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Carbon Pricing and CCUS: Evidence from China

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Abstract

While carbon capture, utilization and storage (CCUS) technologies play a pivotal role in mitigating the adverse impact of global climate change, rising economic uncertainty, geopolitical conflicts and oil price volatility make the deployment of CCUS technologies rather sluggish. To this end, carbon emission trading mechanism can be an effective tool for promoting the deployment of CCUS projects. However, recent literature demonstrates that the emission trading scheme is still immature in a developing economy like China, where carbon pricing seems to be a key strategy to lower the CO_2 discharges from power generation. In this study, we thus investigate the volatility dynamics of Chinese carbon market. In particular, we examine the presence of time-varying jumps in emission prices. Since the jump-induced volatility represents an important element of risk, precise information on such risk is important for increasing the efficiency of carbon trading. Employing the GARCH-jump process, we find that time-dependent jumps do occur in Chinese emission market and that key uncertainty indicators including economic policy uncertainty, crude oil volatility index and geopolitical risk can successfully explain the jump-induced volatility for the carbon market in China. These results offer important implications to policymakers and socially responsible investors.

Keywords: CCUS; Carbon trading; Climate change; China; Time-varying jumps

JEL classifications: Q54; Q56; Q58

1. Introduction

Carbon capture, utilization and storage (CCUS) technologies play a pivotal role in mitigating the adverse impact of global climate change. The main goals of CCUS include managing emissions from heavy industry and exterminating carbon from the atmosphere. CCUS is now considered one of the most efficient tools for achieving net-zero targets. However, although CCUS has recently received much attention from governments, policymakers and investors, the deployment is rather sluggish. For instance, a recent report, published by the International Energy Agency (IEA), reveals that the yearly investment for promoting CCUS technologies amounts to only 0.5% of the worldwide investment in generating renewable and sustainable energy. Besides , the economic downturn and low oil prices due to COVID-19 pandemic emerge as major obstacles for the future development of CCUS technologies.

To this end, carbon emission trading mechanism can be an effective tool for promoting the deployment of CCUS projects (Lin & Tan, 2021). Given that the current economic environment may not be sufficient to prompt the rapid investments in CCUS technologies, an upgraded emission trading system can significantly improve the investment value of the project. Additionally, carbon pricing offers policymakers the flexibility to determine the cheapest ways to reduce carbon pollution.

However, the emission trading scheme is still immature in a developing economy like China, where carbon pricing seems to be a key strategy to lower the CO_2 discharges from power generation. At the same time, the CCUS technologies in China are somewhat underdeveloped to combat climate change. In addition, the slow deployment of CCUS is also a major concern for reaching carbon neutrality. It is thus essential for the Chinese government to increase the efficiency of carbon trading market. Doing so would help the policymakers accelerate the deployment of CCUS projects.

It is also worth noting that being a new financial asset class, the Chinese emission trading market could be highly volatile (Weng & Xu, 2018). Therefore, precise estimates of time-varying volatilities of carbon trading market are of utmost importance for understanding its market efficiency. Qi et al. (2022), for instance, argue that accurate forecasts of the Chinese carbon market volatility are essential for investors and regulators to make proper investment decisions, which would further help the government to reduce CO_2 pollution. Besides, (Lin & Tan, 2021) shed light on the importance of improved and efficient emission trading market in China, which is a major strategy to develop the CCUS projects.

Given the significance of carbon trading for the deployment of CCUS technologies, a growing body of literature investigates the volatility dynamics of Chinese emission market. For example, Wang and Guo (2018) examine the volatility linkage between carbon and energy markets. Xu (2021)) explores how energy market uncertainties impact the volatility Chinese emission prices. Besides, Chun (2018) estimate the volatility cross effects between the Chinese and EU emission markets. Some other notable works include (Ji et al., 2019; Lin & Chen, 2019; Zhu et al., 2020).

While the number of studies focusing on the Chinese emission trading scheme continue to grow, not a single paper has investigated the jump behavior of carbon pricing. Time-varying jumps, which are often observed in this type of immature market, could cause a substantial increase in the volatility levels. Such jump-induced volatility in fact represents an important element of risk which requires special attention when modeling the volatility of carbon market[1]. In this study, our main objective is to examine whether time-varying jumps occur in the Chinese emission prices. In addition, we also attempt to assess if relevant variables including oil price risk, economic policy uncertainty and geopolitical risk could explain the jump-induced volatility (henceforth, JV). Identifying the factors that influence carbon price volatility would help the policymakers to precisely estimate the underlying risk linked to emission trading. Overall, this strand of research has important implications for the development of CCUS technologies in China, which is essential for achieving the net-zero targets.

