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RESEARCH ARTICLE

Rui TANG, Dingyao YU, Yanping LI, Yongbo TAN, Wen-Long SHANG, Chunjia HAN, Mu YANG, Petros IEROMONACHOU

Accelerating the global energy transition through carbon pricing: An ex-post analysis of emissions reduction effects and mechanisms based on international data

Abstract In response to the pressing challenge of global climate change, advancing a low-carbon energy transition has emerged as a key international priority. As an integral policy instrument to guide this transition, carbon pricing is increasingly adopted by countries and regions worldwide. Drawing on a spatial panel model and covering 115 countries, this study investigates the effects of carbon pricing on carbon emission reduction and compares the outcomes between single and composite carbon pricing instruments. The spatial spillover effects of carbon pricing policies exhibit multidimensional heterogeneity. Hybrid carbon pricing policies form a cross-regional emission reduction network through regional synergistic governance mechanisms. In contrast, carbon tax and emissions trading systems (ETS) are associated with the 'pollution paradise hypothesis' and the 'race to the bottom effect', respectively. Further, it elucidates how different carbon pricing policies leverage unique economic and energy-related mechanisms to facilitate emission abatement. The findings offer important insights for policymakers aiming to optimize carbon pricing schemes that effectively support the global energy transition.

Keywords carbon pricing, emissions reduction, ex-post analysis, spatial spillover effects

1 Introduction

As early as 1979, at the first World Climate Conference, scientists had already made the case that increasing carbon dioxide concentrations would lead to a warming of the planet. It is generally accepted in the scientific community that the rise in the concentration of greenhouse gases in the atmosphere is mainly caused by human activities, and therefore various climate problems, including global warming, are mainly triggered by human activities. Greenhouse gas emissions are a fundamental contributor to climate change, and energy is closely linked to climate change. At present, three quarters of global greenhouse gas emissions originate from the production and use of energy, and a shift in the production and use of energy is the first priority in addressing the issue of climate change. Increased use of fossil fuels leads to increased carbon emissions, while environmentally relevant technologies have a positive impact on environmental quality (Shang and Lv, 2023), and more stringent environmental policies have a negative impact on carbon dioxide emissions (Baz and Zhu, 2025)。

In this context, carbon pricing policies (currently mainly carbon taxes and carbon emissions trading systems (ETSs)), as market-based environmental policy instruments, have gradually become a strategic focus of

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Rui TANG, Yanping LI
Chinese Research Academy of Environmental Sciences, Beijing 100012, China

Dingyao YU
China Academy of Civil Aviation Science and Technology, Beijing 100028, China

Yongbo TAN
School of Management, Harbin University of Commerce, Harbin 150028, China

Wen-Long SHANG (✉)
Centre for Transport Studies, Imperial College London, London SW7 2AZ, United Kingdom
E-mail: wenlong.shang12@imperial.ac.uk

Chunjia HAN, Mu YANG
Business School, Birkbeck, University of London, Bloomsbury London WC1E 7HX, United Kingdom

Petros IEROMONACHOU
Research & Knowledge Exchange, Greenwich Business School, University of Greenwich, Park Row, London, SE10 9LS, United Kingdom

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global climate governance. The theoretical foundation of carbon pricing's role in driving systemic transformation of energy systems lies in the internalization of carbon emissions' negative externalities. By reshaping energy cost structures, it triggers adaptive responses from market actors and ultimately guides the entire energy system toward decarbonization and clean transition. From a mechanistic perspective, carbon pricing primarily drives systemic transformation through the following pathways:

Firstly, it establishes a clear price signal for carbon emissions, directly elevating the relative cost of fossil energy sources and creating a significant "green premium" disincentive. This compels enterprises and consumers to reduce high-carbon energy consumption and shift toward cleaner alternatives (e.g., renewables, nuclear energy, electrification). Secondly, the carbon price signal guides the accelerated reallocation of critical production factors—capital, technology, and labor—from traditional high-carbon sectors to low-carbon innovation domains through market expectations, thereby optimizing socioeconomic resource allocation. Finally, the stable revenue streams generated by carbon pricing mechanisms (e.g., auction revenues, taxation) provide essential financing support for energy transition. When strategically synergized with complementary policies, such as electricity market reforms and green finance frameworks, these mechanisms amplify transformational impacts while mitigating the limitations of isolated policy instruments.

During the signing of the Paris Agreement in 2015, the World Bank, together with the International Monetary Fund, launched the Carbon Pricing Leadership Coalition (CPLC), which promotes the formation of a carbon pricing network covering 39 countries and 33 regions, and which currently controls about 23% of global carbon emissions. Despite the heterogeneity of policy forms (carbon tax and carbon emissions trading system exist side by side), its mechanism of guiding energy structure optimization and technological innovation through price signals is widely recognized. While carbon prices are increasing in many regions, they are still far from sufficient to generate the pace and scale of change needed to meet the Paris Agreement targets, and most remain well below the range of prices needed to meet the Paris Agreement's 2 °C temperature daily target, which is to reach prices of $40 to $80 per tonne of carbon dioxide equivalent. The price of carbon has been increasing in many regions, but it is still far from sufficient to generate the pace and scale of change needed to meet the Paris Agreement targets. As a result, carbon pricing policies still have significant room for improvement. However, Climate Action Tracker simulations show that global temperature rise will still exceed 2.7 °C under current policies, highlighting the controversial nature of carbon pricing's actual effectiveness: on the one hand, carbon pricing can reduce the elasticity of demand for high-carbon fuels by reshaping the relative cost structure of energy (William, 2018); on the other hand, the correlation between policy intensity, sectoral coverage, and carbon leakage risk, among other factors, lead to significant uncertainty about the effectiveness of emission reductions.

As two major market-based environmental regulatory instruments, carbon tax and ETSs both aim at internalizing the external costs of greenhouse gas emissions and transforming into a low-carbon economy. The core institutional differences between the two are reflected in the pricing mechanism and emission reduction path: carbon emissions trading system is a quantitative policy tool, which forms a market price discovery mechanism for emission allowances through total quantity control; while carbon tax, as a price-based policy tool, builds a carbon price signaling mechanism by determining the tax rate (Xu and Yang, 2024). Existing research suggests that both systems are effective in promoting carbon emission reductions, but key questions at the policy implementation level still need to be explored in depth: What are the differences between the two policy instruments in promoting carbon emission reductions? Is there any difference between carbon tax and carbon emissions trading system in promoting carbon emission reduction pathways? Is there any heterogeneity in the impact of carbon pricing on carbon emissions in different countries? Systematic research on these issues will help optimize policy design and provide more operational solutions for global climate governance. While existing literature explores the overall effects of carbon pricing, this study is unique in that it analyses the underlying mechanisms of energy, industry and trade.

The remaining chapters of this study are structured as follows. Section 2 is the literature review section, Section 3 is the theoretical analysis of carbon pricing and carbon emissions and the formulation of the research hypotheses, Section 4 is the presentation of the research data and models, Section 5 is the analysis of the research results, and Section 6 is the conclusions and policy recommendations.

2 Literature review

2.1 Effect of unitary carbon pricing policy on emissions reduction

2.1.1 Emission reduction effect of carbon emission trading system

Regarding the mitigation effects of ETS, Burniaux was the first to use dynamic general equilibrium modeling to show that if ETS were widely applied, carbon emissions would be substantially reduced worldwide (Burniaux et al., 1992). The carbon emissions of all countries in the world will then be substantially reduced. At present, scholars at home and abroad have gained multi-dimensional empirical support for the question of how ETS can curb carbon emissions (Shang et al., 2023) (Liu et al., 2025). From a broader macro perspective, early studies have focused on the carbon emission profiles of large industrial firms, showing that carbon emissions trading activities have significantly reduced industrial carbon emissions in certain pilot regions.Since then, the focus of research has gradually shifted to estimating total regional carbon emissions, and numerous studies have shown that the ETS has been effective in reducing regional carbon emissions (Jia and Wen, 2024). Given that ETS may also contribute to carbon emission reductions in neighboring regions through demonstration effects, some studies have used spatial analysis to validate the indirect emission reduction effects of ETS on neighboring regions (Green, 2021).In addition, research on the mitigation effects of ETS has been extended to the city level (Wang and Duan, 2025). The existing research literature not only confirms that ETS can significantly reduce carbon emissions in cities, but also examines the variability of ETS in terms of emission reduction effects (Jennie and Hong, 2024), (Yu et al., 2022).

From the meso perspective, the ETS covers a wide range of industries, such as petroleum, chemical, construction and so on. Domestic research mainly focuses on the power industry, and some scholars tend to select these industries based on the industrial dichotomy classification (Wu and Wang, 2022). They found that with the carbon market, the carbon emissions of the restricted industries have decreased significantly (Chen et al., 2022), and the effect of the carbon market on the production side is more significant (Gao et al., 2020).

From a micro perspective, as the source of carbon emissions, enterprises are also the core regulatory target of the ETS (Cheng et al., 2023). Therefore, it is particularly important to study whether and how ETS can effectively guide enterprises to reduce carbon emissions (Guo and Li, 2024). However, due to the difficulty of obtaining data on carbon emissions and the lack of professional standards and statistics for this work, most of the literature generally uses the wastewater fees paid by enterprises to measure the level of carbon emissions. The study found that through technological innovation, ETS has successfully reduced the company's carbon emissions (Ren et al., 2022).

