

Price dynamics in China's national carbon market and their interactions with Shanxi electricity spot market and northern energy hubs

Xianbing Liu✉

Climate Change Unit, Institute for Global Environmental Strategies (IGES), Kanagawa 240-0115, Japan

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ABSTRACT

As China advances its national carbon emissions trading scheme (ETS) alongside reforming its power sector, understanding the price-transmission channels among these markets is vital for effective decarbonization. Utilizing daily data from July 2021 to December 2025, this study examines price interactions among China's national carbon market, electricity prices in the pioneering Shanxi spot market, and regional fossil-fuel prices. Methodologically, it employs an event-study design with a vector error correction model and multivariate regression models. The event study reveals that regulatory announcements are associated with notable event-related price fluctuations in the carbon market. The econometric results confirm a long-run cointegration between carbon and thermal coal prices, reflecting structural energy-to-carbon price linkages. While prices in the electricity spot market remain strongly driven by underlying daily coal and natural gas costs, they display no statistically significant association with daily carbon-price fluctuations, indicating that under the current framework of fully free allowance allocation, carbon costs are yet to noticeably permeate spot-market bidding behavior. These findings demonstrate that deeper power-sector liberalization and technology-neutral carbon benchmarking are needed to unlock effective carbon-to-electricity cost pass-through in China.

KEYWORDS

China's national emissions trading scheme (ETS), carbon price formation, electricity spot market, carbon-cost pass-through, allowance allocation, power-market reform.

1 Introduction

The national carbon emissions trading scheme (ETS) is a central policy instrument in China to achieve its carbon-neutrality target of 2060. Drawing upon the experiences and lessons from regional pilot carbon markets operating since 2013, China's central government officially launched the ETS online trading system on July 16, 2021^[1]. In its initial stage, the market exclusively covered the power-generation sector, including captive power plants across other industries. Coal-fired generation still accounted for 51.1% of China's total electricity supply in 2025, and non-fossil sources are projected to provide more than 90% of total supply by 2050^[2,3]; therefore, decarbonizing this sector is critical for China to achieve its net-zero target, making it a primary focus of the national ETS.

For the carbon market to effectively incentivize power-sector decarbonization, carbon-price signals must influence generation decisions on the supply side while reducing electricity consumption on the demand side. Under China's current national ETS, emission allowances are currently allocated entirely for free using intensity-based benchmarking. While this approach penalizes highly inefficient units, the separate benchmarks for different unit capacities and fuel types do not narrow the absolute cost gap between higher-cost natural gas and lower-cost thermal coal, thereby failing to incentivize the shift from coal to gas^[4]. To create stronger mitigation incentives, the government plans to phase in emission allowance auctioning, requiring generators to purchase a share of allowances upfront and thereby increasing variable operating costs^[5,6].

In practice, the policy effects of carbon-market mechanisms, whether implemented through free benchmarks or future auctions, are fundamentally determined by the operating rules of the power system. In a traditional, heavily regulated power system, generation schedules and retail electricity tariffs are fixed by administrative planning rather than marginal operating costs. Even if allowance auctions or tighter benchmarks increase the actual cost of carbon-intensive generation, power companies cannot pass on these additional costs to end users, and cleaner generators cannot gain a competitive advantage in the dispatch order. Without liberalized electricity markets, institutional barriers risk insulating utility bidding behavior and the broader economy from carbon-price signals, thereby neutralizing the demand-side mitigation impact of the ETS.

Accordingly, the effectiveness of China's national ETS is closely linked to the latest phase of power-sector reform initiated in 2015. The reform is designed to shift the power sector from administrative allocation toward market-based trading platforms, directly determining the extent of carbon-cost pass-through^[7,8]. Guided by these reforms, market-based electricity transactions reached 6,639.4 billion kWh in 2025, representing 64% of total electricity consumption^[9]. As a liberalized power market allows prices to respond to production and environmental costs, the establishment of China's national carbon market and the progress of reform in the power sector must be promoted in parallel. A well-functioning electricity spot market provides the necessary price-clearing mechanism through which carbon costs can be reflected in dispatch schedules, making continued power-sector reform a

✉ Address correspondence to Xianbing Liu, liu@iges.or.jp

vital prerequisite for effective carbon-to-electricity cost pass-through.

To examine how these overlapping market designs operate in practice, this study outlines the unique institutional rules governing China's national carbon market and addresses two main research questions. First, how the national carbon market prices have evolved and whether specific regulatory events are associated with statistically significant price fluctuations, and second, whether daily carbon prices are significantly associated with regional energy prices, particularly in newly liberalized electricity spot markets. While the inquiry into regulatory events offers a novel assessment of the national market's informational efficiency, the second question directly builds upon and extends the regional work of Liu and Jin (2020)^[10]. At the time of their analysis, China's electricity spot markets were in their infancy and electricity prices were available only as monthly aggregates, resulting in a highly limited dataset. This study expands the empirical scope from regional pilots to the national carbon market and uses a continuous, daily time series spanning from July 16, 2021, to December 31, 2025. To capture local spot-market dynamics, electricity-price data are drawn from the pioneering Shanxi electricity spot market, the first one in China to enter formal commercial operation.

This study bridges the existing research gap and makes three contributions to the literature in key respects. First, unlike previous studies of carbon-price responses on regional pilots, this analysis applies an event-study framework to the national ETS. By evaluating major national regulatory updates, including allocation plans and settlement notices, it assesses the national market's informational efficiency and abnormal price movements during the initial phase. Second, while the literature on carbon-energy price linkages in China relies on regional or low-frequency data, this study examines the long-run cointegration and short-term dynamics between national carbon market prices and regional fossil-fuel benchmarks using a continuous daily dataset. The dataset captures localized dynamics at major energy transshipment and generation hubs serving the northern grid. Third, this study extends the existing literature on carbon-electricity price transmission in China by linking the national carbon market to a continuously operating electricity spot market. The analysis thus provides a meaningful empirical baseline for assessing how an intensity-based, fully free-allocation framework shapes utility bidding behavior. The findings reveal that while spot electricity prices remain highly responsive to coal and natural gas price shocks, daily carbon-price fluctuations do not yet noticeably affect spot-market clearing. These results provide empirical evidence on institutional reforms and benchmarking adjustments needed to enable effective carbon-to-electricity cost pass-through in China.

The rest of the paper is organized as follows. Section 2 reviews the literature, and Section 3 details the econometric methodology, including the event-study framework, multivariate regressions, and the vector error correction model (VECM). Section 4 describes the operational status of China's national carbon market, and Section 5 reviews power-sector reform and the fossil-fuel price datasets. Section 6 reports and discusses the empirical results. Finally, Section 7 summarizes the main conclusions and offers policy recommendations for further market development.

2 Literature review

Carbon market prices provide a real-time signal of emission allowance scarcity, playing an essential role in optimizing resource

allocation, minimizing abatement costs, and driving low-carbon investment. Under an integrated energy-climate framework, carbon prices interact with other energy-market signals, operating within a multimarket system in which regulatory decisions shape allowance supply, fossil-fuel markets influence the generation costs, and electricity markets determine whether these costs are absorbed or passed through to consumers. The following review indicates that these markets are structurally connected through price-transmission channels, which motivates our empirical analysis of China's national carbon market price fluctuations and their interactions with regional energy markets.

