Differences in carbon risk spillovers with green versus traditional assets: Evidence from a full distributional analysis

Kun Duan (School of Economics, Huazhong University of Science and Technology, China)

Yang Liu (School of Economics, Huazhong University of Science and Technology, China)

Cheng Yan (Essex Business School, University of Essex, Colchester, UK)

Yingying Huang (School of Management, Harbin Institute of Technology, China)

Accepted for publication in **Energy Economics**

Abstract

This paper studies the dynamic risk spillover of carbon and financial markets through a quantile-based framework. Potential asymmetry of the cross-market spillover is examined from the perspectives of the data distribution, differences in financial asset types, and pre and post periods of the COVID-19 pandemic onset. Using an international daily dataset covering the recent decade, our empirical analysis offers supportive evidence of established theoretical expectations. The empirical results demonstrate a unidirectional risk spillover from the carbon market to both traditional and green asset markets. The spillover is weakly positive under various market conditions, indicating a consistent diversification gain of carbon commodities against financial assets. Carbon's sheltering role is further enhanced as a hedge for green assets, in particular conditions when the risk levels of carbon and green markets are high and low, respectively. In addition, the onset of the pandemic is found to strengthen cross-market risk spillovers.

Differences in carbon risk spillovers with green versus traditional assets: Evidence from a full distributional analysis

Abstract: This paper studies the dynamic risk spillover of carbon and financial markets through a quantile-based framework. Potential asymmetry of the cross-market spillover is examined from the perspectives of the data distribution, differences in financial asset types, and pre and post periods of the COVID-19 pandemic onset. Using an international daily dataset covering the recent decade, our empirical analysis offers supportive evidence of established theoretical expectations. The empirical results demonstrate a unidirectional risk spillover from the carbon market to both traditional and green asset markets. The spillover is weakly positive under various market conditions, indicating a consistent diversification gain of carbon commodities against financial assets. Carbon's sheltering role is further enhanced as a hedge for green assets, particularly in conditions when the risk levels of carbon and green markets are high and low, respectively. In addition, the onset of the pandemic is found to have strengthened cross-market risk spillover.

Keywords: Carbon market; Financial market; Value at risk; Causality-in-quantiles test; Quantiles-on-quantiles approach

1. Introduction

Since the establishment of the first emission trading system in 2005, the European Union Emission Trading Scheme (EU ETS) has demonstrated its effectiveness in carbon reduction, offering a promising solution to global climate change.[1] As one of the most mature carbon markets worldwide, the EU ETS features various trading patterns, including not only spot transactions but also derivate trading. Considering the rising pace of global financialization, carbon investment has therefore attracted emerging attention as a potential vehicle for portfolio construction and risk management (Tan et al., 2017). Despite its importance, limited but ongoing literature has focused on the linkage of the carbon market with the financial ecosystem, especially during the recent financial turmoil associated with the COVID-19 pandemic (Ben Amar et al., 2021; Narayan, 2021; Bannigidadmath and Narayan, 2022; Harjoto et al., 2020; Jusoh et al., 2023; Xue et al., 2023). Given the presence of a risk premium, in which adverse shocks in one market further deter the risk-bearing of investors in related markets, the risk dynamics across various securities involving financial assets and commodities can feature cross-market spillovers (Duan et al., 2023; Huang et al., 2023; Ren et al., 2022). However, existing inferences regarding the linkage have mainly been drawn via the price channel, while little effort is made to interpret cross-market risk spillover. Moreover, the potential dynamics of risk spillover across different market conditions and in the face of pandemic shock still lack in-depth investigation despite their importance for risk management and financial stability.

Against the above backdrop, our paper analyzes the potentially different risk spillovers between carbon and financial markets with traditional and green asset types. Having reviewed the extant literature, we develop theoretical hypotheses related to our research questions. In the

[1] The EU ETS has rapidly grown to be the world's largest carbon emission trading system built on a "cap and trade" principle. It covers around 40% of greenhouse gas emissions from more than 10,000 carbon-intensive installations being regulated throughout the EU. (Data source: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en#a-cap-and-trade-system)

associated empirical investigation, using a quantile-based framework, we provide a full-distributional framework in which the potential asymmetry of both the causal direction and intensity of cross-market spillover can be measured. Such asymmetry is examined from three perspectives involving different quantiles of the joint data distribution of carbon commodities and financial assets, financial market types (i.e., traditional and green markets), and the pandemic outbreak. In the employed quantile-based framework, the asymmetric causal relationship across markets is examined using a non-parametric causality-in-quantile test, and the intensity of the relationship is then measured using a quantile-on-quantile (QQ) approach. The downside risk of each target market is measured by its value at risk (VaR), whose level in traditional and green financial markets is represented by considering major component assets in the corresponding market types worldwide in the form of value-weighted indices. Following the existing literature (Naeem and Karim, 2021; Huang et al., 2021), the green asset index is built using four major green assets: Dow Jones Sustainability World Index (SWI), S&P ESG Leader Index (ESGLI), S&P Green Bond Index (GBI), and S&P Global Clean Energy Index (GCEI). In addition, the financial asset index is constructed using five major financial equities: the Toronto Stock Exchange Index (TSX), Financial Times Stock Exchange 100 Index (FTSE), STOXX Europe 600 Index (STOXX), Australian Securities Exchange Index (ASX), and S&P 500 Index (SP500). In addition, to further investigate the role of the pandemic on market dependence, sample stratification is made before and after the pandemic onset. The dynamics of the risk spillover when facing such a shock are then analyzed.

Our research contributes to the existing literature in the following ways. First, unlike the existing research, which studies the carbon–financial market linkage based merely on price information, our research moves a step further by studying cross-market risk spillover. Moreover, given the potential information bias caused by market inefficiencies in real situations, inferences related to market linkage directly drawn from price information might lead to erroneous interpretation, further highlighting the importance of analyzing information spillover via risk level. In addition, potential differences in the patterns of cross-market risk spillover of carbon with traditional and green financial assets are further analyzed. Second, in contrast to the volatility measure, which fails to capture tail risk, the employed VaR approach regards loss as a downside risk of each target market and is robust to distributional assumptions using the GARCH model to capture the cluster effect (Alexander et al., 2013; Peng et al., 2018). Moreover, rather than relying on a mean-based estimation, we employ a quantile research framework to capture the potential asymmetry that exists in both the direction and intensity of the causal relationship between carbon and financial markets. By using a non-parametric causality-in-quantiles test, we examine the direction of the cross-market causal relationship over different quantiles of the data distribution. The intensity of the cross-market interaction over the joint distribution of both dependent and independent variables is then gauged using the QQ approach. Through this, we uncover the causal linkage between carbon and financial markets across various market conditions. Third, by splitting the sample before and after the COVID-19 pandemic onset, our research extends the static imposition by considering the dynamics of the cross-market risk spillover when facing the pandemic shock.

Consistent with our theoretical expectations, several important empirical findings emerge and are summarized as follows. First, the carbon market features a more evident downside risk than financial markets, and the strength of the risk fluctuations associated with both carbon and financial markets is strengthened after the pandemic onset. Second, the cross-market risk spillovers from carbon to both traditional and green markets are shown to be unidirectional. Third, the risk spillover from the carbon market to financial markets is weakly positive over the joint data distribution, indicating the consistent diversification gain provided by carbon commodities for financial investment portfolios. The sheltering role of carbon commodities can be strengthened as an effective hedge against green assets, particularly in conditions when the risk level of green assets is high and that of carbon commodities is low. Fourth, the cross-market spillover pattern is shown to be strengthened after the pandemic outbreak, which demonstrates the dynamics of the risk spillover in the face of pandemic shock. Additional analyses, such as alternative estimation techniques, replacement of financial markets, and alternative calculation of VaR series, reassure the robustness of our findings.

The remainder of the paper proceeds as follows. Section 2 reviews the related literature and proposes research hypotheses. Section 3 presents the data and preliminary analysis. Section 4 describes the estimation techniques employed. Section 5 discusses our empirical results and their corresponding theoretical explanations. Section 6 concludes with a discussion of the policy implications.

2. Related literature and research hypotheses

Our research is linked with the extant literature in strands involving the carbon–financial market interaction and the role of the COVID-19 pandemic in driving market dynamics. A succinct and detailed review of the related key literature is summarized in Table A1 in Appendix A. Concerning the carbon–financial market interaction, existing studies have reported the unidirectionality of the relationship between carbon markets and financial markets. With regard to the green finance market, Ren et al. (2022) find that carbon futures prices exhibit a one-way Granger causality with green bonds but not vice versa. Such one-way causality is also found in the existing literature (e.g., Hammoudeh et al., 2020). Carbon and green bond markets share the same intention of reducing greenhouse gas emissions toward environmentally friendly economic development (Tolliver et al., 2020; Flammer, 2021), indicating the presence of a linkage between the two markets. Concurrently, the existing literature points out that the green bond market appears to be a net information receiver in its relationship with the carbon market, given that the green market is still at an early stage with a smaller market depth compared to the relatively mature carbon market (Dong et al., 2023; Reboredo and Ugolini, 2020).

As for the traditional finance market, previous research has found that establishing and improving the carbon market will profoundly impact the national economy and that these impacts will also be reflected in the stock market from both macro and micro perspectives (Jiménez-Rodríguez, 2019; Tan et al., 2020). Studies on the relationship between China's stock market and the carbon market have revealed a bidirectional Granger causal relationship between these two markets (Wen et al., 2020; Yuan and Yang, 2020; Sun et al., 2021). This speaks in favor of the fact that stock market dynamics in China are largely dictated by policy, with a rapidly increasing number of low-carbon industry-supporting policies, indicating the existence of the reverse relation from stock to carbon markets (Zhang and Xu, 2023). However, the reverse relationship might not exist in other regions outside China, including in capitalist economies where policy's impact on stock market dynamics is relatively weak. Zhao et al. (2023) provide evidence of spillover effects from carbon prices to stock markets in the Middle East and Gulf Cooperation Council (GCC) countries. They find co-movements between carbon and stock prices in the Middle East and GCCs in a unidirectional manner from carbon to stock markets. Based on the above discussion, we propose our first hypothesis:

Hypothesis 1. *The carbon market has a unidirectional relationship with financial markets.*

Regarding the intensity of the carbon–financial market relationship, existing studies have emphasized that the carbon market and traditional asset market feature different linkage patterns (Duan et al., 2023; Huang et al., 2023). Liu et al. (2023) find that in the early phase of the carbon market, which was a bullish market situation, carbon trading hurt the stock prices of most industries. They document that with the evolution of the carbon market, different industries exhibit various impact patterns. Specifically, the agriculture industry is positively impacted by the carbon market due to the fact that the development of agriculture and forestry can neutralize carbon dioxide. The impact pattern is the opposite for the mining industry, as rising carbon prices will make the industry less profitable in unfavorable economic situations. Demiralay et al. (2022) document that the average correlation between carbon commodity futures and stocks tends to be low, and adding carbon futures to a stock portfolio provides diversification benefits for stock markets. The above literature discussion indicates that the carbon market can have a weak but positive effect on the traditional financial market, showing a diversification role.

