An event study of price changes in China's national carbon market

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[Abstract] Using the available information sources and an econometric approach for the time series dataset, this study tests the price volatility of the national carbon market, and identifies the interactions between electricity, carbon and fossil fuel prices in China. The result confirms an overreaction of carbon market prices to the considered events. There exists a long-term co-integration between carbon price and the prices of coal. Conversely, coal prices have no impact on the short-term dynamics of carbon prices. The prices of electricity spot market are significantly and positively associated with LNG prices and the first difference of coal prices, but indicate no significant relationship with the first differences of carbon prices. This analysis gives some implications on the synergy between power sector reform and national carbon market in China. On the one hand, the liberalization of the power industry should be further advanced to create conditions for passing carbon costs onto the electricity markets. On the other hand, the national ETS should apply simpler and stricter benchmarks, as well as conduct auctioning to allocate the emission allowances in the power sector for the formation of substantial carbon prices and the shift to a low-carbon power supply portfolio.

Key words: Carbon market, electricity, fossil fuel, price interaction, power sector reform, China

1. Introduction

The greenhouse gases emission trading scheme (ETS) has been developed as a core policy toward carbon neutrality in China. Based on the operation experiences of pilot carbon markets at the local levels since 2013, the National Development and Reform Commission (NDRC) announced to start the establishment of a national ETS and released a development plan in December, 2017. According to this plan, the first stage was to prepare the necessary infrastructure for the national ETS, including a unified data reporting system, an emission allowance registry system and a trading system, over the course of a year. Operational testing of these systems would be carried out in 2019, then the trading of carbon emission allowances would be launched formally in 2020. In addition to the schedule, the plan also clarified that China's national ETS would only cover the power generation sector (including captive power generators in other industries) initially. In reality, coal-fired power generation contributed to nearly 60% of the total electricity supply of China in 2023 (CEC, 2024a). Without doubt, it is the most important sector for achieving the country's overall climate target, i.e., to peak CO_2 emissions before 2030 and realize carbon neutrality before 2060. Despite some delay compared to the planned schedule, online trading of China's national carbon market was formally launched on July 16, 2021, and has been operated for over 3 years (Xinhua Net, 2021).

There remain some limitations in China's national ETS. The scheme sets 4 benchmarks for power generators with different installation capacities and fuel types. This implies that coal-fired power plants would only compete against each other within the same category, not to mention gas turbines with much lower emission intensities. The intensity-based approach for emission allowance allocation could promote the efficiency of target power plants, but might not encourage the shift toward a cleaner fuel mix. Meanwhile, the planned auction of an increasing portion of emission allowances in the future could raise operation costs for power generators, which would be difficult to pass on to electricity end users under the current electricity pricing mechanism and due to over-capacity of power sector (Spencer et al., 2017). One priority of China's power industry was the expansion of installation capacity to satisfy the soaring demand of heavy industries. Instead of an economic merit order dispatch applied in many other countries according to the operation cost of each power generator, the 'Annual Power Generation Plan' has been adopted in China for thermal power plants. This administrative approach lacks flexibility and was one of the reasons for severe curtailment of solar and wind power around 2016. The existing regulations of power sector in China would be a critical barrier for the national carbon market to function effectively. To a large extent, the success of China's national ETS would depend on the liberalization reform of power sector.

Fortunately, the highest level of Chinese authority pushed ahead with further reforms to address major pain points in the country's power industry in March, 2015. Overall, the new round of reforms aims for: 1) restructuring of regulation and business model for the grid companies; 2) an end to the administrative allocation of annual operation hours to each coal-fired power unit; and, 3) new electricity wholesale markets. In practice, the price of electricity transmission and distribution has been verified for all the provincial-level power grids for 3 regulatory circles since 2017, with each circle covering 3 years (NDRC, 2023). The change in power dispatch has been an essential component of power sector reform. According to NDRC and NEA (2017), the planned operation hours of existing coal-fired power units will be reduced gradually to give priority to market-traded electricity. The total amount of electricity traded in power markets of China reached 5,667.94 billion kWh in 2023, an increase of 7.9% from the previous year and accounting for 61.4% of the total electricity consumption. Among which, the electricity traded through the forward market was about 4,428.89 billion kWh, increased by 7% from the previous year (CEC, 2024b).

In summary, the development and operation of a national carbon market and the reform of power sector in China have been advanced in parallel and should be closely watched. The formation pattern of carbon market prices and the pass-through of price signals are particularly essential for China's national ETS to really exert policy effects. There remains a long way to go until the true costs of China's power companies, including the part coming from carbon market prices, flow through electricity prices to the end users. It would thus take some time for the national ETS to have any ripple effect at the energy demand side.

Under such a policy transition process, this study aims to clarify the unique institutions governing power industry and the operation of national carbon market in China. The focus is to carry out an analysis to confirm how the carbon market prices have been changing, and whether the carbon prices have influenced the prices in an electricity spot market. Meanwhile, the relationship between carbon market price and fossil fuels prices is also identified by the data gathered. Limited by the real policy progress and data availability, this analysis could be conducted by the time series prices of carbon, electricity and fossil fuels during July 16, 2021 and the end of May 2024. Nevertheless, it may bridge the gap in understanding the latest progress of policies with relevance and provides some implications for better practice of the national ETS in China.

The contents consist of the following sections. Section 2 explains methodology for the analysis referring to the existing studies. Section 3 shows the operation results of China's national carbon market. Section 4 describes the reform of power sector in China and prices of electricity and fossil fuels gathered for this analysis. Section 5 summarizes the analysis results and discussions. Lastly, section 6 provides a summary of this study and topics for further research.

2. Methodology

2.1 Design of an event study to examine carbon price volatility

An event study is developed to examine carbon price changes in this analysis. The timeline of an event study may be shown as in Fig.1. The event, event time, estimation window and event window are key elements of an event study. The estimation window is a period before the event, during which, there would be no relevant factors affect the target event and normal changes could be measured. The event window is a period before and after the event, which measures the event short-term effect. The estimation window and event window cannot overlap in principle.

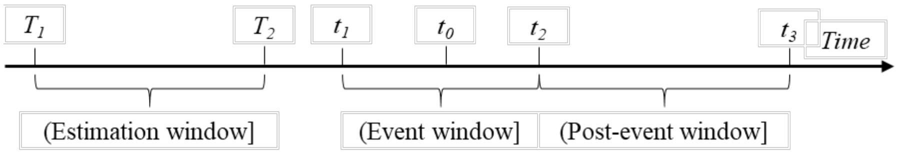

Fig.1: The timeline of an event study.

(Note: T_1 to T_2 represents the estimation window; t_1 to t_2 is the event window; t_2 to t_3 is the post-event window.)