2.1 The impact of policy adjustments on carbon market prices

A carbon market's operational efficiency depends partly on how market participants absorb information. Major policy adjustments such as tighter allocation rules, allowance expansions, or compliance deadlines can materially alter the supply-demand balance of emission allowances. Focusing on mature markets, Fan et al. (2017)^[11] examined how policy adjustments impact EU ETS carbon prices by classifying regulatory events into six categories. They found that the aggregate effect of these events was limited, with negligible effects for events that did not alter the allowance balance. Meanwhile, Ye and Xue (2021)^[12] examined the effect of news sentiment on EU ETS carbon prices from 2017 to 2020, finding that media information has become increasingly rapidly incorporated in carbon prices.

In nascent markets such as China's national ETS, where trading is dominated by compliance-bound power-sector entities rather than institutional investors, information asymmetry can trigger market overreaction or concentrated volatility spikes near compliance deadlines. Determining whether regulatory adjustments are associated with statistically significant abnormal price fluctuations is critical because it reveals whether the market generates stable price signals that can interact rationally with broader energy markets or remains vulnerable to illiquidity and information shocks. Based on earlier empirical evidence, Zhou et al. (2022)^[13] identified market reactions that led to overbuying or overselling in China's pilot markets, arguing that enhanced information disclosure is necessary to mitigate investor overconfidence. Similarly, Qi et al. (2022)^[14] analyzed daily trading data from China's national carbon market and concluded that prices were primarily driven by allowance supply and demand dynamics. However, due to a generous allowance allocations, limited sectoral coverage, and a narrow range of trading products, market liquidity remained volatile and prices stayed relatively low.

2.2 The interrelationship between carbon, fossil fuels, and electricity prices

The theoretical literature suggests that carbon prices are fundamentally driven by marginal abatement costs, which are inherently tied to fuel-switching behavior in the power sector^[15]. In mature trading markets such as the European Union's (EU) ETS, increases in the price of a primary generation fuel such as coal or natural gas alters the relative running costs of generation units, prompting power companies to shift toward cleaner, more efficient alternatives. This mechanism directly influences demand for emission allowances, establishing a clear transmission channel from fossil-fuel prices to variations in carbon price^[16]. Empirical evidence from European and U.S. markets generally supports a long-run negative correlation between coal and carbon prices driven by these structural shifts.

Lin and Xu (2021)^[17] analyzed the relationship between energy prices and carbon prices in China, identifying differences in how coal and renewable energy prices affect carbon markets, and recommended differentiated policy measures across development stages. Using a novel probabilistic forecast model to analyze the Hubei pilot market, Cao et al. (2023)^[18] evaluated the influence of external factors, including energy prices, economic conditions, international carbon markets, and public concern, on carbon prices. They identified coal prices as the most significant factor while confirming the influence of geopolitical risks and economic uncertainty. Similarly, Yu and Luo (2024)^[19] examined the price linkage between China's carbon and coal markets, noting that major economic and political events considerably alter this relationship and emphasizing that understanding these market linkages and structural shifts is essential for designing effective national energy and climate policies.

Some empirical studies, such as Zhu et al. (2019)^[20], have identified a positive statistical correlation between electricity and carbon prices; however, this association need not reflect a causal relationship. As emissions stem primarily from fossil-fuel combustion in power generation, carbon prices, which reflect the cost of these emissions, are far more likely to drive electricity prices by raising the marginal cost of fossil fuel-based generation. As argued by Ioannidis et al. (2025)^[21], the direction of causality runs from carbon to electricity prices, rather than the reverse. Lyu et al. (2024)^[22] confirmed that carbon prices actively drive wholesale price volatility in markets such as Nord Pool. However, the strength of this carbon-to-electricity transmission channel is heavily mediated by two institutional prerequisites: the allowance-allocation method and the degree of liberalization in the power sector.

In the Chinese context, Zhu et al. (2020)^[23] found that electricity prices positively influence carbon prices across pilot markets, as rising electricity prices coincide with increased coal consumption, thereby increasing emissions and driving up carbon allowance demand. Wu and Wang (2022)^[24] employed a time-varying difference-in-differences model to assess the impact of carbon prices on total factor productivity in these markets, revealing a consistent and statistically significant positive causal relationship. In an examination of regional dynamics, Cui et al. (2023)^[25] assessed the cost-effectiveness of carbon pricing in five southern provinces, discovering that electricity market integration lowers the carbon price signal and overall abatement costs. Furthermore, Feng et al. (2024)^[26] demonstrated that carbon prices significantly foster green innovation, particularly among large state-owned enterprises in power- and carbon-intensive sectors. However, Li et al. (2022)^[27] cautioned that a moderate carbon price may fail to drive meaningful emission reductions without a concurrent reform in the power sector.

2.3 Research motivation

Unlike the EU ETS, where market mechanisms are relatively mature and carbon costs flow directly into wholesale power prices, China's national carbon market operates within a state-managed framework. Carbon prices in China are largely policy-driven, and their pass-through into electricity prices likely remains limited. To bridge the gap between mature Western cap-and-trade models and China's transitioning economy, this study extends the analytical framework to examine the concurrent evolution of power-sector reforms and national carbon market development.

The literature suggests that market integration can lower abatement costs; however, empirical evidence on daily cost pass-

through remains limited. Prior China-based studies rely heavily on low-frequency or aggregated monthly data from the early stages of power-sector reform, leaving a gap regarding how carbon-price signals permeate daily electricity spot-market clearing. To address these limitations, this paper conducts two complementary empirical tests. First, it develops an event-study framework, centered on major regulatory milestones, such as allocation plans and settlement notices, to evaluate how national carbon prices respond to policy-driven shocks. Second, the national carbon market is connected with upstream energy inputs and local power markets using a continuous daily dataset. Specifically, a VECM framework is used to estimate the long-run equilibrium relationship between national carbon prices and thermal coal markets. In parallel, multivariate regression analysis is applied to test the short-term cost pass-through channels linking daily carbon price fluctuations, regional coal indices, and liquefied natural gas (LNG) prices directly to price formation in the newly formalized Shanxi electricity spot market.

3 Methodology

3.1 Analytical framework

The analytical framework of this study is depicted in Figure 1. The analysis comprises two main components, each addressing a specific research question. The first component identifies key events in the implementation of China's national ETS and examines whether these events induced significant fluctuations in carbon market prices. The second component assesses the extent to which carbon prices are passed through to electricity prices, within the context of China's power-sector reform and the development of its electricity spot market. Given that carbon market prices and thermal coal prices are identified as nonstationary, their long-term relationship is also analyzed to characterize linkages between China's carbon and energy markets.

3.2 Design of an event study to examine carbon-price changes

An event study is employed to examine carbon-price dynamics. As shown in Figure 2, the main elements of this methodology include the event itself and the event date, estimation window, and event window. The estimation window is the period prior to the event that is free of event-related factors, enabling estimation of normal price movements. The event window encompasses the period immediately before and after the event to capture its short-term effects. By design, the estimation and event windows do not overlap.

As illustrated in Figure 2, the estimation window spans from day 1 to day n . The event window spans days $n + 1$ to $n + v$, where v represents the number of trading days, including the event date. The post-event window covers the period from day $n + v + 1$ to day $n + v + p$, where p denotes the number of trading days in this interval.