At the same time, the existing literature has further documented that time horizons might affect the carbon–green market relationship, which can be negative in the short term but turn to be positive with a small magnitude in the long term. Ren et al. (2022) find that the carbon futures market can have negative effects in the short term when the green bond market is in a bear condition. The impact becomes positive for most time frames and market conditions. This is consistent with the existing findings that show that the impact of the carbon market on the financial market tends to be different over various investment horizons and across the data distribution (e.g., Li et al., 2023). Qiu et al. (2023) concluded that in the long run, the relationships between the carbon market and the stock market and between the carbon market and the renewable energy market are weakly positive. Therefore, it is concluded that the price impact of the carbon market on the green bond market tends to evolve toward weakly positive in the long term.

Moreover, existing studies have found that the impact pattern of carbon prices can be asymmetric over different quantiles of the data distribution (Feng et al., 2023). Ren et al. (2020) point out that the correlation between decomposed oil shocks and the inefficiency degree of the carbon market is different over different quantiles of the data distribution and at different time frequencies. Similarly, Jin et al. (2020) find that green bonds serve as an effective hedge against adverse fluctuations in carbon risk, especially during periods of extreme turmoil. According to Duan et al. (2023), although green assets are emerging, due to a short period of development, they still feature a relatively limited market depth compared to traditional assets, leading to a higher risk of investing in green assets. Overall, based on the above literature discussion, we propose the following hypothesis:

Hypothesis 2. *The relationship of the carbon market with financial markets is weakly positive and varies in different market conditions and for different financial asset types.*

Moreover, the COVID-19 pandemic has demonstrated its severe destructiveness to economic and financial systems, spreading across the system worldwide (Haldar and Sethi, 2020; Narayan et al., 2022; Narayan, 2022). The adverse shock associated with the pandemic onset has not only resulted in a prolonged economic crash with great fluctuations but has also changed the relationship patterns across markets (Liu, 2022). A limited but growing body of literature focuses on the role of the onset of COVID-19 in altering the market interaction between financial assets and commodities. Huang et al. (2023) study the time-varying market linkages between Bitcoin and green assets before and during the COVID-19 pandemic using a time-very parameter VAR model. They find that the investment sheltering role of Bitcoin for green assets is enhanced in post-pandemic periods. Given that the pandemic has caused a marked rise in production inputs, including the price of fossil energy sources, the heightening pressure on industrial production costs could further encourage the usage of renewable and clean energy financed by green projects, while Bitcoin activities would instead encounter higher costs due to the high electricity usage (Le et al., 2021a). Accordingly, the investment sheltering role of Bitcoin against green assets is enhanced after the pandemic, as demonstrated by a more negative relationship between the two assets. Qiu et al. (2023) highlight that due to the impact of the epidemic, the carbon market has a stronger negative impact on the stock market, which may be due to the epidemic exacerbating the decline in the stock market. Zhao et al. (2022) obverse that after the onset of the COVID-19 pandemic, the positive impact of the carbon market on the stock and commodity markets becomes weakened and even turns to be negative due to the heightening pressure caused by the green and low-carbon transitions of many firms. This results in a rise in carbon prices and a subsequent increase in production costs, which are significant negative signals of firms' financial performance (Wen et al., 2020). Based on the above discussion, we propose our third hypothesis:

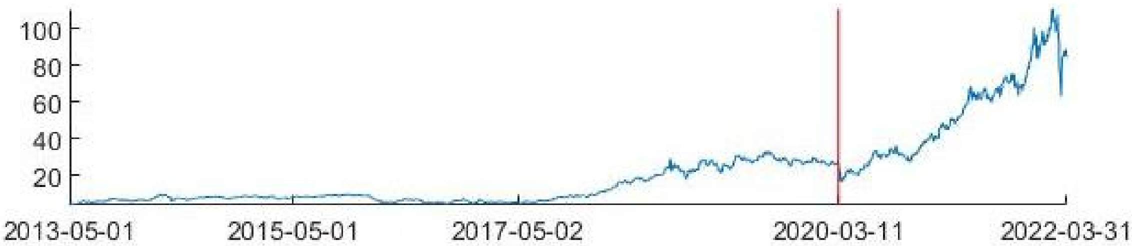
Hypothesis 3. *The pandemic onset changes the relationship between carbon and financial markets.*

3. Data and Preliminary Analysis

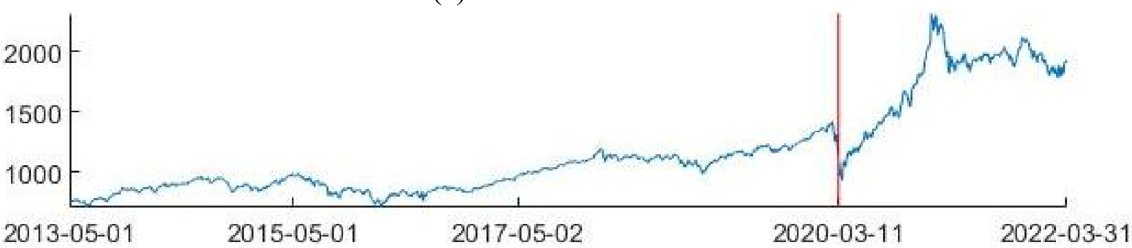
Following the extant literature (e.g., Duan et al., 2021), we construct a series of daily closing prices of the ECX EUA carbon futures from the Intercontinental Exchange.[2] Moreover, in the spirit of the extant literature (Huang et al., 2021, 2023; Wei et al. 2022), two value-weighted indices of green assets and financial equities, respectively termed the green asset index and financial asset index, are constructed by utilizing four major green assets: Dow Jones Sustainability World Index (SWI),

[2] See details about data of ECX EUA carbon futures at https://www.theice.com.

S&P ESG Leader Index (ESGLI), S&P Green Bond Index (GBI), and S&P Global Clean Energy Index (GCEI). In addition to green assets, the following major financial equities are used as well: Toronto Stock Exchange Index (TSX), Financial Times Stock Exchange 100 Index (FTSE), STOXX Europe 600 Index (STOXX), Australian Securities Exchange Index (ASX), and S&P 500 Index (SP500). The original daily price of green assets is from the S&P Dow Jones Indices database,[3] while the daily price of financial equities is from Investing.[4] Our sample period spans from 01 May 2013 to 30 April 2022 and is divided into two sub-samples before and after 11 March 2020, the day COVID-19 was announced as a pandemic by the WHO.[5] Following the extant literature (see, e.g., Goodell and Goutte, 2021; Huang et al., 2021), the sub-samples of 01 March 2018–10 March 2020 and 11 March 2020–30 April 2022 are used to represent the pre- and post-COVID-19 periods, respectively.



(a) carbon futures

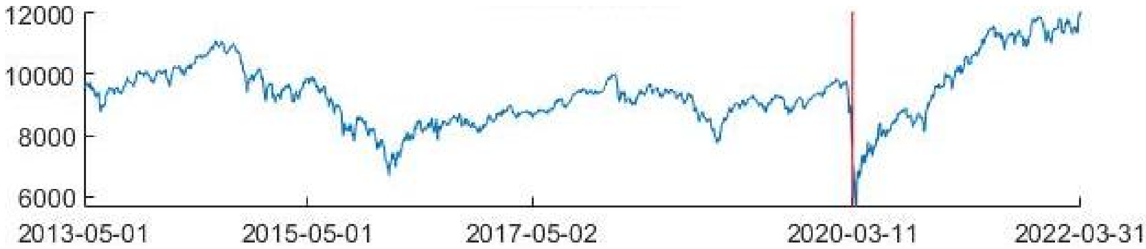


(b) green asset index

[3] See details about data of green assets at https://www.spglobal.com.

[4] See details about data of financial equities at https://www.investing.com.

[5] See details about key dates of COVID-19 announced by the WHO at https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline.



(c) financial asset index

Figure 1. Time series plots of three variables

Note: This figure exhibits daily price series of carbon future, green asset index, and financial asset index from 01 May 2013 to 30 April 2022, as shown in Panels (a), (b), and (c), respectively.

The time series plots of the daily price of carbon futures, green asset index, and financial asset index are shown in Figure 1. It can be seen that the considered series witnessed severe turbulence since 11 March 2020, i.e., the announcement date of COVID-19 as a pandemic. Almost all of the series continued to climb after the sharp drop, although the indices of green assets and financial equities fluctuated steadily thereafter. This provides a visual demonstration of the separation of our whole data to investigate the pandemic impact on cross-market linkages. To explore the risk spillover of carbon futures with the green asset and financial asset indices, the considered series are transformed into the return format by obtaining the first-differenced natural logarithms of the original values and multiplying them by 100. Mathematically, this is represented by the following equation: $Y_t = (\log(P_t) - \log(P_{t-1})) \times 100$. Table 1 shows the descriptive statistics for the return series in sub-samples of the pre- and post-COVID-19 periods. Briefly, the return series were found to possess larger mean values with higher standard deviations after COVID-19 is announced as a pandemic. At the same time, all the returns present standard deviations greater than their mean values, showing relatively high volatilities in both the pre- and post-COVID-19 periods.

Table 1. Descriptive Statistics

	Mean	Std. dev.	Minimum	Maximum	25th Quantile	75th Quantile	Skewness	Kurtosis

Panel A: Pre-COVID-19								
Carbon futures	0.120	3.153	-20.065	19.563	-1.542	1.782	-0.372	5.626
Green asset index	0.028	0.858	-7.831	3.095	-0.366	0.489	-1.164	8.273
Financial asset index	-0.011	0.883	-11.102	3.435	-0.429	0.492	-1.714	17.397
Panel B: Post-COVID-19								
Carbon futures	0.235	3.459	-19.356	16.118	-1.547	2.102	-0.759	4.947
Green asset index	0.104	1.575	-11.318	8.488	-0.625	0.850	-0.904	9.665
Financial asset index	0.095	1.421	-13.185	10.456	-0.399	0.697	-1.623	25.566

Note: This table descripts the summary statistics for the return series of carbon futures, green asset index, and financial asset index in the pre- and post-COVID-19 periods, respectively. Std. dev. refers to the standard deviation.

4. Methodology

In this section, we present a two-step approach used to study risk spillovers of ECX EUA carbon futures with green asset index and financial asset index. First, we estimate the Value-at-Risk (VaR) of each return series and then test the quantile causal relationship between carbon risk and the risk of either green asset index or financial asset index. Second, based on the estimated Granger causalities across quantiles, we explore risk spillovers between these two pairwise series by using a quantile-on-quantile regression.