2.1.2 Emission Reduction Effect of Carbon Tax

The extant literature on the carbon tax has predominantly evaluated its role, effect, and economic impact from economic, energy, and environmental perspectives. The findings indicate that the carbon tax can efficaciously reduce carbon dioxide emissions (Sen and Vollebergh, 2018), and the imposition of a sector-specific carbon tax can yield enhanced emission reduction outcomes However, the implementation of a carbon tax will concomitantly result in a diminution in economic growth (Dorband et al., 2019). The introduction of a carbon tax rebate has the potential to engender a "double dividend" for the economy and the environment in the study of carbon taxes primarily entail the utilization of computable general equilibrium (CGE) simulation analysis. In 1991, Whalley proposed a static CGE model encompassing international trade and carbon emissions, and subsequently conducted an analysis of the impacts of a carbon tax on international trade and the environment during the production and consumption stages (Olabisi et al., 2009). In 1992, Burniaux put forward a dynamic CGE model. GE model with global recursion. Since then, many scholars at home and abroad have applied the CGE model to analyze problems related to carbon tax and environmental pollution control (Burniaux et al., 1992).

2.2 The effect of hybrid carbon pricing policy on emissions reduction

The extant literature on the emission reduction effect of the composite system is scant. However, numerous scholars have confirmed the rationality of combining the two systems after in-depth theoretical discussions. These scholars believe that when the two systems are implemented at the same time, they can complement each other, thus improving the efficiency of carbon emission reduction. Mandell has highlighted that hybrid carbon pricing policy is more efficient than a standalone policy from the perspective of efficiency loss (Mandell, 2008). Nevertheless, the implementation of compound carbon pricing policies has been demonstrated to concomitantly reduce emissions and to impose financial burdens. Diego R. and Maximilian's study of a European carbon tax and a carbon market reveals that, while both policies are effective in reducing emissions, the economic cost of the European carbon market exceeds that of the national carbon tax (Känzig and Konradt, 2023).

The extant research evidence on the effectiveness of carbon pricing in reducing carbon emissions is limited (Metcalf and Stock, 2020). As Green has noted, a relatively small number of papers have examined the ex post impact of carbon pricing on carbon emissions at the aggregate national level (Green, 2021).

2.3 Literature gaps

The effectiveness of carbon pricing policies in reducing emissions has become an important topic of ongoing academic interest. Existing research has mainly unfolded along two paths: the micro effects of carbon emissions trading systems on firms' emissions reduction behavior (Liu et al., 2025), and the implementation effects of carbon tax policies in local emissions reductions (Gugler et al., 2023).It is worth noting that there are three major theoretical gaps in the existing literature: first, there is a relative lack of systematic ex-post empirical studies, especially cross-regional comparative analyses focusing only on European economies (Green, 2021); second, the research on synergistic effects in the context of carbon pricing has not yet formed a complete theoretical framework, and most of the results are still stuck at the level of isolated analyses of a single policy instrument (Elkins and Baker, 2008); and finally, there is a significant lack of macro-level studies of national emission reduction mechanisms (Green, 2021). Finally, the research on national emission reduction mechanisms is obviously insufficient, and the empirical samples of the existing results are limited to the firm or city scale.

3 Theoretical analysis and research hypothesis

3.1 Theoretical model

The initial influences on carbon emissions are derived using the Logarithmic Mean Divisia Index(LMDI) method, which is combined with the reality of the impact of carbon pricing on carbon emissions, and from there the mechanism of the impact of carbon pricing on carbon emissions is clarified (Kohlscheen and Moessn, 2021b). The specific form of LMDI based on Kaya's constant equation is:

$$\begin{aligned} CO_2^i &= \frac{CO_2^i}{GDP^i} \times GDP^i = \frac{CO_2^i}{E^i} \times \frac{E^i}{GDP^i} \times GDP^i \\ &= \frac{CO_2^i}{E^i} \times \frac{\sum E_k^i}{\sum Y_k^i} \times GDP^i \\ &= \frac{CO_2^i}{E^i} \times \sum \left[\frac{E_k^i}{Y_k^i} \times \frac{Y_k^i}{\sum Y_k^i} \right] \times GDP^i \\ &= EC^i \times \sum_k \left[EI_k^i \times y_k^i \right] \times GDP^i, \end{aligned} \tag{1}$$

where CO_2^i is the CO$_2$ emissions of region i and E^i is the energy consumption of region i. EC^i is the combined energy emission factor for region i, i.e., the amount of carbon dioxide produced per unit of energy consumption, representing the change in the energy consumption structure. EI_k^i reflects the energy intensity of industry k in region i and represents the variation in energy efficiency. y_k^i indicates the effect of the industrial structure and represents the share of the output of industry k in the GDP of region i.

Drawing on Ang and Liu (2001)'s definition of the decomposition effect equation, the amount of change in CO$_2$ emissions from period 0 to period t is expressed in the following form:

$$\Delta CO_{2_{i,k}} = \Delta CO_{2_{i,k}}^{EC} + \Delta CO_{2_{i,k}}^{EI} + \Delta CO_{2_{i,k}}^{y} + \Delta CO_{2_{i,k}}^{GDP}, \tag{2}$$

$$\Delta CO_{2_{i,k}}^{EC} = \sum_k L(CO_{2_{k,i}}^t, CO_{2_{k,i}}) \ln(EC_{k,\tau}^i / EC_{k,t}^i), \tag{3}$$

$$\Delta CO_{2_{i,k}}^{EI} = \sum_k L(CO_{2_{k,\tau}}^t, CO_{2_{k,i}}) \ln(EI_{k,\tau}^i / EI_{k,t}^i), \tag{4}$$

$$\Delta CO_{2_{i,k}}^{y} = \sum_k L(CO_{2_{k,\tau}}^t, CO_{2_{k,i}}) \ln(y_{k,\tau}^i / y_{k,t}^i), \tag{5}$$

$$\Delta CO_{2_{i,k}}^{GDP} = \sum_k L(CO_{2_{k,\tau}}^t, CO_{2_{k,i}}) \ln(GDP_{k,\tau}^i / GDP_{k,t}^i), \tag{6}$$

$$L(x,y) = \begin{cases} (x-y)/(\ln x - \ln y), & x \neq y \\ x, & x = y \end{cases} \tag{7}$$

where $L(x,y)$ is the weighting function. $\Delta CO_{2_{i,k}}^{EC}$ denotes the change in carbon emissions due to the change in energy mix, $\Delta CO_{2_{i,k}}^{EI}$ denotes the change in carbon emissions due to the change in energy efficiency, $\Delta CO_{2_{i,k}}^{y}$ denotes the change in carbon emissions due to the change in industrial structure, and $\Delta CO_{2_{i,k}}^{GDP}$ denotes the change in carbon emissions due to the economic scale effect. This results in four factors that affect carbon emissions: energy mix, energy efficiency, industrial structure, and economic scale. Since the role of carbon pricing on economic scale is complex and indirect, it is not analyzed as an emission reduction mechanism.

3.2 Carbon pricing and carbon emissions

The dialectical relationship between carbon pricing and carbon emissions reflects the complex interaction between market instruments and the management of externalities in environmental economics. Theoretically, carbon pricing internalizes the social cost of greenhouse gas emissions and relies on price signals to guide market participants to optimize energy mix and technology paths, thereby achieving the optimal solution for emissions reduction under market equilibrium when marginal abatement costs converge to the carbon price (Cleary and Willcott, 2024). Empirical studies show that the implementation of carbon tax and emissions trading system can significantly reduce regional carbon emission intensity (Zhang et al., 2024), but their effectiveness is affected by policy design rigor, market coverage, and price elasticity heterogeneity, which show significant spatial differences (Kohlscheen et al., 2021a).

H0: Carbon pricing policies can contribute to carbon emission reductions.

3.3 Carbon pricing and industry structure

There is a significant dynamic coupling between the carbon pricing mechanism and industrial restructuring, and its logic of action is rooted in the economic mechanism of cost transmission and factor reallocation (Boyce et al., 2023).Carbon pricing internalizes the negative externalities of carbon emissions into firms' production costs, directly affecting high-carbon industries (e.g., energy-intensive manufacturing) and shifting the marginal cost curve to the left (Amiri-Pebdani et al., 2025). If the carbon price level exceeds the marginal abatement cost threshold of high-carbon firms, their profit margins will be squeezed (Wu et al., 2023), triggering a market exit mechanism (e.g., production capacity elimination or regional relocation), which in turn frees up factors of production such as land, capital, and labor (Kaestner et al., 2025). Such factors are driven by the market mechanism to flow into low-carbon efficiency sectors (e.g., clean technology industries or services), creating an endogenous impetus for decarbonizing the industrial structure (Sha et al., 2024).

Based on the above analysis, the following hypotheses are proposed:

H1: Carbon pricing can promote the low-carbon transformation of industrial structure and thus realize carbon emission reduction.

