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Coordination Effects and Driving Mechanisms of the Electricity and Carbon Markets: Evidence from China's Early Carbon Trading Pilot Regions

Cuihua Jia[1,a], Luyao Zhang[1,b], Wei Shi[1,c,*]

[1]*College of Geography and Environmental Science, Northwest Normal University, Lanzhou, China*
[a]*belove991@163.com*, [b]*zhangluyao3367@163.com*, [c]*shiwei0716@163.com*
**Corresponding author*

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Abstract: Under the goals of carbon peaking and carbon neutrality and the development of a new-type power system, electricity–carbon market coordination can reduce abatement costs and improve energy allocation. Using panel data from six early carbon-trading pilot regions in China from 2017 to 2022, this study evaluates the development and coordination of the electricity and carbon markets through the entropy weighting method, coupling coordination model, and geographical detector. The results show that both markets developed steadily and their coordination generally improved. Guangdong's coordination degree rose markedly and reached 0.80 in 2021, while Hubei remained stable at about 0.60. The other regions were still in a state of basic imbalance. Government intervention remained the dominant driver, while the relative importance of human capital declined. All factor interactions exhibited enhancement effects, including bi-factor enhancement and nonlinear enhancement, especially those involving government intervention.

1. Introduction

Achieving carbon peaking and carbon neutrality is central to China's green and low-carbon transition[1]. As both a major source of carbon emissions and a key driver of energy transformation, the power sector faces persistent challenges in energy-structure adjustment and market development. Carbon emissions trading introduces an explicit carbon cost and creates incentives for power enterprises to improve efficiency, shift fuels, and adopt low-carbon technologies. China has therefore advanced the national "1+N" policy framework, deepened electricity market reform, and expanded the national carbon market to promote emission reduction through market-based mechanisms [2-3]. The electricity market reflects power supply, demand, and system costs, while the carbon market signals allowance scarcity and abatement costs. Their interaction affects the generation mix, trading decisions, and energy consumption. However, weak institutional links may limit the pass-through of carbon costs to electricity prices, distort price signals, and reduce emission-reduction efficiency. These challenges highlight the need to examine the coordination between the electricity and carbon markets and identify the mechanisms that drive it.

International studies began relatively early to examine the effects of the European Union Emissions Trading System on electricity prices, corporate profits, and emission levels. They further explored the extent to which carbon costs are passed through to electricity prices and how this process is affected by market structure [4-5]. Research in China has gradually shifted from the operation of a single market to the interaction between the electricity and carbon markets. Studies have mainly used system dynamics, equilibrium models, threshold regression, and scenario simulation to examine the relationships among carbon prices, electricity prices, and firms' trading behavior [6-8]. Existing studies provide an important basis for understanding the interaction between the two markets, but two limitations remain. First, most studies focus on the national or cross-regional macro level, with limited quantitative analysis of institutional adjustment and development differences among the early pilot regions. Second, many studies emphasize price transmission or policy simulation. Few studies combine fine-grained data on electricity market transactions, such as electricity prices and spot price fluctuations, with data on compliance behavior in the carbon market to identify the multiple factors that drive coordination between the two markets.

In view of these limitations, this study examines six pilot regions for carbon emissions trading in China. It uses the entropy weighting method, the coupling coordination model, and the geographical detector to assess the overall development and coordination levels of the electricity and carbon markets and to identify their underlying driving mechanisms. Based on the findings, the study proposes policy recommendations for promoting coordinated development between the two markets. It aims to provide theoretical support for improving the coordination mechanism between the electricity and carbon markets and to support the development of market-based emission-reduction pathways under the "1+N" policy framework.

2. Methods and Data

2.1. Methods

2.1.1. Entropy Weight Method

To objectively determine indicator weights and reduce the influence of subjective judgment, the entropy weight method is used to calculate the comprehensive development indices of the electricity and carbon markets. First, all indicators are normalized using the min–max method according to their positive or negative attributes. The proportion of indicator j for observation i is calculated as:

$$\mathbf{P_{ij}=\frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}}} \tag{1}$$

The entropy value of indicator j is calculated as:

$$\mathbf{e_j=-\frac{1}{\ln n}\sum_{i=1}^{n} P_{ij}\ln p_{ij}} \tag{2}$$

The information utility value and weight of indicator j are given by:

$$\mathbf{W_j=\frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)}} \tag{3}$$