4.1 VaR estimation

The VaR is appropriate to estimate the potential risk of return series, which is defined as the maximum expected loss within the confidence interval considered (see, e.g., Candelon and Tokpavi, 2016; Jorion, 2017). Let r_t be the return for one of variables (i.e., carbon future c_t, green asset index g_t, and financial asset index f_t) at period t, the VaR of the θ_α-quantile of conditional probability distribution, denoted by VAR_t, is specified as:

$$\text{Prob}\{r_t < VAR_t\} = \theta_\alpha \tag{1}$$

To estimate the VaR, an GARCH process is appropriately applied, which is widely accepted and utilized in the literature (see, e.g., Alexander et al. 2013; Candelon and Tokpavi, 2016; Peng et al., 2018). With the GARCH model for return r_t measured by the conditional quantile regression following Xiao and Koenker (2009), the θ_α-quantile VaR of VAR_t is then given by,

$$\widehat{VAR}_t(\theta_\alpha) = \hat{\beta}_0 + \sum_{j=1}^{p} \hat{\beta}_j r_{t-j} + \hat{\gamma}_0(\theta_\alpha) + \sum_{j=1}^{q} \hat{\gamma}_j(\theta_\alpha) h_{t-j} + \sum_{j=1}^{l} \hat{\delta}_j(\theta_\alpha) \left| h_{t-j} z_{t-j} \right|, z_t \sim N(0,1) \quad (2)$$

4.2 Nonparametric causality-in-quantile test

To examine the nonlinear Granger causality between the VaR of carbon futures and that of green asset index /financial asset index measured in Section 3.1, a quantile-based approach is employed following Nishiayama et al. (2011) and Jeong et al (2012). This nonparametric causality-in-quantile test is well applicable and further improved by Balcilar et al. (2016, 2018) and Fasanya et al. (2021). Let $F_{i_t|S_{t-1}}(i_t|S_{t-1})$ represent the conditional distribution function of either green asset index (g_t) or financial asset index (f_t), $i_t \in (g_t, f_t)$, given a q-lag vector of green/financial index and carbon future (c_t), $S_{t-1} = (i_{t-1}, ..., i_{t-q}, c_{t-1}, ..., c_{t-q})$, which is assumed to be absolutely continuous in i_t for almost all S_{t-1} following Jeong et al. (2012). Then, the probability of $F_{i_t|S_{t-1}}\{Q_\rho(i_t|S_{t-1})\} = \rho$ will be 1 if denoting $Q_\rho(S_{t-1}) \equiv Q_\rho(i_t|S_{t-1})$. The hypotheses to be tested are thus formulated as:

$$H_0 = P\{F_{i_t|S_{t-1}}\{Q_\rho(i_t|S_{t-1})\} = \rho\} = 1 \quad (3)$$

$$H_1 = P\{F_{i_t|S_{t-1}}\{Q_\rho(i_t|S_{t-1})\} = \rho\} < 1 \quad (4)$$

To consistently test the hypothesis in Equation (3), a distance measure D proposed by Jeong et al. (2012) is used, and a feasible kernel-based method to estimate D as follows:

$$\hat{D}_T = \frac{1}{T(T-1)b^{2q}} \sum_{t=q+1}^{T} \sum_{k=q+1,\, k \neq t}^{T} K\left(\frac{S_{t-1} - S_{k-1}}{b}\right) \hat{\epsilon}_t \hat{\epsilon}_s \quad (5)$$

where $K(\cdot)$ is the kernel function with a bandwidth of b. T is the sample size, and $\hat{\epsilon}_t$ is an estimated regression error, specified as $\hat{\epsilon}_t = \mathbf{1}\{i_t \leq \hat{Q}_\rho(Z_{t-1})\} - \rho$. Using the nonparametric kernel method, the ρ th conditional quantile of i_t given I_{t-1} is further measured as $\widehat{Q}_\rho(I_{t-1}) = \widehat{F}^{-1}_{i_t|I_{t-1}}(\rho|I_{t-1})$, where the $\widehat{F}_{i_t|I_{t-1}}(i_t|I_{t-1})$ is the Nadaraya-Watson kernel estimator computed by $\frac{\sum_{k=q+1,\,k\neq t}^{T} K'\left(\frac{I_{t-1}-I_{k-1}}{b}\right)\mathbf{1}(i_k \leq i_t)}{\sum_{k=q+1,\,k\neq t}^{T} K'\left(\frac{I_{t-1}-I_{k-1}}{b}\right)}$ with the kernel function of $K'(\cdot)$ and a bandwidth of b.

4.3 Quantile-on-quantile regression

We follow Sim and Zhou (2015) to conduct the quantile-on-quantile (QQ) regression method to further investigate the risk spillovers of carbon futures with green asset index and financial asset index, respectively. Rather than the ordinary least squares (OLS) method and the quantile regression method, the QQ regression is robust to outliers and non-normality in real data, and is able to test the specific marginal influence between variables under each quantile (see, e.g., Ren et al., 2022; Duan et al., 2021). The QQ regression for the ϑ-quantile of index return (i.e., green asset index or financial asset index) $i_t \in (g_t, f_t)$ as a function of τ-quantile of carbon futures c_t, denoted by c^τ, is defined by using the first-order Taylor expansion:

$$i_t = \mu_0^\vartheta(c^\tau) + \mu_1^\vartheta(c^\tau)(c_t - c^\tau) + \varepsilon_t^\vartheta \tag{6}$$

The parameters of Eq. (6) are estimated by solving the following equation:

$$\begin{pmatrix} \hat{\mu}_0(\vartheta,\tau) \\ \hat{\mu}_1(\vartheta,\tau) \end{pmatrix} = \arg\min_{\mu_0,\,\mu_1} \sum_{t=1}^{T} \pi_\vartheta[i_t - \mu_0 - \mu_1(c_t - c^\tau)] K''\left(\frac{F(c_{t-1}) - \tau}{h}\right) \tag{7}$$

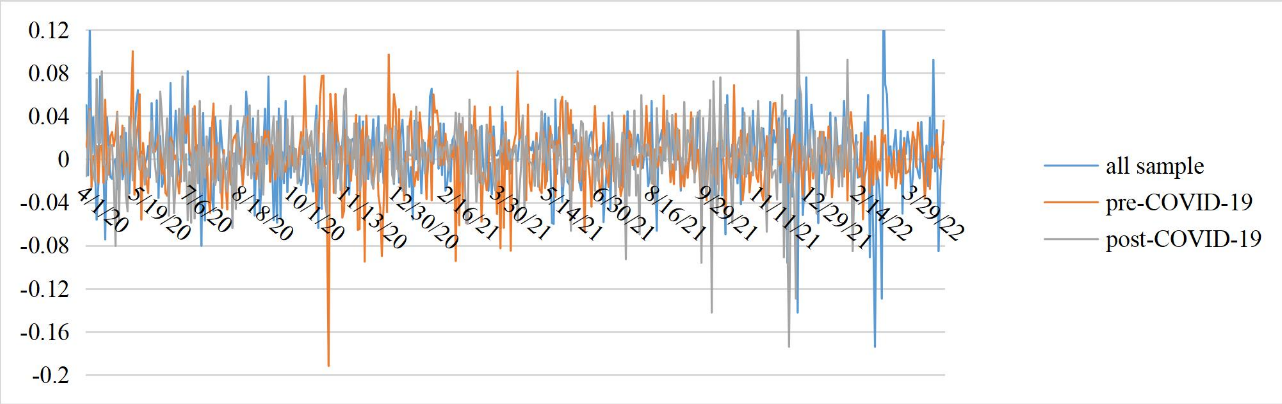
where $\pi_\vartheta(x) = x\big(\vartheta - A_{\{x<0\}}\big)$ with A_y being the function of the set y, $K''(\cdot)$ is the kernel function with a bandwidth of h.

5. Empirical Results

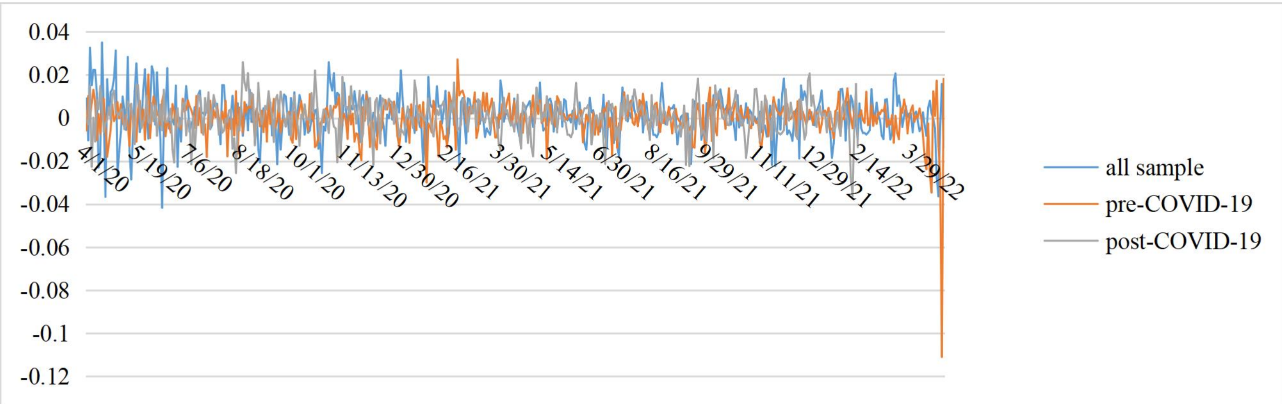
In this section, we discuss the empirical results of the analysis of the carbon market with green and traditional financial markets. Specifically, the downside risks measured by VaR are first explored in Section 4.1, and then quantile causality relationships between the carbon market and different types of financial markets are examined through the Granger test in Section 4.2. The spillovers of the carbon market with green and financial asset markets are further illustrated using QQ regression in Section 4.3. We also consider the pandemic onset and compare the results of the pre-COVID-19 and post-COVID-19 periods in these three sections. To further test the accuracy of our main results, we conduct two robustness checks by comparing QQ estimates using quantile regression (QR) and replacing one of the green indices.

5.1 Downside risk analysis

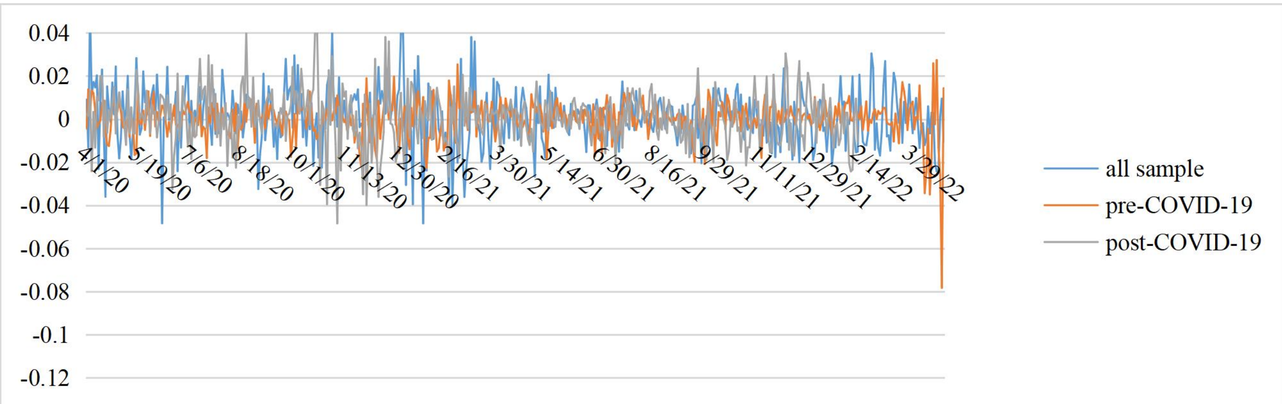
We use VaR estimates to measure the downside risks of the carbon market, green asset market, and traditional financial market. The VaR estimates for the 500-day forecast horizon are shown in Figure 2. The VaR of carbon futures fluctuate greatly compared to those of the green asset and financial asset indices, indicating that the carbon market represents a higher downside risk than the green and traditional finance markets. Moreover, higher volatilities are observed for carbon futures and the two financial indices during COVID-19 than before the pandemic. This implies that the downside risks are strengthened after the pandemic onset in all three markets, which is in line with the findings of Demiralay et al. (2022), suggesting that the risks of the carbon market and stock market rise during the COVID-19 period. When comparing the three markets, we observe that the VaR of carbon futures is the most volatile after the COVID-19 pandemic, showing that the carbon market is more vulnerable to structural breaks caused by COVID-19 than the green and traditional asset markets.



