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Economic Policy Uncertainty, Geopolitical Dynamics, Energy Prices, and Green Bond Returns

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Abstract

This study investigates the asymmetric effects of economic policy uncertainty (EPU), geopolitical risk (GPR), and liquefied natural gas (LNG) prices on green bond returns in China from August 2012 to July 2022. Using quantile-on-quantile regression (QQR), quantile Granger causality, and wavelet coherence analysis, we examine the relationships between these factors and green bond prices across different quantiles. Our findings reveal significant asymmetric impacts of EPU, GPR, and LNG prices on Chinese green bond returns. Specifically, EPU, geopolitical threats (GPRT) and LNG prices show strong positive effects on green bonds across most quantiles and frequencies. In contrast, geopolitical acts (GPRA) generally exhibit negative relationships with green bond returns. The quantile Granger causality tests confirm bidirectional relationships between the variables across multiple quantiles. The wavelet coherence analysis demonstrates time-varying co-movements between the factors and green bond prices, with stronger correlations observed in recent years, particularly at medium to high frequencies.

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The results show that green bonds can be used as an effective hedge against economic uncertainty and geopolitical risks. At the same time, the findings have important implications for investors, policymakers, and market participants to develop effective risk management strategies and promote sustainable finance in the face of global economic and geopolitical challenges.

Keywords: Economic policy uncertainty, geopolitical risks, green bond returns, quantile-on-quantile, wavelet analysis

JEL Classification*:* F51, Q54, G12, C58

1. Introduction

The financial sector has increasingly explored ways to leverage financial instruments to promote the United Nations Sustainable Development Goals (SDGs), reflecting growing global concerns about climate change and sustainable production and consumption patterns. In this context, green bonds have emerged as a novel and potentially efficient means of financing sustainable development initiatives (Monasterolo and Raberto, 2018; Akhtaruzzaman *et al*., 2022). Developed in response to climate change challenges and the pressing need for environmental sustainability, these bonds are specifically designed to fund projects with environmental benefits, ensuring that the capital raised is exclusively allocated to conservation and sustainability efforts (Tolliver *et al*., 2020). Green bonds not only contribute to the promotion of a low-carbon economy and sustainable development but also offer investors a sustainable, long-term investment option (Bhutta *et al*., 2022). Consequently, green bonds have become a focal point of research for numerous scholars and investors. The rapid development of this market is evidenced by global green bond issuance surpassing USD 2 trillion by the third quarter of 2022, according to a report from the Climate Bonds Initiative.

The recent COVID-19 pandemic, coupled with the frequency of significant geopolitical events worldwide, such as the Russia-Ukraine conflict, has exacerbated economic policy uncertainty and geopolitical risk. Meanwhile, as a key energy commodity, the price fluctuations of natural gas are directly affected by geopolitical events. As a financing tool to support low-carbon transition, the price of green bonds may be affected asymmetrically by the above factors, that is, under different market conditions, the direction or intensity of the influence is different. Several studies have investigated the impact of various uncertainty factors on green bond returns. Agoraki *et al*., (2022) believed that GPR has a significant negative effect on stock market returns, while EPU has a weak negative effect. Given the distinctions between green bonds and conventional bonds, Sheenan (2023) analyzed the relationship between these two types of bonds and geopolitical risks. The research results indicate that geopolitical risk exerts a more pronounced influence on green bonds in the context of heightened uncertainty, whereas its effect on traditional bond markets is negligible. Pham and Nguyen (2022) expanded the research on the relationship between uncertainty and green bonds by examining the effects of oil price fluctuations and stock price variations on green bonds. They noted that the connectivity between uncertainty and green bonds exhibits temporal variability, becoming more pronounced during periods characterized by elevated uncertainty. Conversely, in conditions of low uncertainty, the impact of uncertainty on the green bonds is minimal. Consequently, studying the impact of uncertainty factors on green bonds is essential. Additionally, although natural gas is a fossil energy source, it is often considered a "transition fuel" from high-carbon energy sources such as coal to low-carbon or renewable energy sources. In the energy transition, it plays a crucial role in reducing greenhouse gas emissions (Wang *et al*., 2022). This is consistent with the idea that green bonds support projects that contribute to environmental benefits and sustainable development. Meanwhile, the volatility of LNG in the face of geopolitical pressures often prompts investors to hedge their risks by diversifying into green assets, which can provide diversified returns for investors. Therefore, considering LNG's role as a transition fuel and its contribution to diversification and risk management, it makes sense to include it in the green bond analysis.