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[1] Dutta (2018) shows that the EU emission market also experiences such jumps, which play a pivotal role in volatility modeling and risk management.

Methodologically, we employ the GARCH-jump model proposed by (Chan & Maheu, 2002) and find that time-dependent jumps do occur in Chinese emission market. Our findings further show that key uncertainty indicators including economic policy uncertainty, crude oil volatility index and geopolitical risk can successfully explain the jump-induced volatility for the carbon market in China. Given that precise information on jump-induced volatility is important for increasing the efficiency of carbon emission market, our analysis offers important implications to policymakers and socially responsible investors.

2. Literature Review

China, as the largest emitter of CO_2 in the world, is facing ethical and normative pressure to reduce its greenhouse gas emissions and adopt sustainable energy development policies. During the UN General Assembly's 75th session, President Xi Jinping announced that China is dedicated to achieving its CO_2 emissions peak by 2030 and carbon neutrality by 2060. Furthermore, he has urged the global community to pursue innovative, coordinated, green, and open development for the betterment of humanity. Under the vision, carbon pricing can substantially reduce carbon emissions (Mo et al., 2023; Yan & Yang, 2021; Zhao et al., 2022). China's carbon markets are evolving with commodity and financial attribution (Wen et al., 2022) and regulating the most significant emissions globally (Liao et al., 2022) . The carbon pricing mechanism in the carbon markets mainly revolves around three forms: emissions trading systems (ETS), a.k.a. cap and trade, carbon tax, and a hybrid approach (Narassimhan et al., 2018).

Carbon pricing in the form of carbon tax provides a double dividend by improving economic efficiency by redistributing collected carbon tax revenue and reducing greenhouse gas (GHG) emissions (Kojima & Asakawa, 2021). Empirical literature (Compernolle et al., 2022; Landis et al., 2021; Li et al., 2018; Mo et al., 2023; van den Bergh & Savin, 2021; Venmans et al., 2020; Wen et al., 2022) is vast on carbon pricing across the contexts and cover both classical and emerging issues of carbon economics. Lin & Jia (2019) explore the role of both carbon trading and carbon tax on China’s environment, energy, and economy and conclude that both can substantially reduce carbon emissions. However, the carbon tax is advantageous over carbon trading on emission reduction efficiency. They also point out the negative effect of carbon trading on the output of the energy industry and energy-intensive industry, including many invisible costs of setting up a carbon trading market. Thus, they suggest levying a carbon tax on fossil fuels in China to reduce CO_2 emissions effectively. Mo et al. (2023) show that China’s carbon emission trading scheme (ETS) with carbon price stabilization mechanism (CPSM) has a different level of impact on Chinese firms’ productivity: an ETS with explicit price corridors could improve total factor productivity (TFP) by 0.381, whereas an ETS with no explicit price corridors could influence TFP by 0.198 while the ETS without CPSM has lessened TFP by 0.352. Extant works (Känzig, 2023; Ko & Lee, 2022; Wen et al., 2022) reveal nonlinear asymmetric and unstable effects of carbon prices on economic agents and urge for the equitable development of carbon policy and market.

Essentially, carbon market development is credited to the positive acknowledgment of carbon pricing, which strengthens resource distribution and optimization and has a decisive role in the carbon trading system (Fang et al., 2018). Carbon pricing as a policy instrument for climate mitigation has been in practice in many countries though its application is heterogeneous across contexts. Political systems, domestic business nature, competition, and influence over local authorities, including international bindings and obligations, contribute significantly to the design, adoption, and implementation of carbon pricing systems (Khan & Johansson, 2022). In 2005, the European Union (EU) first launched the carbon market in its territory, which set the foundation of that emerging policy-based market in various other locations worldwide. China started its journey in the carbon energy market in 2013 by setting up seven carbon pilot markets, subsequently with a national carbon market on 16 July 2021. With heavy energy-intensive industries, China has significant potential for a robust carbon market. However, a significant gap exists between the mature carbon market in the West and the infant carbon market in China because of the differentiation in carbon price fixation, carbon quota allocation, carbon emission coverage sources, and other contextual factors (Hua & Dong, 2019).