(a) Carbon futures



(b) Green asset index



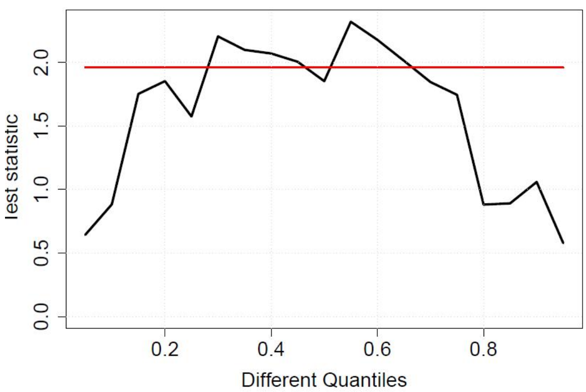
(c) Financial asset index

Figure 2. VaR of carbon and financial markets

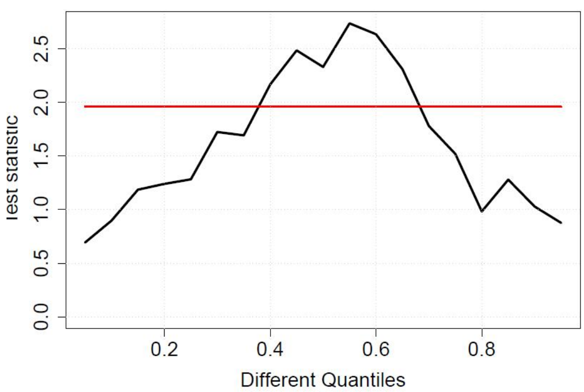
Note: This figure shows the estimated VaR series of carbon futures, green asset index, and financial asset index for the last 500-day forecast horizon (from 01 April 2020 to 30 April 2022). To clearly show the visible patterns, axis dispersions for VaR of carbon futures, green asset index, and financial asset index are set in a range of -0.2 and 0.12 (increasing by 0.04), -0.12 and 0.04 (increasing by 0.02), as well as -0.08 and 0.06 (increasing by 0.02), respectively.

5.2 Causality test analysis

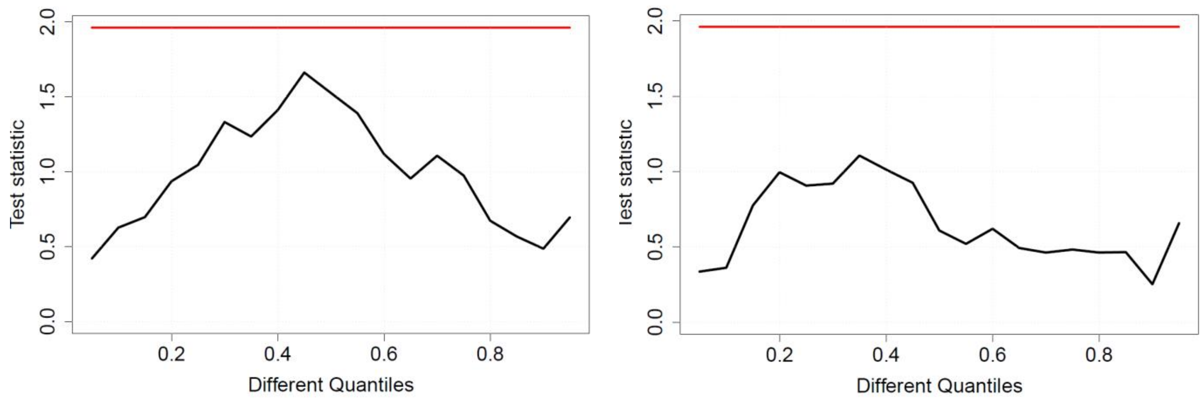
The quantile Granger causality results among carbon futures, green asset index, and financial asset index are shown in Figure 3. From Figures 3(a) and 3(b), we find that the null hypotheses of no Granger causality-in-quantile from carbon futures to both green asset and financial asset indices are rejected around the median quantile. This indicates that the carbon market can Granger cause green and traditional finance markets with regard to normal market conditions. However, the range of significant area of the Granger causality-in-quantile from carbon futures to the financial asset index (see Figure 3(b)) is larger than that of carbon futures to the green asset index (see Figure 3(a)). This suggests that the predictive power of the carbon market with respect to traditional market is stronger than with respect to the green market. Moreover, as shown in Figures 3(c) and 3(d), the null hypothesis of no Granger causality-in-quantile from green asset and financial asset indices to carbon futures cannot be rejected, meaning that green and traditional finance markets cannot Granger cause the carbon market. These findings reveal the existence of a unidirectional quantile causality relationship between carbon and different types of financial markets, being consistent with the findings of Ren et al. (2022), which shows that carbon futures price unilaterally Granger cause the green bond index.



(a) Carbon futures on green asset index



(b) Carbon futures on financial asset index

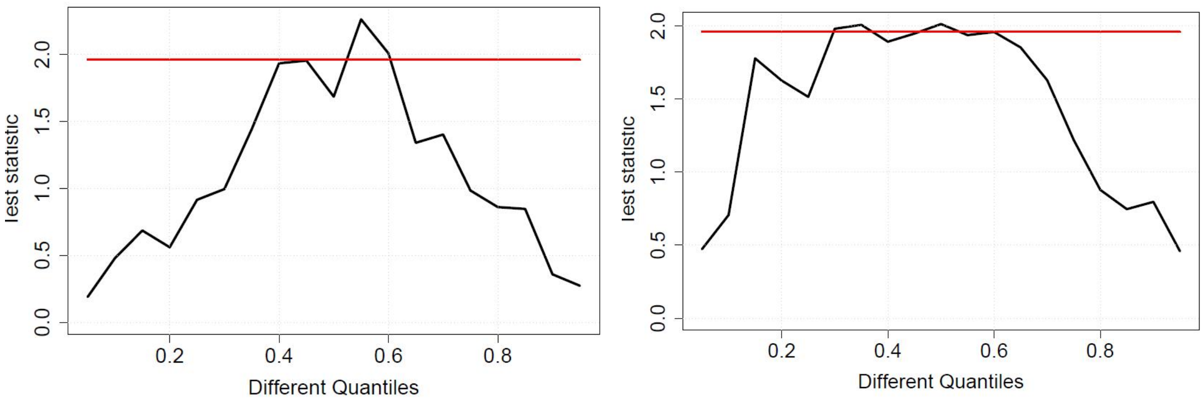


(c) Green asset on carbon futures (d) Financial asset index on carbon futures

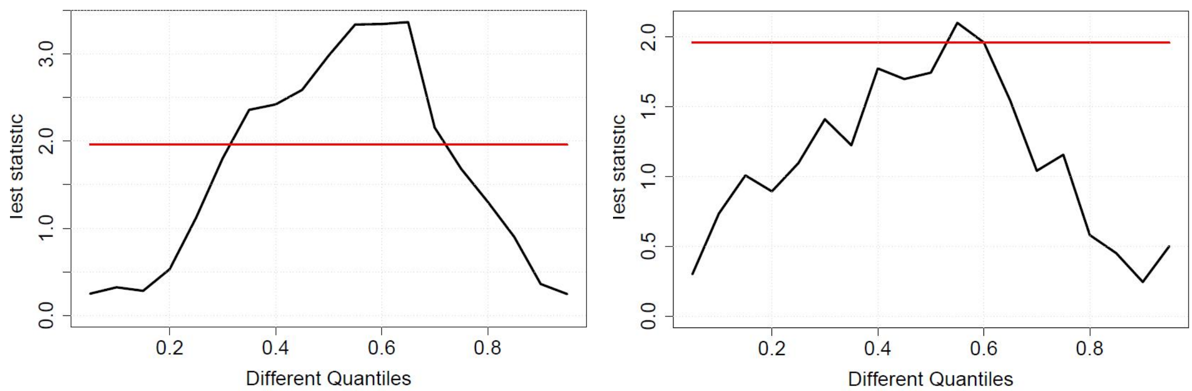
Figure 3. Granger causality-in-quantile test

Note: This figure displays the results of granger causality-in-quantile test among carbon futures, green asset index, and financial asset index. The horizontal red solid line denotes the estimate of the 5% critical value. The x-axis reports the quantile levels (a total of 19 from 0.05 to 0.95) and the y-axis shows the test statistics of the null hypothesis.

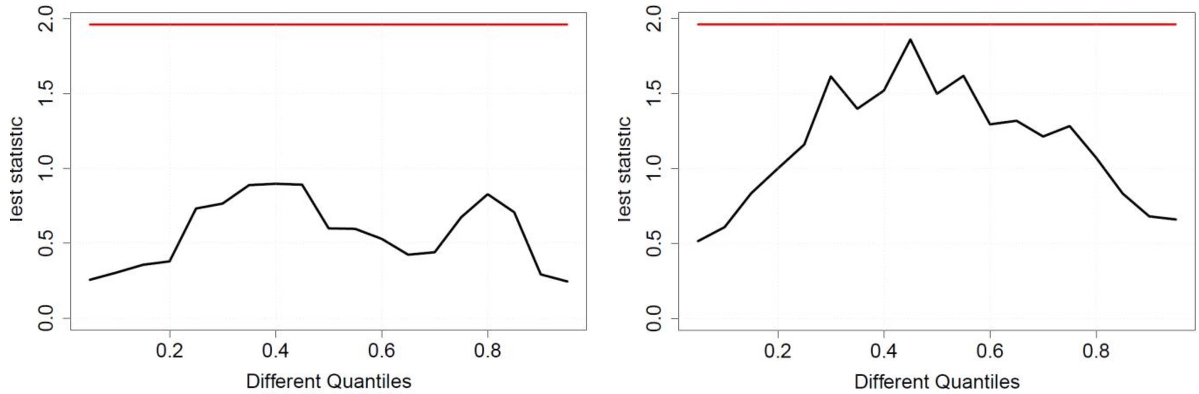
Moreover, when considering the impact of the pandemic onset, the quantile causality results of carbon futures with green asset and financial asset indices in the pre- and post-COVID-19 periods are presented in Figure 4. As seen in Figures 4(a) and 4(b), the range of significant area of the Granger causality-in-quantiles from carbon futures to green asset and financial asset indices are larger before COVID-19 than after the pandemic, showing that the pandemic onset greatly affects the Granger causality relationship between the carbon market and green and traditional finance markets. Notice that the impact of COVID-19 on the causality of carbon futures with financial asset index is much more significant compared to that with green assets. In addition, as presented in Figures 4(c) and 4(d), both the green asset index and financial asset index do not Granger cause carbon futures in the pre- and post-COVID-19 periods, which verifies the unidirectional relationship of the carbon market with both the green and traditional finance markets shown in Figure 3.