The considered events and their occurrence date, event window and estimation window are defined in Table 1. The events include the announcements of Ministry of Ecology and Environment (MOEE) on the allocation plan of emission allowances and the allowances settlement in various period, and the release of "Interim Regulations on Carbon Emissions Trading Management" approved by the State Council. Assuming the event date (*t*) is 0, the event window is [-10, 30] (totally 41 trading days). Limited by the effective trading days before the event date, the estimation window of event No.1 is 50 days. The estimation window of other four events is [-135, -15], namely 121 trading days.

Table 1: Definition of the events considered in this study

No.	Event	Date	Event window	Estimation window
1	Notice on emission allowances settlement in the initial compliance period	26/10/21	12/10/21-07/12/21	16/07/21-28/09/21
2	Release of draft emission allowances allocation plan for 2021 and 2022 for public comment	03/11/22	20/10/22-15/12/22	14/04/22-13/10/22
3	Release of emissions allowances allocation plan for 2021 and 2022	15/03/23	01/03/23-27/04/23	22/08/22-22/02/23
4	Notice on emission allowances settlement in 2021 and 2022	17/07/23	03/07/23-28/08/23	22/12/22-26/06/23
5	Release of "Interim Regulations on Carbon Emissions Trading Management"	05/02/24	22/01/24-27/03/24	20/07/23-15/01/24

The daily carbon price volatility is defined as:

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

Where, V_t is the carbon price volatility on day t, P_t is the price on day t, P_{t-1} is the price on day $t-1$.

The average carbon price volatility in the estimation window is defined as:

$$\bar{V} = \frac{1}{n} \times \sum_{t=1}^{n} V_t$$

If the price volatility in the event window is significantly higher or lower than the average volatility in the estimation window, the market is confirmed to have an overreaction to the event.

2.2 Analysis of interaction between carbon and energy prices

The existing literature demonstrates high interest to reveal the interrelationship between carbon and energy prices (Ji et al., 2018). Various methodologies have been applied in previous studies. Assuming gas turbines to operate on the margin in peak hours and coal-fired units to operate in off-peak hours, Frontier Economics (2006) conducted simple OLS regressions, in which electricity and gas prices are the forward prices, coal prices are spot prices, and carbon prices are the market prices of EU allowances. According to Alberola et al. (2008), the formation of electricity prices may be dynamic, and complex relationships should be considered for interactions of electricity and input prices. Coal and natural gas prices would likely influence not only the electricity price but also the price of carbon, given the marginal technologies in the electricity supply system. The multivariate approach of simultaneous equations can deal with the possible endogeneity problems due to these interactions. Estimations by Freitas and Silva (2015) applied a co-integrated vector error correlation model (VECM), which encompasses long-term equilibrium and short-term effects in the dynamic interactions between electricity price and the prices of inputs like carbon and fossil fuels. In Freitas and Silva (2015), the electricity series are the day-ahead prices, the natural gas and coal prices are the spot price or index. The price variables were transformed into natural logarithms to reduce the variability. Ji et al. (2018) analyzed dynamic effects between carbon and energy markets in Europe, adopting a systemic time-series approach, and showing that electricity price is the biggest information receiver of carbon market.

Similarly, this study aims to clarify the relationship between the price of electricity and input prices, including carbon, coal and natural gas. For this purpose, the related information was gathered and summarized to figure out the latest progress of the national ETS and the development of electricity spot market in China. Historical data of four price series were collected as much as possible from the accessible sources. All the available prices are daily data. After the data collection and compilation, Stata was applied for the statistical tests and regressions, following a standard and systemic approach for the analysis of time-series data. The electricity spot market prices were confirmed to be stationary in this study. The multivariate OLS was applied by converting all the non-stationary input price series into the stationary variables and using them as the independents.

Since carbon and coal prices are non-stationary and their first differences are stationary, co-integrated VECM was performed when analyzing the linkage between them. The VECM model allows for analyzing the long-term interactions and the short-run adjustment to the co-integrated relationship. The specification of this model follows Johansen (1991). Taking the variables in first differences, with Δ as the difference operator ($\Delta P_t = P_t - P_{t-1}$), data generating process P_t can be implanted into the VECM model with $k-1$ lags, as in equation below.

$$\Delta P_t = \prod P_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta P_{t-1} + \mu_t + \varepsilon_t$$

Where, $\prod = \sum_{i=1}^{k} A_i - I$; $\Gamma_i = -\sum_{j=i+1}^{k} A_j$; P_t represents a vector of P nonstationary endogenous variables; the matrix Π contains information about the long-term relationship among endogenous variables, and Π can be further factorized as $\Pi = \alpha\beta$, where β denotes the co-integration vectors and α denotes the matrix with the estimation on the speed of adjustment to the equilibrium.

3. The operation result of China's national carbon market

3.1 Target sector and the number of entities under China's national ETS

As so far, China's national ETS solely covers power generation sector. Companies or other economic organizations in power generation sector (including captive power generators in other industries) whose emissions in any one year between 2013 and 2021 were 26,000 t-CO_2 or above (comprehensive energy use of approximately 10,000 tons of standard coal equivalent) are selected as the targets of China's national ETS (referred as key emitting entities) (MOEE, 2020a; 2023).

According to MOEE (2020b), China's national ETS covered a total of 2,225 key emitting entities in power generation sector during 2019 and 2020. In practice, the first compliance period (2019-2020) actually covered a total of 2,162 key emitting entities, with annual emissions of approximately 4.5 billion t-CO_2 (MOEE, 2021). Sourced from the National Carbon Market Information Network (URL: https://www.cets.org.cn/xxgk/index.jhtml), the number of key emitting entities became 2,430 in 2024. The detailed number of key emitting entities in power generation sector by the region in the initial compliance phase (2019-2020) and 2024 is depicted in Fig.2.