The differences between the EU emissions trading system (ETS) and China's national emissions trading system (ETS) are not counterproductive; instead, linking these two systems can open potential economic and political gains (Zeng et al., 2016). Furthermore, the international cooperation on carbon pricing through linking carbon markets can deliver economic benefits by lowering carbon reduction costs and environmental benefits by reducing carbon emissions and leakage (Thube et al., 2021). China's national carbon market is in its early stages and requires necessary additions and improvements. Till now, the most successful EU carbon market can provide valuable lessons for developing China's national carbon market (J. Liu et al., 2022). For instance, carbon finance is a new trend in the global carbon market with many legal and policy complexities. However, applying the EU rules on carbon finance to the specialized regulatory regime of China's carbon market can help it function well(Chen & Wu, 2023). More importantly, Chinese firms' total factor productivity (TFP) can go up approximately by 22.73% if China's carbon emissions price equals that of EU ETS (Wu & Wang, 2022). However, the sensitivity of the Chinese market to the cross-border carbon policy, especially in light of the European Union Carbon Border Adjustment Mechanism (EU CBAM), is a matter of concern as China's exports to the EU heavily rely on carbon-intensive goods. Therefore, without carbon policy adjustment and reconciliation, cross-border trade between the EU and China may be affected (Shen et al., 2023).

The carbon trading market is valuable to increase the attention of investors in the carbon capture utilization and storage (CCUS) development initiatives (Lin & Tan, 2021). CCUS systems are critically important in tackling global climate change (McLaughlin et al., 2023; Roy et al., 2023). However, CCUS is still at the early demonstration stage, and there are many uncertainties in the business model and policy incentives that the traditional method can no longer handle (Ye et al., 2022). For effective installations of CCSU technologies in a region, initiatives like setting up regional corridors for optimization of scale, societal engagement to the CCUS projects, carbon pricing, public-private partnership for CCSU financing, knowledge and technology transfer, and stakeholders' engagement are crucial (Lau et al., 2021).

3. Status of Carbon Capture Storage and Utilization (CCUS) in China

China is the first country to initiate the CCUS concept to reduce CO_2 emissions globally (Qin et al., 2015), even having the most comprehensive experience of CCUS projects aiming at balancing economic expansion and carbon emissions (Yao et al., 2023). Moreover, with the CCUS installations strategy, China can avoid stranding assets from the current industry setup, including support from the business community in fighting climate challenges. An estimated 3120 GtCO2 carbon storage capacity indicates the future of CCUS in China (Xu & Dai, 2021). Chen et al. (2022) out that the the "Golden Age" of CCUS formation ranges from 2040 to 2060 globally, while 2030–2050 for China. However, the actual scale of CCUS is still not up to the mark in China, stressing the importance of continuous government support for CCUS as a component of the governmental plan for energy efficiency and transitioning towards a low-carbon future (Jiang & Ashworth, 2021).

CCUS has been a vital policy part of the Chinese government over the last two decades. Chronologically, in 2007, China government enlisted CCUS as a critical technology in the battle against carbon control, with subsequent actions in 2013 to carry out CCUS demonstration projects, including environmental impact assessment and monitoring. In 2017, the emphasis was on CCUS technologies development from the government side, which got a boost in 2021 by implementing CCUS pilots in various parts of China (Xu & Dai, 2021). These initiatives led to an expectation about CCUS at various levels of economic and political agents in China (Yin & Xu, 2022). However, Ma et al. (2023) reveal several areas for improvement in China's multi-state department generated CCUS policy. First, they show that supply-side policy needs to be more balanced as it relies heavily on technology research and demonstration. Second, Environment-type policies must be revised in relevance and operability, especially legislations, standards, and incentives. Finally, demand-type policies should be present in the current policy system, essential to driving the demand for CCUS technology in national and international markets. A well-designed implementation strategy with a proper balance of CCUS technology and other objectives can work hand in hand in China.

CCUS development at the maximum level can help China to achieve carbon neutrality by 2054-2058, which can defer to 2061-2064 in case of low CCUS development in China (Sun et al., 2022). Chinese oil companies have been using CO_2 storage technologies for many years, constantly producing positive results, even though no large-scale CCUS technology installation has occurred in China's oil industry (Che et al., 2022). The CCUS technologies also probe grace to the China crude steel industry. Wei et al. (2022) show that the impact of CCUS will lie between 17.6%-56.5%, contingent upon the carbon price mechanism or aiding government policies for China's steel industry. Therefore, CCUS can be a catalyst for the green transition of the Chinese steel industry. Furthermore, China's coal-fired power plants can transform into CCUS projects with economic, environmental, and energy considerations. Han et al. (2023) point out that the three-dimensional model of the Chinese CCUS coal-based power plant can reach the 0.99 level in terms of the goodness-of-the-fit with a benefit ratio of 5:9:1 in the economic, environmental, and energy dimensions, respectively. Similarly, CCUS can benefit China's coal chemical, and cement industries (Guo et al., 2023; Xie et al., 2022).The projected benefit of a pipeline network model of CCUS can be a yearly emission reduction of 280 million tons of CO_2, including a yearly net income of USD 2.20 billion collectively and unit wise net income of USD 7.85 per ton of CO2 (Xie et al., 2022).