3.4 Carbon pricing and energy mix, energy efficiency

The mechanism of interaction between the carbon pricing mechanism and energy mix transformation can be deconstructed as energy substitution elasticity and technology bias effects driven by price signals (Jing et al., 2024). Carbon pricing through the promotion of fossil energy hidden costs (such as coal-fired power generation of carbon cost additional), change the relative price ratio between different energy varieties (Xu and Lien, 2025), so as to stimulate the market under the marginal elasticity of substitution to adjust the portfolio of energy consumption: When the carbon price breaks through the critical cost of coal power and renewable energy, will trigger the energy system "high carbon lock-in". When the carbon price breaks through the critical cost difference between coal power and renewable energy (Kölle et al., 2024), it will trigger a break in the "high carbon lock-in" in the energy system, prompting enterprises to prioritize the procurement of low-carbon energy (such as photovoltaic and wind power) or the implementation of cleaner coal power transformation (Yi et al., 2024).

Based on this, the following hypotheses are proposed in this paper:

H2: Carbon pricing can optimize the energy mix and thus achieve carbon emission reduction.

The relationship between carbon pricing and energy efficiency can be developed based on the triple mechanism of internalization of externalities, elasticity of factor substitution, and induction of technological innovation. Firstly, carbon pricing transforms the social cost of carbon emissions into the production cost of firms (Ahmad et al., 2024), corrects the negative externality distortion of energy consumption, and forces firms to rebalance the efficiency of energy inputs in their profit-maximizing decision (Tan et al., 2023).When the carbon price level exceeds the marginal abatement cost threshold of enterprises, market participants will prioritize the implementation of energy efficiency improvement strategies, including: (1) the technology substitution path, i.e., the use of high-efficiency equipment (e.g., supercritical power generation units) or process optimization (Amin et al., 2025); (2) the scale adjustment path, to reap the benefits of economies of scale by intensifying production and compressing energy intensity (Venizelou and Poullikkas, 2025); (3) the management innovation path, to eliminate inefficient operational losses with the help of digital monitoring systems to achieve dynamic energy planning (Yan and He, 2024). Management innovation path, with the help of digital monitoring system to realize energy dynamic scheduling, eliminate inefficient operation loss (Deng et al., 2024), (Shang et al., 2025) .

Secondly, carbon pricing reshapes the direction of technological development by changing the relative prices of factors (Tan et al., 2023), which induces R&D resources to be directed toward energy-efficient technologies, such as smart grids or industrial Internet of Things applications, allowing energy efficiency gains to break out of the traditional linear pattern of improvement and shift toward exponential trajectories of technological progress (Jing et al., 2024). It is worth noting that energy rebound effects can undermine the abatement benefits of energy efficiency improvements (Gollier, 2024), but the dual disincentive mechanism of carbon pricing can effectively mitigate this problem (Zhang et al., 2025a). On the one hand, the carbon cost surcharge maintains the rigidity of energy service prices and suppresses the consumption rebound triggered by energy efficiency improvement (Bompard et al., 2022); on the other hand, the dynamic carbon price design further compresses the space for high-carbon energy demand through the incremental cost increase (Venizelou and Poullikkas, 2025).

Empirical studies have shown that the EU ETS has led to an average annual improvement of 2.3% in the energy efficiency of covered companies, contributing to about 19% of cumulative emission reductions (Lan et al., 2022). However, the effectiveness of this mechanism is limited by barriers to technology diffusion and market completeness, and it is necessary to build a reinforcing loop of "price signal - technology lock-in breakthrough - positive feedback in the market" through the synergistic policies of carbon pricing, energy efficiency standards, and green technology subsidies to ultimately achieve the goal. The Pareto optimization of energy efficiency improvement and carbon emissions decoupling should be built through the policy synergy of carbon pricing, energy efficiency standards, and green technology subsidies (Chen et al., 2021).

Based on this, the following hypotheses are proposed in this paper:

H3: Carbon pricing can reduce carbon emissions by improving energy efficiency.

3.5 Carbon pricing and international trade competitiveness

The transmission effect of carbon pricing policies on international trade competitiveness is a key issue for global climate policy and the prevention and control of carbon leakage (Siy et al., 2023). The internalization of carbon costs triggers a dual adjustment mechanism by reshaping the production function of firms: first, cost-driven industrial location shifts (e.g., high-carbon industries moving to low-carbon regions) lead to the race-to-the-bottom effect described in the pollution paradise hypothesis, creating the risk of carbon leakage (Mundaca et al., 2021). Second, the substitution of low-carbon technologies forces firms to rebuild their competitive advantage through clean innovation, resulting in a "green productivity premium" (Antweiler and Schlund, 2024). Trade policy instruments, such as the EU's Carbon Border Adjustment Mechanism (CBAM), construct "carbon cost symmetry" trade barriers (Ernst et al., 2023) by regulating the life-cycle carbon emissions of imported goods, and promote the convergence of low-carbon standards in the global industrial chain while curbing carbon leakage. Based on the above mechanisms, the research hypothesis is proposed:

H4: Carbon pricing can significantly inhibit a country's carbon emissions through the channel of international trade competitiveness.

3.6 Spatial spillovers of carbon pricing

Regardless of geographic location or administrative boundaries, spillovers are not confined to the initial location alone, especially in the case of carbon emissions. Therefore, the spatial spillover effects of carbon pricing should be taken into account (Wang et al., 2024). The spatial spillover effects of carbon pricing are transboundary and systemic in nature, and their mechanism of action needs to be included in the comprehensive consideration of environmental economic policies (Zhang et al., 2025b). In the dimension of environmental externality, carbon leakage breaks through the geographical boundary through the dual path of physical diffusion of atmospheric circulation and industrial location reconfiguration (Zheng et al., 2025), leading to the spatial transfer of emission reduction benefits, especially the inter-regional flow of high-carbon capital-intensive industries such as electric power and iron and steel, which is a typical carrier (Schreiner et al., 2021). On the economic efficiency dimension, carbon pricing triggers asymmetric spatial effects through technological innovation incentives and factor reallocation: total factor productivity (TFP) increases in implementing regions due to the diffusion of low-carbon technologies and upgrading of industrial structure (Jing et al., 2024), while TFP is suppressed in uncovered regions due to the "high-carbon lock-in" of transferring industries, a phenomenon in line with the logic of the "pollution paradise hypothesis" (Candau and Dienesch, 2017).

H5: Carbon pricing affects carbon emissions in neighboring regions through spatial spillover effects.

4 Data and models

4.1 Variables and measures

4.1.1 Dependent variables

The dependent variable is carbon emissions (CE), which include carbon dioxide CO_2 emissions generated during the consumption of solid, liquid and gaseous fuels, as well as the combustion of natural gas.

4.1.2 Independent variables

The independent variables are carbon pricing policies, which are hybrid carbon pricing policy (HCPP) and unitary carbon pricing policy (UCPP). Among them, the UCPP includes carbon tax (CT) and ETS. CT and ETS are set as two dichotomous dummy variables, and the implementation of CT or ETS alone in a country is regarded as 1, and vice versa as 0. The hybrid carbon pricing policy is defined as HCPP = CT × ETS, i.e., HCPP takes the value of 1 only when the CT and ETS are implemented at the same time, and 0 in all other cases.

4.1.3 Mediating variables

Four mediating variables — industrial structure (IS), energy mix (ES), energy efficiency (EE) and international trade competitiveness (ITC) — were selected based on the theoretical analysis in chapters 3.1 to 3.5.Among them, the industrial structure is selected as a proportion of industrial value added; the energy mix is measured as the percentage of renewable energy consumption in total final energy consumption, reflecting the degree of cleanliness of the energy mix; and the energy efficiency is selected as the level of primary energy intensity, reflecting the amount of energy used per unit of output, with the lower the primary energy intensity, the higher the energy efficiency, which indirectly reflects the improvement of the energy technology. There is no directly usable variable for international trade competitiveness. The trade competitiveness index is used to represent international trade competitiveness (Amiri-Pebdani et al., 2025). Trade competitiveness index is equal to import and export trade surplus/total import and export, which takes into account both import and export aspects and assesses the development level of domestic and international markets from the side. Thus, the formula for international trade competitiveness is shown below:

$$ITC_{i,t} = \frac{X_{i,t} - M_{i,t}}{X_{i,t} + M_{i,t}}. \tag{8}$$

In the above equation, $X_{i,t}$ and $M_{i,t}$ denote the export and import value of country i in period t. The value of ITC usually falls within the range of −1 to 1. If it is more than 0, it means that the industry's productivity has exceeded international standards and therefore has a clear competitive advantage in the global market; if ITC is less than 0, it means that the industry's productivity has not reached international standards and faces a clear competitive disadvantage.

4.1.4 Control variables

Referring to the existing studies, five control variables are selected. The economic level is measured by GDP data, taking logarithmic processing. Population is measured by the total population of each country. Unemployment rate is used as the proportion of unemployed people in the labor force. The urbanization level is measured using the proportion of urban population. The technology level is measured by the total number of patents filed by residents. The degree of openness to the outside world is represented by the ratio of total trade to GDP.

4.1.5 Description of data sources

Information on the emissions trading system comes from the International Carbon Action Partnership (ICAP), and information on the carbon tax is obtained from World Bank (WB) statistics. The main sources of economic data for each country are the World Bank, the International Monetary Fund (IMF), and the EPS database. See Table 1 for details.