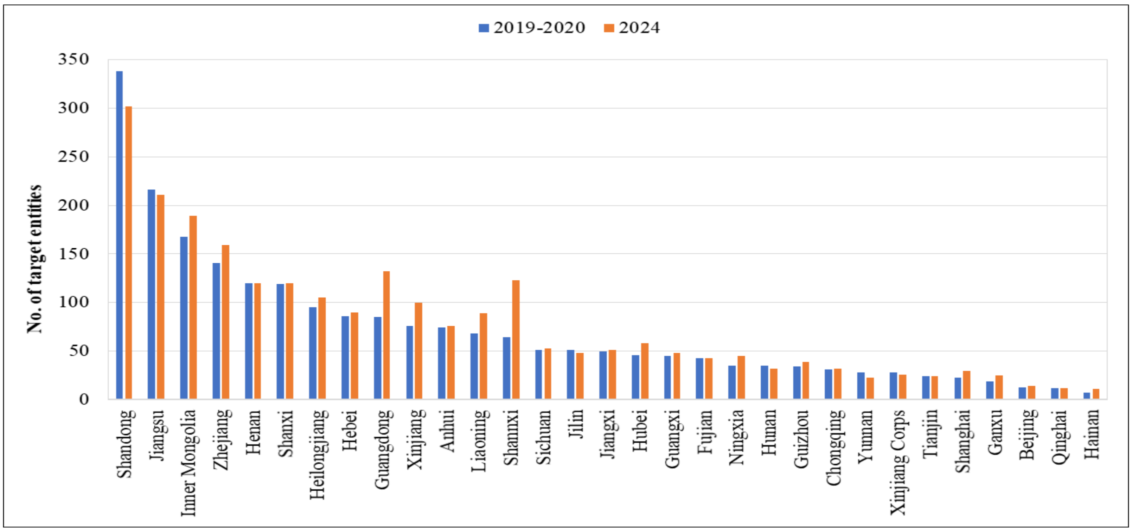

Fig.2: No. of key emitting entities in power generation sector by region (2019-2020 and 2024).

Obviously, key emitting entities are concentrated in the regions with large power loads, i.e., Shandong, Jiangsu and Zhejiang province, and areas rich of coal resources, i.e., Inner Mongolia and Shanxi province.

3.2 Allowances allocation and benchmark values for power sector under China's national ETS

Generally, a benchmarking approach has been applied for the setting of emission allowances of power companies under China's national ETS, including power generation only and the cogeneration. Table 2 specifies the benchmark values for power generation units by unit category and the compliance year.

Table 2: Benchmark values of emission allowances of power generation units in China

No.	Unit category	Power supply (t-CO_2/MWh)			Heat supply (t-CO_2/GJ)		
		2019-2020	2021	2022	2019-2020	2021	2022
I	Conventional coal-fired unit above 300 MW class	0.877	0.8218	0.8177	0.126	0.1111	0.1105
II	Conventional coal-fired unit of 300 MW class and below	0.979	0.8773	0.8729			
III	Unconventional coal-fired unit burning coal gangue, coal slime, coal water slurry (including coal-fired circulating fluidized bed unit)	1.146	0.9350	0.9303			
IV	Gas turbine	0.392	0.3920	0.3901	0.059	0.0560	0.0557

Source: MOEE (2020a; 2023).

There was a significant change of the benchmark values for both power supply and heat supply by coal-fired power generation units in 2021 from 2019-2020. The values for coal-fired power supply were tightened by 6.3% to 18.4%, and that for coal-fired heat supply was tightened by 11.8% in 2021 compared with the levels of 2019-2020. Whereas, the benchmark value for power supply by gas turbines was not changed, aiming to encourage power generation by this type of units with much lower carbon intensity. The benchmark values of 2022 were further tightened but very slightly by around 0.5% from the levels of 2021.

3.3 Operation result of China's national carbon market

Online trading of China's national carbon market was officially launched on July 16, 2021. As shown in Fig.3, the trading was once concentrated in about one month and a half around the deadline of the first compliance period (December 31, 2021). This is the characteristic of a carbon market at the early stage, and the purpose of trading is mainly for the key emitting entities to fulfill their obligations. Since the beginning of 2022, the trading amount declined dramatically. There appeared a recovery in trading amount around December, 2022. This may be attributed to the impact of the release of 'Implementation Plan for the Setting and Allocation of National Carbon Emissions

Allowances for 2021-2022 (draft version for the public comment)' by MOEE in November, 2022. Compared to the levels of 2019-2020, the benchmark values for allowances allocation would become much stricter. There were concerns about the tightening of supply and demand of emission allowances in next years, and the trading became more active temporarily.

2023 is the year for the compliance of emission allowances of 2021 and 2022. Along with the release of finalized policy documents on the allowances setting and allocation, emissions reporting and verification, and the obligation fulfillment, market trading motivation increased. Accordingly, the trading amount increased significantly during August to December, 2023. The daily carbon prices in 2023 ranged at 50.5 to 81.7 Yuan/t-CO_2, and the average price of 2023 was 68.2 Yuan/t-CO_2, an increase of 23.2% compared to the average price of 2022 (SHEX, 2023).

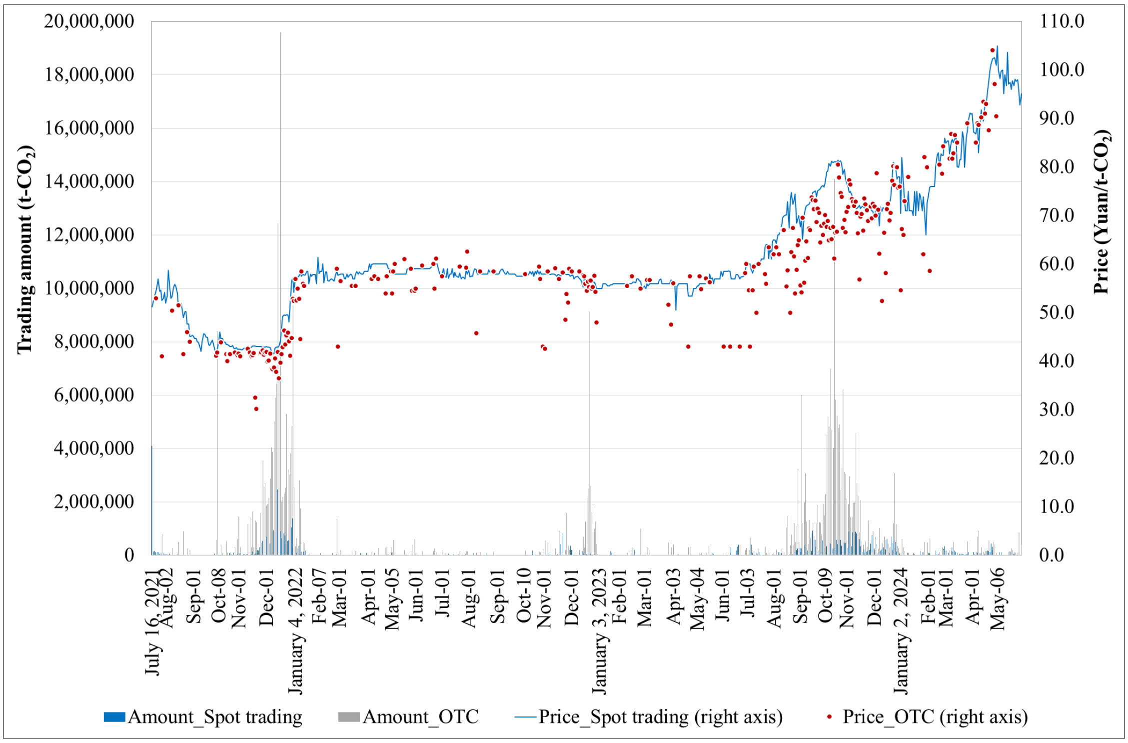

Fig.3: Trading amounts and prices in China's national carbon market (by May 31, 2024).