Finally, the comprehensive development index is calculated as:

$$\mathbf{S_i=\sum_{j=1}^{m} w_j Z_{ij}} \tag{4}$$

2.1.2. Coupling and Coordination Model

(1) Coupling Degree Model

To overcome the limitations of the traditional coupling degree model in characterizing the degree of interaction between subsystems, this study adopts a modified coupling coordination degree model to measure the coupling relationship between the electricity market and the carbon market[9]. The modified coupling degree for the two markets can be expressed as:

$$C=\sqrt{\left[1-\left|S_1-S_2\right|\right]\frac{\min(S_1,S_2)}{\max(S_1,S_2)}} \tag{5}$$

Where S_1 and S_2 represent the comprehensive index of the electricity market and the comprehensive index of the carbon market, respectively, C denotes the coupling degree between the two markets, within the range of [0, 1], and the larger the value, the higher the coupling degree of the system.

(2) Coupling and Coordination Model

The coupling degree reflects only the strength of interaction between the two systems. It cannot determine whether the two systems are sufficiently integrated. Therefore, a coupling coordination degree model is constructed to further assess the degree of integration between the electricity and carbon markets. Because subjective weighting may affect the validity of the coupling coordination model, the composite index (T) of the two systems is calculated using the arithmetic weighting method. The coupling coordination degree (D) between the electricity and carbon markets is then calculated using the comprehensive evaluation method. Following the relevant literature[10], the weights of the electricity market and the carbon market are both set to 0.5. The model is calculated as follows:

$$T=aS_1+bS_2 \tag{6}$$

$$D=\sqrt{C\times T} \tag{7}$$

Where a and b are the weights assigned to the electricity and carbon markets, with a=b=0.5; D is within the range of [0, 1], and the larger the value, the higher the coordination degree of the system.

2.1.3. Geographical Detector

The geographical detector is a statistical model used to analyze spatial data[11]. This study applies factor detection and interaction detection to identify the main drivers of coordination between the electricity and carbon markets and to examine the interaction effects among the factors. The expressions is as follows:

$$q=1-\frac{\sum_{h=1}^{L} N_h\sigma_h^2}{N\sigma^2} \tag{8}$$

Where h = 1, 2,..., L indexes the strata of factor X; N_h and N, respectively, denote the number of elements in layer h and the total number of elements in the entire area. σ_h^2 represents the variance of layer h; σ^2 represents the total variance of the entire area. The q value represents the explanatory power of factor X for attribute Y, with a range of [0, 1]. The larger the q value, the greater the influence of this factor on the coupling coordination degree.

2.2. Indicator System and Data Sources

Considering methodological rigor and data availability, this study draws on Liu Dunnan et al. to construct an electricity market development index based on nine indicators across three dimensions[12][13]. Supply–demand conditions are measured by electricity consumption, installed power generation capacity, and the electricity supply–demand ratio, reflecting market balance and resource allocation efficiency. The electricity pricing mechanism is assessed using the average electricity price, electricity price growth rate, and electricity trading volume, reflecting price levels, price stability, and market activity. Clean energy development is measured by the share of clean energy in total power generation, the growth rate of installed clean energy capacity, and the renewable energy consumption rate, reflecting progress in energy structure optimization. Following Zhang Xiufan et al., the carbon market development index also includes nine indicators across three dimensions[14]. Carbon emission conditions are measured by total carbon emissions, per capita carbon emissions, and carbon emission intensity, reflecting emission-reduction performance. Carbon trading conditions are assessed using the carbon trading price, trading volume, and carbon price volatility, reflecting market activity and stability. Economic factors are measured by the economic growth rate, energy consumption growth rate, and consumer price index, reflecting carbon market demand and development potential.

Considering economic development, industrial and energy conditions, government intervention, and human capital, five indicators were ultimately selected as the driving factors for the synergy of the development levels of the electricity market and the carbon market. They include per capita GDP (yuan) (X_1), energy consumption intensity (X_2), the proportion of the secondary industry's added value in GDP (%) (X_3), the ratio of environmental fiscal expenditure to GDP (%) (X_4), and the proportion of people with a college degree or above in the total population (%) (X_5).

