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The spatial impact mechanism and policy spillover of carbon emission trading pilot policy on regional industrial energy efficiency-a case study of China

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In response to the pressing energy crisis, China embarked on a comprehensive pilot program for carbon emissions trading in 2013, experimenting with this mechanism across seven provinces and cities, focusing on high-carbon emitting industries. The aim is to leverage carbon pricing through emissions trading to propel China towards its "dual carbon" targets. Drawing on carbon market data spanning 2008 to 2019, this study introduces definitions for industrial single-element and green complex-element energy efficiency. It then investigates the influence of carbon emission trading pilot policy on these two different kinds of regional energy efficiency, utilizing non-spatial panel model, system GMM model, and spatial panel model. Furthermore, the study employs a dynamic spatial Dubin model to delve into the spatial implications and policy spillovers of carbon trading on these efficiency metrics. The finding reveals that carbon emissions trading policies bolster both kinds of regional energy efficiency and exhibit policy spillover effects. However, the immediate and long-term impacts of these policies vary. Specifically, carbon trading enhances single-element energy efficiency in pilot regions by optimizing industrial structures and energy consumption patterns. Meanwhile, it elevates the green complex-element energy efficiency through increased openness and a higher proportion of tertiary industries. Based on these insights, the paper offers a set of policy recommendations.

KEYWORDS

carbon emission trading, regional industrial energy efficiency, dynamic space dubin model, spatial impact mechanism, the policy overflow

1 Introduction

The overall goal of the Paris Agreement is to "limit global temperature increases to less than 2°C this century, while seeking measures to further limit temperature increases to 1.5°C." As a member of a Contracting Party, the primary climate issue is to choose the right policy instruments to ensure the achievement of *the Paris Agreement* and the intended Nationally Determined Contributions. In September 2020, China clearly put forward the "double carbon" strategic goal, namely, to achieve carbon peak by 2030 and carbon neutrality by 2060. The "dual carbon" goal is a broad and profound economic and social transformation, and a higher goal of China's green development path. For a long time, China's energy endowment condition is dominated by the traditional energy, coal,

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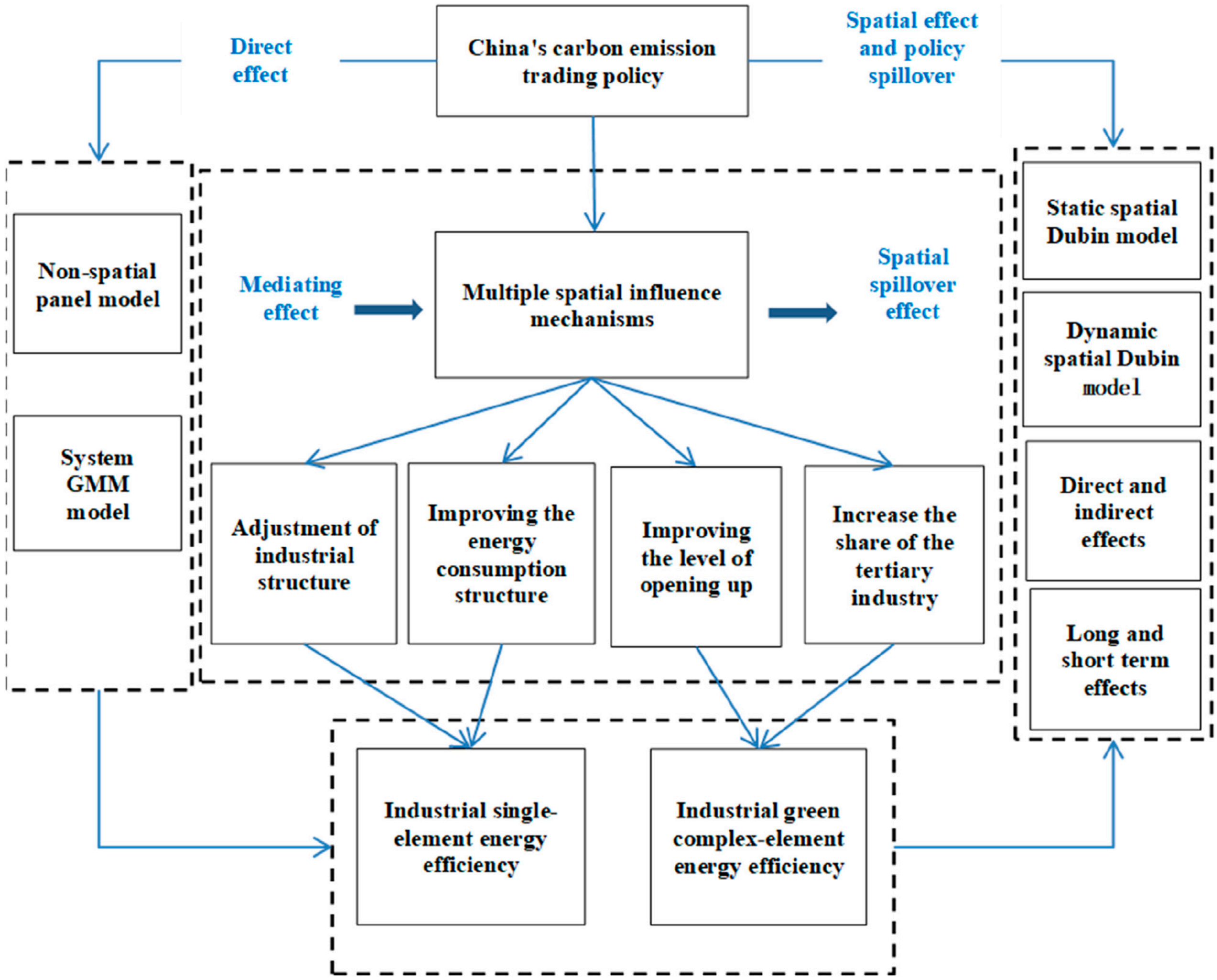

FIGURE 1
The logical structure diagram of the research.

showing the typical characteristics of "rich coal, poor oil and little gas". In China, the proportion of non-fossil energy in the primary energy mix has always been low, and the increasing energy demand is still mainly met by fossil energy, resulting in low energy utilization efficiency in all sectors and serious environmental pollution. According to the statistics of the National Bureau of Statistics, by the end of 2023, the total energy consumption in the year was 5.72 billion tons of standard coal, with traditional coal energy consumption accounting for 55.3% of the total energy consumption, ranking first in the world in coal consumption, while the external dependence of oil and natural gas is still high, and the energy reserve guarantee ability is poor. As the largest sector of energy consumption, industry has always accounted for more than 70% of energy consumption, facing double pressure from both ends of energy supply and demand. According to the clear timeline of the "double carbon" goal, it is driven by the general trend to build a green, low-carbon and efficient comprehensive energy utilization system as soon as possible.

In our research, we explored the spatial effects and their mechanisms of China's pilot carbon trading policy on the different kinds of regional energy efficiency. We had used two kinds of regional energy efficiency in the study, including single-element energy efficiency (SF) and green complex-element energy efficiency (TF). Carbon emission trading policy is seen as an innovative mean of environmental management using market mechanisms. It can stimulate the industrial enterprises to reduce the use of traditional energy sources significantly, reduce environmental pollution, improve business performance, thus improve the efficiency of energy conservation and emission reduction. This is of great research value for China to take a higher level of green development including the "dual carbon" target in the future. Theoretically, carbon emissions cause environmental pollution and can be regarded as negative public goods, and reasonable pricing of carbon emission rights can give them market-oriented attributes, and correct market failures by encouraging technological innovation and market innovation in pilot areas. By assessing the impact of the price of carbon trading rights on their business performance, industrial sectors weigh and choose whether to purchase carbon emission rights, use clean energy, reduce output or carry out green technology innovation and other business decisions.