By May 31, 2024, the accumulated trading amount in China's national carbon market was around 459.6 million t-CO_2, with a total transaction amount of around 26.47 billion Yuan, resulting in an average carbon price of approximately 57.6 Yuan/t-CO_2. In which, the amount of spot trading was around 77.8 million t-CO_2 (16.9% of the total), with a transaction amount of around 4.90 billion Yuan (18.5% of the total). The remainder 381.8 million t-CO_2 (83.1% of the total) was realized via over-the-counter (OTC) trading, with a transaction amount of 21.57 billion Yuan (81.5% of the total). Overall, China's national carbon market has been operating in an orderly manner, and the trading prices have shown a steady upward trend.

3.4 Compliance result of key emitting entities under China's national ETS

In the first compliance period (2019-2020), emission allowances allocated to the 4 categories of power generation entities, including conventional coal-fired power units of 300 MW class and over, conventional coal-fired power units below 300 MW class, non-conventional coal-fired power units and gas turbines, individually accounted for 32.4%, 48.3%, 18.4% and 0.9% of the total. By the end of 2021, 1,833 key emitting entities completely fulfilled their obligations for the clearance of emission allowances, and 178 entities could fulfil their obligations partially, resulting in an overall allowances compliance rate of 99.5%. During the first compliance period, 847 key emitting entities had a shortage in emission allowances, totally amounting to 188 million t-CO_2, and approximately 32.73 million tons of CCER were used to fulfil the allowance clearance obligations (MOEE, 2022).

A questionnaire was sent to 2,162 key emitting entities through the National Carbon Emissions Registry, and 735 of them responded. As the result, over 80% of the sampled companies have appointed full-time staffs to manage their carbon assets after the initial compliance period. Nearly 90% of the key emitting entities have given greater emphasis on data quality and management, actively cooperated with emissions reporting and verification, and integrated carbon emissions data into their company's daily management and statistics. Among the key emitting entities that got revenues from the national carbon market, 45.7% planned to invest the revenues in energy saving and emissions reduction projects and activities (MOEE, 2022).

4. Electricity spot market in China and energy prices for this analysis

4.1 The development of electricity spot market in China

China has further deepened reforms of the country's power sector since 2015 and the electricity market system has been continuously improved. The development of electricity spot market is an important component of power sector reform. In 2017, pilot projects for the establishment of electricity spot markets in China were officially launched. In 2022, the 'Guidance on Accelerating the Construction of a National Unified Electricity Market System' proposed to speed up the construction of a multi-level unified electricity market system (NDRC and NEA, 2022).

According to the guidance, the overall target by 2025 is to establish a national unified electricity market system preliminarily, with the national market operating in coordination with provincial and regional markets. The integrative design and joint operation of medium and long-term forward, spot, and ancillary service markets will be realized. The market trading and electricity pricing mechanisms will be more conducive to the development of new energy and energy storage. By 2030, a national unified electricity market system will be basically completed to adapt to the new power system. The national market will operate jointly with the provincial and regional markets. New energy will fully participate in market trading. Market entities may compete equally and make independent choices. Power resources will be further optimized and allocated across the country (NDRC and NEA, 2022).

On December 27, 2018, Shanxi electricity spot market launched the operation on trial. From then on, the operation cycle started from a single day and gradually extended to a week, half a month, a full month, two months and finally realized continuous operation. If a spot market in a province or region, or between provinces has been operating continuously for more than one year, and electricity dispatch and settlement are based on the market clearance results, it can be moved to formal operation according to the required procedures (NDRC and NEA, 2023).

In September, 2023, Shanxi electricity spot market was evaluated with a conclusion that the conditions for shifting from trial to formal operation are satisfied. On December 22, 2023, formal operation of Shanxi electricity spot market started firstly in China (SXPEB and SXERO, 2023). After that, the formal operation of electricity spot market in Guangdong and Shandong province started on December 28, 2023 and June 17, 2024, respectively (SDERO, 2024).

4.2 Operation result of Shanxi electricity spot market

By the end of May, 2024, there were a total 17,435 registered market entities on the trading platform of Shanxi Power Exchange Center (SXPX), including 593 power generation companies, 415 electricity sales companies, and 16,427 electricity users (SXPX, 2024). Fig.4 shows the change of daily real-time trading prices of Shanxi electricity spot market with accessible data during August 31, 2022 and May 31, 2024, which is used in this analysis. There existed two discontinuous intervals, October 16 to 22, 2022 and April 26 to July 14, 2023, since the data for these two periods are not available. The prices ranged from 21.02 to 1,446.44 Yuan/MWh, indicating a large scale of fluctuations (SXPX, 2024).

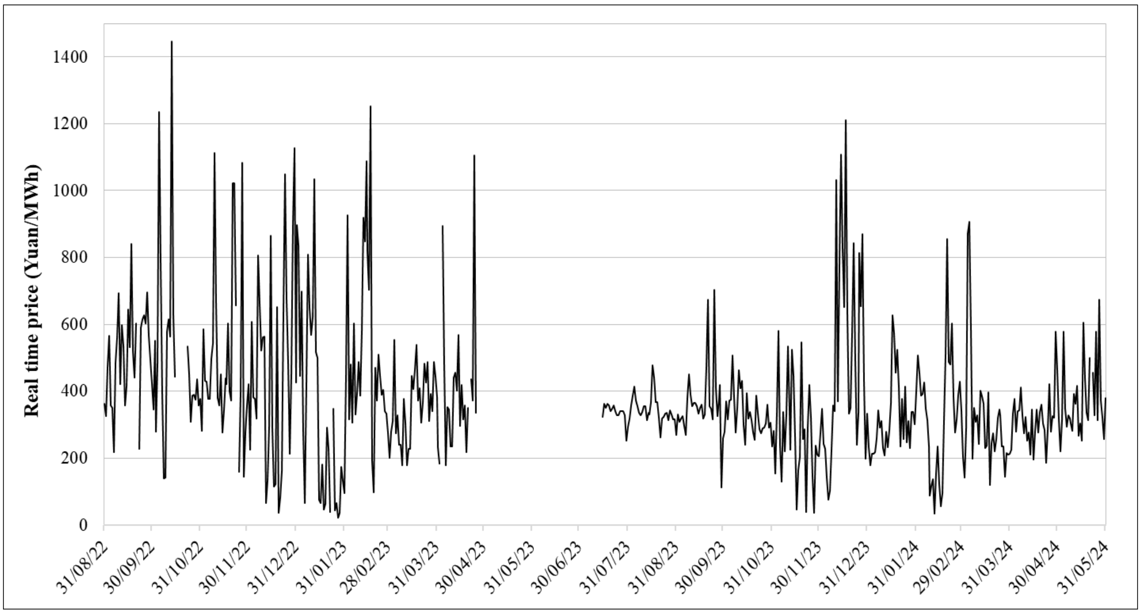

Fig.4: Daily real-time trading prices of Shanxi electricity spot market (31/08/2022-31/05/2024).

