in Hebei Province transforming to a hotel. Through partial or overall industrial upgrading, the efficiency and enterprise value have been improved. This is also consistent with the existing research (Hu et al., 2020; Tang et al., 2021).

5.6 Robustness test

5.6.1 Placebo test

Although the DID model can overcome the endogenous problem to some extent, there are still other unobservable random factors that impact the conclusion. Therefore, this article, referring to the treatment methods of Ren et al. (2019) and Shi and Li (2020), carries out the placebo test on the measurement results. The specific method is to randomly select 244 cities from the sample of 281 prefecture-level cities as the treatment group and the remaining 37 cities as the virtual control group. The random sampling is repeated 1,000 times, and the distribution of T values is observed according to the operation of model (1). The purpose of this is to randomly select the experimental group and extract the T value by multiple repetitions, and observe and compare the real policy effect with the placebo result. If the real policy effect (Table 3) is significantly different from the placebo test result, it can be considered that the result is not random, but the result of the real policy impact is. The kernel density distribution of the explained variables in this article is shown in Figure 2. It can be seen from the figure that after 1,000 sampling times, the T value of most sampling estimation coefficients changed in a small range and became significantly invalid, indicating that the CETS had no significant treatment effect in random sampling simulation, excluding the impact of other factors on the robustness of the conclusion, and passed the strictly set placebo test.

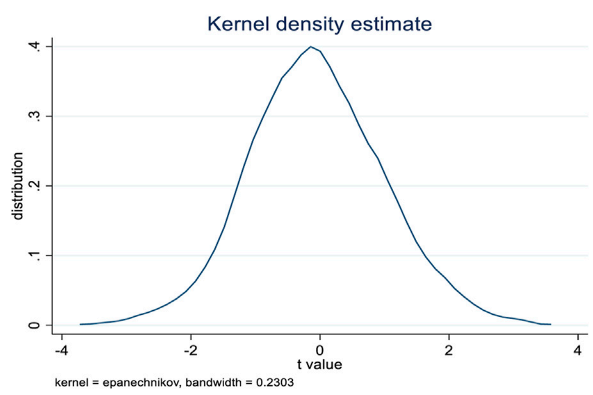

FIGURE 2
Placebo test.

5.6.2 PSM–DID

Due to the differences between the treatment group and the control group in terms of the economic development level and city scale, in order to avoid the differences between groups affecting the empirical results, this study refers to the research ideas of Li and Yan (2018) and uses the PSM–DID method to re-estimate the model (1). Before the PSM–DID method is used for evaluation, the collinearity test was carried out for all variables. The test results show that the variance expansion factor (VIF) of all variables was far less than 10, so it can be concluded that there was no multi-collinearity between the selected variables. Then, the propensity matching score was obtained by logit regression, which reduced the difference between the treatment group and the control group. This study used kernel matching estimation to verify the robustness of the CETS on GTFP. Table 6 shows the test results of propensity score matching balance.

The matching process effectively reduces the deviation (within 10% after matching) and meets the requirements of PSM for data balance. On the basis of PSM treatment, OLS regression continued to be used to re-estimate model (1) at the same time to observe its average treatment effect. The results are shown in Table 7. Compared with Table 3, it can be found that there was no significant difference in both significance and coefficient estimates, so the result can be considered as robust.

5.6.3 Eliminate other policy interference

Statistics show that in addition to the carbon emissions trading system, the Chinese government also carried out the pilot pollutant emission right trading system in 11 provinces such as Tianjin and Hebei in 2007. According to the research of Ren et al. (2019), the pollutant emission right trading system also has a certain impact on

TABLE 6 Propensity score matching balance test.