The public and stakeholders influence strategic CCUS investment decisions (Liu et al., 2021; Sitinjak et al., 2023) CCUS are sensitive technologies and require public understanding and acceptance. Even if a significant percentage of newsletter reports positively present CCUS technologies in the mainstream Chinese media, more is needed to tackle technical misperceptions and comprehensive subject matter of CCUS technologies (Jiang et al., 2022) General cognition positively influences mass acceptance, and perceived benefits have a more substantial effect on acceptance than perceived risks in China. Therefore, the authorities and leading clean energy players in China should strengthen the publicity and incentive system for various CCUS technology issues to make it a reality in combating carbon emissions in China (Liu et al., 2021).

4. Methodology

The jump approach has received enormous attention in recent studies (Dutta, 2017; Dutta et al., 2022; Dutta & Das, 2022; Fowowe, 2013; Gronwald, 2019; Kuttu, 2017; Zhou et al., 2019). Following (Chan & Maheu, 2002), we employ the GARCH-jump model as follwos[2]:

$$r_t = \pi + \mu r_{t-1} + \epsilon_t \tag{1}$$

where r_t indicates the logarithmic difference for the CEP index at time *t*, and ϵ_t refers to the innovation term specified as:

$$\epsilon_t = \epsilon_{1t} + \epsilon_{2t} \tag{2}$$

where ϵ_{1t} will follow the GARCH (1,1) specification:

$$\epsilon_{1t} = \sqrt{h_t} z_t, \quad z_t \sim NID(0,1)$$

$$h_t = \omega + \alpha \epsilon_{1t-1}^2 + \beta h_{t-1} \tag{3}$$

In addition, ϵ_{2t} denotes a jump innovation defined as:

$$\epsilon_{2t} = \sum_{l=1}^{n_t} J_{tl} - \theta \lambda_t \tag{4}$$

where J_{tl} is the jump size with a mean value θ and a variance ϑ^2, $\sum_{l=1}^{n_t} J_{tl}$ refers to the jump factor, and n_t represents the jump frequency at time *t*, following a Poisson distribution given by:

$$P(n_t = j | I_{t-1}) = \frac{e^{-\lambda_t} \lambda_t^j}{j!}, j = 0,1,2, \ldots \tag{5}$$

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[2] The choice of the AR(1) specification based on the Akaike information criterion.

with an autoregressive conditional jump intensity (ARJI) given as:

$$\lambda_t = \lambda_0 + \rho\lambda_{t-1} + \gamma\xi_{t-1} \tag{6}$$

In equation 6, λ_t indicates the time-varying conditional jump intensity parameter, λ_0 is the constant jump intensity, and ξ_{t-1} denotes the intensity residual. (Chan & Maheu, 2002) assume that $\lambda_t > 0$, $\lambda_0 > 0$, $\rho > 0$, and $\gamma > 0$.

We define the log-likelihood as:

$$L(\Theta) = \sum_{t=1}^{T} \log f(X_t | I_{t-1}; \Theta)$$

where $\Theta = (\pi, \mu, \omega, \alpha, \beta, \theta, \vartheta, \lambda_0, \rho, \gamma)$ and $I_{t-1}$is the information set.

Note that the jump-induced volatility (JV) is given as:

$$JV_t = \sqrt{(\theta^2 + \vartheta^2)\lambda_t} \tag{7}$$

Next, we examine whether crude oil volatility index, clean energy asset price volatility and the EU emission price volatility could explain the jump-induced volatility defined in Equation 7. To serve this purpose, we estimate the following model:

$$JV_t = \varphi_0 + \varphi_1 U_{t-1} + \varepsilon_t \tag{8}$$

where, *U* indicates a vector of uncertainty indexes. If case when $\varphi_1$is significantly different from zero for a particular uncertainty measure, we can infer that it may explain the jump-induced risk linked to the Chinese emission prices[3].

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[3] Many recent studies have found significant linkages between the Chinese carbon and global energy markets (see Ji et al., 2019; Lin and Chen, 2019; Zhu et al., 2020; Gong et al., 2021; Xu, 2021 etc.).