Given that China’s pilot carbon emissions trading markets began operation in 2013, and considering data availability, this study selects the period from 2017 to 2022 and constructs a panel dataset covering six pilot regions. The data are obtained from the China Statistical Yearbook, China Electricity Statistical Yearbook, China Annual Development Report of the Electric Power Industry, China Energy Statistical Yearbook, regional statistical yearbooks, and carbon trading data released by regional carbon exchanges. Missing values are imputed using linear interpolation.

3. Results and Analysis

3.1. The Development Levels of the Two Markets

Figure 1 illustrates the changing trends of the two markets. From 2017 to 2022, the comprehensive electricity market indices of the six pilot regions increased overall, reflecting progress in market-based trading, power supply capacity, and clean energy development. Guangdong showed the strongest growth, with its index rising from 0.4282 to 0.6209 at an average annual rate of 7.72%. Hubei, Beijing, and Tianjin increased gradually despite fluctuations, while Shanghai and Chongqing remained relatively stable and recovered after 2021. Regional differences were mainly associated with reform progress, industrial demand, and power-generation structure. The carbon market indices also increased with fluctuations. Guangdong continued to improve and peaked in 2021, while Hubei grew steadily, particularly after 2020. Tianjin and Chongqing remained relatively stable, whereas Beijing and Shanghai changed moderately. Overall, the institutional, compliance, and trading foundations of the pilot markets improved, but regional disparities persisted in market liquidity, price discovery, and participant engagement.

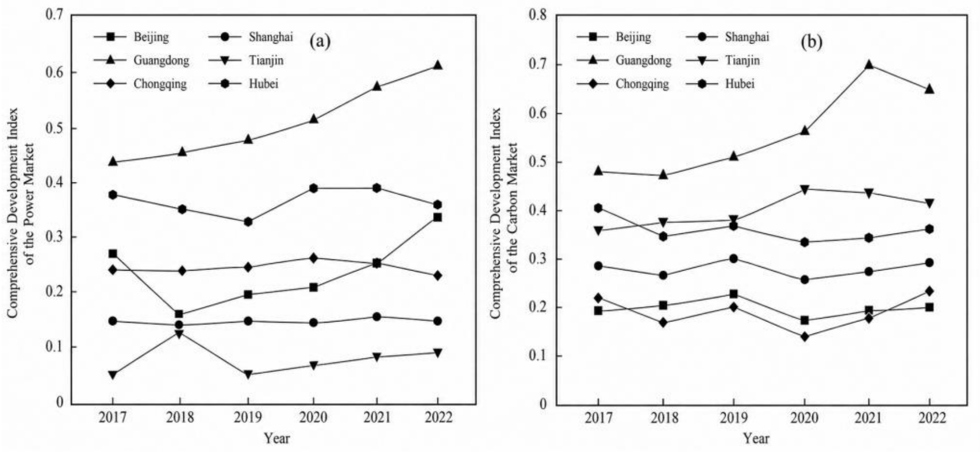

Figure 1: Development Levels of the Electricity Market (a) and the Carbon Market (b).

3.2. Coupling Coordination Level and Regional Differences

As shown in Figure 2 (a), the coupling degree remained generally high in Beijing, Shanghai, Guangdong, Chongqing, and Hubei, while Tianjin showed greater fluctuations. However, a high coupling degree does not necessarily imply strong coordination, as two markets with low development levels may still move in the same direction. The results should therefore be interpreted together with the comprehensive development indices and the coupling coordination degree.

The coupling coordination degree improved overall in all six regions, although substantial regional differences persisted (Figure 2 (b)). Guangdong reached 0.7971, approaching the threshold of the highly coordinated category in 2021. This advantage was supported by its large electricity trading volume, relatively mature market rules, strong clean energy base, and sustained carbon-management policies. Hubei remained stable at around 0.60, indicating relatively balanced development, but further progress depends on stronger carbon-cost transmission and greater market depth. Beijing, Shanghai, Chongqing, and Tianjin generally remained in the basically imbalanced category. Although their coordination degrees increased, integration between the two markets was still limited. In Beijing and Chongqing, the carbon market developed relatively faster, while electricity market reform and carbon-cost transmission remained weak. Shanghai experienced faster development in its electricity market, but its carbon market showed relatively low trading activity and limited regulatory effects. Tianjin showed the greatest fluctuations. Early policy support led to short-term improvements, but limited awareness of carbon asset management among enterprises, weak willingness to participate, and high dependence on conventional energy constrained further coordination. These results indicate that establishing market institutions is only the starting point for coordinated development. The coupling relationship can develop into substantive coordination only when electricity pricing mechanisms, carbon price signals, firms' trading behavior, and clean energy investment form stable links.