4.2 Spatial econometric model

4.2.1 Spatial panel model

Macroeconomic factors are controlled and the spatial panel model is constructed to quantify the effects of carbon pricing policies on carbon emissions. The spatial panel model is as follows:

$$\ln CE_{i,t} = \rho W \ln CE_{i,t} + \alpha P_{i,t} + \beta X_{i,t} + \theta W X_{i,t} + \mu, \tag{9}$$

$$\mu = \lambda W \mu + \varepsilon,\ \varepsilon \sim N[0,\ \sigma^2 I], \tag{10}$$

where i and t represent regions and years, respectively, $CE_{i,t}$ represents carbon emissions, $P_{i,t}$ is the carbon pricing policy variable, $X_{i,t}$ represents the set of control variables, and $\varepsilon_{i,t}$ represents the random error term.

Spatial weighting matrices commonly used in research include spatial proximity matrix, geographic distance weighting matrix, economic distance weighting matrix and economic-geographic nesting matrix. Among them, the spatial proximity matrices based on edge adjacency (ROOK) and mixed adjacency (QUEEN) assume that the correlations between regions are equal, but this is often inconsistent with the actual situation, especially in environmental pollution research, where the correlations between geographically similar places are more significant. Therefore, instead of the ROOK and QUEEN matrices, three other spatial weighting matrices are used, which are calculated based on the latitude and longitude coordinates of 115 countries and the GDP per capita data for the past 20 years.

Table 1 Summary of variables design and measures

Variables		Operationalization	Symbols	Sources
DV	Carbon emissions	Carbon dioxide CO_2 emissions	CE	IEA, WB
IV	Carbon pricing policies	Hybrid carbon pricing policy	HCPP	ICAP, WB
		Unitary carbon pricing policy (carbon tax, emissions trading system)	UCPP (CT, ETS)	
MV	Industrial structure	Proportion of industrial value added	IS	WB
	Energy mix	Percentage of renewable energy consumption	ES	WB
	Energy efficiency	Primary energy intensity	EE	WB
	International trade competitiveness	Trade competitiveness index	ITC	WB
CV	Economic level	Gross domestic product	GDP	WB
	Population	Total population of each country	Pop	WB
	Unemployment rate	Proportion of unemployed people in the labor force	Unemp	WB
	Urbanization level	Proportion of urban population	Urban	WB
	Technology level	Patents filed by residents	Tech	WB, IMF
	Degree of Openness	Ratio of total trade to GDP	Open	WB, EPS

4.2.2 Mechanism Testing Model

The effect mechanisms are revealed from four aspects: industrial structure effect, energy mix effect, energy efficiency effect and competition effect. Referring to the article of Jiang (Jiang, 2022), the following model is used to test the mechanism:

$$\ln CE_{i,t} = \beta_0 + \beta_1 P_{i,t} + \alpha X_{i,t} + u_i + \eta_i + \varepsilon_{i,t} \ , \tag{11}$$

$$M_{i,t} = \theta_0 + \theta_1 P_{i,t} + \gamma X_{i,t} + u_i + \eta_i + \varepsilon_{i,t} \ , \tag{12}$$

where $M_{i,t}$ is a mechanism variable measuring structural, technological, and competitive effects, $P_{i,t}$ is a policy variable measuring carbon pricing, and the others are consistent with the baseline regression model.

5 Results and findings

5.1 Analysis of the emission reduction effect of carbon pricing policies

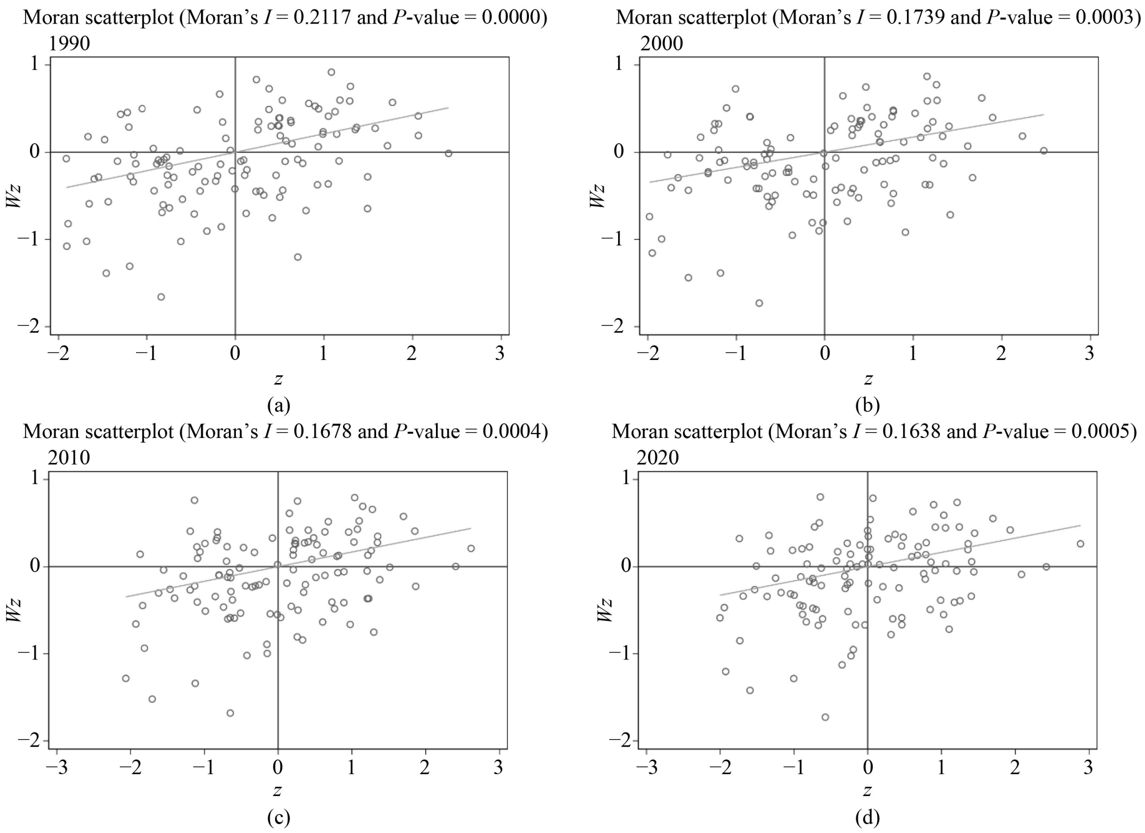
5.1.1 Model testing

(1) Spatial correlation test

To verify the rationality of the spatial econometric model, this study conducted a spatial correlation test on the dependent variables in the model and calculated the global Moran index under each weight matrix, and plot the relevant data in Figs. 1–3. The results show that there is a significant positive spatial correlation between the carbon emissions of countries at the 1% confidence level, indicating that there is a spatial clustering phenomenon of“high-high”and“low-low”carbon emitting countries, with obvious spatial dependence and clustering effect. The research plotted localized Moran scatter diagrams for countries under the three spatial weighting matrices for the years 1990, 2000, 2010, and 2020. These scatter plots show that most of the countries are located in the first and third quadrants agglomeration, exhibiting “high-high” and “low-low” aggregation, further confirming the spatial spillover of carbon emissions. From 1990 to 2020, the distribution of countries in each quadrant remains basically stable without significant changes.

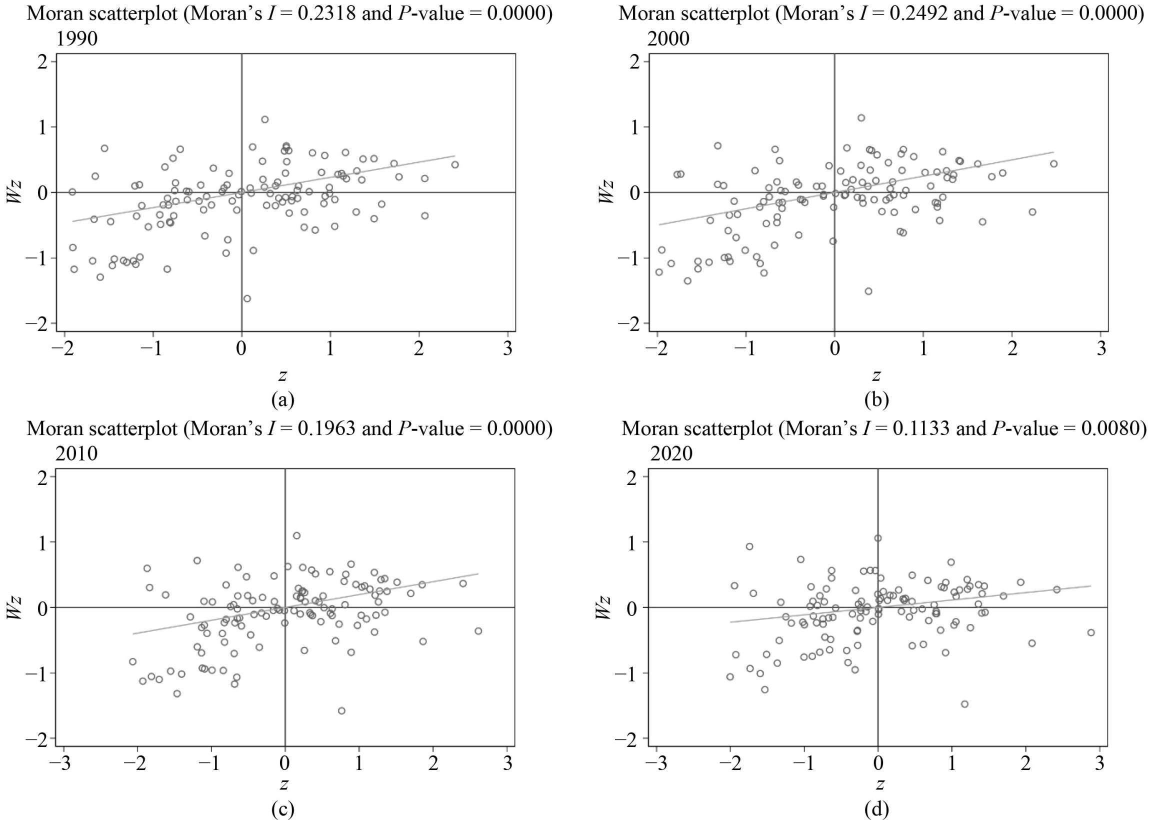
(2) Selection of models

Since the data used in empirical analysis is panel data, it is necessary to select the model using Hausman test, the results of Hausman test are all significant at 5% level, so the fixed effects model should be selected. Through the LR statistic test, it is found that the *P*-value of the test for individual fixed effects, time fixed effects and two-way fixed effects under the three weights is 0.0000, which passes the 1% significance test. Therefore, when constructing the spatial econometric model, the model