Table 1 summarizes the events analyzed, their dates, and the corresponding window settings. These events include announcements by the Ministry of Ecology and Environment (MOEE) regarding emission allowance allocation plans and settlement notices, as well as the release of the "Interim Regulations on Carbon Emissions Trading Management." These regulatory measures may influence carbon prices by changing the supply-demand dynamics of emission allowances. For instance, allocation plans determine whether allowances are distributed free of charge or auctioned, directly affecting supply. Similarly,

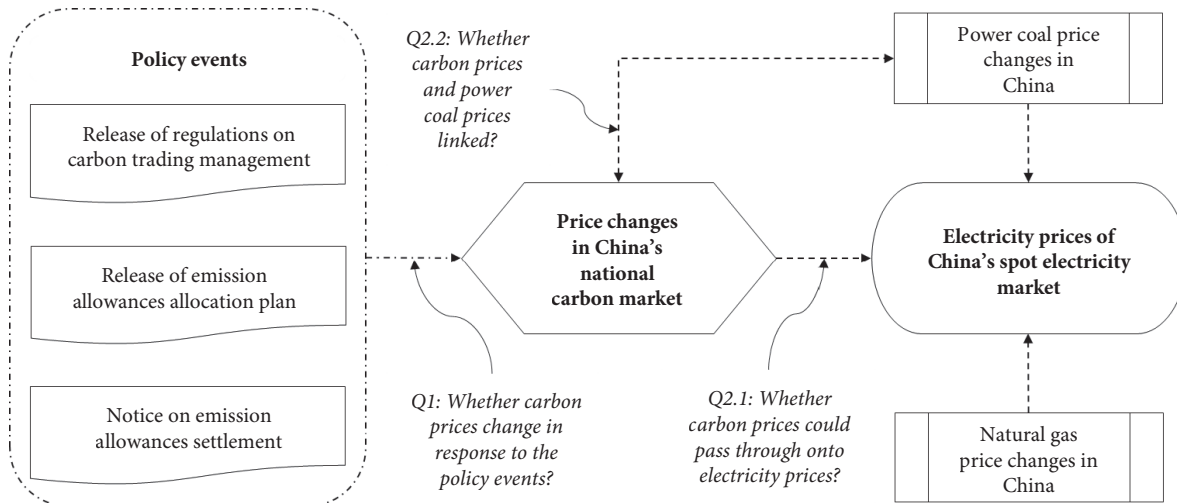


Fig. 1 Analytical framework for the study.

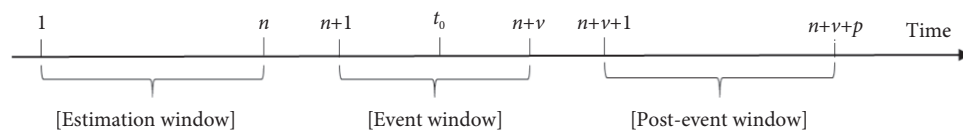


Fig. 2 The timeline of an event study.

Table 1 Events considered in this study and the setting of the event and estimation window.

No.	Event	Date	Event window (Trading days)	Estimation window (Trading days)
1	Notice on emission allowance settlement in the initial compliance period	26/10/21	12/10/21–07/12/21 (41)	16/07/21–28/09/21 (50)
2	Release of the draft emission allowance allocation plan for 2021 and 2022 for public comment	03/11/22	20/10/22–15/12/22 (41)	14/04/22–13/10/22 (121)
3	Release of the emissions allowance allocation plan for 2021 and 2022	15/03/23	01/03/23–27/04/23 (41)	22/08/22–22/02/23 (121)
4	Notice on emission allowance settlement in 2021 and 2022	17/07/23	03/07/23–28/08/23 (41)	22/12/22–26/06/23 (121)
5	Release of “Interim Regulations on Carbon Emissions Trading Management”	05/02/24	22/01/24–27/03/24 (41)	20/07/23–15/01/24 (121)
6	Release of the emissions allowance allocation plan for 2023 and 2024	15/10/24	24/09/24–26/11/24 (41)	21/03/24–13/09/24 (121)
7	Notice on emission allowance settlement in 2025	11/04/25	27/03/25–28/05/25 (41)	12/09/24–20/03/25 (121)
8	Release of the emissions allowance-allocation plan for the iron and steel, cement, and aluminum smelting industries in 2024 and 2025	16/11/25	03/11/25–29/12/25 (41)	28/04/25–27/10/25 (121)

settlement notices provide important information on compliance procedures and offsetting mechanisms, which further influences market stability.

Following Zhou et al. (2022)^[13], this study defines the event date as t_0 and the event window as $[t_0-10, t_0+30]$, totaling 41 trading days. For Event 1, which occurred shortly after the market launch on July 16, 2021, the estimation window is restricted to 50 days due to data availability. For the remaining 7 events, the estimation window is set to 121 days, covering the interval $[t_0-135, t_0-15]$. The daily carbon-price change rate, V_p , is calculated as Eq. (1):

$$V_t = \left| \frac{P_t - P_{t-1}}{P_{t-1}} \right| \times 100\% \quad (1)$$

where P_t and P_{t-1} represent the average carbon prices on days t

and day $t-1$, respectively. The average price change rate during the estimation window is defined as Eq. (2):

$$\bar{V} = \frac{1}{n} \times \sum_{t=1}^n V_t \quad (2)$$

If the price change rates within the event window differ significantly from $\bar{V}$, the market is considered to overreacted to the event. A one-sample t -test was applied to identify whether an event induces statistically significant deviations from baseline price movements, serving as an indicator of information shocks.

3.3 Analysis of relationships between carbon and energy prices

To explore interactions between carbon and energy prices, this study builds upon established econometric approaches. Previous

research (e.g., Frontier Economics, 2006)^[28], utilized ordinary least squares (OLS) regressions to examine the pass-through of allowance costs to electricity prices, using first differences to eliminate spurious correlations. Other studies, including Freitas and da Silva (2015)^[29], applied a VECM to capture long-term equilibrium and short-term dynamics between cointegrated variables. Consistent with this literature, this study examines the relationship between electricity spot prices (the dependent variable) and carbon, coal, and natural gas prices (independent variables). Daily price data were analyzed using Stata. Preliminary tests confirmed that electricity spot-market prices are stationary. Consequently, multivariate OLS regressions were performed after converting nonstationary input prices into stationary variables by first differencing.

Furthermore, as carbon and thermal coal prices were found to be nonstationary (but stationary in their first differences), a VECM was employed to analyze their relationship. Following Johansen (1991)^[30], the VECM is specified as Eq. (3):

$$\Delta P_t = \Pi P_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta P_{t-i} + \mu_t + \varepsilon_t \quad (3)$$

where $\Pi = \sum_{i=1}^k A_i - I$; $\Gamma_i = -\sum_{j=i+1}^k A_j$. Here, P_t represents a vector of nonstationary endogenous variables. The matrix Π captures the long-term relationship and can be factorized as $\Pi = \alpha\beta'$, where β denotes the cointegrating vectors and α represents the speed of adjustment to equilibrium.