Industry is a big consumer of energy and its energy efficiency is very important. The effects of carbon trading policy on the two different types of regional energy efficiency include multiple spatial mechanisms. In this paper, regional single-element energy efficiency and green complex-element factor energy efficiency are included in the research system, and combined with the dual research perspectives of non-spatial impact and spatial impact, the effectiveness of carbon emission trading pilot policy on different types of regional energy efficiency is studied, which can provide diversified policy perspectives and reference basis for policymakers. The development history of China's carbon market mainly includes the pilot stage and the comprehensive stage. We looked at China's pilot carbon market, which was fully implemented in 2013. The research results of this paper aim to provide useful guidance and reference for China's national carbon emission trading market to gradually get on the right track and operate efficiently. At the same time, we can also analyze the operation of China's national carbon trading market in the future, further explore the institutional structure of the national carbon market policy and its mechanism of action on regional industrial energy efficiency, and make a comparative analysis of the national carbon market policy and the pilot carbon market policy to reveal the differences in the implementation of the system and the evolution law behind it.

2 Literature review

"Porter hypothesis" points out that scientific and moderate environmental regulation policy can promote the enthusiasm of enterprises to carry out research and development activities, offset the corresponding regulatory costs caused by enterprises to cope with environmental pollution through the innovation compensation effect. In this way, the comprehensive efficiency and comprehensive competitiveness of enterprises are improved (Porter and Van der linde, 1995). However, the traditional view holds that environmental regulation will increase the cost of environmental management and reduce the innovation drive of enterprises, which may initially reduce their combined energy efficiency.

2.1 The role of energy policy in energy efficiency

Scholars have conducted in-depth discussions on how various energy policies affect energy efficiency and the mechanism design behind them. It can be divided into three kinds: promotion theory, inefficiency theory and nonlinearity theory. Among them, most of the literature supports the "promotion theory" of energy policies.

From the perspective of single policy impact, Arias and Colmenarez (2024) found that energy policies in oil-exporting developing countries could improve the sustainability of the energy sector, on the one hand, significantly reduced harmful emissions at the national level, and on the other hand, improved resource efficiency. Zheng et al. (2023) found that global climate policies played a significant role in reducing carbon emissions, but policy performance varied across countries. Bildirici et al. (2023) found through empirical research that energy policies could successfully reduce carbon emissions through several ways, including the impact of renewable energy and technological innovation.

From the synergistic effect of multiple policies, Jiang et al. (2022) found that the collaborative use of emission rights and carbon emission rights, two environmental regulation tools, would produce a good emission reduction agreement. Huang and Guo (2024) found that low-carbon city construction and carbon emission trading, two types of low-carbon policies, had outstanding synergistic emission reduction effects, and could scientifically control all kinds of pollution and carbon emissions.

In addition to the mainstream "promotion theory" of energy policy for energy efficiency, the proponents of the "ineffective theory" of energy policy have the following views. You and Gao (2013) took Xinjiang region as an example and believed that government environmental regulation has not produced a good effect on reducing emissions, but had the opposite effect, which was still significant in the third lag period. Zhang and Wang (2022) confirmed that China's energy conservation policies and comprehensive resource use policies had no obvious effect on CO_2 emission reduction. Zhao and Wang (2023) believed that due to the diminishing marginal effect of policies and poor timeliness of policies, China's renewable energy industry policy could not well support the optimization and transformation of traditional energy-consuming industries.

However, proponents of the "non-linear" effects of energy policy argue the following. Zhou et al. (2020) found that the intensity of environmental regulation in China has a nonlinear relationship with energy efficiency, showing an inverted "U" shape. Galeazzi et al. (2024) studied decarbonization policies in the energy sector in more than 100 developing countries over the past 40 years and found that they tended to have negligible or negative effects after 3 years of implementation, with significant effects occurring more than 5 years later.

2.2 The effectiveness of China's carbon emission trading policy in energy conservation and emission reduction and the intermediate mechanism

It had been more than 10 years since China's carbon emission trading pilot policy was fully launched in 2013, and the main research content mainly focuses on its energy saving and emission reduction role.

Qi and Han (2020) found that carbon emission trading policies had succeeded in effectively controlling the total amount of carbon dioxide emissions, and the total effect could be divided into several important factors: share of clean energy, energy intensity, GDP level, urbanization level and total regional population. Zhang et al. (2023) found that the carbon emission trading policies could achieve social sustainable development goals by improving the ESG performance of enterprises, and this effect was more obvious for enterprises with high digital degree and low-carbon enterprises. The intermediate mechanism included internal control means and research and development investment. Gao et al. (2024) found that the carbon emission trading policies could effectively reduce the regional environmental pollution level, and the governance effect was different in different regions. The important intermediate mechanism included two ways to increase the proportion of clean energy and promote enterprises to carry out innovative activities. Feng et al. (2024) found that after the implementation of carbon emission trading policies in pilot areas, carbon emissions had been significantly reduced, but the emission reduction effect was different among different cities. The main intermediate mechanism was the level of technological innovation. The optimization of industrial structure did not show significant effect.

In recent years, some experts have found that carbon emission trading policies could not only reduce carbon intensity, but also reduced $PM_{2.5}$ and SO_2. This effect showed obvious regional differences, with the most obvious effect on the west and the weakest effect on the east (Zhang et al., 2022). Some researchers with different views have found the synergistic emission reduction effect of carbon emission trading policies and other environmental regulatory tools, such as emission rights policy and fiscal policy (Zhu and Yu, 2023; Bashir et al., 2024). Some scholars had also found that carbon emission trading policies could promote the improvement of the health level of Chinese residents, in which the level of environmental pollution played a significant regulatory role (Guo et al., 2022).

In terms of the impact of carbon emission trading policies on energy efficiency, Chen et al. (2021) found that carbon trading policy could improve single-factor energy efficiency and all-factor energy efficiency in provinces, and the intermediate mechanism included technological innovation and marketization level of enterprises. Zhu and Sun (2022) found that carbon trading policy could improve China's total factor energy use efficiency, and the intermediate mechanism included the role of market mechanism, technological progress, and R&D innovation channels. Gao and Teng (2022) found that carbon trading policy could improve green total factor energy efficiency, and the intermediate mechanism included marketization, the relationship between government and market, and low-carbon technology innovation. Li and Ma (2024) found that carbon trading policy could improve urban energy utilization efficiency, and the influencing mechanism included the increase of carbon price and the correction of energy resource mismatch.

2.3 Other important factors and ways to improve energy efficiency

In addition to environmental regulation tools, scholars have also studied other important factors and ways to improve energy efficiency. For example, Su and Hong (2024) found that the construction of transportation infrastructure produced a great impact on the energy use efficiency of different places in China, and the intermediate mechanism was market integration. Zhang and Xiang (2024) found that renewable energy consumption substitution could improve energy efficiency, and this effect showed phased characteristics, the proportion between 20% and 45% was the best. Zhao and Wang (2023) empirically verified that digital economy could promote the improvement of complex-element energy efficiency, and the transmission mechanism was industrial agglomeration, technological progress, and environmental regulation.