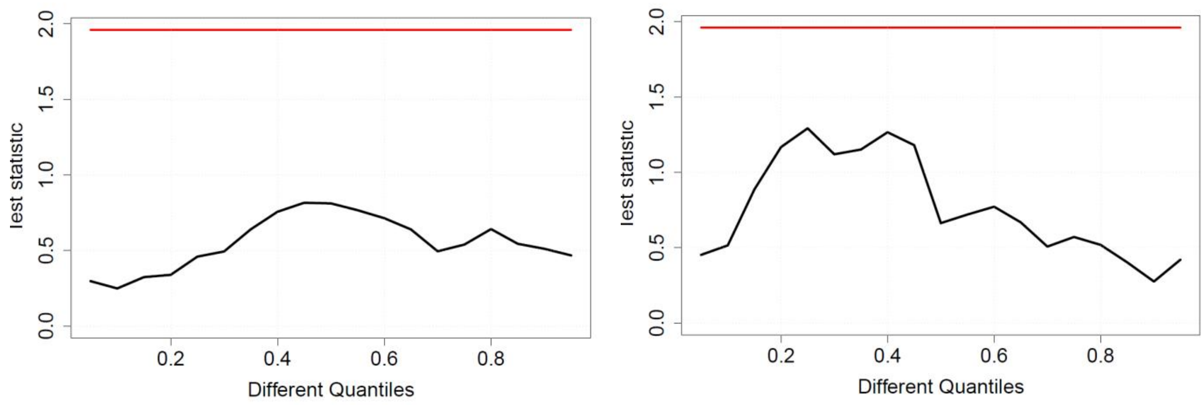
(a) Carbon futures on green asset index in the pre- and post-COVID-19 periods



(b) Carbon futures on financial asset index in the pre- and post-COVID-19 periods



(c) Green asset index on carbon futures in the pre- and post-COVID-19 periods



(d) Financial asset index on carbon futures in the pre- and post-COVID-19 periods

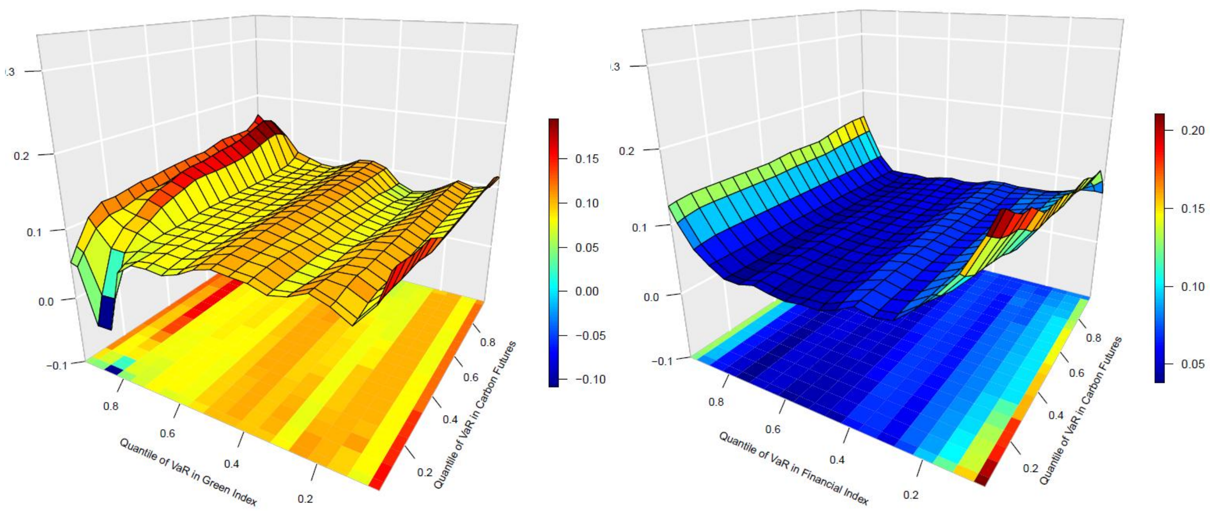
Figure 4. Granger causality-in-quantile test in the pre- and post-COVID-19 periods

Note: This figure shows the results of granger causality-in-quantile test among carbon futures, green asset index, and financial asset index in the pre- and post-COVID-19 periods. A detailed description of the horizontal red solid line as well as x-axis and y-axis is in note of Figure 3.

Overall, the empirical results of the causality test can be concluded as follows. First, carbon risk unidirectionally Granger causes the risk of both green and traditional finance markets, which supports Hypothesis 1 that *the carbon market has a unidirectional relationship with financial markets*. The corresponding significance is relatively strong, especially in normal market conditions. Second, the predictive power of the carbon market with respect to the traditional market appears to be stronger than with respect to the green market. Third, the causal relationship of the carbon market with green and traditional asset markets experienced an evident change from before to after the pandemic outbreak, and the significance of the causality is relatively weakened after the pandemic onset. This provides empirical evidence in support of Hypothesis 3 that *the pandemic onset changes the relationship between carbon and financial markets*. This finding is consistent with the existing literature (e.g., Ren et al., 2022), which states that carbon futures price unilaterally Granger causes the green bond index. Similarly, Hammoudeh et al. (2020) also find that there is a causal linkage from carbon futures price to the price of green bonds but not the other way around. Zhao et al. (2022) document that the causality from the stock market to the carbon market is significant and unidirectional.

5.3. Quantile-on-quantile regression analysis

Applying the QQ approach, the risk spillovers of the carbon market on green and traditional finance markets are obtained, and the results are displayed in Figure 5. It can be seen from Figure 5(a) that the impact of carbon futures on the green asset index is weak and positive in most conditions, indicating that the carbon market has a diversification effect on the green asset market. Moreover, a significant decline is observed when the quantile of VaR in the green asset index is high while that in carbon futures is extremely low. This shows the hedging role of the carbon market in the joint condition of a highly risky green asset market and a relatively low-risk carbon market. These findings are in line with those of Rannou et al. (2021) and Jin et al. (2020). Rannou et al. (2021) provide a possible explanation for this: power firms may progressively abandon carbon markets to issue more green bonds to finance their transmission to clean energy production systems, which prompts a depression in the carbon market and makes the green asset market highly active. In this context, green bonds are substitutes for carbon futures, resulting in the carbon market having a risk-hedging effect on the green asset market.



(a) Impact of carbon futures on green asset index (b) Impact of carbon futures on financial asset index

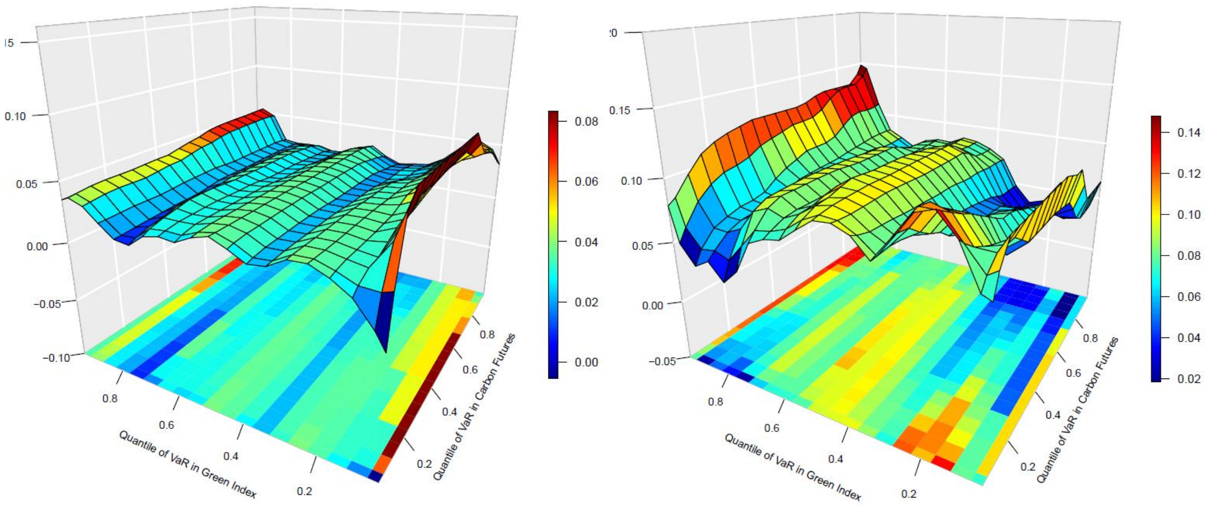
Figure 5. QQ regression results for the impact of carbon futures on financial assets

Note: This figure exhibits risk spillovers of carbon futures on green asset index and financial asset index. The x-axis and y-axis report the quantile levels (a total of 19 from 0.05 to 0.95) and the z-axis shows the values regarding the impact of carbon futures on financial assets.

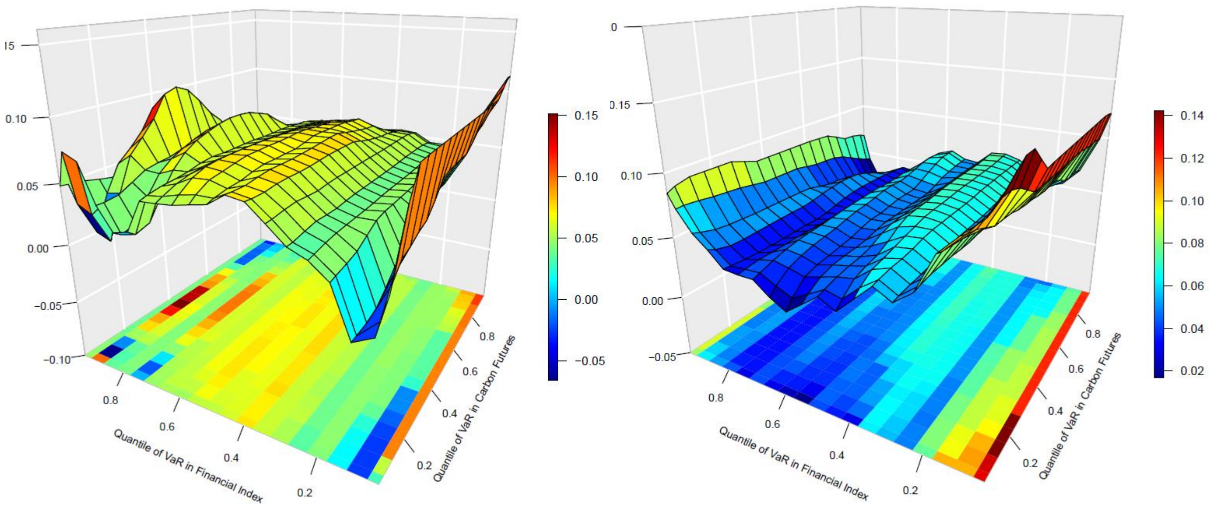
Moreover, as shown in Figure 5(b), the impact of carbon futures on financial asset index is mostly positive and relatively stable, and this relationship reaches a peak when both the VaR in the financial asset index and carbon futures are at extremely low quantiles. This indicates the diversification effect of the carbon market on the traditional financial market, which is consistent with Wen et al. (2020), who show that China's carbon emissions trading market has a positive impact on companies' stock returns, and Demiralay et al. (2022), who show that carbon commodities have diversification potential for equities. These results can be explained by the hypothesis that stock returns exist as a carbon premium, since companies participating in the carbon market have higher carbon exposures and might face higher carbon prices to face catastrophic climate change. Meanwhile, carbon risk is non-diversifiable, which generates a risk premium determined by societal risk aversion.