4 Operational status of China's national carbon market

4.1 Target sectors and key emitting entities

At its inception, China's national ETS exclusively covered the power-generation sector. The regulated targets, defined as key emitting entities, include companies and other economic organizations within this sector (including captive power generators in other industries) with annual emissions of at least 26,000 t CO₂ (equivalent to a comprehensive energy consumption of approximately 10,000 tons of standard coal)^[31,32]. The regional

distribution of these entities during the initial compliance phase (2019–2020) and in 2024 is shown in Figure 3.

Although the MOEE initially projected coverage of 2,225 entities for 2019–2020, the first compliance cycle ultimately included 2,162 entities, representing annual emissions of approximately 4.5 billion t-CO₂^[33,34]. By 2024, the number of key emitting entities rose to 2,430, primarily concentrated in high-demand regions, including eastern coastal provinces such as Shandong, Jiangsu, and Zhejiang and resource-rich regions, such as coal-abundant areas in the northwest, specifically, Inner Mongolia and Shanxi.

4.2 Benchmark values for allowance allocation

Emission allowances for power plants, covering power-only and cogeneration units, are determined using benchmark values. Table 2 presents the benchmark values by unit type and compliance year.

Overall, the benchmarks have been progressively tightened. Significant adjustments occurred in 2021 for coal-fired units, with benchmarks for power supply tightened by 6%–18% and those for heat supply by over 10% compared with 2019–2020 levels. Conversely, benchmarks for gas turbines remained unchanged in 2021 to incentivize lower-intensity power generation. The benchmarks were marginally tightened in 2022. In 2023, while electricity benchmarks appeared stable, stringency was maintained despite a change in the functional unit from “power supply” to “power generation.” However, benchmarks for coal-fired and gas-turbine heat supply were tightened that year. Further tightening continued into 2024.

4.3 Market operation and trading results

Online trading officially began on July 16, 2021. As indicated in Figure 4, initial trading activity was highly concentrated near the first compliance deadline (December 31, 2021), a pattern typical of immature carbon markets where entities primarily trade to meet immediate regulatory obligations.

After declining sharply in early 2022, trading recovered later that year, likely in response to the draft 2021–2022 allocation plan, which signaled tighter future benchmarks and raised concerns

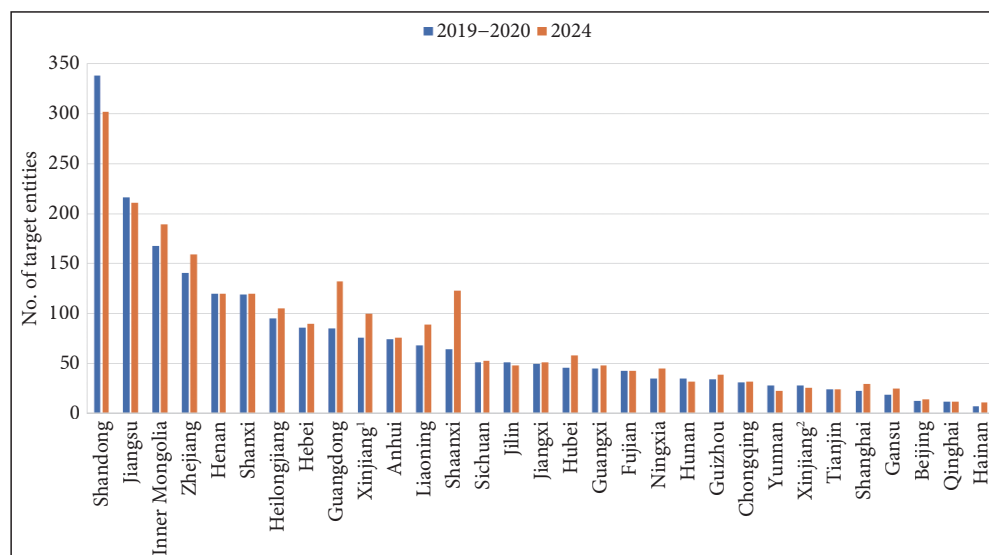
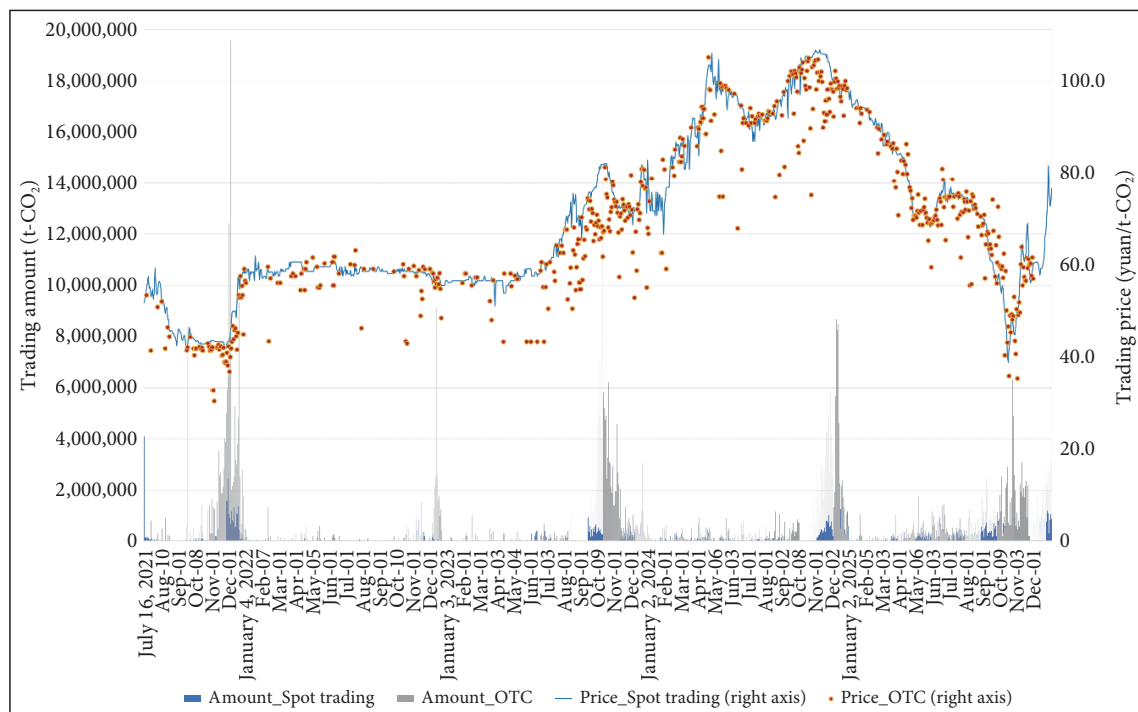


Fig. 3 Number of key emitting entities in the power-generation sector by region (2019–2020 and 2024). Note: Xinjiang¹ represents Xinjiang Uygur Autonomous Region; Xinjiang² represents Xinjiang Production and Construction Corps.

Table 2 Benchmark values of emission allowances of the power sector in China.