2.4 Research gaps and contributions

2.4.1 Research gaps

(1) Industry is a large energy consumer, and its energy efficiency is very important. However, the existing literature does not distinguish the different kinds of regional industrial energy efficiency, and lacks a clear definition of industrial single-element energy efficiency and industrial green complex-element energy efficiency and a comparative study between the two.
(2) The specific effects of carbon trading policy on the two different kinds of regional energy efficiency, and the multiple intermediate mechanisms through which the policy affect the two different kinds of regional energy efficiency, have not been deeply discussed by scholars. In the current literature, there is a lack of difference analysis on the impact of carbon emission trading policy on the two different kinds of regional energy efficiency.
(3) The mainstream research literature on carbon emission trading policy are limited to non-spatial panel models, without considering the very important spatial impact mechanism. The current research literature fails to fully explore the spatial impact of carbon emission trading policy on regional energy efficiency and the spillover of policy effects between different regions, which results in incomplete and biased assessment of policy effects.

2.4.2 Our Contributions

(1) At the same time, regional single-element energy efficiency and green complex-element energy efficiency are included in our research system, and the impact of carbon emission trading mechanism on their heterogeneity and intermediate mechanism is studied. Combining the dual research perspectives of non-spatial impact and spatial impact, non-spatial panel model, system GMM model and spatial panel model are used for comparative research to study the utility of carbon emission trading pilot policy on different kinds of regional energy efficiency. It can provide diversified policy perspectives and reference basis for policymakers.
(2) This paper uses SUPEBM model to measure the green complex-element energy efficiency. The SUPEBM model integrates the EBM model and super efficiency model to adopt a more optimized method to evaluate the green complex-element energy efficiency. This model solves the limitation of traditional SBM model that does not consider non-radial relaxation distance, and includes five key environmental pollutants as non-expected output factors, thus significantly improving the accuracy and practicability of efficiency measurement.
(3) Based on the spatial effect analysis framework, we adopted static and dynamic spatial Durbin models to compare and explore the spatial effects of China's carbon emission trading policy on the different kinds of regional energy efficiency. The dynamic spatial Durbin model is used to disassemble the spatial total effects, study the direct and indirect spatial effects, long-term and short-term effects of carbon emission trading policy on regional energy efficiency, and analyze four kinds of spatial improvement channels and policy spillover effects of

carbon emission trading policy on the different kinds of regional energy efficiency.

(4) Our research explores the spatial transmission mechanisms of emissions trading systems in promoting socio-economic welfare. Through a combination of theoretical analysis and empirical research, this paper seeks to build a more comprehensive and in-depth framework to better understand how emissions trading systems, through a series of intermediary mechanisms, have a profound and complex impact on regional industrial energy efficiency, so as to provide a scientific basis for policymakers to help achieve environmentally friendly and low-carbon sustainable development goals.

3 Methods and data sources

3.1 SUPEBM model

EBM model was first constructed by Tone and Tsutsui (Tone and Tsutsui, 2010). The model combines radial and non-radial distance functions, and can also incorporate five important environmental pollutants in the green complex-element energy efficiency as negative outputs into the model, which can effectively strengthen the effectiveness of efficiency measurement. Since the model includes the ε parameter, it is called the Epsilon-Based Measure. The super-efficiency model was first proposed by Andersen et al. (2013) who proposed an improved method to address the shortcomings of traditional data envelope model, which could not compare and rank DMU units with efficiency values higher than 1, allowing efficiency values greater than 1 to better measure and compare all DMU units.

In this paper, the advantages of these two models are combined to obtain a SUPEBM model containing undesirable outputs, which is defined as follows:

$$R^{*} = \min \frac{\theta - \varepsilon^{-}\sum_{i=1}^{m}\frac{\omega_i^{-}s_i^{-}}{X_{i0}}}{\varphi + \varepsilon^{+}\left(\sum_{r=1}^{s}\frac{\omega_r^{+}s_r^{+}}{Y_{r0}} + \sum_{p=1}^{q}\frac{\omega_p^{u-}s_p^{u-}}{u_{p0}}\right)} \tag{1}$$

$$\begin{aligned} \text{s.t.}\quad & \sum_{j=1}^{n} X_{ij}\lambda_j + s_i^{-} = \theta X_{i0} \\ & \sum_{j=1}^{n} Y_{rj}\lambda_j - s_r^{+} = \phi Y_{r0} \\ & \sum_{j=1}^{n} u_{pj}\lambda_j + s_p^{-} = \phi u_{p0} \\ & \lambda_j \geq 0, s_i^{-}, s_r^{+}, s_p^{-} \geq 0 \end{aligned}$$

In Equation 1, R^{*} is the value of regional industrial energy efficiency when returns to scale are stable. n represents how many decision units DMU there are. X_{i0}、Y_{r0}、u_{p0} represent, one by one, the input elements, the expected output outcomes, and the unintended (or undesirable) output outcomes of the decision-making entity. θ is the efficiency value of the radial condition. There are m+1 parameters in the model. ε, whose value ranges from [0,1], is a key parameter that determines the importance of the non-radial part of the optimal efficiency value. ω represents the relative importance of each element. $s_i^{-}, s_r^{+}, s_p^{u-}$ represent input redundant variables, expected output redundant variables and unexpected output redundant variables one by one.

3.2 Dynamic spatial dubin model

Existing studies have revealed that there is an obvious spatial interaction between energy use and carbon emission trading policies. If the cross-border effects of carbon emission trading policies are not taken into account, the assessment of policy effects may be incomplete or omitted. Therefore, this paper intends to use the spatial panel model to carry out empirical research. This model has been very mature in the study of spillover effect of policy effect and has been recognized by scholars (Xu and Jiang, 2020; Zhang et al., 2021; Li and Wang, 2021; Hu and Ye, 2022).

While the dummy variable of carbon trading pilot policy (CTP) is included in the model, taking into account the path-dependent characteristics of carbon emissions over time, we incorporate the lag effect of carbon emission trading policy variables on the basis of the static spatial model, and then construct the dynamic spatial panel Durbin model:

$$\begin{aligned} Y_{it} = {} & \beta_0 + \beta_1 Y_{it-1} + \alpha_1 \sum_{i=1}^{n}\omega_{ij}Y_{it} \\ & + \beta_2 P_i \cdot E_t + \alpha_2 \sum_{i=1}^{n}\omega_{ij}G_i \cdot D_t \\ & + \alpha_3 \sum_{i=1}^{n}\omega_{ij}X_i t + \beta_3 \sum X_{it} + \varepsilon_{it} \end{aligned} \tag{2}$$

In Equation 2, Y_{it} refers to the regional energy efficiency, and Y_{it-1} refers to the regional industrial energy efficiency lagging one period.

In order to deal with the time inertia of energy efficiency and its influence on current energy efficiency, this paper constructs a dynamic spatial Durbin model with time lag variable of energy efficiency. This approach aims to mitigate the endogeneity of missing variables by taking into account the time lag of the explained variables.

P_i represents the dummy variable of province and city. If region i is the pilot region of carbon emission trading, $P_i = 1$; otherwise, $P_i = 0$. E_t represents the year dummy variable. Considering that the overall pilot work of carbon emission trading did not start to run fully until 2013, our research uses 2013 as the year of comprehensive policy implementation, that is, when t ≥ 2013, $E_t = 1$; otherwise, $E_t = 0$; $CTP_{i,t} = P_i{*}\ E_t$; ω_{ij} is the spatial weight matrix used to represent the spatial adjacency relationship between different regions. Three different spatial weight matrices, namely, the spatial adjacency weight matrix, the inverse geographical distance weight matrix, and the asymmetric economic-geographical space weight matrix, are selected for calculation. β_1、β_2、β_3 and α_1、α_2、α_3 represent the coefficients of the main explanatory variables, control variables and their corresponding time-space lag variables. ε_{it} denotes the random disturbance term. Considering that there are many influencing factors of energy utilization efficiency, referring to relevant literature, introducing the related control variable group X_{it} (Macdonald et al., 2020; Liu et al., 2020).