Variable	Match before/after	Control	Treatment	Bias (%)	Pr (T > *t*)
Lnpgdp	Before	8.7691	8.921	25.1	0.000
	After	8.8806	8.914	5.5	0.470
Lnpmidu	Before	5.6576	6.2443	73.6	0.000
	After	6.2426	6.2333	−1.2	0.842
Lnenergy	Before	6.973	7.0432	7.3	0.148
	After	7.0143	7.0272	1.4	0.857
Lndensity	Before	5.6576	6.2443	73.6	0.000
	After	6.2094	6.2443	4.4	0.475
LnFDI	Before	9.9568	10.729	43.9	0.000
	After	10.756	10.703	−3.0	0.671
Lnfd	Before	9.9671	10.334	38.3	0.000
	After	10.313	10.317	0.5	0.953
Lnie	Before	1196.2	2,284.6	50.3	0.000
	After	2003.4	2,181.7	8.2	0.294

TABLE 7 Robustness test (PSM−DID).

Variable	OLS-DID	
	(1)	(2)
Treat×Time	0.2509***	0.1777***
	(6.99)	(4.77)
Lnpgdp		0.1642***
		(6.58)
Lnpmidu		0.0479**
		(2.49)
Lnenergy		−0.1111***
		(−5.57)
Lndensity		−0.0053
		(−0.82)
LnFDI		−0.0374***
		(−4.62)
Lnfd		0.1347***
		(7.19)
Lnie		−0.0001***
		(−5.09)
_cons	1.2818***	−0.5425**
	(122.32)	(−2.32)
Control variables	No	Yes
Observations	2,160	2,160
R-squared	0.022	0.073

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

TABLE 8 Robustness test (eliminating pollutant emission right) (PCSE).

Variable	(1)	(2)
Treat×Time	0.3512***	0.2494***
	(4.78)	(4.55)
Lnpgdp		0.1261***
		(4.49)
Lnpmidu		0.0471***
		(3.22)
Lnenergy		−0.1099***
		(−5.37)
Lndensity		0.0059
		(0.63)
LnFDI		−0.0264***
		(−2.61)
Lnfd		0.1029***
		(2.81)
Lnie		−0.0001**
		(−2.31)
_cons	1.2700***	−0.1127
	(23.87)	(−0.59)
Control variables	No	Yes
Observations	2,403	2,403
R-squared	0.026	0.065

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

technological innovation and productivity. Therefore, in order to eliminate the interference of this part of factors, three pilot provinces of Chongqing, Tianjin, and Hubei were deleted in the control group, and the model (1) was re-estimated. It can be seen from Table 8 that after excluding the interference of the pollutant emission right trading system, the significance of the estimated results has been improved, reaching more than 1%. The estimated value of the coefficient is also significantly higher than that before elimination (Table 3), which also proves the robustness of the conclusion.

5.7 Regional heterogeneity analysis of policy effects

Based on the purpose of the policy experiment, China's carbon emissions trading pilot adopts the practice of decentralized selection. From the perspective of geographical distribution, it basically covers the eastern, central, and western regions of China[3], which also provides richer samples for later policy effect evaluation. In terms of geographical location, resource endowment, and industrial structure, there are great differences between regions. Among them, the eastern provinces are geographically close to the sea and have the densest population. However, due to the lack of mineral resources, light industry, and textile industry are the main economic composition in history, and thermal power, steel smelting, and chemical industries account for a relatively low proportion in the whole industrial composition, typically such as Zhejiang and Shanghai. The traffic in the central and western regions is relatively backward, but due to the wide area and rich minerals, the industrial distribution is mainly the heavy chemical industry, such as Shanxi Province and Hubei Province. Moreover, with the differences in investment policies caused by environmental regulation, the original heavy chemical industry in the east also began to transfer to the central and western regions, which indirectly exacerbated the distribution of high energy-consuming enterprises in the central and western regions (pollution paradise). The research of Wu et al. (2017) has verified the existence of this effect. Therefore, in terms of emission reduction pressure, the central and western regions are notably higher than that in the eastern regions. Then, will this regional heterogeneity in resource endowment, industrial composition, and emission reduction pressure have heterogeneous interference with the policy effect of the carbon emission trading system?