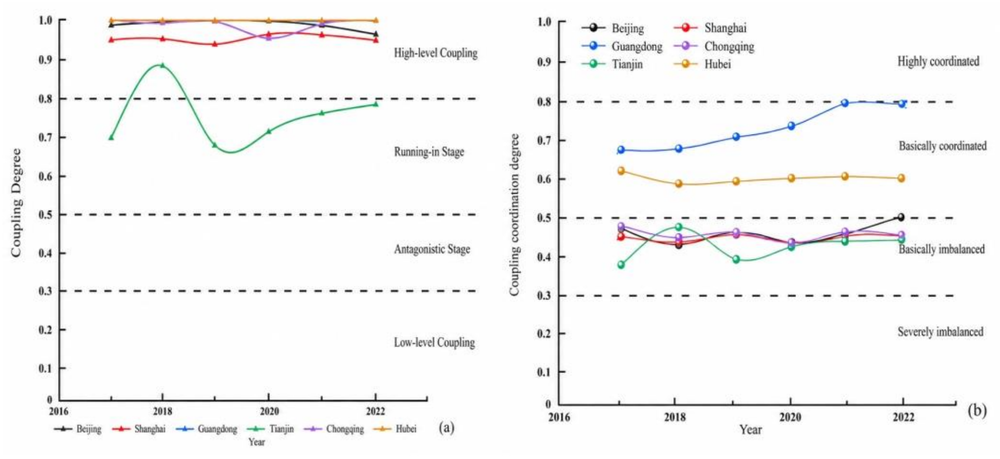

Figure 2: Trend of Coupling Degree (a) and Coupling Coordination Degree Changes (b).

3.3. Driving Mechanisms

3.3.1. Single-Factor Detection Analysis

The factor detection results show that all five driving factors passed the significance test, but their explanatory power differed considerably. In 2017, the factors were ranked by explanatory power as follows: X_4 (0.9044)>X_5 (0.8493)>X_1 (0.5457)>X_2 (0.3481)>X_3 (0.1238). X_4 and X_5 were strongly associated with coordination between the two markets. During the early pilot stage, market rules, allowance management, compliance supervision, and financial support were still being developed. The government's ability to establish clear, stable, and enforceable institutions directly affected enterprise participation and market operation. Carbon accounting, trading decisions, power dispatch, and the application of low-carbon technologies also require a high level of professional expertise. Therefore, the availability of skilled personnel and innovation capacity is particularly important for linking the two markets.

In 2022, the ranking changed to X_4 (0.8436)>X_1 (0.5987)>X_3 (0.5655)>X_5 (0.4858)>X_2 (0.1155). X_4 remained the leading factor, while the explanatory power of X_1 and X_3 increased markedly. This suggests that as the pilot institutions gradually became more stable, the main constraint on coordinated development shifted from whether market rules had been established to whether economic and industrial conditions could support further coordination. Regions with stronger economic foundations generally have greater capacity for green investment, digital supervision, and risk management. A shift toward a low-carbon and technology-intensive industrial structure changes electricity demand, the energy mix, and firms' emission-reduction costs. This can strengthen the influence of carbon price signals on the electricity market.

3.3.2. Multifactor Interaction Detection Analysis

Interaction analysis (Figure 3) shows that the explanatory power of any two factors acting together is higher than when they act alone, indicating no completely independent relationships. The primary interaction types are bi-factor enhancement and nonlinear enhancement. In 2017, the combinations with the highest explanatory power were $X_4 \cap X_5$ (0.9224), $X_4 \cap X_1$ (0.9221), and $X_1 \cap X_5$ (0.9124); in 2022, these were $X_4 \cap X_1$ (0.9214), $X_4 \cap X_3$ (0.8837), and $X_4 \cap X_5$ (0.8764). Although X_2 as a single factor had a q-value of only 0.1155 in 2022, its average explanatory power increased to 0.6348 when interacting with other factors, suggesting that energy constraints can only be effectively transformed into market synergistic momentum when integrated with industrial upgrading, policy guidance, and technological progress. The driving mechanism has gradually shifted from an early dominance of "policy–talent" to a joint effect of "policy–economy–industry," implying that isolated subsidies, singular regulation, or mere market expansion cannot sustainably improve coordination levels.