3.3 The data source

In this paper, two kinds of regional energy efficiency are defined. Among them, regional single-element energy efficiency (SF), which is demonstrated by the scale obtained by dividing regional industrial output value and regional industrial energy consumption. This ratio not only directly reflects the energy utilization efficiency of industrial production activities, but also serves as a key economic and environmental performance indicator. It has important statistical and decision-making value for evaluating the sustainability of regional industrial development, monitoring the effectiveness of energy conservation and emission reduction, and formulating and adjusting related policies. The second important research object is regional green complex-element energy efficiency (TF), which is computed by the SUPEBM model in the research. When determining the input variables of the model, we choose total industrial fixed capital, labor force and total industrial energy consumption as core input indicators. On the other hand, we consider five key sources of industrial pollution - CO_2 and SO_2 emissions, smoke emissions, wastewater emissions, and solid waste generation - as non-desired output variables. The expected output is defined as the gross industrial output of the region. Industrial green complex-element energy efficiency is an index that measures the economic benefits and environmental impact of the economy in the production activities. Based on the traditional complex-element productivity analysis, it further includes the factors of energy consumption and environmental pollution, so as to evaluate the sustainability of economic activities in a more comprehensive way.

The control variables in this paper include the following: enterprise property right attribute (A1), calculated as the ratio of public enterprises to the total number of enterprises. Industrial structure (A2) is the ratio of industrial output value to the total regional output value. Level of foreign investment (A3), calculated as the scale of foreign direct investment to gross regional product. Urban sprawl (A4) is the proportion of urban population to total population. Financial support (A5), calculated as the scale of regional fiscal expenditure to the total output value. Environmental innovation degree (A6), which is taken from the analysis index of regional environment and innovation in *China Regional Innovation Capability Evaluation Report*. Financial activity (A7), calculated as the ratio of total deposits and loans to total regional output. Quality of Employed Persons (A8), calculated by the proportion of university-educated employed persons to the total employed population.

Since there were many missing data before 2008, in addition, the COVID-19 outbreak that started at the end of 2019 had a great impact on China's economy and society. In addition, China launched a national carbon market after 2019, which cross-interferes with the research in this paper, so we set the study period as 2008–2019. The study covers all 30 provincial-level administrative units in China. Hong Kong, Macao, Tibet and Taiwan are excluded from our study due to lack of research data. All data involving prices are deflated from the year 2000 base period.

4 Analysis of influencing mechanism

The research object of this paper covers two different types of energy efficiency. Single-element energy efficiency mainly focuses on measuring the utilization efficiency of a certain kind of energy in the production or use link, and does not include the role of other production factors on energy efficiency. The scope of consideration of green complex-element energy efficiency is more comprehensive, which not only covers energy factors, but also includes other production factors such as labor and capital, and includes very important environmental pollution factors.

The improvement of single-element energy efficiency reduces the energy consumption per unit of output, and then promotes the improvement of green complex-element energy efficiency to a certain extent. The improvement of green complex-element energy efficiency means that industrial enterprises need to pay attention to environmental protection factors while pursuing economic efficiency improvement. This may encourage industrial enterprises to adopt more advanced energy utilization and environmental pollution treatment technologies, thereby indirectly improving single-element energy efficiency. In the process of exploring the promotion of energy efficiency by carbon trading policies, it is necessary to comprehensively weigh the respective characteristics and requirements of these two energy efficiency indicators, so as to achieve the simultaneous improvement of economic benefits, environmental benefits and social benefits.

The carbon emission trading policy gives carbon emission right the attributes of marketization and commercialization. It encourages the reduction of carbon dioxide emissions by clearly defining property rights, flexibly pricing carbon emissions, and internalizing the external costs of pollution generated by production. Carbon emission trading policies are an important enabling tool for States parties to ensure the achievement of *the Paris Agreement* and the goals of their intended Nationally Determined Contributions. Reasonable pricing of carbon emission rights can guide capital to flow into the green investment industry, improve the energy utilization efficiency and comprehensive competitiveness of enterprises, encourage enterprises to create more green ecological value through technological innovation and progress and mass production of green and low-carbon products, and enable more consumers to create more green ecological value through using green and environment-friendly products. Carbon trading policies promote innovation and upgrading of production and consumption patterns by improving energy allocation. The power sector is steadily transitioning to zero carbon emissions, the application range of clean energy is expanding, coupled with the establishment of carbon emission trading system and the establishment of reasonable carbon prices, effectively helping industrial enterprises to smoothly enter the low-carbon development track.

Through literature review, we find that the implementation of carbon emission trading policy can not only promote energy conservation and emission reduction, but also bring regional employment growth benefits. (Yu and Li, 2021), reduce the income gap between urban and rural areas (Yu et al., 2021), and promote the improvement of industrial economic benefits (Duan et al., 2021). At the same time, it can encourage the control unit to carry out technology research and development and innovation activities (Fang and Ma, 2021) to improve production and operation efficiency (Chen et al., 2021) and comprehensive competitiveness (Luo et al., 2021). Therefore, carbon emission trading has a positive impact on local industrial single-element energy efficiency and industrial green complex-element energy efficiency. In addition, as a key environmental management tool, carbon emission trading policy not only has a direct impact on the energy conservation and emission reduction behavior of local industrial units, but also has a spatial knock-on effect on industrial enterprises in neighboring areas (Li and Wang, 2021). From the previous analysis, this paper constructs the following assumptions.

Hypothesis A: The carbon emission trading policy has strengthened regional single-element energy efficiency and regional green complex-element energy efficiency, and triggered the cross-border transmission of policy effects.

Hypothesis B: The carbon emission trading policy has strengthened regional green complex-element energy efficiency, and triggered the cross-border transmission of policy effects.

As a market-based regulation method, carbon emission trading policy needs to go through the stage of problem identification and definition, policy consultation and policy planning, while policy implementation needs to go through the process of policy publicity, policy experiment, comprehensive implementation, coordination and monitoring, and readjustment. Therefore, the immediate and long-term effects of emissions trading policy on the two kinds of regional energy efficiency are different, and the spillover effects of these immediate and long-term effects are also different. From the previous analysis, this paper constructs the following assumptions.

Hypothesis C: The short-term and long-term effects of carbon emission trading policy on the two kinds of regional energy efficiency are different.

From the micro-market perspective of specific enterprise operations, the “dual carbon” policy is a positive driving force to promote the transformation of Chinese industrial enterprises to a green development model. More and more green and low carbon concepts are introduced into the production and operation process of industrial enterprises, and the relevant emerging manufacturing industry is full of vitality in the face of various opportunities. Take the new energy vehicle industry as an example. According to statistics, between 2006 and 2021, there were about 550 financing events in the field of new energy vehicles, with a total amount of more than 320 billion yuan. More than 70 percent of the financing time occurred after the implementation of the carbon emission trading policy. We can observe that after the implementation of the carbon trading policy, such green industries are favored by the capital market, and the investment and financing enthusiasm is increasingly vigorous. The rational adjustment of industrial structure can achieve more coordinated division of labor and cooperation by rational utilization of resources, provide more and richer kinds of green products and services, and promote the application of advanced industrial technology, thus to obtain better economic benefits. The huge market opportunity will attract investment to green industry sectors. The implementation of the carbon trading policy will lead to a significant increase in the demand for green technology in industrial enterprises, promote industrial green transformation, improve energy utilization efficiency through technological innovation, cultivate new green industrial clusters, and constitute a new economic growth point.