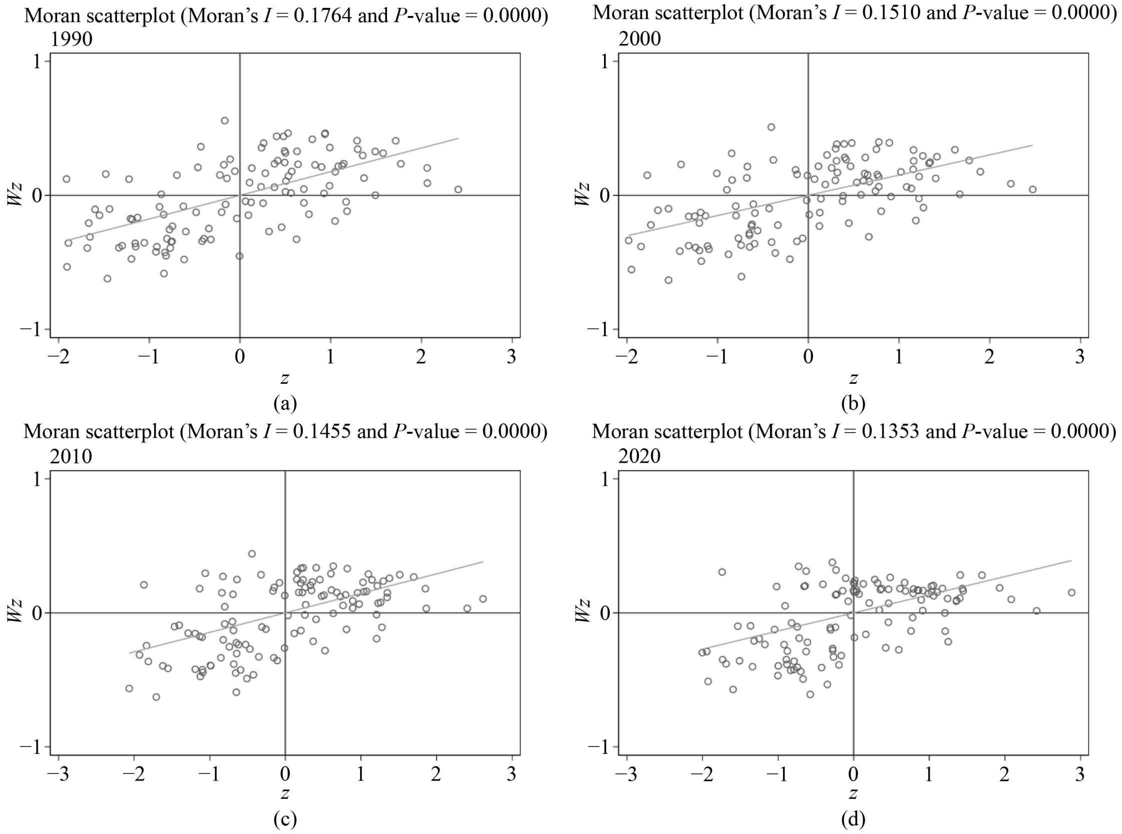
(a) (b) (c) (d)

Fig. 1 Localized Moran's index plots under geographic distance weighting matrix in 1990 (a), 2000 (b), 2010 (c), and 2020 (d).



(a) (b) (c) (d)

Fig. 2 Localized Moran's index plots under economic distance weighting matrixin 1990 (a), 2000 (b), 2010 (c), and 2020 (d).



(a) (b) (c) (d)

Fig. 3 Localized Moran's index plots under economic-geographic nesting matrixin 1990 (a), 2000 (b), 2010 (c), and 2020 (d).

that includes both time and individual two-way fixed effects should be selected, and both spatial and time effects should be considered.

The spatial model selection test adopts the Wald test and the LR test, aiming to determine whether the spatial Dubin model will deteriorate into a spatial error model (SEM) or a spatial lag model (SLM). According to the test results, all three weight matrices rejected the hypothesis that the spatial Dubin model degenerates into a SEM model or SLM model under both the Wald test and the LR test, so the spatial Dubin model was determined to be the optimal choice.

5.1.2 Benchmark regressions and analysis of spatial spillover effects

(1) Benchmark regression and spatial effects analysis of HCPP

In Table 2, the coefficients of HCPP are all significantly negative, while the estimated coefficients of W × HCPP are significantly negative under both spatial weights of W1 and W2, which indicates that the HCCP significantly contributes to the reduction of carbon emissions. Specifically, the estimated coefficients of HCPP are significantly negative under either spatial weighting matrix of the results, which means that HCCP has a significant inhibitory effect on total carbon emissions. According to the estimated coefficients, the HCCP has a better emission reduction effect under the geographic distance spatial matrix and the economic distance spatial matrix. In terms of the spatial lag term W × HCPP, it is significantly negative (at the 1% confidence level) at both geographic and economic distances, indicating that the implementation of the HCCP in one country will have significant inhibiting effects on the carbon emissions of its geographically or economically proximate countries as well.

The decomposition results of the spatial effects in Table 3 show that the direction of the effects of the independent variables on carbon emissions is basically the same under the three spatial weight matrices. The direct effects of HCCP on carbon emissions are all significantly negative, while the spillover effects on neighboring countries are also significantly negative, and the spatial spillover effects are much larger than the direct effects, indicating that neighboring countries can obtain the benefit of carbon emission reduction at lower costs, and that there is a strong motivation for "free-riding" behavior. From the viewpoint of the currently implemented international carbon pricing policies, only the carbon tariff policies of Europe and the United States, the "climate club" of developed countries, and the "carbon floor price" policies of national institutions may have certain constraints on this, but none of these policies have been widely implemented, and it is not known whether their effects can effectively address "free-riding" behavior.

Table 2 Spatial Dubin model regression results for HCCP

	W1	W2	W3
HCPP	−0.152***	−0.156***	−0.069**
	(−5.66)	(−5.95)	(−2.46)
lnGDP	0.715***	0.663***	0.634***
	(31.14)	(28.49)	(28.47)
lnPop	0.904***	0.903***	0.723***
	(22.47)	(22.95)	(15.25)
Unemp	−0.001	−0.001	−0.001
	(−0.48)	(−0.67)	(−0.64)
Urban	0.023***	0.023***	0.020***
	(17.37)	(16.48)	(15.55)
Open	0.00036*	0.00018	0.001***
	(1.74)	(0.90)	(3.52)
lnTech	−0.006*	−0.008***	−0.006**
	(−1.95)	(−2.67)	(−2.21)
W × HCPP	−1.460***	−0.166**	−0.212
	(−6.29)	(−2.47)	(−1.05)
W × lnGDP	0.123	0.176***	1.160***
	(0.75)	(2.61)	(7.37)
W × lnPop	−0.189	−0.106	0.066
	(−0.67)	(−0.88)	(0.28)
W × Unemp	−0.017	0.032***	0.001
	(−1.19)	(5.74)	(0.08)
W × Urban	0.075***	0.013***	0.127***
	(5.87)	(3.20)	(11.91)
W × Open	0.009***	0.001	0.008***
	(4.61)	(0.52)	(5.41)
W × lnTech	−0.008	−0.052***	0.005
	(−0.27)	(−5.56)	(0.21)
rho	−0.307***	0.075*	0.111
	(−3.43)	(2.31)	(1.40)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
N	3565	3565	3565
R2	0.845	0.877	0.773

Note: ***, **, and * denote significance at the 1%, 5%, and 10% statistical levels, respectively. The criteria for the level of significance are the same as in the subsequent tables and are therefore not repeated.

(2) Benchmark regression and spatial effects analysis of CT

Before testing the carbon emission reduction effects of CT and ETS, countries that have implemented CT are excluded from the ETS sample and countries that have implemented ETS are excluded from the CT sample in order to exclude the interaction of the two policies.