5. Data

In this study, we use the information on Shenzhen carbon emission trading price (henceforth, CEP) due to its high quality and long duration. While there are currently eight carbon emission trading pilots in China, the Shenzhen carbon emission trading market has received much attention in recent studies (H. Chen & Xu, 2022; Zheng et al., 2021). The sample incudes daily observations spanning from August, 2013 to August, 2022. As mentioned earlier, our analysis has considered several influencing factors including crude oil volatility index (OVX), economic policy uncertainty (EPU) and geopolitical risk (GPR). The data on OVX are collected from the DataStream database, while the GPR index is found in the website of economic policy uncertainty. Notably, the EPU index for China has been recently introduced by (Lee et al., 2023). We obtain the data from their website (twitterchnepu.github.io).

Next, Table 1 shows the descriptive statistics for emission prices, OVX, EPU and GPR. It is observed that carbon market returns are positively skewed. This is also true for all the uncertainty indicators. Besides, all the series are found to be leptokurtic and hence they violate the normality assumption. The Jarque-Bera test also leads to the same conclusion.

Table 2 displays the outcomes of the augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. The null hypothesis of these tests is that the data follow a non-stationary process. The results are reported for both levels and first differences. These findings suggest that all the uncertainty measures are stationary even at levels. The carbon price index, on the other hand, appears to be non-stationary at levels when the ADF test is employed. After considering the logarithmic differences for the CEP index, both ADF and PP tests find it stationary.

Fig.1, which depicts the Chinese emission price index, demonstrates that carbon prices fall significantly during the COVID-19 pandemic periods, while the prices have increased substantially during the ongoing Russia-Ukraine war periods. It is also observed that during the period 2014-2015, when the global crude oil markets witness a downturn, carbon prices drop significantly. it thus seems that carbon prices in China maintain a close positive correlation with traditional energy prices.

6. Empirical findings

6.1. Findings of GARCH-jump process

Table 3 shows the estimates of the GARCH-jump process. For comparison purposes, we have also included the estimates of GARCH(1,1) model and constant jump intensity(CJI) process. The CJI process, developed by (Jorion, 1988), assumes that $\lambda_t = \lambda_0$, (i.e., the jump intensity parameter is constant with respect to time).

These results demonstrate that the GARCH parameters (α, β) are statistically significant in all these models. We also notice that the sum of $\hat{\alpha}$ and $\hat{\beta}$ are close to unity, showing the evidence of volatility persistence. When looking at the CJI process, we find that the mean parameter (θ) for jumps is insignificant, whereas the variance parameter (ϑ) is statistically significant. Notably, the positive coefficient of the jump variance indicates that the volatility of carbon prices increases with the increment in the volatility caused by abnormal information.

Moving to the GARCH-ARJI process, we observe two interesting results. Firstly, the parameter λ_0, which appears to be significant in the CJI model, is no longer significant. Secondly, the ARJI parameters (ρ, γ) are strongly significant at 1% level, suggesting that jumps exist in the Chinese carbon market and that such jumps evolve over time. Note that the parameter ρ being 0.9973 reveals that the intensity of jumps is highly persistent. Besides, the significant value of γ suggests a diminishing effect (0.0456) on the intensity of future jumps. It is also noteworthy that the ARJI parameters (ρ, γ) are found to be exceeding the zero value, satisfying the positivity constraints. The log-likelihood values shown in the last row also confirm the superiority of the GARCH-ARJI process.

Fig.2 depicts the jump intensities for the Chinese carbon market. This graph evidently shows that the intensity of jumps tends to be time-dependent. More importantly, λ_t seems to increase during the crisis period. For example, we witness several huge spikes throughout the COVID-19 pandemic period. Previous studies (Dutta et al., 2021; Dutta et al., 2022) also claim that jumps in energy prices tend to rise amid the periods of market downturns.

Our findings are consistent with earlier research. Dutta (2018), for instance, shows that time-varying jumps represent a common event in the EU carbon emission market. The author also argues that modeling such jumps plays a pivotal role in understanding the volatility of carbon prices more precisely. We, therefore, recommend the application of GARCH-ARJI process when studying the volatility dynamics of carbon prices in China.

6.2. Determinants of jump-induced volatility

In this section, we intend to examine whether leading uncertainty measures could explain the jump-induced volatility for the Chinese emission market. Table 4 shows the impacts of OVX, EPU and GPR on the volatility of jumps. These findings show that all the uncertainty indicators have substantial effects on the jump-induced volatility as the corresponding parameters are statistically significant at 1% level. Notably, OVX and EPU influence the jump-induced volatility positively, whereas GPR has a negative impact on the same. Moreover, the R^2 statistics show that the volatility of jumps is better explained by the economic uncertainty in China when compared to crude oil volatility or geopolitical risk. These significant linkages could be due to the high correlations between energy and emission prices, geopolitics for oil and inflation, investors' concern for climate change, and financial market integration.