According to national statistics, power enterprises in the industrial sector contributed more than 50% of the carbon emission reduction in China’s carbon trading market system. However, from the perspective of power generation structure, thermal power, the traditional energy source, still occupies the absolute proportion, with the installed capacity accounting for more than 55% and the annual power generation accounting for more than 75%. When looking from the cost of energy use, according to the historical experience of the European carbon market, in the future, the total control of carbon quotas in China’s carbon trading market will be more and more severe, and the carbon price will gradually increase, resulting in more and more difficulty for power enterprises to obtain free carbon quotas. Even it will be necessary to buy carbon emission right quotas by auction, and the comprehensive cost will increase significantly. Therefore, in the face of carbon price and emission reduction costs, power enterprises need to weigh and consider, and tend to use low-carbon clean energy to replace traditional energy, so as to optimize their energy consumption composition and improve the efficiency of energy use. From the previous analysis, this paper constructs the following assumptions.

Hypothesis D: Through the adjustment of industrial structure and improving the energy consumption structure, the carbon emission trading policy accelerates the enhancement of regional single-element energy efficiency.

Attracting foreign investment is an important window to observe the level of regional opening-up. By optimizing the industrial structure and improving the quality of industries, various regions in China will attract more foreign investment, which will bring more new opportunities for foreign investment to flow into high-tech industries. By enhancing the level of regional opening to the outside world, carbon trading mechanism can effectively enhance the market competitiveness of industrial enterprises in the region and the overall economic efficiency, encouraging industrial enterprises to strengthen cooperation with other economic entities, exchange and learn from each other, introducing advanced green technologies and low-carbon products, and reallocating resources. In the process of improving green complex-element energy efficiency, from the perspective of input, we will optimize the technical level of industrial personnel, attract strategic investment capital with more cost advantages, and introduce more advanced foreign energy saving technologies. Moreover, more efficient production equipment can be used at the output end to improve the comprehensive economic output performance, and advanced foreign environmental protection technology can be used to reduce environmental pollution, to strengthen the regional green complex-element energy efficiency.

Modern service industry comes into being with the development of knowledge economy and information technology. It is a service industry with deep application of modern technology, management and mode. It has the characteristics of high concentration of intellectual capital, high value-added output, low resource consumption and low environmental pollution. In the process of promoting the modern service industry, the development of clean transportation has a positive role in accelerating the green and low-carbon transformation of the transportation industry. Through transportation electrification, it can help improve the operation efficiency of the power grid and absorb more renewable resources. To reduce emissions from high-polluting vehicles in the traditional transport sector by setting stricter emission standards and regulations for diesel vehicles and promoting green freight services. Green finance business is widely involved in environmental protection, energy conservation measures, clean energy development, green travel solutions and green building practices, and aims to provide customers with comprehensive and comprehensive financial solutions through project investment, financing arrangements, project operation management and risk prevention and control measures. It can guide industrial enterprises to green transformation and economical and efficient utilization through high-quality and low-cost financial financing channels. The manufacturing service industry is the penetration and integration of the service industry into the manufacturing industry. Through advanced consulting, design, cloud computing, system development and other measures, it can help industrial enterprises improve their product competitiveness and comprehensive strength, and promote industrial enterprises to improve energy utilization efficiency and low-carbon transformation. Due to the huge potential of green economic benefits of modern service industry, by encouraging the growth of modern service industries, emissions trading policy can strengthen regional green complex-element energy efficiency. From the previous analysis, this paper constructs the following assumptions.

Hypothesis E: Carbon emissions trading policy promotes regional green complex-element energy efficiency by increasing the degree of openness and increasing the proportion of tertiary industry.

The logical structure of this paper is shown in Figure 1.

5 Results and discussion

5.1 Spatial impact of carbon emission trading system on regional industrial energy efficiency

As an important environmental regulation tool, carbon emission trading policy will also produce policy spillovers to industrial enterprises in surrounding areas. For this, this paper uses spatial panel model to study.

Before the parameter estimation of the spatial panel model, we need to carry out a pre-processing step, the purpose is to verify whether the explained variables have correlation in spatial dimension through the global Moran index before establishing the spatial panel model. Considering that policy spillovers generally exert effects on geographically close regions, the inverse geographic weight matrix is selected as the spatial weight matrix in spatial metrology model. The results show that the global Moran index of the two kinds of energy efficiency is positive and statistically significant in most years. This indicates that the two kinds of regional energy efficiency have a significant positive correlation in space.

Next, in order to evaluate the spatial effects of carbon emission trading policy on the two energy efficiency, we adopt the spatial Dubin model and introduce three different spatial weight matrices: spatial adjacency weight, inverse geographical distance weight, asymmetric economic geographical weight. These matrices help us to understand more fully how carbon trading affects energy efficiency in spatial dimensions. By comparing the regression coefficients of carbon emission trading under the three weight matrices, the regression coefficients are significantly positive only under the inverse geographical distance weight matrix, which indicates that in the spatial dependence of geographical distance, carbon trading policy have shown significant positive effects on each kind of regional energy efficiency.

Commonly used spatial models include spatial Durbin, spatial lag (SL) and spatial error (SE). When selecting the spatial econometric model, the panel data of the two kinds of energy efficiency in China were analyzed by LM test, and the analysis results are shown in Table 1. The results show that both LM_Lag and LM_Error pass the significance test, indicating that both SA model and SE model can be accepted. Wald test and LR test are carried out in depth, and the results show that the spatial Dubin model cannot be simplified to a spatial lag model or a spatial error model, which strongly opposes the hypothesis of model degradation. According to Anselin criterion, spatial Dubin model is selected for estimation in our research (Anselin et al., 2013).

To improve the robustness of the research results, this paper adopts six types of models to compare and analyze the relationship between carbon emission trading policy and the regional industrial energy efficiency. It includes non-spatial panel model (random effect and fixed effect), non-spatial dynamic panel model (system GMM model), static spatial Dubin model (random effect and fixed effect) and dynamic spatial Dubin model (fixed effect). The verification results are shown in columns (1)–(6) of Tables 2, 3. We can see that the carbon emission trading policy has a positive impact on the two kinds of regional industrial energy efficiency, and the regression coefficients of the main explanatory variables of most models show positive significance. However, due to potential endogeneity or spatial correlation, the results of some non-spatial panel models are not ideal.

In addition, we add a DID model to verify the robustness of the model. The empirical results show that the two types of energy efficiency in the pilot area are significantly improved after the implementation of the carbon emission trading policy.

According to the results of spatial Dubin model which considerate spatial factor, both static spatial Dubin model (random effect and fixed effect) and dynamic spatial Dubin model (fixed effects), have verified the spatial impact of carbon emission trading policy on the two kinds of regional energy efficiency in the region is significant, and can reach a significant level of 1%. By comparing columns (1)–(6) of models in Tables 2, 3, the regression coefficients of carbon emission trading policy variables are all greater than zero, which further demonstrates the robustness of carbon trading policy to improve the two kinds of regional energy efficiency in this region.

Our discussion will focus on the dynamic spatial Dubin model, which has excellent statistical properties.

According to the dynamic spatial Dubin model, the regression coefficient of the carbon trading policy dummy variable on the spatial lag term of the single-element energy efficiency is −1.5426, but it fails to pass the significance test, indicating that the implementation of carbon trading pilot policy has a certain

TABLE 1 LM test results.

Test	SF	TF
Lag	12.450***	27.618***
Error	5.665**	48.551***

Note: Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.

inhibitory effect on the single-element energy efficiency in neighboring areas, but this effect is not obvious. The regression coefficient of the spatial lag term of the dummy variable of carbon trading policy on the green complex-element energy is 0.1403, and the significance test reveals that the results are significant at the significance level of 1%, indicating that the implementation of carbon trading pilot policy not only improves the local green complex-element energy efficiency, it can also improve the green complex-element energy efficiency in neighboring areas.

In conclusion, **Hypothesis A** and **Hypothesis B** are verified.