Unit category	Power supply (t-CO ₂ /(MWh))			Power generation (t-CO ₂ /(MWh))		Heat supply (t-CO ₂ /GJ)				
	2019–2020	2021	2022	2023	2024	2019–2020	2021	2022	2023	2024
I	0.877	0.8218	0.8177	0.7950	0.7910					
II	0.979	0.8773	0.8729	0.8090	0.8049	0.126	0.1111	0.1105	0.1038	0.1033
III	1.146	0.9350	0.9303	0.8285	0.8244					
IV	0.392	0.3920	0.3901	0.3305	0.3288	0.059	0.0560	0.0557	0.0536	0.0533

Unit category: I: Conventional coal-fired unit above the 300-MW class; II: Conventional coal-fired unit in the 300-MW class or below; III: Unconventional coal-fired unit burning coal gangue, coal slime, or coal-water slurry (including coal-fired circulating fluidized bed unit); IV: Gas turbine unit. Source: Refs. [31,32,35]

**Fig. 4** Trading amounts and prices in China's national carbon market (by December 31, 2025).

about potential allowance shortages. In 2023, the finalization of compliance requirements and reporting documents further increased market activity, particularly from August to December. During this period, the average carbon price rose to 68.2 yuan/t-CO₂, a 23.2% increase over 2022^[36].

By the end of 2024, the closing price reached 97.5 yuan/t-CO₂^[37]. However, the market became more volatile in 2025: prices dropped to approximately 40 yuan/t-CO₂ in October before rebounding to over 70 yuan/t-CO₂ by the end of the year. As of December 31, 2025, the cumulative trading volume reached 864.4 million t-CO₂, with a total value of 57.63 billion yuan. Notably, over-the-counter trading dominated the market, accounting for 78.1% of total transactions.

4.4 Compliance and corporate management

Compliance rates remained consistently high. During the first compliance period (2019–2020), the compliance rate was 99.5%, despite 847 entities facing a total shortage of 188 million t-CO₂^[38]. Compliance improved to 99.98% in 2023 and 99.99% in 2024^[37,39].

The national ETS has also influenced internal governance. In a survey of 735 entities, over 80% of the respondents appointed

dedicated staff for carbon asset management. Nearly 90% reported improving data-quality management and integrating carbon emissions into daily operations. Among the profitable entities, 45.7% planned to reinvest revenues into energy-saving and emission-reduction projects^[38].

5 Electricity spot market in China and energy price datasets

A primary objective of this study is to clarify the relationship between the carbon market and energy prices. In China, the price-transmission mechanism between carbon and electricity markets is characterized by complexity and ongoing structural evolution. Current market designs and operational frameworks, especially allowance-allocation methods and electricity-pricing regulations, may impede carbon-cost pass-through to electricity prices. Consequently, further deepening power-sector reforms is imperative for achieving coordinated development in these two markets^[40]. Section 5 reviews power-sector reforms, focusing on the development of China's electricity spot markets and the operations of the Shanxi electricity spot market. Additionally, it

describes the datasets compiled for electricity, thermal coal, and LNG prices applied to this analysis.

5.1 Development of the electricity spot market in China

Since 2015, China has implemented a new round of power-sector reforms, leading to the continuous development and refinement of its electricity market. A central component of this reform is the development of electricity spot markets. Pilot programs for spot-market development were officially launched in 2017. In 2022, the “Guidance on Accelerating the Construction of a National Unified Electricity Market System” was issued, aiming to expedite the creation of a multi-tier, unified market system^[41].

The Shanxi electricity spot market began trial operations on December 27, 2018. Operations began on a single-day basis and gradually extended to weekly, semi-monthly, monthly, and bi-monthly intervals before achieving continuous operations. According to the regulations, if a provincial or regional spot market operates continuously for over one year, with dispatch and settlement based on market-clearing results, it may transition to formal operations following mandated procedures^[42]. In September 2023, the Shanxi market was evaluated and deemed to have met the criteria for formal operation. On December 22, 2023, the Shanxi electricity spot market became the first market in China to enter formal operations^[43]. Subsequently, formal operations were launched in Guangdong (December 28, 2023), Shandong (June 17, 2024), and Gansu (September 5, 2024)^[44,45]. Subsequently, the interprovincial electricity spot market commenced operations on October 15, 2024, following nearly 1,000 days of testing^[46].

5.2 Operational status of the Shanxi electricity spot market

Figure 5 illustrates the daily real-time market prices of the Shanxi electricity spot market from August 31, 2022, to December 31, 2025.

By the end of 2025, the Shanxi Power Exchange Center trading platform had hosted 22,538 registered market participants, including 701 power-generation companies, 440 electricity sales companies, 21,320 electricity users, 23 independent energy storage companies, 10 virtual power plants, 40 ancillary service aggregators, and 4 distributed generators. Two data gaps occur in

Figure 5 (October 16–22, 2022, and April 26–July 14, 2023). Prices exhibited significant volatility, ranging from 22.80 to 1,446.44 yuan/(MWh)^[47]. These observations indicate that Shanxi spot-market prices effectively reflect changes in generation costs and play an important role in balancing electricity supply and demand^[48].

To maintain data integrity and avoid artificial smoothing, interpolation techniques were not employed to fill in missing electricity spot prices because interpolation could smooth out the extreme volatility of spot markets. For days within the two intervals, the corresponding daily carbon, coal, and LNG observations were excluded from the OLS regressions. This ensured that no unmatched or artificial data compromised the validity of the regression estimates. This analysis uses the prices of the Shanxi electricity spot market because Shanxi was the first market in China to enter formal operations. It thus serves as a regulatory blueprint for China’s nationally unified electricity market. As a major energy-exporting province, its market rules, pronounced price volatility, and high concentration of power-market participants offer a robust, transparent platform for evaluating cost pass-through dynamics that may not be observable in less mature provincial pilots.

5.3 Fossil-fuel price datasets

Thermal coal prices were obtained from the China Electricity Council (CEC). The CEC Index (CECI), jointly established by the CEC and power-generation firms, represents China’s only generation-side thermal coal price index^[49]. This analysis uses the CECI Caofeidian Index, which serves as a primary baseline for daily thermal coal pricing used by major domestic power-generation companies^[50]. The index reflects pricing at Caofeidian, a major northern shipping port in Hebei Province and China’s primary coal trans-shipment hub, making the data highly representative of power-sector fuel costs.

Because of insufficient valid observations, the CECI Caofeidian Index experienced a period of unreliable data and was suspended from February 16, 2022, to May 28, 2023. To maintain time-series consistency, weekly data from the CECI Coastal Index were substituted during this period by holding the weekly opening

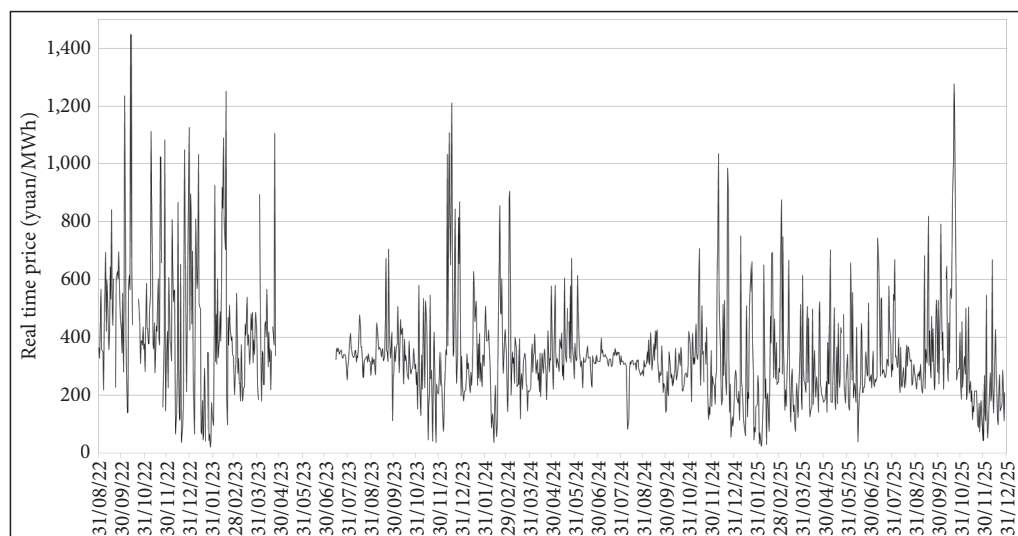


Fig. 5 Daily real-time market prices of the Shanxi electricity spot market (31/08/2022–31/12/2025).

trading price constant across all subsequent trading days of each respective week. To address the resulting attenuated daily variance, model robustness was confirmed by re-estimating the specifications using first differenced coal prices over periods with active daily indices.