Table 4 shows that the estimated coefficients of CT are

Table 3 Decomposition results of spatial effects of HCCP

	W1			W2			W3		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
HCPP	-0.141^{***}	-1.095^{***}	-1.237^{***}	-0.157^{***}	-0.192^{***}	-0.349^{***}	-0.068^{**}	−0.254	−0.322
	(−5.05)	(−5.75)	(−6.80)	(−5.83)	(−2.84)	(−4.65)	(−2.40)	(−1.17)	(−1.57)
lnGDP	0.715^{***}	−0.070	0.645^{***}	0.664^{***}	0.244^{***}	0.909^{***}	0.636^{***}	1.380^{***}	2.016^{***}
	(32.11)	(−0.64)	(5.93)	(29.72)	(3.86)	(14.11)	(29.74)	(7.92)	(11.67)
lnPop	0.912^{***}	-0.371^{*}	0.541^{***}	0.907^{***}	−0.046	0.861^{***}	0.728^{***}	0.142	0.871^{***}
	(23.22)	(−1.72)	(2.65)	(24.07)	(−0.37)	(6.80)	(16.14)	(0.55)	(3.67)
Unemp	−0.001	−0.013	−0.014	−0.001	0.034^{***}	0.033^{***}	−0.001	0.001	−0.0001
	(−0.45)	(−1.23)	(−1.32)	(−0.53)	(5.88)	(5.51)	(−0.69)	(0.07)	(−0.01)
Urban	0.023^{***}	0.052^{***}	0.075^{***}	0.023^{***}	0.016^{***}	0.039^{***}	0.020^{***}	0.144^{***}	0.165^{***}
	(17.76)	(5.44)	(7.85)	(17.41)	(3.63)	(8.28)	(16.40)	(9.88)	(11.20)
Open	0.0003	0.007^{***}	0.007^{***}	0.0002	0.0003	0.0005	0.001^{***}	0.009^{***}	0.010^{***}
	(1.55)	(4.34)	(4.47)	(0.97)	(0.52)	(0.76)	(3.74)	(4.93)	(5.28)
lnTech	-0.006^{*}	−0.004	−0.009	-0.009^{***}	-0.056^{***}	-0.064^{***}	-0.006^{**}	0.006	−0.0005
	(−1.86)	(−0.16)	(−0.44)	(−2.72)	(−5.44)	(−5.83)	(−2.10)	(0.21)	(−0.02)

significantly negative no matter the results under which spatial weighting matrix, which means that CT has a significant inhibitory effect on carbon emissions. According to the estimated coefficients, the effects of emission reduction under the three weights are comparable. The spatial lag term W × CT is significantly negative at economic distance and significantly positive at the other two distances (at the 1% confidence level), indicating that the implementation of CT in countries with closer economic distance also has significant inhibiting effects on carbon emissions in other countries.Under geographic and economic-geographic distance, the implementation of CT in one country increases carbon emissions in other countries which are closer, reflecting the fact that a CT policy under geographic distance can contribute to the transfer of pollutant emissions, hence contributing to the phenomenon of "pollution havens."

As shown in Table 5, through the decomposition of spatial effects of CT, the effects of CT on carbon emissions are basically the same under the three spatial weight matrices, and the direct effects of CT on carbon emissions are all significantly negative. Meanwhile, the spillover effect on neighboring countries is significantly positive under geographic distance and economic-geographic distance, and significantly negative under economic distance. From the estimated coefficients, the spatial spillover effects are much larger than the direct effects, suggesting that in the case of CT implementation in one country, the geographic neighboring countries and economic-geographic neighboring countries may have negative effects on carbon emission. That is, CT implementation will generate carbon leakage, and when a country implements CT, its domestic high-carbon emitting firms may relocate to neighboring countries with lax carbon pricing policies to reduce production costs.

(3) Benchmark regression and spatial effects analysis of ETS

In Table 6, the estimated coefficients of ETS are significantly negative under either spatial weighting matrix, which means ETS has a significantly inhibitory effects on carbon emissions. From the estimated coefficients, the emission reduction effects under the three weights are comparable. From the spatial lag term W × ETS, it is significantly negative only under economic distance (at 1% confidence level), indicating that the implementation of ETS in countries with closer economic distance also has a significant inhibitory effect on carbon emissions in other countries. Significantly positive at economic-geographical distance, indicating that the implementation of ETS in economically and geographically closer countries will increase carbon emissions in other countries.

Table 7 shows the decomposition results of the ETS spatial effects, and the ETS direct effects on carbon emissions under the three spatial weight matrices are all significantly negative, indicating that the ETS benefits the country's carbon emission reduction. In terms of spatial spillover effects, ETS in one country will reduce carbon emissions in economically neighboring countries. According to the estimated coefficients, the spatial spillover effects are much larger than the direct effects, and unlike the CT policy, countries with neighboring economic levels may receive positive effects on carbon emissions, this may be a demonstration effect of the policy. The economic basis for the implementation of carbon emission reduction policies in countries with similar economic levels is the same, and after a country implements ETS policies, economically similar countries are prone to introduce similar measures, thus bringing about a positive

Table 4 Spatial Dubin model regression results for CT

	W1	W2	W3
CT	−0.189***	−0.108**	−0.143***
	(−4.29)	(−2.55)	(−3.31)
lnGDP	0.719***	0.679***	0.699***
	(25.75)	(24.95)	(25.2)
lnPop	0.710***	0.749***	0.731***
	(14.7)	(15.34)	(14.28)
Unemp	−0.001	0.002	0
	(−0.52)	(0.81)	(0.08)
Urban	0.024***	0.024***	0.025***
	(14.44)	(14.21)	(15.33)
Open	0.001***	0.001***	0.001**
	(3.88)	(2.86)	(2.43)
lnTech	−0.009**	−0.007*	−0.006
	(−2.53)	(−1.95)	(−1.61)
W × CT	0.318**	−2.200***	1.312***
	(2.10)	(−9.67)	(5.71)
W × lnGDP	0.036	0.474***	1.465***
	(0.56)	(5.79)	(5.19)
W × lnPop	−0.404***	−0.496***	−0.202
	(−2.87)	(−3.17)	(−1.01)
W × Unemp	−0.005	0.063***	−0.086***
	(−0.77)	(7.3)	(−4.48)
W × Urban	0.021***	0.012**	0.065***
	(4.86)	(2.21)	(4.22)
W × Open	0.002***	0.001	0.003**
	(2.8)	(1.27)	(2.55)
W × lnTech	−0.003	−0.073***	0.036
	(−0.33)	(−6.24)	(1.56)
rho	−0.105***	−0.054	−0.009
	(−3.45)	(−1.38)	(−0.09)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
N	2790	2790	2790
R2	0.792	0.859	0.797

carbon emission reduction effect.

5.1.3 Robustness testing

(1) Alternative dependent variable

The alternative dependent variable is Greenhouse gas (GHG) emissions, sourced from the Emissions Database for Global Atmospheric Research (EDGAR) constructed by the European Commission, the Joint Research Center (JRC), and the Netherlands Environmental Assessment Agency (PBL), which accounts for GHG emissions consisting of total carbon dioxide, which excludes short-cycle biomass burning (e.g., agricultural waste combustion and savannah combustion), but includes other biomass burnings (e.g. forest fires, post-burn decay, peat fires, and drainage peatland decay), all anthropogenic methane sources, nitrous oxide sources, and fluorinated greenhouse gases (HFCs, PFCs, and sulfur hexafluoride). After replacing the dependent variable, the results of the carbon emission reduction effects of the core independent variables with different weights are consistent with the results of the baseline model, indicating that the empirical results of the above sections are robust (See Supplementary Material for results).

(2) Heterogeneity analysis based on countries with different levels of economic development

To reveal the emission reduction effects of the implementation of carbon pricing policies in different countries more precisely, referring to the World Bank's division criteria, the economies are divided into three groups of high, middle, and low according to their income levels. However, since there are 434 low-income countries in the selected sample and none of these countries have yet been able to adopt CT or ETS policies, the low-income countries are excluded, and panel regression analyses are conducted separately for middle-income countries, high-income countries, and all the countries in the upper middle-income range. The results show that the carbon emission reduction effects of HCCP are only established in high-income countries and have no significant effect on middle-income countries.

Developed countries are generally more advanced than low and middle income countries in terms of project selection, formulation of environmental regulations and technological innovation, which enables them to effectively manage and reduce carbon emissions (See appendix for results). In contrast, some middle-income countries face the risk of becoming pollution transfer destinations because of their imperfect environmental policies and their reliance on resource-intensive development patterns, which have resulted in large amounts of carbon emissions in the process of meeting international market demand.

The emission reduction effects of CT policies are significant in both high and middle income countries, and the emission reduction effects of CT are much larger in middle income countries than in high income countries. The ETS policy is also significant in both high and middle income countries, and in terms of the magnitude of the impact, middle income countries are also affected to a similarly large extent.