Through the above analysis, we confirm that the carbon emission trading policy has indeed significantly improved the two kinds of regional industrial energy efficiency, and produced spatial spillover effects. However, the spillover effect of single-element energy efficiency is not significant. The factors of single-element energy efficiency are simple, and the energy efficiency between different provinces is often viewed in isolation, lacking cross-regional exchanges and cooperation. As a result, the improvement of single-element energy efficiency mainly depends on technological progress and management optimization within the region, which is difficult to achieve through cross-regional learning and imitation, and thus difficult to produce policy spillover effects.

5.2 Decomposition of short-term and long-term effects

To explain the spatial effect of carbon trading policy, this paper further decomposes the effect of carbon emission trading mechanism on the improvement of regional energy efficiency in the dynamic spatial Dubin model, and divide them into direct effects and indirect effects of short-term and long-term. As shown in Table 4.

In the short term, the direct and indirect effects of the implementation of carbon trading policy on the single-element energy efficiency are positive and significant, indicating that the carbon trading policy played a positive role soon after the implementation of the policy, and significantly promoted the improvement of the single-element energy efficiency in and around the pilot area. However, in the long run, the direct effect of carbon trading policy implementation on the single-element

TABLE 2 Spatial impact of carbon emission trading policy on regional single-element energy efficiency (SF).

Variable	SF Non-spatial panel model fixed effect (1)	SF Non-spatial panel model random effect (2)	SF Non-spatial dynamic panel model (3)	SF Dubin model of static space Random effect (4)	SF Dubin model of static space Fixed effect (5)	SF Dynamic spatial dubin model Fixed effect (6)
Lag.1	—	—	0.8405*** (0.0167)	—	—	2.3053*** (0.0347)
CTP	0.2485*** (0.0830)	0.3058*** (0.0873)	0.1892** (0.0938)	0.2798*** (0.0955)	0.1759* (0.1025)	0.1488** (0.0617)
W*CTP	—	—	—	−0.4352 (0.3550)	−0.8455 (0.6862)	−1.5426 (0.4084)
A1	0.1581** (0.0717)	0.1549* (0.0829)	−0.1846 (0.3513)	0.1944* (0.1137)	0.0793 (0.0961)	−0.6732*** (0.0599)
A2	−0.4935*** (0.1399)	−0.5393*** (0.1609)	−0.0387 (0.1753)	−0.3150* (0.1797)	−0.3665** (0.1564)	−0.1891** (0.0948)
A3	0.0306* (0.0174)	0.0375** (0.0190)	0.0599 (0.0759)	0.0221 (0.0239)	−0.0294 (0.0234)	0.0682*** (0.0145)
A4	−0.4368* (0.2505)	−0.4634* (0.2792)	0.3426 (0.4321)	−0.5523* (0.3020)	−0.5252** (0.2661)	−0.0596 (0.1674)
A5	−0.4984* (0.2892)	−0.4730 (0.3341)	0.7333 (0.5672)	−0.7968** (0.3738)	−0.7089** (0.3285)	3.1899*** (0.1990)
A6	0.4838*** (0.1142)	0.4669*** (0.1240)	0.2059* (0.1150)	0.5007*** (0.1407)	0.5076*** (0.1321)	−0.2792*** (0.0829)
A7	0.0703* (0.0369)	0.0585 (0.0421)	0.0594 (0.0978)	0.0607 (0.0479)	0.0134 (0.0435)	−0.3511*** (0.0267)
A8	0.2315** (0.0912)	0.2158** (0.0974)	−0.0664 (0.0760)	0.2428* (0.1341)	0.5128*** (0.1238)	0.0613 (0.0815)
Fixed effect	YES	NO	NO	NO	YES	YES
sigma2_e	—	—	—	0.1461*** (0.0119)	0.1482*** (0.0110)	0.0590*** (0.0038)
R-quared	0.4030	0.4014	—	0.7762	0.8588	0.4854
Obs	360	360	360	360	360	360

Note: LAG.1 represents time Lag term, W represents space Lag term.
Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.
The t values in parentheses represent the robust standard errors.

TABLE 3 Spatial impact of carbon emission trading policy on regional green complex-element energy efficiency (TF).

Variable	TF Non-spatial panel model fixed effect (1)	TF Non-spatial panel model random effect (2)	TF Non-spatial dynamic panel model (3)	TF Dubin model of static space Random effect (4)	TF Dubin model of static space Fixed effect (5)	TF Dynamic spatial dubin model Fixed effect (6)
Lag.1	—	—	−0.0455 (0.1436)	—	—	0.4972*** (0.0652)
CTP	0.0722 (0.0448)	0.1130*** (9.0395)	0.0567 (0.0388)	0.1649*** (0.0375)	0.2754*** (0.0420)	0.1403*** (0.0405)
W*CTP	—	—	—	0.4133*** (0.1441)	1.3594*** (0.2816)	0.7498*** (0.1677)
A1	0.2484*** (0.0387)	0.2414*** (0.0685)	0.3397 (0.2511)	0.2391*** (0.0832)	0.1254*** (0.0396)	0.1646 (0.1017)
A2	0.2932*** (0.0755)	0.5877*** (0.1032)	0.6579*** (0.1915)	0.3660*** (0.1178)	0.0314 (0.0646)	0.5111*** (0.1328)
A3	0.0266*** (0.0094)	0.0473*** (0.0095)	0.0306 (0.0195)	0.0292*** (0.0094)	−0.0201** (0.0096)	0.0301*** (0.0097)
A4	0.6176*** (0.1352)	0.4409** (0 0.1727)	0.1862 (0.3788)	0.8898*** (0.1870)	0.8201*** (0.1093)	0.3568 (0.2397)
A5	−0.3116** (0.1561)	−0.3527 (0.2354)	1.1147* (0.6629)	0.1195 (0.2747)	0.0017 (0.1347)	0.7795** (0.3372)
A6	0.3455*** (0.0616)	0.0333 (0.0615)	−0.2195*** (0.0585)	−0.0007 (0.0674)	0.1656*** (0.0542)	−0.0438 (0.0651)
A7	0.0235 (0.0199)	−0.0067 (0.0280)	−0.1362*** (0.0425)	−0.0393 (0.0305)	−0.0282 (0.0178)	−0.0502* (0.0298)
A8	−0.0225 (0.0492)	0.0015 (0.0476)	0.0440 (0.0437)	−0.0215 (0.0575)	0.1913*** (0.0509)	−0.0168 (0.0609)
Fixed effect	YES	NO	NO	NO	YES	YES
sigma2_e	—	—	—	0.0163*** (0.0013)	0.0249*** (0.0020)	0.0136*** (0.0010)
R-quared	0.5104	0.3147	—	0.4208	0.8469	0.5340
Obs	360	360	360	360	360	360

Note: LAG.1 represents time Lag term, W represents space Lag term.
Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.
The t values in parentheses represent the robust standard errors.

TABLE 4 Decomposition of long-term and short-term spatial effects based on dynamic spatial Dubin model.

Decomposition of effects		SF (1)	TF (2)
Short term	Direct effect	0.1458** (0.0707)	0.1536*** (0.0377)
	Indirect effect	1.1672** (0.5589)	0.9723*** (0.2107)
	Total effect	1.3130** (0.5363)	1.1259*** (0.2196)
Long term	Direct effect	0.6528 (7.6691)	0.2230*** (0.0846)
	Indirect effect	−0.5747 (7.6681)	0.3870*** (0.1320)
	Total effect	0.0781 (0.0263)	0.6100*** (0.1112)
Control variables		Control	Control
Fixed effect		YES	YES
sigma2_e		0.0590*** (0.0038)	0.0136*** (0.0010)
R-sq		0.4854	0.5340
Obs		360	360

Note: The t values in parentheses represent the robust standard errors.
Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.

energy efficiency is positive but no longer significant, while the indirect effect of carbon trading mechanism implementation on the single-element energy efficiency changes from positive to negative, but also insignificant. This indicates that as time goes by, the effect of carbon trading mechanism on the improvement of SF in this region is weakened, and it begins to inhibit the improvement of SF in the surrounding region. The spatial spillover effect of carbon trading mechanism on the improvement of SF is not smooth.