Our findings are in line with earlier literature (Dutta, 2018; Viteva et al., 2014). For example, Dutta (2018) also shows that OVX exerts a positive impact on the volatility of EU emission prices. One plausible explanation is that with the increase in crude oil volatility, energy prices tend to decrease, which in turn promotes the usage of traditional energy sources, resulting in increased volatility for the emission prices. This finding also establishes that energy and emission prices move in the same direction. In addition, we observe that the EU and Chinese emission prices react in a similar manner to crude oil volatility. Moreover, the positive association between economic policy uncertainty and jump-induced volatility implies that rising economic uncertainty tends to raise the policy uncertainty for sustainable investments, which would lift the volatility levels for the emission market in China . Finally, the negative association between GPR and jump-induced volatility could be attributed to the fact that with the upsurge in geopolitical risk, crude oil, which is highly sensitive to such risk (Tiwari et al., 2020), seems to be replaced by renewable energies, leading to a rise in emission prices. As a consequence, a significant drop in the levels of volatility is observed.

7. Additional tests: Do jumps exist for outlier-free carbon prices?

We now explore whether the Chinese carbon prices involve outliers. We then check if jumps still exist after correcting for such outliers. In doing so, we employ the methodology, proposed by (Ané et al., 2008), to identify the potential outliers.

Suppose, R_t denotes the log return for carbon price on day *t*. Then the AR(1)-GARCH(1,1) process is defined as:

$$R_t = b_0 + b_1 R_{t-1} + \varepsilon_t \tag{9}$$

$$\sigma_t^2 = a_0 + a_1 \varepsilon_{t-1}^2 + a_2 \sigma_{t-1}^2 \tag{10}$$

where $\varepsilon_t = \sigma_t z_t$ with z_t being an i.i.d. process such as $z_t / I_{t-1} \sim IIN(0,1)$; I_{t-1} indicates the filtration of information at time $t-1$.

Then R_{t+1} is assumed to be an outlier if it does not fall in the following interval:

$$R_{t+1} \in [R_{t,t+1} \pm F(1 - \frac{\alpha}{2}) \sigma_{t,t+1}]$$

where, $R_{t,t+1}$ refers to the one-step ahead prediction, which is modelled as:

$$R_{t,t+1} = E(R_{t+1}/I_t) = b_0 + b_1 R_t + b_2 R_{t-1}$$

and $\sigma_{t,t+1}^2$ is the one-step ahead risk prediction specified as:

$$\sigma_{t,t+1}^2 = \mathrm{var}(R_{t+1}/I_t) = a_0 + (a_1 + a_2)\sigma_t^2$$

Additionally, $F\left(1 - \frac{\alpha}{2}\right) = P(z_t \leq 1 - {}^{\alpha}/_{2})$ refers to a fractile of the presumed conditional distribution. This process keeps rolling over until the end of our sample.

Our empirical analysis has detected several outliers in emission prices. These outliers mainly occur during the crisis periods such as 2014 oil market downturns, COVID-19 pandemics, etc. We now re-estimate the jump process after deleting these outliers from our original dataset and report the results in Table 5. We find that time-dependent jumps exit even after removing the outliers. This result holds for both CJI and ARJI models. Hence, we conclude that modelling jumps is important for risk assessment purpose. Besides, detecting such jumps is also crucial for increasing the efficiency of carbon trading in China.

8. Conclusions policy implications

While carbon capture, utilization and storage (CCUS) technologies are now considered one of the most efficient tools for achieving net-zero targets, rising economic uncertainty, geopolitical conflicts and oil price volatility make the deployment of CCUS technologies rather sluggish. To this end, carbon emission trading mechanism can be an effective tool for promoting the deployment of CCUS projects. However, recent literature demonstrates that the emission trading scheme is still immature in a developing economy like China, where carbon pricing seems to be a key strategy to lower the CO_2 discharges from power generation. In this study, we thus investigate the volatility dynamics of Chinese carbon market. In particular, we examine the presence of time-varying jumps in emission prices. Since the jump-induced volatility represents an important element of risk, precise information on such risk is important for increasing the efficiency of carbon trading. Employing the GARCH-jump process, we find that time-dependent jumps do occur in Chinese emission market and that key uncertainty indicators including economic policy uncertainty, crude oil volatility index and geopolitical risk can successfully explain the jump-induced volatility for the carbon market in China.