Fig.5 lists the monthly averages of real-time trading prices of Shanxi electricity spot market from

July, 2021 to December, 2023. With a range at around 250 to 500 Yuan/MWh, the monthly average prices exceeded 480 Yuan/MWh in summer of 2021 and 2022. Nevertheless, the yearly average price was below 1.2 times of benchmark price of coal-fired power generation in Shanxi (332 Yuan/MWh), and the increase was lower than most provinces during the same period. This implies that the spot market prices reflect electricity supply and demand relationships and the changes in generation costs well, and play a positive role in adjusting the power balance (Tong, 2023).

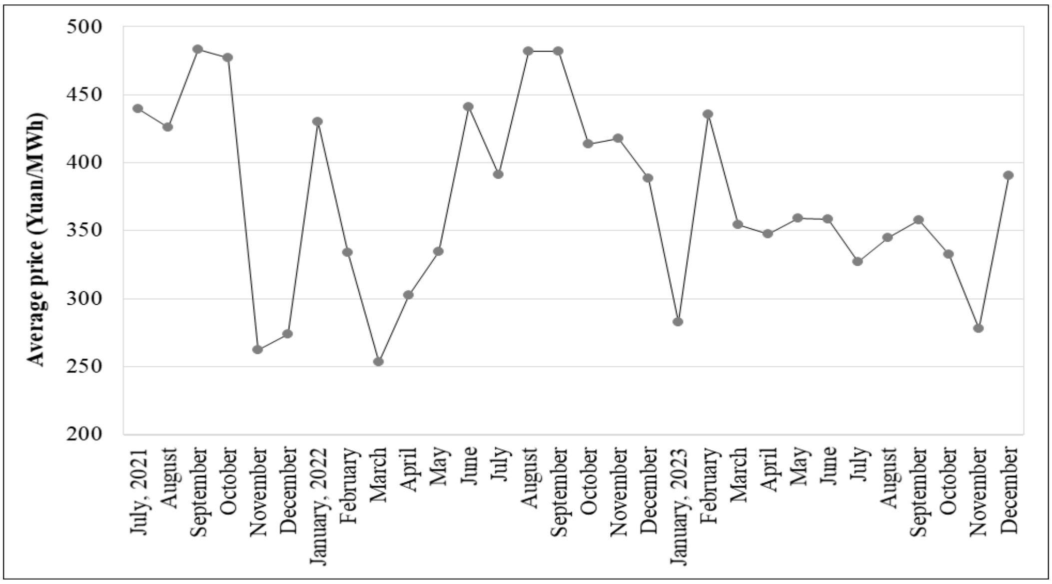

Fig.5: Monthly average prices of Shanxi electricity spot market (July, 2021 - December, 2023).

4.3 Fossil fuel prices gathered for this analysis

The prices of power coal were collected from the website of China Electricity Council (CEC). Jointly created by CEC and major domestic power generation companies, China Electricity Coal Index (CECI) is the only power coal price index system in China at the generation side. The indices that have been publicly released include the CECI Coastal Index, the CECI Caofeidian Index (Caofeidian is a newly developed district located in Bohai Sea coastal area of Hebei province and serves as a crucial northern shipping port for power coal), the CECI Import Index and the CECI Purchasing Managers Index (CEC, 2024c). Among which, CECI Caofeidian Index timely and accurately reflects the daily price level of power coal spot trading in Caofeidian port area and is used in this analysis (CEC, 2021). Due to the lack of valid samples, the release of CECI Caofeidian Index was suspended during February 16, 2022 and May 28, 2023. The weekly data of CECI Coastal Index, which reflects the real prices of spot trading at Northern ports of China, was used as a supplementary for this period.

Chongqing Petroleum and Gas Exchange (CQPGE) collects and releases LNG plant and station prices of three regions in China, including Northwest, Sichuan and Chongqing, and Bohai Rim. The price is the daily average of selling prices of LNG plants or receiving stations in the corresponding region, which are converted by a gasification rate of 1,400 m^3 per ton and include value-added tax (CQPGE, 2024). The prices of LNG in Bohai Rim are used in this analysis.

Fig.6 depicts the changes of power coal and LNG prices of Bohai Rim in China from July 16, 2021 to May 31, 2024. During this period, power coal prices fluctuated frequently with a range of 768 to 1,714 Yuan/t. More specifically, the price of power coal exceeded 1,000 Yuan/t in mid-September, 2021, and continue to increase to over 1,500 Yuan/t in mid-October, 2021. After a short stabilization at this high level for around 1 month, the price quickly declined to below 1,000 Yuan/t in mid-November, 2021. This number rebounded quickly from around 800 Yuan/t in mid-January, 2022 to over 1,700 Yuan/t in mid-March of the same year. From then on, power coal prices have been remained at a high level with a range of around 1,200 to 1,600 Yuan/t until the end of May, 2023. After a sudden decline around that time, power coal prices became relatively stable and remained at lower levels of around 800 to 1,000 Yuan/t till the end of May, 2024.