TABLE 5 The spatial influence channel of carbon emission trading policy on the single-element energy efficiency (SF).

Variable	SF (1)	SF (2)	SF (3)	SF (4)	SF (5)
IS	0.1677* (0.0937)	0.1649* (0.0941)	0.1603* (0.0956)	0.1664* (0.0959)	0.2296** (0.0988)
ECSP	0.0888 (0.1021)	0.0899 (0.1032)	0.1323 (0.1362)	0.1346 (0.1406)	0.1234 (0.1425)
CTP*IS	0.1204** (0.0554)	0.1206** (0.0560)	0.1172** (0.0568)	0.1143** (0.0580)	0.1428** (0.0584)
CTP*ECSP	0.4500** (0.1774)	0.4587** (0.1810)	0.4137** (0.2043)	0.3940* (0.2223)	0.4401** (0.2203)
W*IS	0.2237 (0.6506)	0.1310 (0.6921)	0.1033 (0.6961)	0.1443 (0.6969)	0.7060 (0.7411)
W*ECSP	−0.3289 (0.7432)	−0.3065 (0.7543)	−0.0251 (1.0009)	−0.1920 (1.0243)	−0.1428 (1.0340)
W*CTP*IS	0.2707 (0.3898)	0.2152 (0.4170)	0.2103 (0.4182)	0.1734 (0.4250)	0.3751 (0.4234)
W*CTP*ECSP	−0.02251 (1.3000)	−0.2290 (1.3177)	−0.5293 (1.4541)	−0.8574 (1.5507)	−0.6578 (1.5472)
Fixed effect	YES	YES	YES	YES	YES
sigma2_e	0 0.0526*** (0.0037)	0.0526*** (0.0037)	0.0525*** (0.0037)	0.0525*** (0.0037)	0.0515*** (0.0037)
R-sq	0.6676	0.6679	0.6661	0.6636	0.6626
Obs	360	360	360	360	360

Note: The t values in parentheses represent the robust standard errors.
Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.

In the short term, the direct and indirect effects of carbon trading policy on the green complex-element energy efficiency are both positive and significant, this indicates that the carbon trading policy played a positive role soon after the implementation of the policy, and significantly promoted the improvement of the green complex-element energy efficiency in this region and its surrounding areas. In the long run, the direct and indirect effects of the green complex-element energy efficiency are both positive and significant, indicating that the carbon emission trading mechanism has continued to play a positive and stable role after the implementation of the policy, and continued to promote the improvement of the green complex-element energy efficiency in this region and its surrounding areas. At the same time, the direct effect of long-term is stronger than the direct effect of short-term, this indicates that the effect of carbon trading mechanism on improving TF in this region is becoming stronger, and the long-term indirect effect is smaller than the short-term indirect effect, indicating that the spatial spillover effect of carbon trading mechanism on the green complex-element energy efficiency in the surrounding region is weakening.

In conclusion, **Hypothesis C** is verified.

Through the above analysis, we verify the spatial effects of carbon trading mechanism on the two kinds of regional energy efficiency in the long and short term. Single-element energy efficiency only considers the proportional relationship between energy input and output, and ignores the influence of other production factors (such as capital, labor, etc.). It can not fully reflect the various complex factors in the process of energy utilization, such as technological progress, industrial structure changes, so its long-term effect is often not significant. Relatively speaking, green total factor energy efficiency is considered comprehensively, which can reflect the influence of complex factors such as technological progress and industrial structure change, and therefore produce significant long-term effects.

5.3 The spatial improvement channel of carbon emission trading policy on regional industrial energy efficiency

To explore the channel through which carbon emission trading mechanism affects the single-element energy efficiency in the spatial dimension, this paper introduces the interaction terms between carbon trading policy variable (CTP) and industrial structure (IS) and energy consumption structure (ECSP), and successively adds control variables such as governance structure, policy support, innovation environment level and human capital to the model to conduct robustness tests. The industrial structure is the proportional relationship between the output value of the secondary industry and the tertiary industry, and the energy consumption structure is the ratio of clean energy consumption and total energy consumption. The empirical results are shown in Table 5.

From the perspective of the industrial structure channel, the industrial structure has a significant positive driving effect on the regional industrial single-element energy efficiency, but the positive effect on the surrounding regional single-element energy efficiency is not significant. The regression results show that at the significance level of 5%, the coefficient of the interaction term between the carbon trading policy variable and the industrial structure is significantly positive, while the coefficient of the spatial lag term is positive but does not reach statistical significance. This indicates that the industrial structure channel plays a significantly stronger role in improving SF in the pilot region than other regions, and the carbon trading policy generates spatial spillover through the industrial structure channel, but it is not significant.

From the perspective of the energy consumption structure channel, the energy consumption structure has a positive driving effect on the single-element energy efficiency in the region, but it is not significant. Under the significance threshold of 5%, the regression coefficient of the interaction between carbon trading

TABLE 6 The spatial influence channel of carbon emission trading policy on the green complex-element energy efficiency (TF).

Variable	TF (1)	TF (2)	TF (3)	TF (4)	TF (5)
OPE	0.0606*** (0.0087)	0.0568*** (0.0091)	0.0634*** (0.0103)	0.0613*** (0.0101)	0.0600*** (0.0106)
TIP	0.4540*** (0.0826)	0.5866*** (0.0852)	0.5544*** (0.0855)	0.3325*** (0.0936)	0.2656* (0.1369)
CTP*OPE	0.0988*** (0.0213)	0.0854*** (0.0213)	0.0895*** (0.0213)	0.0924*** (0.0205)	0.0914*** (0.0213)
CTP*TIP	0.0423** (0.0173)	0.0655*** (0.0179)	0.0645*** (0.0182)	0.0340* (0.0185)	0.0348* (0.0189)
W*OPE	0.4018*** (0.0666)	0.4420*** (0.0651)	0.4950*** (0.0743)	0.5162*** (0.0762)	0.5060*** (0.0856)
W*TIP	1.0241** (0.4540)	1.6259*** (0.4720)	1.4423*** (0.4879)	0.3335 (0.5601)	0.5208 (0.9169)
W*CTP*OPE	0.1588 (0.1162)	0.0868 (0.1139)	0.0615 (0.1136)	0.0778 (0.1094)	0.0717 (0.1142)
W*CTP*TIP	0.3737*** (0.1108)	0.4901*** (0.1117)	0.5122*** (0.1125)	0.3405*** (0.1133)	0.3406*** (0.1148)
Fixed effect	YES	YES	YES	YES	YES
sigma2_e	0.0446*** (0.0032)	0.0419*** (0.0030)	0.0412*** (0.0029)	0.0380*** (0.0027)	0.0379*** (0.0027)
R-sq	0.7805	0.8310	0.8495	0.8608	0.8559
Obs	360	360	360	360	360

Note: The t values in parentheses represent the robust standard errors.
Symbol "***", "**", "*" means that it is significant at the level of statistical significance of 1%, 5% and 10%.

policy variables and energy consumption structure shows a significant positive relationship, but the regression coefficient of the spatial lag term does not show a significant relationship. This indicates that the carbon trading policy has improved the single-element efficiency in the pilot areas through the channel of industrial structure adjustment, but its spatial spillover effect is not significant.