(3) Heterogeneity analysis based on NDC and non-NDC countries

Nationally Determined Contributions (NDCs) is a core mechanism of the Paris Agreement, in which countries can independently choose their climate goals and actions, which also reflects a country's initiative and willpower to

Table 5 Decomposition results of spatial effects of CT

	W1			W2			W3		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
CT	−0.193***	0.307**	0.114	−0.091**	−2.100***	−2.191***	−0.142***	1.293***	1.151***
	(−4.21)	(2.26)	(0.89)	(−2.04)	(−9.90)	(−10.48)	(−3.20)	(5.40)	(4.73)
lnGDP	0.718***	−0.033	0.685***	0.675***	0.420***	1.094***	0.698***	1.464***	2.162***
	(26.62)	(−0.65)	(12.38)	(25.7)	(6.28)	(16.00)	(26.2)	(4.83)	(7.12)
lnPop	0.724***	−0.441***	0.283**	0.758***	−0.516***	0.242*	0.737***	−0.216	0.520***
	(15.47)	(−3.40)	(2.21)	(16.20)	(−3.50)	(1.66)	(15.00)	(−1.11)	(2.83)
Unemp	−0.001	−0.004	−0.006	0.001	0.060***	0.061***	0	−0.086***	−0.085***
	(−0.52)	(−0.77)	(−0.99)	(0.62)	(7.31)	(7.20)	(0.08)	(−4.34)	(−4.33)
Urban	0.024***	0.018***	0.041***	0.024***	0.010**	0.034***	0.025***	0.065***	0.090***
	(14.57)	(4.27)	(10.33)	(14.76)	(2.01)	(6.20)	(15.70)	(3.81)	(5.23)
Open	0.001***	0.002***	0.003***	0.001***	0.001	0.001**	0.001**	0.003**	0.003***
	(3.88)	(2.62)	(3.76)	(2.94)	(1.18)	(2.03)	(2.53)	(2.24)	(2.66)
lnTech	−0.009**	−0.002	−0.011	−0.007*	−0.069***	−0.075***	−0.006	0.036	0.03
	(−2.41)	(−0.17)	(−1.09)	(−1.74)	(−5.99)	(−6.24)	(−1.54)	(1.54)	(1.27)

reduce emissions. This study divides countries into two types of NDC countries and non-NDC countries according to whether they submit NDC or not, and analyzes the effectiveness of carbon pricing under different emission reduction initiatives. There are 187 countries have submitted carbon-neutral (climate-neutral or zero-carbon) climate targets by December 2024. In the country sample of CT, there are no countries in non-NDC countries that adopt CT policies, so only NDC countries are analyzed in CT policies. In terms of the core variables, HCPP, CT, and ETS all have significant carbon emission reduction in NDC countries, with comparable emission reduction effects.The ETS policies have significant emission reduction effects in both NDC and non-NDC countries. (See Supplementary Material for results)

5.2 Analysis of the mechanisms of carbon pricing policies

5.2.1 Emission reduction mechanism analysis of HCPP

According to the results in Table 8, columns (1) and (2) show that the higher the industry proportion in the industrial structure, the higher the carbon emissions, but the improvement effect of the HCPP on the industrial structure is not significant at present. From column (3) and column (4), HCPP is conducive to optimize the energy mix, increase the proportion of renewable energy consumption, and indirectly improve the emission reduction effect, and the optimization of energy mix can directly facilitate carbon emissions reduction. From columns (5) and (6), HCPP cannot only directly improve energy efficiency, but also reduce carbon emissions through energy efficiency optimization. From columns (7) and (8), HCPP is unable to reduce carbon emissions by enhancing international trade competitiveness. However, the stronger the international trade competitiveness, the greater the advantage in international competition, the better the resulting emission reduction effect.

5.2.2 Emission reduction mechanism analysis of CT

According to the results in Table 9, unlike HCPP, columns (1) and (2) show that CT can improve the industrial structure and reduce carbon emissions by reducing the proportion of industry. From columns (3) and (4), CT does not have a significant effect on the optimization of energy mix, but increasing the consumption proportion of renewable energy can directly reduce carbon emissions. From columnss (5) and (6), CT cannot only directly improve energy efficiency, but also reduce carbon emissions by optimizing energy efficiency. From columns (7) and (8), the effect of CT on international trade competitiveness is not significant, but international trade competitiveness can facilitate carbon emissions reduction.

5.2.3 Emission reduction mechanism analysis of ETS

According to the results shown in Table 10, unlike HCPP and CT, all four mediating mechanisms of ETS have significant carbon emissions reduction effects. Columns (1) and (2) show that ETS can improve industrial structure and reduce carbon emissions by reducing the proportion of industry. From columns (3) and (4), ETS can indirectly reduce carbon emissions through energy mix optimization. From columns (5) and (6), ETS cannot only directly improve energy efficiency, but also optimize carbon

Table 6 Spatial Dubin model regression results for ETS

	W1	W2	W3
ETS	−0.232***	−0.166***	−0.175***
	(−8.62)	(−5.87)	(−5.69)
lnGDP	0.695***	0.657***	0.644***
	(27.19)	(25.18)	(25.46)
lnPop	0.757***	0.738***	0.687***
	(16.38)	(15.69)	(14.43)
Unemp	0	0.002	0
	(0.11)	(0.90)	(0.13)
Urban	0.021***	0.021***	0.022***
	(14.42)	(14.10)	(15.23)
Open	0.001***	0.001***	0.001***
	(3.68)	(3.38)	(4.70)
lnTech	−0.008**	−0.009***	−0.007**
	(−2.39)	(−2.67)	(−2.11)
W × ETS	−0.029	−0.213**	0.341***
	(−0.45)	(−2.55)	(4.00)
W × lnGDP	0.014	0.277***	1.637***
	(0.22)	(3.57)	(6.65)
W × lnPop	−0.117	−0.367**	0.082
	(−0.94)	(−2.52)	(0.35)
W × Unemp	−0.006	0.058***	−0.031*
	(−1.05)	(7.20)	(−1.88)
W × Urban	0.022***	−0.001	0.060***
	(5.17)	(−0.24)	(4.25)
W × Open	0.002***	0.001	0
	(3.24)	(1.29)	(0.10)
W × lnTech	0.005	−0.063***	0.028
	(0.51)	(−5.63)	(1.24)
rho	−0.103***	0.021	−0.001
	(−3.35)	(0.58)	(−0.01)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
N	3038	3038	3038
R2	0.841	0.879	0.808

emission reduction effects by improving energy efficiency. From Columns (7) and (8), the mediating mechanism of international trade competitiveness under ETS is significant. The implementation of ETS enhances international trade competitiveness, which in turn improves the effect of carbon emission reduction.

6 Conclusions and policy recommendations

The carbon emission reduction effects, spatial spillover effects, and carbon emission reduction mechanism of hybrid carbon pricing policy and unitary carbon pricing policy are analyzed using spatial panel models. In particular, both hybrid carbon pricing policy and unitary carbon pricing policy have significant emission reduction effects.

The spatial spillover effect of the carbon pricing policy is characterized by multidimensional heterogeneity. First, the hybrid carbon pricing policy has a significant negative spillover effect on both geographically adjacent and economically connected regions, indicating that it forms a transregional emission reduction network through a regional synergistic governance mechanism; Second, the carbon tax policy shows negative spatial interactions in economically distant neighborhoods, but triggers positive spillovers in the dimension of geographic proximity, in line with the carbon leakage mechanism of the “pollution paradise hypothesis,” i.e., geographically neighboring countries avoid carbon costs through industrial transfers; Finally, carbon market policies have a significant positive spatial effect in economically and geographically proximate regions, reflecting the “race to the bottom” effect of carbon emissions across regions, suggesting that economically and geographically proximate regions may compete for advantage by relaxing environmental regulations. This interaction between policy instruments and spatial dimensions suggests that the cross-cutting impacts of carbon pricing need to be systematically assessed in the context of geographic proximity, economic relevance, and institutional competitiveness.

The emission reduction effects of carbon pricing policies are characterized by significant heterogeneity across countries. The emission reduction effect of hybrid carbon pricing policy is significant only in high-income countries, but not in middle-income countries. It appears that hybrid policies are first applicable to high-income countries. This difference stems from differences in institutional capacity and development mode: high-income countries can effectively internalize policy costs and achieve emission reduction targets through strong environmental regulatory systems (such as pollution emission standards), advanced low-carbon technology applications (such as clean energy penetration), and efficient carbon emission management systems; while middle-income countries are forced to undertake high-carbon industrial transfers due to imperfect environmental regimes, lagging environmental protection concepts, and a crude growth model. Middle-income countries are forced to undertake high-carbon industrial transfers due to imperfect environmental systems, lagging environmental protection policies, and crude growth patterns, and are caught in the “pollution shelter” predicament, where the effectiveness of their local emission reductions is offset by cross-border carbon leakage.