Next, we decompose our QQ regression analysis of the impact of the carbon market on financial markets into two sub-samples of the pre- and post-COVID-19 periods, and the results are displayed in Figure 6. Overall, the pandemic onset is found to alter the risk spillover pattern between the carbon market and two types of financial markets. Specifically, as represented in Figure 6(a), the relationship from carbon futures to green asset index is mostly positive before the COVID-19 pandemic, but this relationship turns negative when their VaR is at extremely low quantiles. This shows the risk diversification of carbon futures on green assets in most conditions, along with the existence of a risk hedging effect when the risk associated with these two markets is relatively low in the pre-COVID-19 period. However, in the post-COVID-19 period, the impact of carbon futures on the green asset index is always positive and reaches a peak at extremely high quantiles of VaR in carbon futures and green asset index, indicating that the carbon market has a diversification effect on the green asset market over different quantiles of the distribution.

These findings suggest that the COVID-19 pandemic influences the impact of the carbon market on the green asset market, which supports the argument of Wang et al. (2022) that turbulence in financial markets can exacerbate network connectivity and that this characteristic is particularly evident during the COVID-19 pandemic, thus driving increased linkages between carbon and green bonds. Li et al. (2022) explain that the pandemic onset accelerates the transition of the energy mix toward renewable energy sources. Thus, more and more enterprises are under pressure to transition to a low-carbon economy during the pandemic and will invest more in green bonds. This leads to a closer relationship between the carbon market and the green asset market.



(a) Impact of carbon futures on green asset index in the pre- and post-COVID-19 periods



(b) Impact of carbon futures on financial asset index in the pre- and post-COVID-19 periods

Figure 6. QQ regression results for the impact of carbon futures on financial assets in the pre- and post-COVID-19 periods

Note: This figure shows risk spillovers of carbon futures on green asset index and financial asset index in the pre- and post-COVID-19 period. A detailed description of x-axis and y-axis is in note of Figure 5.

As for the impact of carbon futures on the traditional asset index before and after the COVID-19 pandemic shown in Figure 6(b), we find results similar to the effect on the green asset index. That is, the carbon market has a diversification effect on the traditional finance market in most instances, but there exists a risk hedging effect in some joint conditions in the pre-COVID-19 period, while after the COVID-19 pandemic, the carbon market is always risk-diversified in the traditional finance market. There are only two main differences between the relationship of carbon futures with the traditional asset index and carbon futures' relationship with the green asset index. First, the hedging role of carbon before COVID-19 is found in multiple joint conditions when both carbon and traditional finance markets are at relatively low risk levels or when the risk of the traditional finance market is extremely high and the risk associated with the carbon market is either extremely low or relatively high. Second, the relationship after the pandemic reaches its peak when the risks of both carbon and traditional finance markets are extremely low.

From the above findings, we can conclude that COVID-19 alters the impact of the carbon market on the traditional finance market, which is supported by the findings of Zhao et al. (2022), who find that the COVID-19 pandemic weakens the positive effect of the carbon market on the stock market. This is reasonable due to the fact that a large number of enterprises are under pressure to transition to a low-carbon economy during the pandemic (Li et al., 2022). Moreover, the stock return exists at a lower carbon premium since enterprises participating in the carbon market have fewer carbon exposures before the pandemic (Demiralay et al., 2022). Thus, the positive effect of the carbon market on the stock market is weakened during the COVID-19 pandemic.

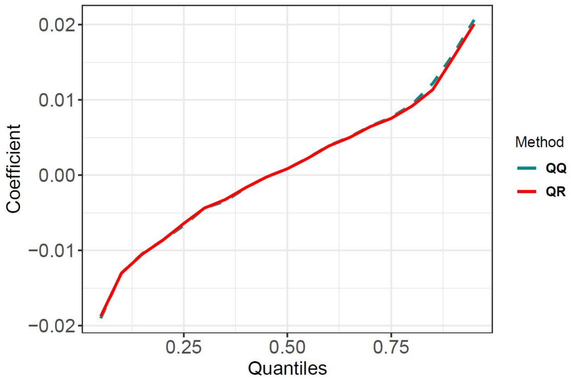
Overall, our empirical findings of quantile-on-quantile regression can be concluded as follows. First, the impact of carbon commodities on green asset index is weakly positive in most conditions, indicating the diversification effect of carbon on green investments. Second, the sheltering role of carbon commodities is further enhanced as a hedge, particularly against green asset index in specific conditions of a highly risky green asset market and relatively low-risk carbon market. The findings are consistent with the existing literature (see, e.g., Rannou et al., 2021), which states that green bonds complement carbon futures used for firms' short-term hedging and act as a substitute for carbon futures for firms' long-term hedging. In addition, the results are in line with Jin et al. (2020), who show that green bonds serve as an effective hedge for adverse fluctuations in carbon risk. Third, similar to the green asset index, the risk spillover effects of carbon futures on traditional assets are positive, with magnitudes lower than one, indicating the diversification effect of carbon commodities on the financial asset index. This is consistent with the existing findings of a positive relation between carbon and stock returns (Wen et al., 2020), as exemplified by the positive impact of China's carbon emissions trading market on companies' stock returns. Demiralay et al. (2022) also report the diversification potential of carbon commodities for equities. The above findings empirically support Hypothesis 2 that *the relationship of the carbon market with financial markets is weakly positive and varies in different market conditions and for different financial asset types.* Fourth, the pandemic onset is found to alter the risk spillover pattern between the carbon market and financial markets; in particular, the risk spillovers of carbon–financial market linkages are closer after the pandemic onset. Such empirical evidence is in line with Hypothesis 3 that *the pandemic onset changes the relationship between carbon and financial markets* and corroborates existing findings (e.g., Wang et al., 2022) that financial turbulence would drive increasing connectivity of the network across financial markets.

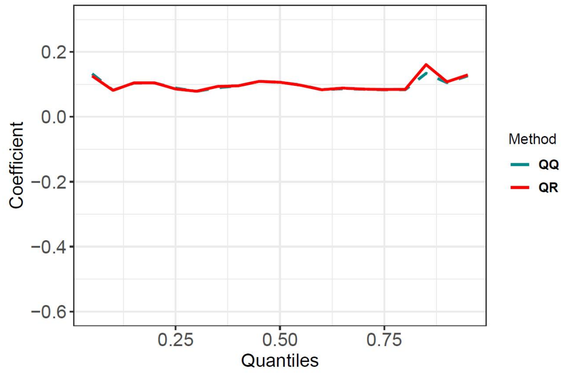
5.4. Robustness

How robust are our findings to changes in the research design? In this section, we test accordingly and show that our results remain consistent with an alternative estimation strategy, the replacement of key research variables, and an alternative forecast horizon of the VaR calculation.

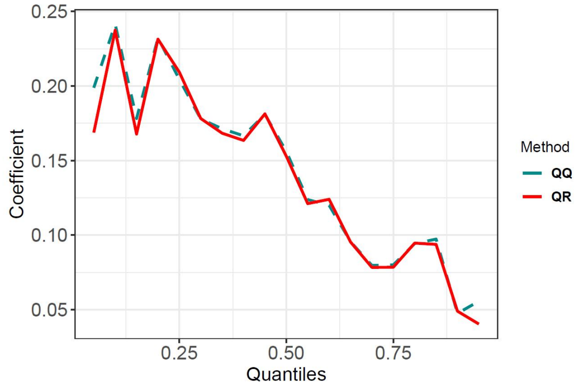
5.4.1 Alternative estimation technique: The τ-averaged QQ estimation and quantile regression

To examine the validity of our main findings, following the existing literature (Duan et al., 2021), we obtain the results of the τ-averaged QQ estimation and the QR in the same plot and then compared the tendency of both results across quantiles. The corresponding results comparison is reported in Figures 7 and 8. Specifically, for the carbon and green asset markets (see Figure 7), the results for the intercept of carbon futures, the impact of carbon futures on green asset index, and the impact of lagged green asset index obtained by the QR method (represented by the solid red lines) and the QQ regression method (represented by the dashed green lines) almost coincide. For the carbon market and traditional finance market (see Figure 8), the results of the QR method and QQ regression method are not much different, except that the impact of lagged financial asset index obtained by the QQ method is slightly larger than that obtained by the QR method.





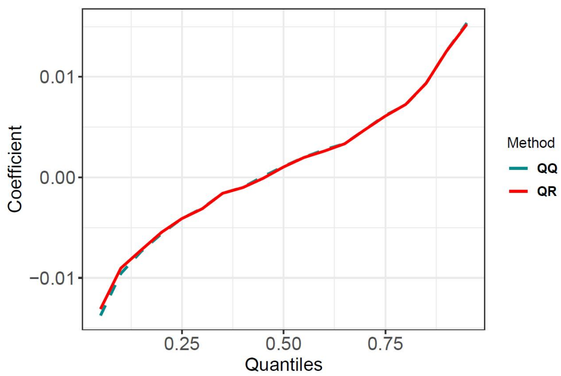
(a) Intercept of green asset index (b) Impact of carbon futures on green asset index

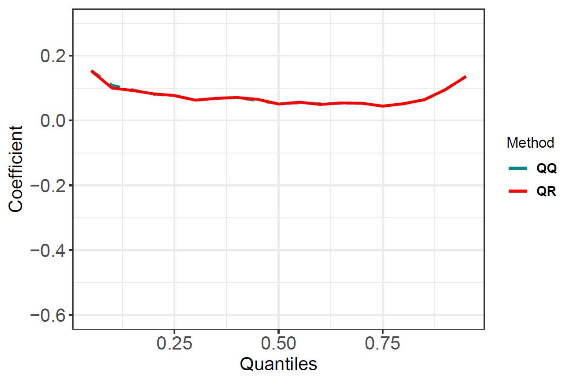


(c) Impact of carbon futures on lagged green asset index

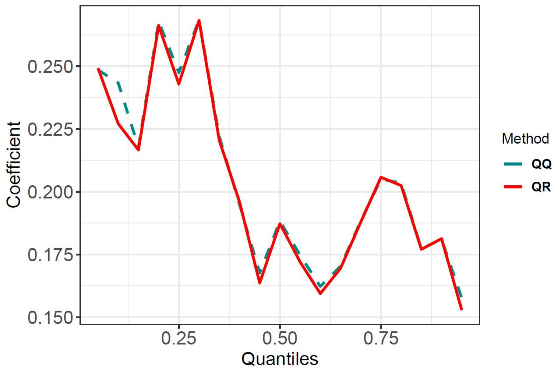
Figure 7. Comparison of the results from QR and QQ estimates (carbon futures and green asset index)

Note: This figure displays estimates of QR and QQ parameters regarding the averaged impacts of carbon futures on green asset index. The x-axis reports the quantile levels (a total of 19 from 0.05 to 0.95) and the y-axis shows the values of QR and QQ parameters.