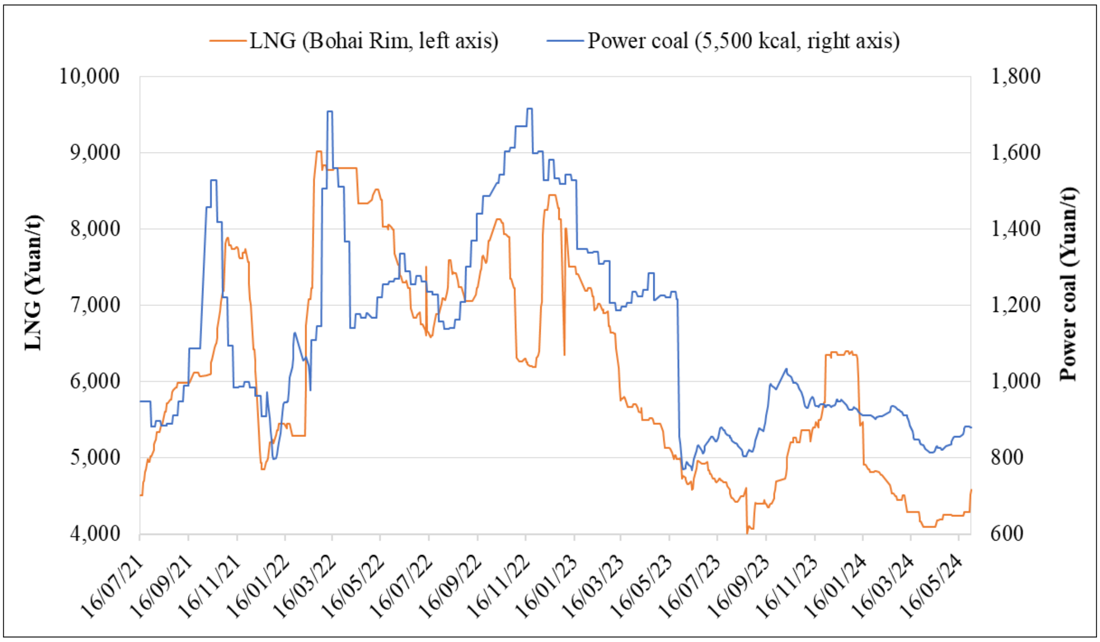

Fig.6: Prices of power coal and LNG used in this analysis (16/07/2021-31/05/2024).

The prices of LNG in Bohai Rim indicate a similar trend as the prices of power coal. In particular, LNG prices were increasing from around 4,500 Yuan/t in mid-July, 2021 to nearly 8,000 Yuan/t at the beginning of November, 2021. After around 1 month, the prices quickly declined to less than 5,000 Yuan/t in mid-December of the same year. After some fluctuations, LNG prices began to increase again from mid-February, 2022 to the highest level over 9,000 Yuan/t by the end of February, 2022. More recently, LNG prices in Bohai Rim declined to a low level of around 4,000 Yuan/t in the end of August, 2023. During mid-March, 2023 and the end of May, 2024, the prices of LNG have been fluctuated between around 4,000 to 6,400 Yuan/t.

5. Analysis results and discussions

5.1 Statistical results of various series of prices

One of the main purposes of this research is to clarify the relationship between the price of electricity and the generation input costs, including the prices of carbon emission allowances, coal and natural gas. The analysis could only focus on the period with the data available from July 16, 2021 to May 31, 2024. Table 3 lists the detailed statistics of the four series of prices used in this analysis. The result indicates that the distribution of all the four prices is skewed to the right with a positive skewness value. The kurtosis value of electricity and carbon prices is greater than 3.00, confirming their heavy tailed distribution. The distribution of power coal and LNG prices is light tailed with a kurtosis of less than 3.00.

Table 3: Summary of the statistics of various prices (daily data)

Item	Unit	N	Mean	Median	Min.	Max.	Std. Dev.	Skewness	Kurtosis
P_{-power}	Yuan/MWh	358	400.2	349.6	35.7	1,446.4	211.2	1.605	6.600
$P_{-Carbon}$	Yuan/t-CO_2	695	62.1	58.0	41.5	105.0	13.1	1.070	3.988
P_{-Coal}	Yuan/t	695	1,120.1	1,064.0	768.0	1,714.0	254.0	0.619	2.253
P_{-LNG}	Yuan/t	695	6,151.3	5,978.0	4,009.0	9,014.0	1,403.0	0.304	1.919
Note: P_{-Coal} refers to the price of coal of 5,500 kcal/kg.									

5.2 Empirical test results of prices overreaction in China's national carbon market

The calculation result of daily turnover rate, which is defined as the proportion of daily trading volume and the total trading volume during the analysis period, is plotted in Fig.7.

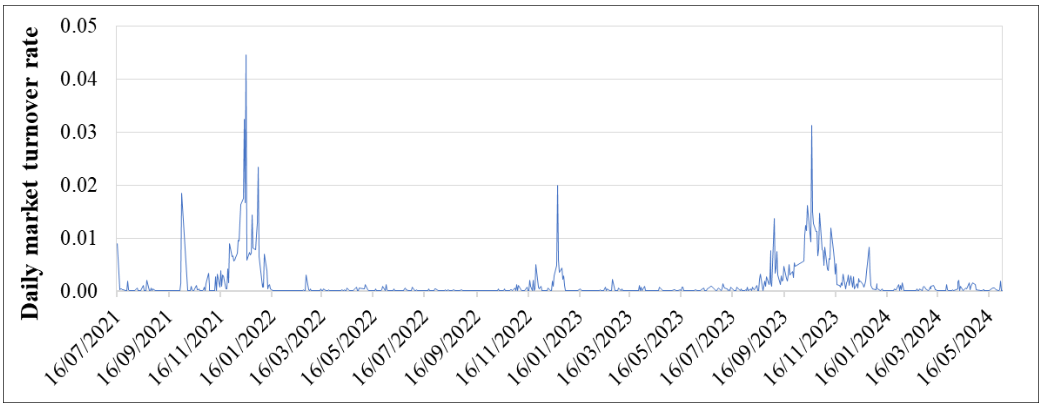

Fig.7: Daily turnover rate of China's national carbon market (16/07/2021-31/05/2024).

Obviously, the trading was once concentrated in the approximately one and a half months leading up to the first compliance due date, 31 December, 2021. Since the beginning of 2022, market trading volume dropped significantly. There appear signs of recovery in trading volume around December 2022. 2023 is the year for the settlement of emission allowances of 2021 and 2022, and the market liquidity gradually increased, with the trading volume growing significantly from August to

December, 2023. This confirms that China's national carbon market is still at an early stage, and the main purpose of trading is for the target entities to fulfill their obligations.

The results of overreactions of China's national carbon market prices to the considered events are listed in Table 4. The market prices were confirmed to have an overreaction to the notices on emission allowances settlement (event No.1 and No.4) and the release of emissions allowances allocation plan and the interim management regulations (event No.3 and No.5). As so far, only the key emitting entities can participate in the trading in China's national carbon market. Their knowledge on carbon market may be insufficient and the information available to them may be incomplete. They tend to count on their own forecast and judgement, which may more likely lead to higher carbon price volatility and ultimately cause overreactions. This result implies that China's national carbon market is not mature. The market transparency and information disclosure should be improved. The capacity building for the target entities should be enhanced and the participation of institutional investors should be also encouraged to avoid the overreaction of market participants and maintain lower carbon price volatility.

Table 4: The result of prices overreaction to the considered event

No. of event	Average price volatility ($\bar{V}$)	V_t - $\bar{V}$				
		Mean	Std. dev.	t-value	p-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**

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

5.3 Results of the unit root test

The analysis of price interactions starts by testing the non-stationarity of all the four series of prices. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests were applied and the results are listed in Table 5.