For investors, this research has significant implications given that precise estimates of financial market volatilities always play a key role in risk management. Our study suggests that when investing in the emission market in China, financial institutions should pay careful attention to time-varying jumps occurring in carbon prices given that the jump-induced volatility might carry important information for understanding the potential risk. Since jumps could lead to a sudden increase in the volatility levels, they should be detected properly. Moreover, as we find that the volatility of jumps could be explained by the key uncertainty indicators, the information on such measure could also be useful for market participants when making investment decisions during the periods of high jumps. Hence, our analysis could be useful for deriving appropriate asset pricing models which could minimize the carbon price uncertainty.

This strand of research also provides several important suggestions for the government and policymakers. Firstly, the government should focus on how to increase the efficiency of the Chinese carbon market. An improved and efficient emission trading market is crucial for accelerating the deployment of CCUS projects in China. To this end, identifying the time-dependent jumps in emission prices would help the policymakers increase the market efficiency. Developing an efficient market is also important for attracting eco-friendly investors, which is a key requirement for the reduction of CO_2 releases. Secondly, in addition to improved carbon market, oil market stability is also a precondition for the successful implementation of CCUS projects. To stabilize oil prices, major steps such as uplifting oil reserves, updating the monitoring policy of crude oil futures market and increasing carbon taxes should be taken into account. Besides, the promotion of renewable energies is also important for reducing the impact of oil price uncertainty and geopolitical conflicts. Thirdly, increasing the efficiency of carbon market should not be the only strategy for encouraging the investors towards sustainable investments. The government in China must concentrate on other promotional activities (such as financial incentives, higher carbon taxes) as well for the deployment of CCUS technologies. Finally, in order to decrease the probability of project failure, the Chinese government should invest more on the research and development department. Doing so would improve the CCUS technologies further.

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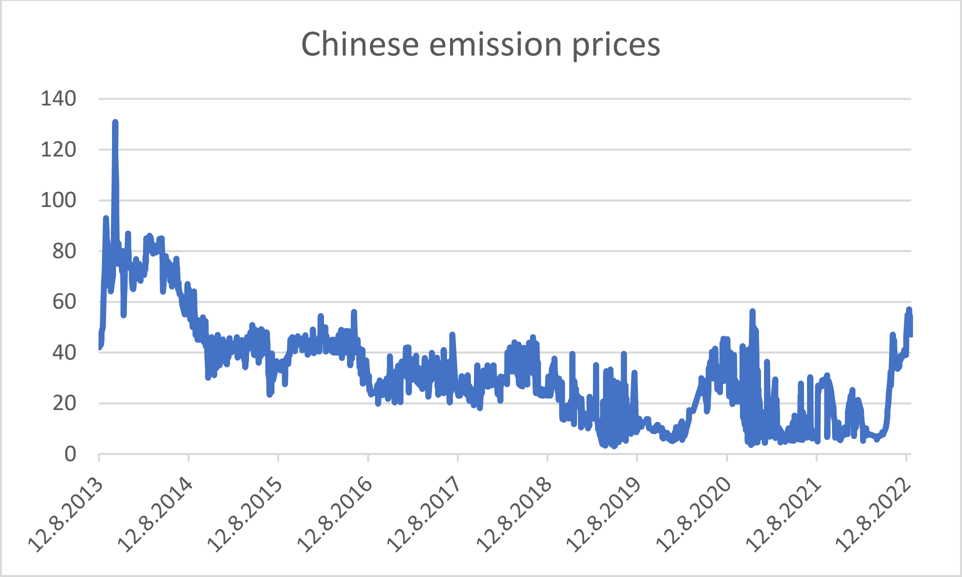