In conclusion, **Hypothesis D** is verified.

To explore the channel through which carbon emission trading mechanism affects the green complex-element energy efficiency in the spatial dimension, this paper introduces the interaction terms between carbon trading policy variable (CTP) and openness level (OPE) and proportion of tertiary industry (TIP). In addition, governance structure, policy support, innovation environment level, human capital and other control variables are added successively to the model to conduct robustness tests. Table 6 shows the corresponding empirical results.

From the perspective of the openness level channel, the openness level has a significant positive driving effect on the green complex-element energy efficiency in both the pilot area and its adjacent areas. At the significance level of 1%, the regression coefficient of the interaction between the carbon trading policy variable and the degree of openness shows a significant positive value, while the regression coefficient of the spatial lag term is positive but insignificant. This indicates that the openness level channel has a significantly stronger effect on the improvement of the green complex-element energy efficiency in the pilot region than other regions, and the carbon trading policy generates spatial spillover through the openness level channel, but it is not significant.

From the perspective of the proportion of the tertiary industry, the improvement of the proportion of tertiary industry has a significant positive driving effect on the green complex-element energy efficiency of the region and the geographical adjacent regions. At the significance level of 1%, the regression coefficient of the interaction term between the carbon trading policy variable and the proportion of the tertiary industry is significantly positive, and the regression coefficient of the spatial lag term is also significantly positive. This indicates that the carbon trading policy improves the green complex-element energy efficiency in pilot areas and geographically adjacent areas through the channel of the proportion of tertiary industry.

In conclusion, **Hypothesis E** is verified.

Existing literature studies have found that green finance policies can improve corporate competitiveness by easing corporate financing constraints and increasing business income (Guo et al., 2024). However, the spatial channels through which carbon trading policy affect different energy efficiency have not been studied.

Through the above analysis, we verify four spatial channels through which carbon trading policy affect regional industrial energy efficiency, including industrial structure, energy consumption structure, opening-up degree, and the proportion of tertiary industry. This is a key finding of the study. No domestic or foreign scholars have yet analyzed these spatial mechanisms. The results of this study provide a solid theoretical support for government departments when planning energy policies.

6 Conclusions and recommendations

Based on a sample of Chinese provinces from 2008 to 2019, combined with the dynamic spatial Dubin model, this paper studies the spatial effects and policy spillovers of carbon emission trading policy on the two kinds of regional industrial energy efficiency. Finally, the spatial impact path of carbon emission trading on the single-element energy efficiency is studied through the channels of industrial structure and energy consumption structure. Meanwhile, the spatial impact path of carbon emission trading on the green complex-element energy efficiency is studied through the channels of openness level and the proportion of tertiary industry. The main research conclusions are as follows.

(1) The non-spatial panel model without considering spatial effects and the dynamic spatial Dubin model with considering spatial effects are tested, and the results show that the carbon emission trading mechanism promotes the improvement of regional single-element energy efficiency and green complex-element energy efficiency, and produces policy spillover effects, but the impact degree is different. The experimental results have passed the robustness test.
(2) The utility of emissions trading policy on the two kinds of regional energy efficiency varies in the short and long term. In the short term, the implementation of carbon trading policy has significantly promoted the improvement of the single-element energy efficiency in this region and its surrounding areas. However, in the long run, carbon trading policies have weakened the improvement of the single-element energy efficiency in this region, and began to inhibit the improvement of the single-element energy efficiency in the surrounding region. In the short term, the implementation of carbon trading policy has significantly promoted the improvement of the green complex-element energy efficiency in this region and its surrounding areas. In the long run, the carbon emission trading policy continues to play a positive and stable role after the implementation of the policy. The carbon trading policy has a stronger role in improving the green complex-element energy efficiency in the region, while its spatial spillover effect on the green complex-element energy efficiency in the surrounding district is weakening.
(3) The analysis of different intermediate links of carbon emission trading policy on regional energy efficiency shows that with the help of industrial structure and energy consumption structure, carbon trading policy has promoted the improvement of the single-element energy efficiency in pilot areas, although the spatial spillover effect of such improvement is not obvious. The carbon trading policy improves the green complex-element energy efficiency of the pilot region through the openness level channel and produces spatial spillover, but it is not significant. The carbon trading policy can enhance the green complex-element energy efficiency in pilot areas through the promotion of the tertiary industry, and this promotion also has obvious spatial diffusion effect.

According to the above research conclusions, this paper puts forward policy suggestions.

(1) It is necessary to give full play to the market-oriented policy attributes of carbon emission trading. It is necessary to set carbon emission trading prices and reward and punishment mechanisms in a scientific and reasonable way.

Specific measures include: The core principle of "cap and trade" for total carbon emissions needs to be followed. In the transaction price setting, the safety valve mechanism and the setting of the upper and lower limits of the price can be used to ensure that the price can reflect the market supply and demand, and can encourage enterprises to reduce emissions. Reward and punishment mechanisms need to take into account regional and industry differences, set reasonable penalties, identify enforcement agencies, and ensure fairness and effectiveness of the mechanism.

(2) Relevant laws and regulations need to be continuously improved to provide a more active carbon emission trading main market trading platform.

Specific measures include: It is necessary to improve the relevant laws and regulations on carbon emission trading, clarify the legal attributes, management models and trading rules, and provide a solid guarantee for the healthy development of the market. It is necessary to establish industry associations to publicize private activities, encourage more high-carbon industries to enter the carbon trading market, and promote technological innovation in energy conservation and emission reduction of industrial enterprises, so as to promote the improvement of comprehensive industrial energy efficiency. It is necessary to actively develop various types of carbon financial derivatives, enrich the product types of carbon trading market, and improve the activity of carbon trading and the liquidity of factor markets.

(3) In view of the spatial spillover characteristics of carbon emission trading policy, government departments at all levels should pay more attention to the construction of cross-regional carbon emission trading mechanisms, and actively promote the establishment and efficient operation of national carbon emission trading markets.

Specific measures include: It is necessary to establish trans-regional carbon markets, promote intra-regional carbon emission trading, and strengthen information sharing and technology exchange. According to the respective resource endowments of different regions, corresponding fiscal guidance policies will be introduced. We will encourage all types of private capital to participate in cross-regional carbon emission trading. Capital needs to be channeled into low-carbon innovation. The construction of the national carbon market should be under a unified market framework, and all regions can trade carbon emission rights according to their own emission reduction needs and capabilities, so as to form a dual role of regional coordinated emission reduction and improve the comprehensive energy efficiency.

(4) It is necessary to fully consider the intermediate channel through which carbon emission trading mechanism affects the regional energy efficiency.

Specific measures include: It is necessary to actively adjust the industrial structure and promote the development of green and low-carbon industries. It is necessary to improve the coordination ability between industries and improve the comprehensive benefits. The operation activities of industrial enterprises should be committed to improving the processing and conversion efficiency of coal, adopting more types of renewable energy and new energy, adjusting and optimizing the energy consumption structure to ensure a good state of the natural ecological environment. It is necessary to remove all kinds of restrictions on foreign trade, develop an open economy, strengthen economic and technological exchanges and cooperation with foreign countries, actively integrate into the international exchange and cooperation arena, participate in international competition, and raise the level of opening up. It is necessary to actively develop modern service industries such as information technology and network communication services, green finance, green transportation services, and some traditional service industries transformed by new technologies, so as to increase industrial added value, reduce environmental pollution, and reduce resource consumption.

Data availability statement

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

Author contributions

JL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. YD: Writing – review and editing. MZ: Writing – review and editing.

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Conflict of interest

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