Table 5: Results of ADF and PP unit root tests

Variable	Level		Variable	First difference	
	ADF	PP		ADF	PP
P_{-power}	-12.463*** (0)	-12.675*** (5)			
$P_{-Carbon}$	-2.727 (0)	-1.887 (6)	$\triangle P_{-Carbon}$	-37.569*** (0)	-39.001*** (5)
P_{-Coal}	-3.101(13)	-2.374 (6)	$\triangle P_{-Coal}$	-25.643*** (0)	-25.769*** (5)
P_{-LNG}	-3.656** (7)	-3.152* (15)			

Note: '△' refers to the first difference of sequential data. The number in parenthesis is the optimum lag.
*** Significant at 1% level; ** Significant at 5% level; * Significant at 10% level.

It is confirmed that electricity and LNG prices are stationary while the other two input price series are non-stationary. Furthermore, the price series of carbon and power coal have stationary first differences at a 1% significant level. This means that the statistical properties of electricity and LNG prices, such as the mean, variance and autocorrelation, are constant over time. The statistical properties of the other two prices change over time.

The test result for the electricity price in this analysis is consistent with some previous studies in Europe. For example, Sijm et al. (2008) documented that spot market price of electricity is quite often stationary. The dataset of the dependent variables in López and Nursimulu (2019) consists of spot electricity prices (hourly and daily average) and forward prices (week, month, quarter and year contracts). Their analysis confirmed that the hourly and daily average spot prices are stationary.

5.4 Relationship between carbon and power coal prices

The AIC (Akaike Info Criterion), SIC (Schwarz Info Criterion) and HQIC (Hannan and Quinn Info Criterion) are used to determine the lag relationship among the two non-stationary price series in the levels of VAR. The result suggests that the appropriate VAR lag length is three (k=3) and the number of lags in the VECM should be 2 (k-1) for this analysis.

With the optimum number of lags determined above, the VECM was run to examine the long run co-integration relationship and the short run dynamics of linkage effects between carbon and power coal prices. The estimation results of VECM model are reported in Table 6. There reveals no problem for this VECM analysis. The Lagrange Multiplier (LM) test confirms no autocorrelation at the lag order, and the post estimation reveals a normal distribution of the model residual. The heteroskedasticity test also confirms that the regression is homoscedastic. The co-integrated vector, which is normalized on $P_{\text{-Carbon}}$ in panel A of Table 6, shows that the estimated coefficient of power coal price is positive and significant at 1% level. This means that, in the long run, power coal price indicates a negative impact on the price of China's national carbon market.

Empirically, previous studies found that the direction of long-term influence of fossil fuel prices on carbon prices is diverse. The result observed from this analysis is consistent with Alberola et al. (2008) and Kim and Koo (2010), which verified that coal price is negatively related to the allowances prices under the EU-ETS and the U.S. carbon market. As one of the limited studies with close relevance in China, Chang et al. (2018) confirmed that there was a large difference in these relationships for various regions and periods of China's pilot ETS given their substantial divergences in industrial structure and market characteristics. For example, coal and oil prices indicated positive impacts on the emissions prices under Beijing ETS pilot during 2014 and 2015. This is opposite to the result of this analysis.

As described earlier, China's national carbon market only covers power generation sector and applies a benchmarking approach for the allocation of emission allowances. The target companies are sensitive to the variations in fossil fuel prices. When power coal prices increased, the efficient power companies would become more competitive, resulting in relatively larger generation amounts by them. The anticipation of more surplus in allowance supply might cause a decrease in carbon prices over the long term.

Table 6: The result of VECM model analysis of carbon and coal prices

A) Co-integration relationship		
Endogenous variables	$P_{\text{-Carbon}}$	$P_{\text{-Coal}}$
Coefficients	1.00	0.1826***
B) Short run dynamics		
	$\triangle P_{\text{-Carbon}}$	$\triangle P_{\text{-Coal}}$
Error correction term	-0.0024*	-0.0648**
$\triangle P_{\text{-Carbon}}$ (-1)	-0.3832***	-0.7423
$\triangle P_{\text{-Carbon}}$ (-2)	-0.1189***	-0.2378
$\triangle P_{\text{-Coal}}$ (-1)	0.0007	0.0298
$\triangle P_{\text{-Coal}}$ (-2)	-0.0017	0.0717*
Constant	0.0913	-0.0033
R-squared	0.1357	0.0120
Log likelihood: -4699.65; AIC: 13.62; HQIC: 13.65; SBIC: 13.71		
Note: *** Significant at 1% level; ** Significant at 5% level; * Significant at 10% level.		

The result of short-term dynamics in Panel B of Table 6 shows that the coefficient of error correction term (ECT) for carbon price is significant at 10% level and negative, and the coefficient of ECT for coal price is significant at 5% level and also negative. This implies that prices in China's national carbon market and power coal prices are adjusting towards a long-term equilibrium with an adjustment speed of 0.24% and 6.48%. Further looking at the short-term parameters in the VECM result, the lagged carbon and coal prices indicate significant impacts on their own current prices. This suggests that the prices of carbon and coal are essentially exogenous in the short term. Nevertheless, the lagged coal prices have no effect on the short-term dynamics of carbon prices. Therefore, carbon market entities cannot use historical information on coal prices to improve their short-term forecast of the spot prices in the national carbon market. This finding contrasts with previous studies in the U.S. and EU. For example, Freitas and Silva (2015) demonstrated that carbon prices and fuel prices exhibit short-term interactions under the EU-ETS. Actually, the trading prices of China's national carbon market lie at a low level. Most of the covered power companies face low pressure due to carbon cost, and thus carbon prices are not sensitive to coal price fluctuations (Chang et al., 2018).

5.5 Regression result with electricity spot price as the dependent

According to the test in Section 5.3, the electricity spot price series is stationary in this analysis. The transformation of the non-stationary variables, i.e., carbon and power coal prices, was performed for them to become stationary. Using electricity spot price as the dependent, two multivariate OLS regressions were carried out. One is to use the first differences of carbon and coal prices as the independents, the other is to include LNG prices as an additional independent variable. The results are listed in Table 7. The results indicate that the electricity spot price in Shanxi province is significantly and positively associated with the first difference of coal price and LNG price.

Table 7: Regression results of electricity spot price and the input prices

Variable entered	**Regression 1**			**Regression 2**		
	Coefficient	t-Statistic	P-Value	Coefficient	t-Statistic	P-Value
β_0	399.58	35.91	0.000	172.95	3.52	0.000
$\triangle P_{\text{-Carbon}}$	-1.08	-0.20	0.845	0.36	0.07	0.946
$\triangle P_{\text{-Coal}}$	1.49	2.24	0.026	1.55	2.39	0.017
$P_{\text{-LNG}}$				0.04	4.73	0.000
F-Value	2.51			9.24		
R-squared	0.014			0.073		

Additionally, it was revealed that there was no significant relationship between the electricity spot price and the first difference of carbon prices. This implies that the change in carbon prices is still not a factor influencing the power company's bidding strategy in electricity spot market. This result is different from previous studies, i.e., López and Nursimulu (2019), which document that carbon and fossil fuel prices are all main drivers for the electricity market, and their effect on electricity prices is similar across various delivery periods.