LNG price data were obtained from the Chongqing Petroleum and Gas Exchange^[51]. This analysis focuses on LNG prices in the Bohai Rim, one of the major clusters of gas-fired power generation in northern China. The data capture daily sale prices at key receiving terminals and plants in this hub, aligning directly with the regional infrastructure that feeds the northern grid. Figure 6 displays the price trajectories for thermal coal and LNG in the Bohai Rim from July 16, 2021, to December 31, 2025.

Over the period, both markets exhibited high volatility and followed broadly synchronized trends. Thermal coal prices fluctuated between 616 and 1,714 yuan/t, with a major peak above 1,500 yuan/t in late 2021 and another surge exceeding 1,700 yuan/t in early 2022, before stabilizing and trending downward to below 700 yuan/t by the end of 2025.

LNG prices in the Bohai Rim followed a similar pattern but moved within a wider range from approximately 3,500 to over 9,000 yuan/t. The natural gas market experienced acute price spikes in late 2021 and early 2022, peaking at over 8,000 and 9,000 yuan/t, respectively, before stabilizing between 3,500 and 4,500 yuan/t, respectively, during the latter half of 2025.

6 Results and discussion

6.1 Descriptive statistics of the price series

In addition to examining carbon-price fluctuations, this analysis tests whether electricity prices are significantly associated with input costs, including coal, natural gas, and emission allowances. Subject to data availability, the analysis covers the period from July 16, 2021, to December 31, 2025. Table 3 presents the descriptive statistics for the price series used in this study.

All price series are right-skewed, as indicated by their positive skewness values. The kurtosis for electricity prices exceeds 3.00, suggesting a heavy-tailed distribution. In contrast, the distributions for carbon, thermal coal, and natural gas prices are light-tailed, with kurtosis values below 3.00.

6.2 Analysis of abnormal price fluctuations in China's national carbon market

The daily share of total trading volume, defined as the ratio of daily trading volume to the total trading volume over the analysis period, is illustrated in Figure 7.

Trading activity was initially concentrated in the 1.5 months prior to the first compliance deadline on December 31, 2021. Market liquidity fell markedly in early 2022, with signs of recovery emerging around December 2022. In 2023, the year for settling 2021 and 2022 emission allowances, trading volume increased

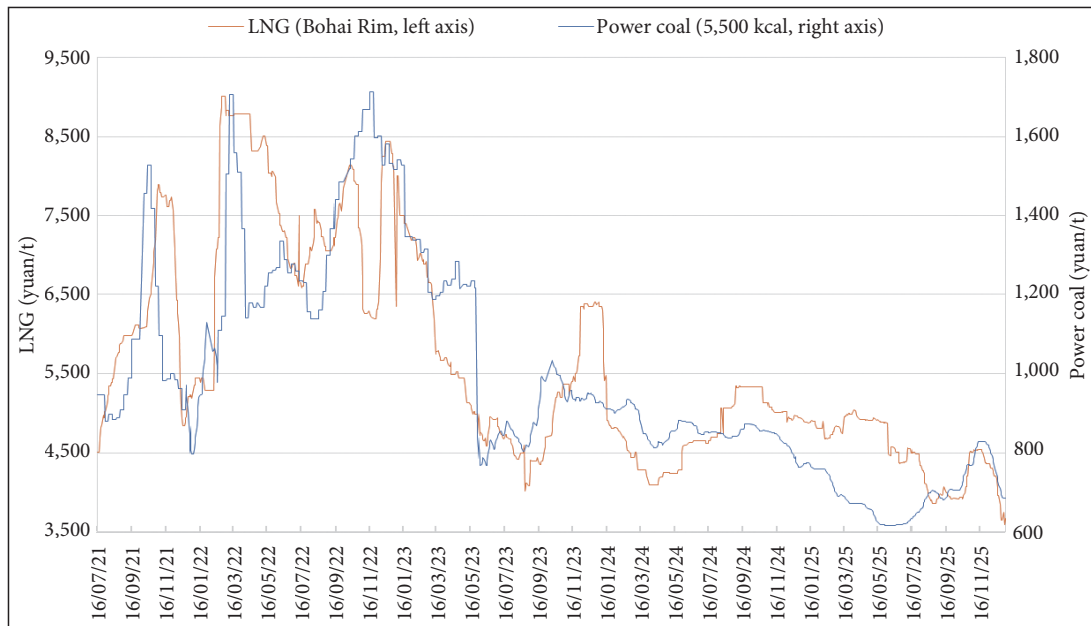


Fig. 6 Price changes of thermal coal and LNG (16/07/2021–31/12/2025).

Table 3 Descriptive statistics of the price series (daily data).

Item	Unit	N	Mean	Median	Min.	Max.	Std. Dev.	Skewness	Kurtosis
P_{power}	yuan/(MWh)	741	359.1	318.6	22.8	1,446.4	192.5	1.842	7.891
P_{Carbon}	yuan/t-CO ₂	1,081	69.0	60.6	38.5	105.7	17.1	0.520	2.170
P_{Coal}	yuan/t	1,081	989.5	897.0	616.0	1,714.0	273.6	0.861	2.838
P_{LNG}	yuan/t	1,081	5,621.2	5,072.0	3,584.0	9,014.0	1,353.8	0.865	2.625

Note: P_{Coal} refers to the price of thermal coal at 5,500 kcal per kg.