According to the administrative division method of the Chinese government, this study generates three sub samples according to the east, middle, and west of the sample and regresses the model (1). The results are shown in Table 9. It can be seen that the policy marginal effect of the CETS in the eastern region is significantly higher than that in the central and western regions. From the perspective of evidence mining, the economy in the eastern region is relatively developed: there is a large accumulation of green innovation technology, and the environmental protection technology and equipment are relatively perfect. Therefore, when facing the constraints of the CETS, the enterprises in the eastern region can respond more quickly. Moreover, the environmental supervision in the eastern region is relatively strict, and the participation enthusiasm of enterprises will be significantly higher than that in the middle and eastern regions, so the implementation effect of the CETS is more significant. However, due to the low emission reduction constraints, backward environmental protection technology, and relatively slow response to policies in the western region, and the impact of policies is limited.

TABLE 9 Regional heterogeneity regression results (PCSE).

Variable	East	Middle	West
	(1)	(2)	(3)
Treat×Time	0.2608***	0.0979*	−0.0818
	(5.15)	(1.65)	(−0.31)
Lnpgdp	0.1312***	0.1372***	0.0475
	(3.09)	(6.57)	(1.36)
Lnpmidu	0.0135	0.0513***	0.03513
	(0.39)	(4.02)	(1.63)
Lnenergy	−0.0319	−0.1170***	−0.0855***
	(−1.03)	(−7.51)	(−3.21)
Lndensity	0.0058	0.0006	0.0212*
	(0.53)	(0.10)	(1.73)
LnFDI	−0.0857***	−0.2943***	0.0138
	(−5.98)	(−4.30)	(1.23)
Lnfd	0.1099***	0.1036***	0.0976***
	(3.54)	(6.57)	(3.28)
Lnie	−0.0001***	−0.0001***	−0.0001
	(−2.68)	(−3.51)	(−0.70)
_cons	0.0601	−0.6702**	0.0891
	(0.16)	(−2.18)	(0.25)
Observations	900	900	729
R-squared	0.117	0.117	0.040

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

5.8 Expand discussion: Differences in the degree of market development

The effect of incentive-based environmental regulation policies depends on a well-developed market system. In theory, a complete market mechanism should include the

3 The eastern region includes 11 provinces (cities) including Beijing, Liaoning, Tianjin, Zhejiang, Hebei, Shandong, Shanghai, Fujian, Jiangsu, Hainan, and Guangdong; the central region includes eight provincial-level administrative regions including Shanxi, Hubei, Jilin, Heilongjiang, Henan, Anhui, Jiangxi, and Hunan; the western region includes 12 provinces (cities) such as Sichuan, Guizhou, Chongqing, Gansu, Yunnan, Tibet, Qinghai, Shaanxi, Ningxia, Xinjiang, Inner Mongolia, and Guangxi. The data of Hong Kong, Macao, and Taiwan are temporarily unavailable.

TABLE 10 Distribution of provincial marketization degree (average value from 2009 to 2017).

Marketization degree	High (9.25–6.87)	Middle (6.86–5.83)	Low (5.55–0.67)
Provinces	Zhejiang, Shanghai, Jiangsu, Guangdong, Beijing, Tianjin, Shandong, Fujian, Chongqing, and Anhui	Liaoning, Henan, Hubei, Sichuan, Jiangxi, Hunan, Jilin, Guangxi, Heilongjiang, and Hebei	Shanxi, Hainan, Inner Mongolia, Shanxi, Yunnan, Ningxia, Guizhou, Gansu, Xinjiang, Qinghai, and Tibet

Note: Data source is China Marketization Index released in past years.