5.6 Insights on China's power sector reform and national carbon market development

The result of this analysis may provide relevant insights for policymakers in China to overcome the challenges in implementing a more effective carbon market at the national level. The preparation and actual involvement of the national ETS may be useful for promoting carbon management of target companies. In practice, measurement and statistics on carbon emissions in energy-intensive sectors, i.e., the cement industry, have been largely improved in recent years due to the preparation of national ETS (Liu and Fan, 2018). China's national carbon market has raised society-wide low-carbon awareness. The target entities in power generation sector have established internal system for carbon emission management, and over 80% of them have assigned staffs for carbon assets management and incorporated it into daily operation activities. A majority of target entities have assessed their emission reduction potential and costs, and some of them have actively adopted emission mitigation measures (MOEE, 2024).

This is obviously not enough from a climate policy perspective since carbon pricing and passing through the real costs of carbon emissions is a rational and intended effect to enhance the efficiency of an ETS by giving incentives to reduce electricity consumption of end users. Measures should be taken for the price formation and pass-through of carbon emissions costs by creating the conditions for competitive power markets and avoiding regulations to hinder carbon cost pass-through onto the markets. Therefore, liberalization and reform of the power industry should be fully advanced in China to expand and improve the electricity market. It is encouraging that the gross transaction volume of electricity market has been steadily increasing in recent years and shared more than 60% of the total electricity consumption in 2023 (CEC, 2024b).

Rather than the fixed cap applied in the EU-ETS, ex-post benchmarking has been adopted for coal-fired power generators and gas turbines in China's national ETS. As listed in Table 2, a total of 4 categories of benchmarks are fixed ex-ante, and the power generation amount is verified ex-post, resulting in a relative cap. The current ex-post benchmarking approach in China seems insufficient to formulate high carbon prices and reflect the ETS-induced cost into electricity prices, which in turn weakens the policy efficacy. A simpler and stricter benchmarking approach is suggested for the allocation of emission allowances in power generation sector under the national ETS. Setting fewer categories of benchmarks may promote competition among thermal power generators of various scales, and with various technologies and fuel types, thereby leading a shift to a cleaner electricity supply mix. Stricter benchmark values may create higher demand for emission allowances and generate higher carbon market prices accordingly.

The competitiveness of power companies in Europe would not be affected even if they have paid for the emissions allowances, since the cost of carbon emissions could be passed through onto electricity prices. This may explain why the emission allowances in EU-ETS for the power sector could be allocated by auctioning. According to this analysis, a change in carbon prices is still not a significant factor determining a power company's operation and electricity pricing strategy. According to Deng et al. (2018), some power companies covered by the pilot carbon markets in China before the launch of national ETS were not willing to manage their carbon allowances in a market-oriented manner. This has been gradually changing since the operation of national carbon market. According to MOEE (2022), most of the surveyed key emitting entities have appointed full-time staff to manage their carbon assets after the initial compliance period of the national ETS. Nevertheless, emission allowances are allocated with no charge so far in China's national ETS. The fee for annual emissions verification is generally paid by the provincial government. The actual cost originating from the national ETS for most target power companies is limited, and the large-scale and efficient coal-fired power plants can even make a profit since they are allocated surplus allowances. This discourages the impact of carbon prices on the electricity bidding and the pass-through of carbon costs onto electricity prices. Therefore, another implication of this study is that an increasing portion of emission allowances should be allocated by auctioning under the national ETS to give substantial pressure on thermal power companies to consider carbon costs in electricity bidding prices.

The collapse of the carbon price weakens the linkage between the carbon market and electricity market, and accordingly, brings risks to the policy goals of an ETS. With low carbon prices, the incentives for power generators to reduce their own emissions and the stimulus for end users to reduce their electricity consumption will dissipate (Freitas and Silva, 2015). Lin et al. (2019) indicated that a carbon price of up to 200 Yuan/t-CO_2 may increase power generation costs but has little or even no impact on the dispatch order in China. Electricity market price effects from carbon costs tend to increase net revenues for efficient thermal generators while reducing them for inefficient ones. For the moment, electricity market reform may increase the portion of coal-fired power generation and complicate efforts to reduce CO_2 emissions. Lin et al. (2019) argued that a carbon price higher than 260 Yuan/t-CO_2 would be needed to avoid the increase in CO_2 emissions during electricity market transition in China. However, the current carbon price in China's national carbon market is still low, with an average level at 65.6 Yuan/t-CO_2 during 2023 (MOEE, 2024). The surveyed cement companies in Liu and Fan (2018) anticipate that the mean of carbon prices under the national ETS would be at around 60 Yuan/t-CO_2, and would increase gradually over time but may not exceed 100 Yuan/t-CO_2 until 2030. When integrating the national carbon market for the power sector into electricity market reforms under such circumstances, policymakers should strike a balance between the market-based and administrative approaches for achieving emissions mitigation goals. During the transition period, more important benefit of carbon market and electricity market reform may be to provide an economic frame for related investments. Further into the future, the carbon market would change power sector fundamentally if the price of carbon could be maintained at a much higher level.

6. Conclusions

Using the available information sources and an econometric approach for the time series dataset, this study tests the price volatility of the national carbon market, and identifies the interactions between electricity, carbon and fossil fuel prices in China. The result confirms an overreaction of carbon market prices to the considered events. There exists a long-term co-integration between carbon price and the prices of coal. Conversely, coal prices have no impact on the short-term dynamics of carbon prices. The prices of electricity spot market are significantly and positively associated with LNG prices and the first difference of coal prices, but indicate no significant relationship with the first differences of carbon prices. This analysis gives some implications on the synergy between power sector reform and national carbon market in China. On the one hand, the liberalization of the power industry should be further advanced to create conditions for passing carbon costs onto the electricity markets. On the other hand, the national ETS should apply simpler and stricter benchmarks, as well as conduct auctioning to allocate the emission allowances in the power sector for the formation of substantial carbon prices and the shift to a low-carbon power supply portfolio.

As a first effort, this study provides empirical evidence on carbon price formation pattern and the impact of carbon prices on electricity prices in China. The use of recorded market data implies that the analysis is ex-post, and the result may not be valid from a long-term perspective. Continuous data collection and analysis in the next a few years may refine the findings, and a long-term assessment could use ex-ante analysis based on simulation with forward looking assumptions. Little is known about the actual reasons for carbon cost pass-through rates onto the power market as confirmed by previous studies in other countries, let alone the values and determinants in the medium and long term. The analysis of other factors, i.e., price elasticity of demand, could be an interesting topic for future research.

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