Fig.1: Chinese emission price index

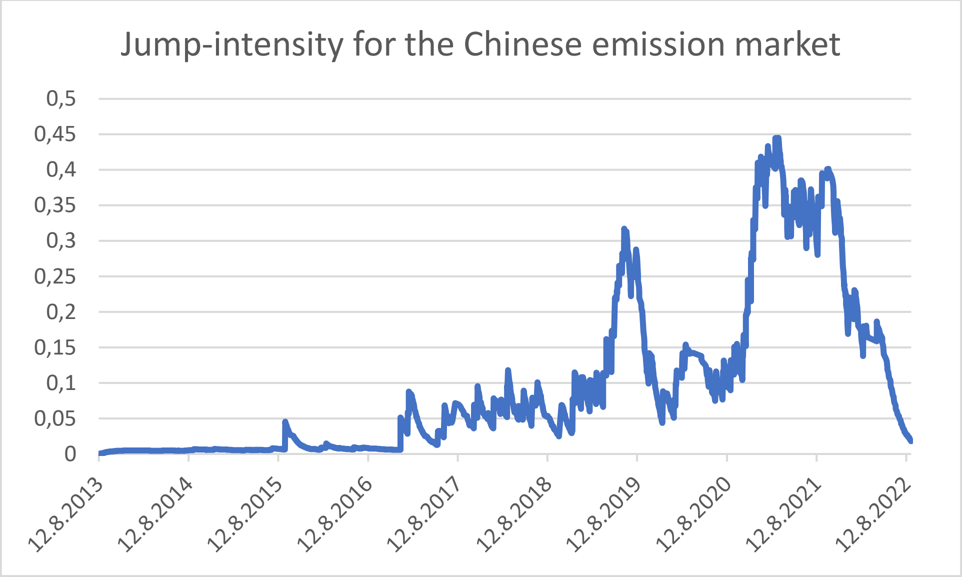

Fig.2: Jump intensity for the Chinese emission price index

Table 1: Descriptive statistics

	CEP returns	OVX	EPU	GPR
Mean	0.0033	36.6066	135.2457	145.4613
Std. Dev.	0.3389	13.61	267.55	1152.40
Skewness	0.3915	2.23	6.66	35.74
Kurtosis	23.03	20.65	71.72	1346.66
Jarque-Bera	30942.00***	24532.16***	362653.30***	134000.01***

Note: This Table presents the summary statistics for all the variables. *** indicates statistical significance at 1% level.

Table 2: Unit root tests

	Augmented Dickey-Fuller test		Phillips–Perron test	
	Level	1st Difference	Level	1st Difference
CEP	-2.55	-27.59***	-4.51***	-83.93***
OVX	-4.40***	-23.34***	-6.15***	-59.21***
EPU	-8.45***	-21.82***	-40.30***	-394.70***
GPR	-42.16***	-19.34***	-42.15***	1781.14***

Note: This Table presents the unit root test results for all the variables. We consider logarithmic differences only for the CEP index. *** indicates statistical significance at 1% level.

Table 3: Estimates of different GARCH models

Models →	GARCH (1,1)		CJI		ARJI	
	Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
π	0.0008	0.0020	-0.0015	0.0016	-0.0023	0.0016
μ	-0.3252***	0.0255	-0.2606***	0.0231	-0.2407***	0.0243
ω	0.0001***	0.00002	0.0003***	0.0001	0.0007***	0.0001
α	0.1229***	0.0108	0.3276***	0.0347	0.4021***	0.0415
β	0.8952***	0.0072	0.6365***	0.0297	0.4831***	0.0430
θ			0.0796	0.0886	0.0089	0.0538
ϑ^2			0.7190***	0.0975	0.6518***	0.0725
λ_0			0.0392***	0.0081	0.0002	0.0002
ρ					0.9973***	0.0025
γ					0.0456***	0.0147
Log-likelihood	853.07		1034.36		1070.65	

Note: This Table presents the findings of different GARCH models for the Chinese emission index. *** indicates statistical significance at 1% level.

Table 4: Determinants of jump-induced volatility

	Estimate	Standard Error	*t*-statistic	*p*-value	R^2
Panel A: OVX					39.54
Constant	0.0302***	0.0049	6.08	0.00	
φ_1	0.0008***	0.0001	8.21	0.00	
Panel B: EPU					41.49
Constant	0.0495***	0.0019	25.99	0.00	
φ_1	0.0001***	0.00001	10.01	0.00	
Panel C: GPR					38.61
Constant	0.1093***	0.0178	6.12	0.00	
φ_1	-0.0111***	0.0038	-2.89	0.00	

Notes: φ_1 measures the impact of OVX/EPU/GPR on the jump-induced volatility for the emission market. *** indicates statistical significance at 1% level.

Table 5: Testing for jumps for the outlier-free carbon market data

Models →	CJI		ARJI	
	Estimate	S.E.	Estimate	S.E.
π	-0.0020	0.0016	-0.0026***	0.0004
μ	-0.2819***	0.0234	-0.2573***	0.0271
ω	0.0003***	0.0001	0.0008***	0.0002
α	0.3224***	0.0346	0.4002***	0.0418
β	0.6468***	0.0287	0.4758***	0.0392
θ	0.1034	0.1012	0.0134	0.0482
ϑ^2	0.7137***	0.0872	0.6562***	0.0414
λ_0	0.0395***	0.0083	0.0004***	0.0001
ρ			1.0002***	0.0004
γ			0.0062***	0.0002
Log-likelihood	955.76		1000.32	

Note: This Table presents the findings of different jump models for the Chinese emission index after correcting for outliers. *** indicates statistical significance at 1% level.