property rights mechanism, competition mechanism, and price mechanism. Coase (1960) believed that a complete market institutional system can significantly reduce transaction costs, undue government interference, and the resulting choices. In law enforcement and endogenous law enforcement (Wang and Wheeler, 2005), as the world's largest emerging market, China's marketization process has a history of only 30 years, the current market system construction is not perfect, and there are still many unfair factors. As a market-based environmental regulation tool, only a sound and fair market trading mechanism and price mechanism are established with the aforementioned basic elements, the innovation incentive effect and industrial adjustment effect of the emission trading system can play a role, and each subject only under the guidance of the endogenous carbon price will complete the "Pareto improvement" under environmental constraints. The process of China's market-oriented reform started in 1992, but restricted by practical and historical factors; the development of the market system in each province is not completely synchronous. With its convenient geographical location, suitable climate, and policy preference, coastal provinces are obviously ahead of other provinces in product market development, factor market development, and non-state-owned economy. According to the calculation of Fan et al. (2011) and other scholars[4], from 2009 to 2017, Shanghai, Guangdong, and other provinces gradually differentiated from other provinces in the construction of the market system, and the index gap was more than 10 times, as shown in Table 110:

It can be seen from Table 10 that the market system basis of Shanghai, Zhejiang, and other provinces is significantly higher than that of other provinces. Shi and Li (2020) believe that under the constraints of market-oriented level, the exertion of the CETS effect will produce great differences, and necessary attention should be paid to policy formulation. Therefore, referring to

TABLE 11 Marketization degree adjustment effect (PCSE).

Variable	(1)	(2)
Treat×Time×Market	0.0329***	0.0234***
	(4.60)	(4.70)
Lnpgdp		0.1341***
		(4.47)
Lnpmidu		0.0492***
		(3.41)
Lnenergy		−0.1144***
		(−5.21)
Lndensity		0.0009
		(0.10)
LnFDI		−0.0288***
		(−2.76)
Lnfd		0.100***
		(2.82)
Lnie		−0.0001**
		(−2.28)
_cons	1.2651***	−0.0884
	(23.96)	(−0.17)
Control variables	No	Yes
Observations	2,529	2,529
R-squared	0.028	0.068

Note: The values in brackets are t values; *, **, and ***, respectively, indicate significance at the level of 10%, 5%, and 1%.

the practices of Fan and Peng (2017), this study takes the marketization degree of each region between 2009 and 2017 as the measurement index of marketization degree, multiplies it with the variables of treat and time, and embeds it into the model (1) for regression to discuss the difference of its effect.

It can be seen from the results in Table 11 that the degree of marketization has a positive regulatory effect on the carbon trading system. From the perspective of the mechanism, the "Porter effect" of the CETS with marketization as the core depends on the perfect competition mechanism and price mechanism, and benefiting from the continuous market construction, Shanghai, Guangdong, and other provinces have improved both the product market and the factor market, basically eliminating the distortion of prices by various administrative monopolies; meanwhile, all kinds of transaction

4 China marketization index is a report on China's marketization degree compiled and regularly published by scholars such as Fan et al. (2011). The index includes five aspects: the relationship between the government and the market, the development of non-state-owned economy, the development of product market, the development of factor market, and the development of market intermediary organizations and the legal system environment (a total of 23 indicators). It comprehensively measures the development degree of marketization in China's provinces.

costs are also significantly lower than those in other provinces, so the role of the CETS will be more significant. Thus, the institutional compatibility between the degree of marketization and emission trading has been verified, which is also consistent with the conclusions of Shi and Li (2020).