(a) Intercept of financial asset index (b) Impact of carbon futures on financial asset index



(c) Impact of carbon futures on lagged financial asset index

Figure 8. Comparison of the results from QR and QQ estimates (carbon futures and financial asset index)

Note: This figure plots estimates of QR and QQ parameters regarding the averaged impacts of carbon futures on financial asset index. A detailed description of x-axis and y-axis is in note of Figure 7.

5.4.2 Replacement of series of financial assets

To further examine the robustness of our main results regarding the risk spillover effect of the carbon market on financial markets, we follow Ren and Lucey in replacing the S&P Global Clean Energy Index (GCEI) with the WilderHill Clean Energy Index (CEI) in the construction of green asset index, and the QQ regression results for the relationship from the carbon market to green asset market are shown in Figure 9. Overall, the results presented in Figure 9 are not much different from the risk spillover pattern before the replacement reported in Figure 5(a). This further supports our conclusion that carbon commodities have a risk diversification effect on green assets in most conditions. Thus, our results are not sensitive to the variable replacement of the employed green assets.

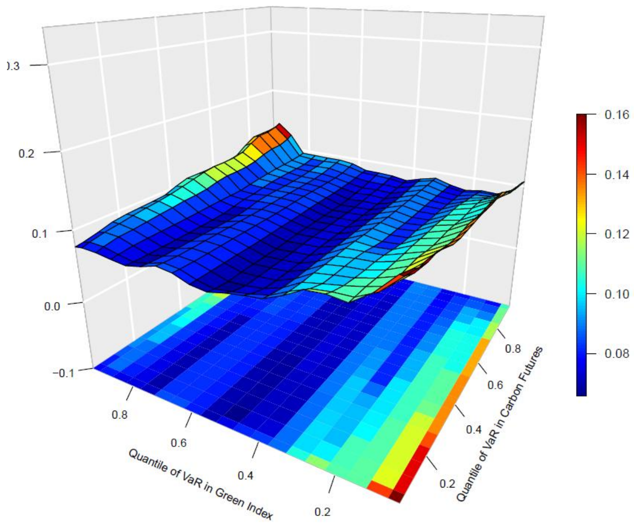
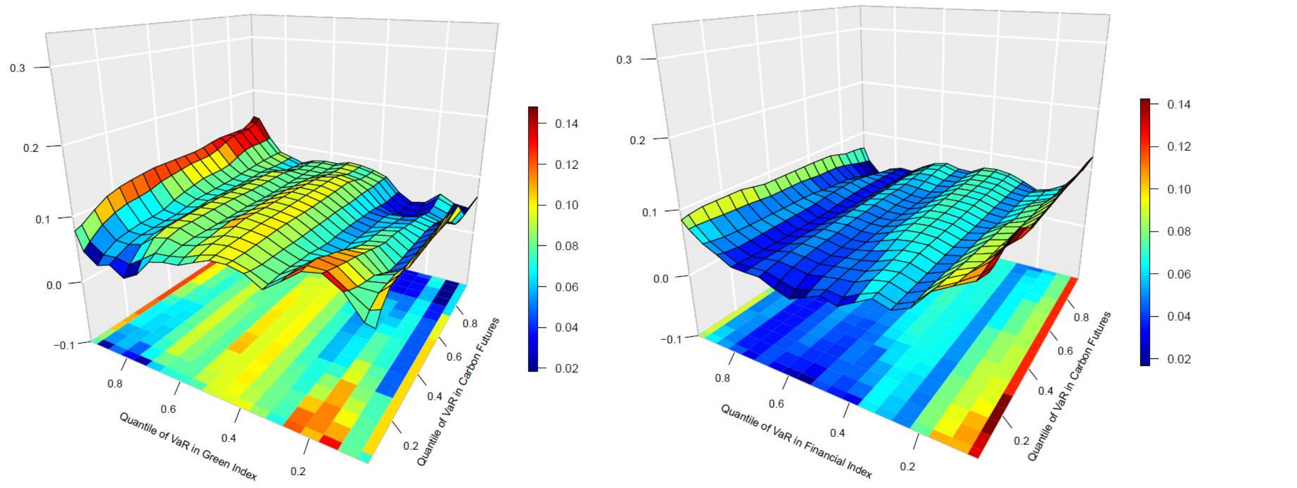


Figure 9. QQ regression results for the impact of carbon futures on adjusted green asset index

Note: This figure depicts risk spillovers of carbon futures on adjusted green asset index. A detailed description of x-axis and y-axis is in note of Figure 5.

5.4.3 Alternative forecast horizon of the VaR calculation

As an additional robustness test, we re-estimate the risk measure of VaR by using an alternative forecast horizon. Specifically, following the extant literature (e.g., Alexander et al., 2013; Li et al., 2020; Peng et al., 2018), we updated the forecast horizon to 450 working days for the VaR calculation using the univariate GARCH rolling density forecast. The cross-market relationships of carbon commodities with green and traditional financial assets shown in Figure 10 are generally consistent with those obtained in our main findings shown in Figure 5, although the impacts of carbon futures in the extreme quantiles are relatively weak. This indicates that our results remain robust in the face of changes in VaR calculation.



(a) Impact of carbon futures on green asset index (b) Impact of carbon futures on financial asset index

Figure 10. QQ regression results for the impact of carbon futures on financial assets with changes in forecast horizon of the VaR calculation

Note: This figure shows risk spillovers of carbon futures on green asset index and financial asset index with the alternative forecast horizon of the VaR calculation. A detailed description of x-axis and y-axis is in note of Figure 5.

6. Conclusion

This paper investigates the asymmetric risk spillovers between the carbon market and different financial markets with traditional and green types using a quantile-based research framework. This asymmetry has been examined from perspectives of the joint data distribution of the above two markets, different types of financial markets, and the COVID-19 pandemic outbreak. The dynamics of both traditional and green asset markets are represented in the form of a value-weighted index that is calculated using the world's major assets in the corresponding market types. The risk level associated with each target market is measured by its value at risk. The spillover direction is examined using a non-parametric causality-in-quantile test, and the corresponding magnitude of the spillover across the joint distribution of both dependent and independent variables is further gauged using a quantiles-on-quantiles approach.

Speaking in favor of established research hypotheses, our empirical results reveal a greater downside risk in the carbon market compared to that of green and traditional finance markets, and the risk strengthened after the onset of the pandemic in all three markets. Moreover, there is one-way causality regarding the risk spillover from carbon to financial markets over the data distribution. The relationship between the carbon market and financial markets is shown to be weak and positive across different quantiles of the data distribution, indicating the general diversification gain provided by carbon commodities for adverse fluctuations in financial assets. The investment sheltering role of carbon commodities can be further strengthened in particular conditions when the risk level in the green market is high and that in the carbon market is low. In addition, the cross-market risk spillover is found to be dynamic and intensified after the pandemic onset.

The results of the quantile-based approaches employed offer important implications against their conventional mean-based counterparts. The quantile causality test reveals that the causal relationship is unidirectional from carbon to financial markets and that the significance of this relationship is strengthened in normal market conditions represented by median quantiles. This indicates a weak predictability of the risk dynamics of carbon to that of financial assets in extreme conditions of market negativity and positivity. Stakeholders can exploit carbon market information in the prediction of risk dynamics in financial markets, especially in normal market conditions. The quantile-on-quantile estimation reveals weakly positive impacts of risk in the carbon market on that in financial markets. Although depicting slight differences, the weak positivity of the impact generally remains consistent across the data distribution and for different financial market types. Overall, a clear comprehension of the diversification role of carbon commodities against adverse fluctuations of both traditional and green assets, especially under normal conditions, allows policymakers to implement effective prevention measures concerning an overheated economy and excessive risks in the financial system. The findings also help market investors optimize the risk management and composition of their investment portfolios of financial assets through the use of carbon commodities. Interpretation of different patterns of the risk spillover of the carbon market with traditional and green financial markets further helps investors better diversify their investments by optimizing portfolio structure, thus contributing to green economic transition and environmental protection.

References

Alexander, C., Lazar, E., & Stanescu, S. (2013). Forecasting var using analytic higher moments for GARCH processes. *International Review of Financial Analysis*, 30, 36–45.

Bannigidadmath, D., & Narayan, P. K., (2022). Economic importance of correlations for energy and other commodities. *Energy Economics*, 107, 105854.

Ben Amar, A., Bélaïd, F., Ben Youssef, A., & Guesmi, K., (2021). Connectedness among regional financial markets in the context of the COVID-19. *Applied Economics Letters*, *28*(20), 1789–1796.

Balcilar, M., Demirer, R., Hammoudeh, S., & Nguyen, D. K. (2016). Risk spillovers across the energy and carbon markets and hedging strategies for carbon risk. *Energy Economics*, 54, 159–172.

Candelon, B. & Tokpavi, S. (2016). A nonparametric test for Granger causality in distribution with application to financial contagion. *Journal of Business and Economic Statistics*, 34(2), 240–253.

Demiralay, S., Gencer, H. G., & Bayraci, S. (2022). Carbon credit futures as an emerging asset: Hedging, diversification and downside risks. *Energy Economics*, 113, 106196.

Dong, Q., Huo, D., & Wang, K. (2023). Risk measurement and application of the international carbon market in the era of global conflict: A data-driven study using FCM. *Journal of Environmental Management*, 342, 118251.

Duan, K., Ren, X., Shi, Y., Mishra, T., & Yan, C. (2021). The marginal impacts of energy prices on carbon price variations: evidence from a quantile-on-quantile approach. *Energy Economics*, 95, 105131.

Duan, K., Zhao, Y., Wang, Z., & Chang, Y. (2023). Asymmetric spillover from Bitcoin to green and traditional assets: A comparison with gold. *International Review of Economics & Finance*, 88, 1397–1417.

Fasanya, I. O., Oliyide, J. A., Adekoya, O. B., & Agbatogun, T. (2021). How does economic policy uncertainty connect with the dynamic spillovers between precious metals and bitcoin markets?. *Resources Policy*, 72, 102077.

Feng, H., Gao, D., Duan, K., & Urquhart, A. (2023). Does Bitcoin affect decomposed oil shocks differently? Evidence from a quantile-based framework. *International Review of Financial Analysis*, 89, 102756.

Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics*, 142(2), 499-516.

Harjoto, M. A., Rossi, F., & Paglia, J. K. (2021). COVID-19: Stock market reactions to the shock and the stimulus. *Applied Economics Letters*, *28*(10), 795–801.