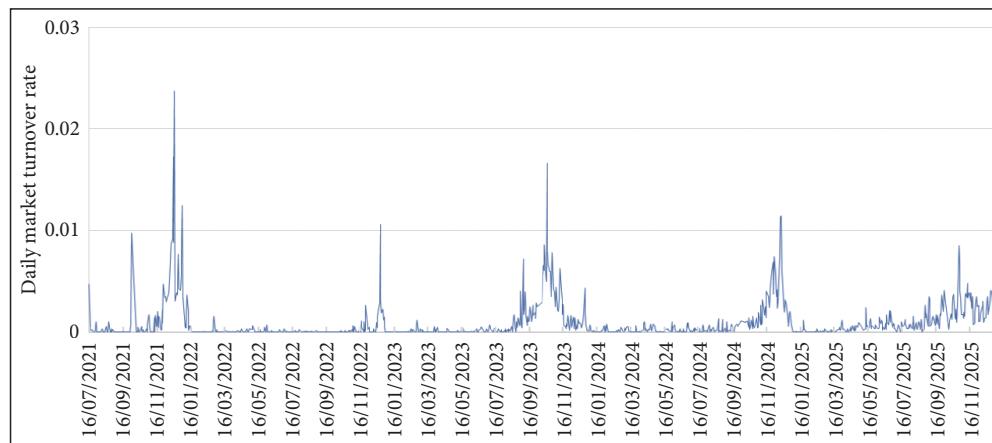


Fig. 7 Daily share of total trading volume of the national carbon market in China (16/07/2021–31/12/2025).

substantially from August to December. Similar patterns were observed in 2024 and 2025, with trading becoming active in November and December. These patterns suggest that trading in China's national carbon market is driven primarily by the compliance requirements of key emitting entities, contributing to unstable market liquidity. Such concentrated trading during compliance periods followed by low activity may suppress carbon prices. Furthermore, difficulties in maintaining liquidity and forming informative price signals may hinder the overall effectiveness of the national carbon market.

A one-sample *t*-test was employed to detect abnormal price fluctuations in the market. A *t*-statistic that is significant at the 10% level ($p < 0.1$) indicates that carbon-price changes within the event window differ significantly from the estimation window average, confirming abnormal price fluctuations. The test results are listed in Table 4.

The results confirm fluctuations in market price in response to notices regarding emission allowance settlements (Events 1, 4, and 7) and the release of allocation plans and interim regulations (Events 3, 5, 6, and 8). Currently, only key emitting entities participate in trading. Their limited market experience and limited access to information force them to rely on subjective forecasts, increasing volatility and the likelihood of abnormal price fluctuations. The concentration of trading volume in the final months of compliance periods naturally drives price volatility. Given the institutional structure of the national ETS, where trading is dominated by compliance-bound entities rather than

institutional investors, allocation plans and settlement notices deliver major updates to an illiquid market, resulting in the acute volatility shifts during these windows. These findings suggest that China's national carbon market is still at a nascent stage, necessitating improvements in market transparency and information disclosure. Capacity-building for emitting entities and the inclusion of more diverse market participants are essential for stabilizing carbon prices.

6.3 Unit root test results

Before estimating the relationships among the variables, nonstationarity in the price series was checked using the augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests (Table 5). The results indicate that electricity and LNG prices are stationary, whereas carbon and thermal coal prices are nonstationary. However, the first differences between carbon and coal prices are stationary at the 1% significance level. The finding that electricity prices are stationary aligns with previous findings for European markets, such as Sijm et al. (2008)^[52] and Mosquera-López and Nursimulu (2019)^[53].

6.4 Relationship between carbon and thermal coal prices

The Akaike, Schwarz, and Hannan–Quinn information criteria were used to determine the optimal lag structure between the two nonstationary price series in the level vector autoregression (VAR) model. The results suggest an optimal VAR lag length of two ($k = 2$), implying a lag length of one ($k - 1 = 1$) for the VECM.

Table 4 Test results of abnormal price fluctuations to specific events.

No. of event	Average price change rate, $\bar{V}$	$V_t - \bar{V}$				
		Mean	Std. dev.	<i>t</i> -statistic	<i>p</i> -value	Degree of freedom
1	2.27%	−0.0184	0.0058	−20.38	0.000***	40
2	0.52%	0.0002	0.0067	0.14	0.445	40
3	0.42%	0.0054	0.0222	1.57	0.062*	40
4	0.64%	0.0123	0.0206	3.83	0.000***	40
5	1.90%	0.0088	0.0265	2.12	0.020**	40
6	1.74%	−0.0087	0.0166	−3.35	0.001***	40
7	0.95%	−0.0028	0.0076	−2.34	0.012**	40
8	1.40%	0.0182	0.0288	4.04	0.000***	40

Note: *, **, and *** denote significance levels of 10%, 5%, and 1%, respectively.

Table 5 Result of the ADF and PP unit root tests.

Variable	Level		Variable	First difference	
	ADF	PP		ADF	PP
P_{Power}	−17.389*** (0)	−16.659*** (0)			
P_{Carbon}	−1.889 (0)	−1.716 (0)	ΔP_{Carbon}	−41.724*** (0)	−41.737*** (0)
P_{Coal}	−2.687 (0)	−1.491 (0)	ΔP_{Coal}	−31.887*** (0)	−31.889*** (0)
P_{LNG}	−4.334*** (7)	−3.489** (7)			

Note: “ Δ ” means the first difference in the time-series data. The number in parentheses is the optimal lag.*** Significant at 1% level;** significant at 5% level;* significant at 10% level.

A cointegration test was also performed on the nonstationary price series. The trace and maximum eigenvalue tests confirmed the existence of one cointegrating vector ($r = 1$).

Using the optimal lag lengths, a VECM was employed to examine the long-run cointegration and short-term dynamics between carbon and coal prices. For the VECM analysis, the daily price series for the overlapping period from July 16, 2021 to December 31, 2025 was applied, yielding 1,078 matched daily observations. The results are presented in Table 6.

The cointegration vector (Panel A), normalized on carbon price (P_{Carbon}), shows a positive coal-price coefficient that is significant at the 5% level. As the cointegrating equation is expressed as an implicit function set to zero with all variables on one side, the signs of the normalized cointegration coefficients must be interpreted in reverse. Consequently, a positive coefficient indicates a negative relationship with the dependent variable. This demonstrates that, in the long term, thermal coal prices are negatively associated with China’s national carbon market prices. At this early stage, the market only covers the power sector and

uses a benchmarking approach for allowance allocation. Rising coal prices enhance the competitiveness of high-efficiency units, thereby increasing electricity generation. The resulting anticipation of a surplus in emission allowances may contribute to lower carbon prices in the long term. This theoretical transmission channel is consistent with empirical evidence, such as in the EU ETS and the US markets, which generally supports a negative correlation driven by fuel-switching^[54–56].

Nevertheless, these results differ from those of Chang et al. (2018)^[57], who observed significant regional and temporal variations across China’s pilot markets. For instance, in the Beijing pilot market, coal prices exerted a positive impact on carbon prices during 2014–2015 but showed no significant impact in 2016. Such discrepancies likely stem from market fragmentation, regional policy nuances, and sector-specific sensitivities. Notably, Beijing’s market primarily encompasses service sectors, which are inherently less sensitive to fuel-switching than the energy-intensive industries covered in the national market.

Panel B confirms that the error-correction term for coal prices is negative and statistically significant at the 10% level, indicating that coal prices adjust toward a long-term equilibrium. The negative coefficient on lagged carbon-price changes suggests mean reversion; price increases trigger subsequent corrective decreases. The short-term results reveal that lagged coal prices are not significantly associated with subsequent carbon-price changes, suggesting a transmission lag; it takes time for coal-price fluctuations to permeate the electricity market and ultimately influence corporate strategies and allowance pricing.

6.5 Regression analysis of electricity prices

As electricity prices are stationary while carbon and coal prices are nonstationary, the latter were differenced for the regression analysis. As listed in Table 7, two multivariate OLS regressions were performed using electricity price as the dependent variable. Regression 1 includes the first differences of carbon and thermal coal prices as independent variables, and Regression 2 additionally includes natural gas prices as an independent variable. This

Table 6 VECM analysis results between carbon and coal prices.