6 Conclusion and policy recommendation

As an important institutional innovation to achieve the goals of "carbon peak and carbon neutrality," the ultimate goal of the CETS is to achieve the two goals of environmental protection and economic benefits. By measuring GTFP and setting quasi-natural experiments, this study verifies the positive role of the CETS in promoting economic transformation. At the same time, in the process of mechanism analysis, it is found that in the face of a more agreeable and compatible emission trading system, enterprises will improve GTFP through innovation compensation and industrial upgrading, so as to obtain competitive advantage. Moreover, through the comparison between Table 4 and Table 5, it can be seen that there is no great difference in the choice of the two paths. In addition, the marginal utility of the CETS is more obvious in the central and western regions where the heavy industry accounts for a high proportion of the economy, but it is not significant in the eastern region. The results of statistical analysis (Table 11) also believe that the incentive effect of the carbon trading system depends on the market system. In areas with a more perfect market system, its effective price mechanism and competition mechanism can save more transaction costs, thus bringing about the effectiveness of policy incentive. Therefore, on the whole, the "Porter effect" of the CETS in China is very significant, and it has an important policy value for green and economic growth. These conclusions and experiences are of great significance to the construction, promotion, and improvement of the CETS in developing countries.

Based on the theoretical and empirical analysis of this study, it is concluded that the CETS plays an important role in improving GTFP, so promoting the carbon emissions trading system has an important policy value for solving the contradiction between greenhouse gas emissions and economic growth. However, the implementation of the system still needs to pay attention to the following problems.

First, the role of the government must be clarified: when carbon emission rights (quotas) are added to production as a capital factor, it will have a great impact on the production function of enterprises. At this time, social managers should carefully treat the decisions made by enterprises according to market signals, should not exert too much external intervention in R&D investment or production transformation and upgrading, and should allow enterprises to make independent choices according to their own constraints, so that the market can reach a new equilibrium and complete Pareto improvement. As the supervisor of the system, the government needs to maintain the fairness and openness of the carbon market and ensure that the price signal is true and effective.

Second, the gradient development strategy is implemented based on the characteristics of different regions. Due to the differences in resource endowments, industrial composition, and energy consumption dependence among regions, in the process of promoting the carbon trading system, we should try to avoid adopting the form of "one size fits all." If necessary, we can adopt the strategy of gradient development to suspend the implementation of light industry intensive areas, focus on the areas with high emissions, and gradually promote it to the whole country in a certain order. The construction of China's carbon market is the best practical evidence of the correctness of this strategy. The gradient development strategy of the CETS will help realize its policy effect.

Third, this study verifies that technological research and development and industrial upgrading are important ways for the CETS to play its role. However, in real operation, the realization of this path often requires a lot of financial support. Therefore, combined with China's current policy situation, it is very necessary to provide credit endorsement for CETS-related assets and allow them to carry out mortgage and other financing activities. This will provide great financial support for enterprises to carry out technological R&D, production transformation and upgrading, and help further amplify the economic effects brought by the CETS.

Finally, developing countries should accelerate the improvement of their own market-oriented system. The promotion of the CETS needs to be based on a perfect market system, which is an important guarantee to give full play to its effect. For developing countries, it is not recommended to force the promotion of the CETS in the absence of relevant exogenous institutional foundation, which will lead to it becoming a mere formality and a mere financing tool. At the same time, the government should strengthen local management and supervision to prevent vicious trade or evasion of environmental responsibility and ensure healthy and green economic development.

This article discusses the policy value of the carbon emission trading system to solve the problem of "growth limit" from the macro level. But in essence, no policy can be completely exogenous, and the CETS is no exception. This means that more factors need to be taken into consideration to explore the policy effect of the carbon trading system, and more scientific research methods are to be used, which puts forward higher requirements for our subsequent research. In the next stage, we will focus on the environmental assessment and evaluation among regional governments, the spatial spillover effect of carbon trading policy, the impact on the effectiveness of market incentive environmental regulation policy, and the impact on the carbon market price mechanism. In terms of methods, we hope to solve the endogenous problems as much as possible in combination with the cutting-edge methods of econometrics. Here, we also call on relevant scholars to explore the aforementioned issues in order to enrich the research framework of the CETS.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

WS: conceptualization, methodology, and supervision. KY: validation and writing—reviewing and editing. ZJ: data curation, writing—original draft preparation, visualization, investigation, and software.

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

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.895539/full#supplementary-material

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