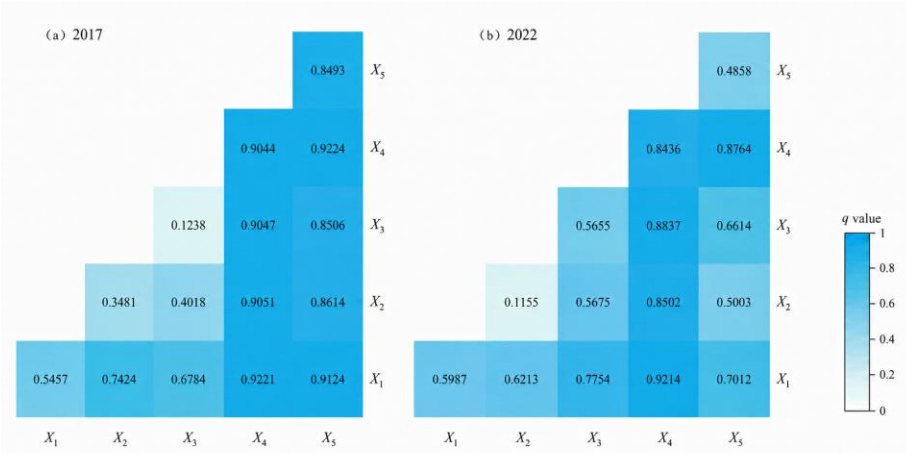

Figure 3: Interaction Detection Results for the Driving Factors.

4. Conclusions and Policy Implications

4.1. Conclusions

First, from 2017 to 2022, the comprehensive development levels of the electricity market and carbon market in the six pilot regions all saw overall improvement. However, there are still significant differences in the development foundation, growth rate, and market maturity among the regions.

Second, the two markets are becoming increasingly interconnected, but there is still considerable room for improvement in the quality of coordination. Guangdong has the highest degree of coordination and is close to the highly coordinated, while Hubei remains stable at the basic level of coordination. Beijing, Shanghai, Chongqing and Tianjin are generally still in a basic imbalance state.

Third, X_4 is the primary driver affecting the level of synergistic effects among the six pilot electricity-carbon markets. X_5 played a prominent role in the initial stage of the pilot project. The interaction among various factors has enhanced the explanatory power of the coupling coordination degree of the electricity-carbon market to varying degrees.

4.2. Policy Implications

Based on the above findings and their practical implications, the following policy recommendations are proposed.

First, adopt region-specific coordination strategies. Policies should be tailored to the development levels of the electricity and carbon markets in each region. Regions with a high level of coordination should further deepen market integration. Regions with poor coordination should give priority to addressing weaknesses in the less-developed market, thereby reducing regional disparities in coordination.

Second, strengthen government coordination and industrial collaboration. A coordination mechanism should be established among the energy, ecological and environmental, and electricity authorities. Electricity market reform, carbon allowance management, and industrial upgrading should be coordinated to improve resource allocation efficiency and market competitiveness.

Support should also be provided for the development of industrial clusters related to clean energy, smart grids, and low-carbon technologies.

Third, improve the mechanism for transmitting carbon costs into prices. Carbon emission costs should be properly incorporated into power generation bids and electricity trading. Effective interaction between electricity prices and carbon prices should be promoted. These market signals can encourage clean energy consumption and emission reductions by carbon-intensive enterprises.

Fourth, strengthen industrial, technological, and human resource support. Investment in the research and development of low-carbon technologies and smart grids should be increased. Clean energy industrial clusters should be fostered, while carbon asset management and professional training systems should be improved. These measures can enhance enterprises' capacity to participate in electricity and carbon trading.

4.3. Research Limitations

Due to data availability, this study examines only six early pilot regions: Beijing, Shanghai, Tianjin, Guangdong, Hubei, and Chongqing. Future research may expand the sample as the national carbon market and unified electricity market develop. It may also use firm-level data, spatial econometric methods, and policy evaluation approaches to further examine price transmission and coordinated emission reduction effects.

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