A) Cointegration relationship		
Endogenous variables	P_{Carbon}	P_{Coal}
Coefficients	1.00	0.0671**
B) Short-term dynamics		
	ΔP_{Carbon}	ΔP_{Coal}
Error-correction term	−0.0033	−0.0854*
$\Delta P_{\text{Carbon}} (-1)$	−0.2345***	−0.3669
$\Delta P_{\text{Coal}} (-1)$	0.0006	0.0318
Constant	0.0354	−0.0014
R-squared	0.0571	0.0045

Note:*** significant at 1% level;** significant at 5% level;* significant at 10% level.

Table 7 Regression results with electricity price as the dependent variable.

Variable entered	Regression 1			Regression 2		
	Coef.	t-statistic	p-value	Coef.	t-statistic	p-value
β_0	359.16	51.10	0.000	137.71	4.12	0.000
ΔP_{Carbon}	3.43	0.89	0.371	3.88	1.04	0.298
ΔP_{Coal}	1.89	3.18	0.002	1.90	3.28	0.001
P_{LNG}				0.04	6.78	0.000
F-value		5.48			19.18	
R-squared		0.015			0.072	

analysis is constrained by the operational timeline and data availability of the Shanxi electricity spot market, which limits the sample size to 741 valid daily observations. The OLS regressions omit dates with missing electricity-price data, ensuring that all reported estimates are derived from a consistent, matched sample of all variables.

Variance inflation factor tests indicated no multicollinearity among the variables. The results indicate that the Shanxi electricity spot-market prices are significantly and positively correlated with LNG prices and the first difference in coal prices. This result highlights that fuel costs remain the primary driver of power-generation costs in China. Notably, no significant relationship was observed between electricity prices and carbon-price fluctuations, suggesting that carbon costs have yet to influence bidding behavior in the spot market, a finding that contrasts more mature markets such as the EU ETS^[53].

The significance of LNG prices in driving Shanxi's electricity spot prices warrants careful economic interpretation. Although natural gas accounts for a minor fraction of coal-rich Shanxi's generation mix, LNG prices are significantly associated with spot electricity prices due to marginal-cost bidding dynamics. In liberalized spot markets, clearing prices during peak demand or tight supply are frequently set by high-cost, gas-fired peaking units. Consequently, while coal prices largely determine baseline generation costs, LNG price fluctuations drive real-time spot price spikes, reflecting peak-load marginal pricing rather than structural gas dominance.

6.6 Policy implications for the interaction between China's carbon and electricity markets

China's national carbon market has successfully improved internal carbon management among emitting entities. For example, data measurement in energy-intensive sectors such as cement has improved significantly, and over 80% of companies in the power sector have established dedicated carbon management systems^[58,59]. However, from a climate policy perspective, current efforts remain insufficient. It is necessary to establish much higher carbon prices and create conditions for cost pass-through. Passing carbon costs through to electricity prices would extend mitigation incentives to end users; however, this requires further liberalization of China's electricity market. While the share of market-based electricity transactions reached 64% in 2025, the current ex-post benchmarking method used for China's national ETS imposes a "relative cap" that fails to generate robust price signals^[49]. Adopting simpler, stricter, and technology-neutral benchmarks for the power-generation sector would encourage competition and accelerate the shift toward a low-carbon electricity mix.

While most key emitting entities now employ full-time carbon management staff, the fact that emission allowances are currently allocated entirely for free limits the actual cost burden on companies. Previous studies suggest that expanding allowance auctions could increase the role of marginal costs in generators' bidding decisions^[56]. Gradually increasing the share of auctioned allowances would compel power-generation companies to pass carbon costs through to electricity prices. While carbon prices up to 200 yuan/t-CO₂ may not affect the electricity dispatch order in China, prices exceeding 260 yuan/t-CO₂ may be necessary to prevent emission increases during the market transition^[60]. The current prices (averaging 95.8 yuan/t-CO₂ in 2024 and 62.4 yuan/t-CO₂ in 2025) remain low^[37,39]. As potential policy options, China

could benefit from implementing mechanisms similar to the price floors employed in the UK or the market stability reserve used in the EU ETS to stabilize expectations and support long-term low-carbon investment^[161,62].

This study empirically confirms that the carbon-cost pass-through channel from China's national carbon market to electricity spot prices is not yet detectable. Resolving the weak linkage between China's carbon and electricity markets requires coordinated and institutional alignment among relevant national regulators. Two potential reform pathways can be used to achieve effective carbon-to-electricity cost pass-through. First, the rapid expansion of the gross-pool electricity spot market, as exemplified by formal operations in Shanxi, Guangdong, and Shandong. This approach requires power generators to compete through day-ahead and real-time security-constrained economic dispatch. For carbon prices to permeate the clearing mechanism of the electricity spot market, allowance allocations should shift from ex-post intensity-based benchmarks toward upfront auctioning. Auctioning forces generators to incorporate carbon liabilities into their short-term marginal-cost bidding strategies. Meanwhile, the second pathway relies on adjusting medium- to long-term contracts in the electricity market. Currently, the majority of electricity is traded through monthly or annual bilateral contracts rather than spot markets. Regulators should introduce a carbon-linked tariff mechanism that enables bilateral power purchase agreements to automatically adjust final retail or wholesale tariffs based on floating national carbon market prices. Changes in policy-driven carbon scarcity would be systematically passed through to end users, stimulating demand-side mitigation.

7 Conclusions

This study examined price dynamics in China's national carbon market and the relationships among carbon, fossil-fuel, and electricity prices. The event study identified statistically significant price movements around seven of the eight policy events at the 10% level or better. A long-run cointegration exists between carbon and coal prices. While electricity spot prices are significantly driven by coal and natural gas costs, they currently show no statistically significant association with daily carbon-price changes. These findings provide empirical evidence of the current carbon-price formation mechanism and the limited pass-through to electricity prices in China. As a theoretical contribution, it provides the first empirical baseline of daily price transmission between the national carbon market and a newly formalized, continuously operating electricity spot market in China.

It should be noted that the electricity spot price data in this study are restricted to Shanxi Province. While the cost pass-through findings of this study apply to this pioneering electricity spot market and similar northern energy hubs, they may not be generalizable to other provinces with different market designs and fuel structures. Future research could expand to other newly launched provincial spot markets, such as Guangdong and Shandong, as longer daily datasets become available. Another limitation is the use of weekly coal prices as a proxy due to the temporary suspension of the daily Caofeidian index, which reduces daily variance during that specific period. Regarding methodology, this study uses a one-sample *t*-test to assess whether policy events are associated with significant disruptions in normal carbon-price trajectories. Advanced modeling analysis could be conducted when China's national carbon market develops greater liquidity and a longer continuous time series. Finally, the

multivariate OLS and VECM analyses in this study identify statistical associations, long-run cointegration, and short-term linkages rather than establishing clear economic causality, which also warrants further research.

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Author contribution statement

Not applicable.

Data availability

The data that support the findings of this study is available from the corresponding author upon reasonable request.

Use of AI statement

None.

Declaration of competing interest

The author has no competing interests to declare that are relevant to the content of this article.

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