The performance of a unitary carbon pricing policy is mixed: carbon taxes have a significant abatement effect

Table 7 Decomposition results of spatial effects of ETS

	W1			W2			W3		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ETS	−0.231***	−0.006	−0.238***	−0.166***	−0.224***	−0.390***	−0.174***	0.337***	0.162**
	(−8.27)	(−0.11)	(−4.22)	(−5.72)	(−2.75)	(−5.20)	(−5.51)	(4.06)	(2.16)
lnGDP	0.695***	−0.051	0.644***	0.656***	0.299***	0.955***	0.643***	1.646***	2.288***
	(28.05)	(−1.03)	(12.62)	(26.05)	(4.38)	(13.48)	(26.25)	(6.01)	(8.34)
lnPop	0.766***	−0.185	0.580***	0.742***	−0.362**	0.380***	0.693***	0.063	0.756***
	(16.96)	(−1.62)	(5.36)	(16.39)	(−2.48)	(2.60)	(15.15)	(0.28)	(3.52)
Unemp	0	−0.006	−0.005	0.002	0.059***	0.061***	0	−0.031*	−0.031*
	(0.13)	(−1.08)	(−1.02)	(0.96)	(7.29)	(7.20)	(0.15)	(−1.92)	(−1.95)
Urban	0.021***	0.018***	0.039***	0.021***	0	0.021***	0.022***	0.060***	0.082***
	(14.58)	(4.64)	(10.42)	(14.74)	(0.09)	(3.85)	(15.73)	(3.83)	(5.18)
Open	0.001***	0.002***	0.003***	0.001***	0.001	0.002**	0.001***	0	0.001
	(3.69)	(3.09)	(4.16)	(3.51)	(1.29)	(2.27)	(4.85)	(0.12)	(1.14)
lnTech	−0.008**	0.006	−0.002	−0.009***	−0.063***	−0.072***	−0.007**	0.028	0.021
	(−2.33)	(0.63)	(−0.22)	(−2.61)	(−5.45)	(−5.90)	(−2.02)	(1.23)	(0.91)

Table 8 Four mediating mechanisms test of HCPP

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IS	lnCE	ES	lnCE	EE	lnCE	ITC	lnCE
HCPP	0.38		0.520***		0.054***		0.015	
	(0.75)		(3.14)		(9.30)		(1.30)	
IS		0.010***						
		(11.60)						
ES				−0.014***				
				(−4.40)				
EE						−2.787***		
						(−46.97)		
ITC								−0.153***
								(−3.90)
lnGDP	7.805***	0.659***	0.187	0.813***	−0.102***	0.434***	0.142***	0.759***
	(17.05)	(27.45)	(0.95)	(28.22)	(−19.41)	(22.36)	(13.72)	(31.52)
lnPop	3.458***	0.940***	1.419***	0.924***	−0.062***	0.764***	−0.077***	0.962***
	(4.50)	(24.35)	(3.95)	(17.46)	(−6.99)	(24.70)	(−4.44)	(24.48)
Unemp	−0.089**	0.002	−0.008	0	0	−0.001	0.004***	0.001
	(−2.52)	(0.95)	(−0.62)	(0.08)	(0.97)	(−0.63)	(5.27)	(0.78)
Urban	−0.044*	0.025***	0.085***	0.016***	−0.004***	0.012***	0	0.024***
	(−1.65)	(18.15)	(6.62)	(8.44)	(−14.09)	(10.56)	(0.29)	(17.49)
Open	0.029***	−0.000**	−0.003**	0.001**	0.000***	0.000***	0.001***	0
	(6.96)	(−2.18)	(−1.98)	(2.31)	(3.28)	(2.71)	(9.47)	(0.11)
lnTech	−0.022	−0.007**	−0.003	−0.001	0.001	−0.006**	0.001	−0.007**
	(−0.35)	(−2.23)	(−0.13)	(−0.38)	(1.11)	(−2.49)	(0.87)	(−2.22)
_cons	−221.273***	−23.367***	−28.426***	−26.420***	4.147***	−12.900***	−2.422***	−25.925***
	(−16.28)	(−33.82)	(−4.62)	(−29.83)	(26.53)	(−21.76)	(−7.90)	(−38.02)

(*Continued*)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IS	lnCE	ES	lnCE	EE	lnCE	ITC	lnCE
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	3565	3565	2415	2415	3565	3565	3565	3565
R2	0.853	0.991	0.639	0.994	0.976	0.994	0.748	0.991
Adj. R2	0.846	0.99	0.617	0.994	0.975	0.994	0.736	0.99

Table 9 Four mediating mechanisms test of CT

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IS	lnCE	ES	lnCE	EE	lnCE	ITC	lnCE
CT	−1.478*		0.284		0.024**		0.015	
	(−1.72)		(1.20)		(2.50)		(0.80)	
IS		0.010***						
		(10.35)						
ES				−0.008**				
				(−2.18)				
EE						−2.772***		
						(−38.98)		
ITC								−0.164***
								(−3.70)
lnGDP	8.704***	0.630***	−0.290	0.756***	−0.090***	0.464***	0.182***	0.749***
	(15.71)	(21.58)	(−1.30)	(22.16)	(−14.53)	(19.66)	(14.54)	(25.40)
lnPop	1.119	0.721***	1.189***	0.631***	0.009	0.751***	−0.075***	0.722***
	(1.17)	(15.04)	(2.87)	(9.94)	(0.86)	(19.26)	(−3.49)	(14.77)
Unemp	−0.094**	0.001	−0.040**	0.003	0.000	−0.000	0.002	−0.000
	(−1.97)	(0.26)	(−2.23)	(1.21)	(0.17)	(−0.06)	(1.64)	(−0.01)
Urban	−0.044	0.025***	0.046***	0.014***	−0.004***	0.014***	0.001	0.025***
	(−1.37)	(15.21)	(3.13)	(6.19)	(−10.41)	(10.11)	(0.84)	(14.77)
Open	0.031***	0.000*	−0.000	0.002***	−0.000	0.001***	0.001***	0.001***
	(6.38)	(1.84)	(−0.13)	(6.04)	(−1.21)	(3.02)	(7.61)	(3.57)
lnTech	−0.049	−0.010***	−0.018	−0.002	0.001	−0.007**	0.003*	−0.010***
	(−0.67)	(−2.75)	(−0.70)	(−0.40)	(1.46)	(−2.42)	(1.78)	(−2.71)
_cons	−199.27***	−19.05***	−10.51	−19.998***	2.648***	−13.528***	−3.393***	−21.676***
	(−11.27)	(−21.13)	(−1.39)	(−17.57)	(13.35)	(−18.25)	(−8.50)	(−23.92)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2790	2790	1890	1890	2790	2790	2790	2790
R2	0.851	0.988	0.610	0.993	0.976	0.992	0.744	0.988
Adj. R2	0.844	0.988	0.584	0.992	0.975	0.992	0.732	0.987

in both high-income and middle-income countries, with a higher elasticity coefficient in middle-income countries, reflecting the structure of their economies, which are more sensitive to price signals; and the emissions trading market, while effective in both groups of countries, has a greater impact in middle-income countries, probably due to the adaptability of its incremental emissions constraints to rapidly developing economies. It is worth noting that composite carbon pricing, carbon tax, and ETS all show similar emission reduction effects in

Table 10 Four mediating mechanisms test of ETS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IS	lnCE	ES	lnCE	EE	lnCE	ITC	lnCE
CT	−2.769***		−0.415**		0.068***		0.024**	
	(−5.37)		(−2.50)		(11.64)		(2.01)	
IS		0.011***						
		(11.35)						
ES				−0.013***				
				(−3.70)				
EE						−2.775***		
						(−42.00)		
ITC								−0.159***
								(−3.78)
lnGDP	7.643***	0.624***	0.208	0.775***	−0.098***	0.416***	0.153***	0.732***
	(15.20)	(23.48)	(1.01)	(24.84)	(−17.31)	(19.16)	(13.30)	(27.38)
lnPop	0.676	0.860***	1.500***	0.815***	−0.014	0.731***	−0.068***	0.872***
	(0.76)	(20.33)	(3.87)	(14.32)	(−1.44)	(21.33)	(−3.35)	(20.19)
Unemp	−0.044	0.001	−0.008	0.002	−0.000	−0.000	0.003***	0.001
	(−1.05)	(0.37)	(−0.49)	(0.97)	(−0.55)	(−0.01)	(2.90)	(0.32)
Urban	−0.089***	0.024***	0.082***	0.014***	−0.004***	0.011***	−0.000	0.023***
	(−3.06)	(16.04)	(6.09)	(6.83)	(−11.41)	(9.41)	(−0.40)	(15.19)
Open	0.036***	0.000	−0.001	0.001***	−0.000	0.001***	0.001***	0.000**
	(7.73)	(0.01)	(−0.59)	(4.36)	(−0.46)	(3.46)	(8.12)	(1.98)
lnTech	−0.036	−0.009***	0.009	−0.002	0.001	−0.006**	0.002	−0.009***
	(−0.55)	(−2.67)	(0.38)	(−0.54)	(1.60)	(−2.20)	(1.00)	(−2.66)
_cons	−166.86***	−21.095***	−30.028***	−23.511***	3.228***	−11.893***	−2.808***	−23.656***
	(−10.18)	(−26.76)	(−4.35)	(−23.53)	(17.45)	(−17.66)	(−7.48)	(−30.06)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	3038	3038	2058	2058	3038	3038	3038	3038
R2	0.857	0.990	0.628	0.994	0.977	0.994	0.743	0.990
Adj. R2	0.851	0.990	0.605	0.993	0.976	0.993	0.731	0.989

countries committed to NDCs, suggesting that the commitment to climate targets can enhance policy synergies; while the carbon trading market is still effective in non-NDC countries, highlighting the advantage of the flexibility of the market mechanism to regulate spontaneously through price transmission. This finding provides empirical evidence for the design of differentiated carbon pricing policies.

The emission reduction channels of carbon pricing instruments are characterized by policy type differentiation. Hybrid carbon pricing policy achieves significant carbon emission reductions through the dual path of optimizing energy mix and improving energy efficiency. Carbon tax relies mainly on the synergistic effect of industrial restructuring (e.g., downsizing of high-carbon industries) and energy efficiency improvement (e.g., technological process improvement) to achieve emission reduction effects.In contrast, ETS has a multi-dimensional transmission mechanism: it forms a composite emission reduction path by promoting the upgrading of industrial structure, optimizing the energy consumption mix, improving the efficiency of energy use, and reshaping international competitiveness (e.g., the advantage of exporting low-carbon products). The differences in the channels of action of different policy instruments reflect the heterogeneity of their design logic and market incentives.

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