Hammoudeh, S., Ajmi, A. N., & Mokni, K. (2020). Relationship between green bonds and financial and environmental variables: A novel time-varying causality. *Energy Economics*, 92, 104941.

Huang, Y., Duan, K., & Mishra, T. (2021). Is Bitcoin really more than a diversifier? A pre-and post-COVID-19 analysis. *Finance Research Letters*, 43, 102016.

Huang, Y., Duan, K., & Urquhart, A. (2023). Time-varying dependence between Bitcoin and green financial assets: A comparison between pre-and post-COVID-19 periods. *Journal of International Financial Markets, Institutions and Money*, 82, 101687.

Jeong, K., Härdle, W. K., & Song, S. (2012). A consistent nonparametric test for causality in quantile. *Econometric Theory*, 28(4), 861-887.

Jiang, W., & Chen, Y. (2022). The time-frequency connectedness among metal, energy and carbon markets pre and during COVID-19 outbreak. *Resources Policy*, 77, 102763.

Jiménez-Rodríguez, R. (2019). What happens to the relationship between EU allowances prices and stock market indices in Europe? *Energy Economics*, 81, 13–24.

Jin, J., Han, L., Wu, L., & Zeng, H. (2020). The hedging effect of green bonds on carbon market risk. *International Review of Financial Analysis*, 71, 101509.

Jorion, P. (2007). *Value at risk: The new benchmark for managing financial risk (3rd ed.)*. New York: McGraw-Hill.

Jusoh, H., El Alaoui, A.O., Dchieche, A., Ismail, A. F., & Rosalan, A. L. I. (2023). Relationship Between Bitcoin and Islamic Stock Indices During the COVID-19 Pandemic and the Russia-Ukraine Crisis. *Asian Economics Letters*, *4*(Early View).

Goodell, J. W., & Goutte, S. (2021). Diversifying equity with cryptocurrencies during COVID-19. *International Review of Financial Analysis*, 76, 101781.

Le, L. T. N., Yarovaya, L., & Nasir, M. A. (2021). Did COVID-19 change spillover patterns between Fintech and other asset classes? *Research in International Business and Finance*, 58, 101441.

Li, H., Zhou, D., Hu, J., & Guo, L. (2022). Dynamic linkages among oil price, green bond, carbon market and low-carbon footprint company stock price: Evidence from the TVP-VAR model. *Energy Reports*, 8, 11249–11258.

Li, K., Qi, S., & Shi, X. (2022). The COVID-19 pandemic and energy transitions: Evidence from low-carbon power generation in China. *Journal of Cleaner Production*, 368, 132994.

Liu, J., Mao, W., & Qiao, X. (2023). Dynamic and asymmetric effects between carbon emission trading, financial uncertainties, and Chinese industry stocks: Evidence from quantile-on-quantile and causality-in-quantiles analysis. *North American Journal of Economics and Finance*, 65, 101883.

Liu, M. (2022). The driving forces of green bond market volatility and the response of the market to the COVID-19 pandemic. *Economic Analysis and Policy*, 75, 288–309.

Narayan, P. K., (2021). COVID-19 research outcomes: An agenda for future research. *Economic Analysis and Policy*, *71*, 439–445.

Nishiyama, Y., Hitomi, K., Kawasaki, Y., & Jeong, K. (2011). A consistent nonparametric test for nonlinear causality—Specification in time series regression. *Journal of Econometrics*, 165(1), 112-127.

Peng, C., Zhu, H., Guo, Y., & Chen, X. (2018). Risk spillover of international crude oil to China's firms: Evidence from granger causality across quantile. *Energy Economics*, 72, 188–199.

Qiu, L., Chu, L., Zhou, R., Xu, H., & Yuan, S. (2023). How do carbon, stock, and renewable energy markets interact: Evidence from Europe. *Journal of Cleaner Production*, 407, 137106.

Rannou, Y., Boutabba, M. A., & Barneto, P. (2021). Are Green Bond and Carbon Markets in Europe complements or substitutes? Insights from the activity of power firms. *Energy Economics*, 104, 105651.

Reboredo, J. C., & Ugolini, A. (2020). Price connectedness between green bond and financial markets. *Economic Modelling*, 88, 25–38.

Ren, X., Wang, R., Duan, K., & Chen, J. (2022). Dynamics of the sheltering role of Bitcoin against crude oil market crash with varying severity of the COVID-19: A comparison with gold. *Research in International Business and Finance,* 62, 101672.

Sim, N. & Zhou, H. (2015). Oil prices, US stock return, and the dependence between their quantiles. *Journal of Bank and Finance*, 55(6), 1–8.

Sun, X., Fang, W., Gao, X., An, H., Liu, S., & Wu, T. (2022). Complex causalities between the carbon market and the stock markets for energy intensive industries in China. *International Review of Economics and Finance*, 78, 404–417.

Tan, X., Sirichand, K., Vivian, A., & Wang, X. (2020). How connected is the carbon market to energy and financial markets? A systematic analysis of spillovers and dynamics. *Energy Economics*, 90, 104870.

Tolliver, C., Keeley, A. R., & Managi, S. (2020). Policy targets behind green bonds for renewable energy: Do climate commitments matter? *Technological Forecasting and Social Change*, 157, 120051.

Wang, X., Li, J., & Ren, X. (2022). Asymmetric causality of economic policy uncertainty and oil volatility index on time-varying nexus of the clean energy, carbon and green bond. *International Review of Financial Analysis*, 83, 102306.

Wei, P., Qi, Y., Ren, X., & Duan, K. (2022). Does economic policy uncertainty affect green bond markets? Evidence from wavelet-based quantile analysis. *Emerging Markets Finance and Trade*, 58(15), 4375–4388.

Wen, F., Zhao, L., He, S., & Yang, G. (2020). Asymmetric relationship between carbon emission trading market and stock market: Evidences from China. *Energy Economics*, 91, 104850.

Xiao, Z., & Koenker, R. (2009). Conditional quantile estimation for generalized autoregressive conditional heteroscedasticity models. *Journal of the American Statistical Association*, 104(488), 1696-1712.

Xue, W., Zhu, C., & Hu, Y. (2023). The Dynamic Impact of World Pandemic Uncertainty on Stock Market Crash Risk: An International Study. *Asian Economics Letters*, 4(Early View).

Yuan, N., & Yang, L. (2020). Asymmetric risk spillover between financial market uncertainty and the carbon market: A GAS–DCS–copula approach. *Journal of Cleaner Production*, 259, 120750.

Zhang, Y., & Xu, S. (2023). Spillover connectedness between oil and China's industry stock markets: A perspective of carbon emissions. *Finance Research Letters*, 54, 103736.

Zhao, L., Liu, W., Zhou, M., & Wen, F. (2022). Extreme event shocks and dynamic volatility interactions: The stock, commodity, and carbon markets in China. *Finance Research Letters*, 47, 102645.

Zhao, Z., Lau, C. K. M., Soliman, A., & Farhani, S. (2023). Energy commodity and stock market interconnectedness: Evidence from carbon emission trading system. *Technological Forecasting and Social Change*, 194, 122669.

Appendix A. Summary of the key literature

Table A1. Summary of the key literature

Authors	Method	Period	Main Variables	Main Finding
Wen et al. (2020)	NARDL model	2013.08.09-2019.04.19	Shenzhen carbon emission trading market, energy intensive sectors and stock market in China	1. Carbon emission trading markets affect both overall and sector level of stock markets in China. 2. Negative long-run asymmetry is found between overall stock market and carbon emission trading market. 3. Carbon prices connect with energy-intensive sectors.
Yuan and Yang (2020)	GAS-DCS-copula approach	2019.01.16-2019.09.26	EU carbon trading market, European stock market uncertainty, Chicago Board Options Exchange crude oil volatility index (OVX)	The existence of considerable asymmetric risk spillover from financial market uncertainty to the carbon market is examined.
Sun et al. (2022)	Pattern Causality method	2013.12.19-2020.09.22	Guangdong carbon emissions trading market, industry index	There exists weak bidirectional causality between carbon market and stock markets
Zhao et al. (2022)	TVP-Vector Autoregressive (VAR) Model	2014.04.28-2021.01.29	Hubei carbon market, Chinese stock market, commodity market in China	1. Stock market unidirectionally Granger causes the carbon market 2. The impact of the carbon market on the stock market fluctuate over time. 3. Sudden extreme events have significant effects on market volatility interactions.
Demiralay et al. (2022)	DCC model	2014.7.31-2021.7.30	Global carbon index, global stock market, global commodity	1. Carbon has hedging and diversification potential for equities, overall. 2. The hedging and diversification effect of carbon futures is weakened during the COVID-19 pandemic.

Xu et al. (2022)	VAR, MFCCA	2014.11-2019.11	Carbon-intensive industry index, industry stock markets in China	Stock returns of carbon-intensive industries and carbon price returns are positively cross-correlated in Shenzhen and Shanghai pilots, while the cross-correlations are negative in Beijing, Guangdong, and Hubei pilots in China.
Li et al. (2022)	Modified DID models	2018.7-2020.6	Monthly power generation, energy production and weather conditions in China	1. The COVID-19 pandemic has increased the low-carbon power generation by 4.59%. 2. The pandemic has accelerated the transition of the energy mix toward renewable energy sources.
Jin et al. (2020)	DCC-APGARCH, DCC-T-GARCH, DCC-GJR-GARCH	2008.12.01-2018.08.31	EUA Carbon futures prices, CBOE VIX index, global green bond, world's commodity index, energy index around the world	Green bond index is an effective hedge for carbon futures and it performs well even during the period of depression.
Hammoudeh et al. (2020)	forward-recursive, rolling and recursive evolving causality	2014.07.30-2020.02.10	S&P green bond index, CO2 emission allowances price in US, US conventional bonds, WilderHill clean energy index	1. The causal relationship of carbon prices to green bonds is shown to be generally significant. 2. There is no significant causality from green bonds to all assets under research.
Wang et al. (2021)	DCC-MIDAS model	2012.03.01-2022.03.02	S&P global clean energy index, EUA, S&P green bond index	1. Turbulence in financial markets can exacerbate the cross-market network connectivity, particularly during the COVID-19 pandemic. 2. EPU serves as a strong predictor in the correlation of clean energy, green bonds, and carbon.

Rannou et al. (2021)	Causality tests, VAR analysis	2013.1-2020.12	EUA ECX, green bonds issued by power firms on European stock exchanges	1. Green bonds complement carbon futures used for firms' short-term hedging. 2. Green bonds act as a substitute to carbon futures used for firms' long-term hedging.
Ren et al. (2022)	MODWT	2013.01.08-2021.03.10	ECX EUA carbon futures prices, S&P green bond index	1. Carbon price Granger causes green bonds, and the causality depicts an evident asymmetry from the quantile Granger test. 2. The impacts of carbon price on green bonds are positive across most quantiles of the data distribution.
Li et al. (2022)	TVP-VAR model	2017.6-2021.5	WTI, SSE green bond index, carbon emission trading price in Beijing, SSE carbon efficiency 180 index	The green bond index has a positive impact on the carbon price in the short and medium terms, and a negative impact on the carbon market efficiency.