In an era of energy transition and escalating global tensions, there is a growing demand for sustainable livelihoods. The 28th United Nations Climate Change Conference emphasized the urgent need to boost climate finance for developing nations and increase investments in climate adaptation strategies. These developments further highlight the significant role of green bonds in addressing the climate crisis (Gök *et al*., 2025). China, as the largest developing country, has been actively involved in the issuance of green bonds and has become the second-largest issuer of green bonds in the world. According to an announcement by the China Banking Association, the balance of green credit within banking financial institutions was recorded at 6.14 trillion yuan at the conclusion of 2012. By 2022, this balance had increased to 3.6 times its original value. Meanwhile, China has been actively developing a green economy in recent years. This includes establishing a green bond certification system and expanding the coordination mechanism of the green bond market. A series of favorable policies have attracted more investors and issuers to pay attention to China's green bond market. Therefore, it is necessary to examine the risk resistance of China's green bond market. This will help us analyze the impact of uncertainty and natural gas prices on green bond returns and provide useful recommendations for investors and policymakers.

As a financing tool for climate adaptation projects, it is of great significance to explore the dynamic interaction between green bonds and EPU, GPR, and LNG. First of all, EPU affects the energy and green bond markets through changes in economic policies set by governments. Higher EPU may weaken investors' confidence in investing in long-term sustainable projects. Second, GPR may amplify the impact of uncertainty by introducing shocks such as trade sanctions, regional conflicts, and so on, which in turn affects investor sentiment (Y. Wang *et al*., 2022). The intensification of GPR conflicts may, to some extent, lead to a shift of capital to safe-haven assets and shelving of green investments in the short term. However, in the case of LNG, policy unpredictability could disrupt its supply stability and cause price volatility. Then escalating GPR and EPU may also accelerate the demand for green bonds as countries prioritize energy independence and reducing carbon emissions in response to the climate crisis. Therefore, this paper aims to analyze how uncertainty affects green bond returns and provide some insights to optimize portfolio resilience (Akhtaruzzaman *et al*., 2023).

Currently, several studies have initiated preliminary investigations into China's green bond market. For instance, Zhang *et al*., (2025) constructed the China GPR index, distinguishing between geopolitical behaviors and threats. They found that geopolitical threats are better predictors of trading stock returns, which may further affect the returns of green bonds. Lee *et al*., (2022) found through empirical research on factors affecting Chinese green bonds that the oil crisis is negatively correlated with green bond returns. Tian *et al*., (2022) through their research that the green bond markets in the United States, China, and Europe display distinct characteristics when confronted with uncertainty. In the short run, only China's green bond market has experienced an asymmetric effect due to this uncertainty. In the long run, the US green bond market exhibits broader asymmetries that resemble those of Europe. Therefore, it is important to analyze the unique changes in China's green bond market subject to uncertainties.

The contributions of this research are four-fold. First, we extend the current literature on the rapidly expanding green bond market, particularly in the context of China, which has emerged as the second-largest issuer of green bonds globally. Given the critical role of green bonds in financing sustainable development, our findings provide valuable insights for promoting sustainability and green growth. Second, we place significant emphasis on the role of geopolitical risks, distinguishing between geopolitical threats (GPRT) and geopolitical acts (GPRA). While the relationship between geopolitical risks and financial markets has been explored, the specific impact on green bonds remains underexamined. Our study provides new evidence on how geopolitical risks asymmetrically affect green bond returns. Thirdly, Fourth, we address the nonlinear dynamics inherent in financial markets by employing advanced quantile-based methods, including Quantile-on-Quantile Regression

(QQR), Quantile Granger causality, and wavelet coherence analysis. These techniques allow us to explore the asymmetric and time-varying relationships between EPU, GPR, LNG prices, and green bond returns across different market states and risk exposures. Finally, our study provides practical implications for policymakers and investors. By demonstrating the resilience of green bonds as a hedge against economic and geopolitical uncertainties, we offer actionable insights for optimizing investment strategies and policy frameworks. This research not only advances the academic understanding of green bond markets but also contributes to the broader discourse on sustainable finance, highlighting the importance of green bonds in achieving long-term environmental and economic goals.

The subsequent chapters of this study are arranged as follows. Section 2 reviews the relevant literature. Section 3 outlines the data utilized in this study and the methodology employed. Section 4 explains a discussion and analysis of the empirical results. Section 5 provides important conclusions.

2. Literature Review and Research Hypothesis

Research suggests that one of the most notable developments in financial markets in recent years has been the rise of green bonds. Investment in these financial instruments not only contributes to environmental sustainability but also has the potential to enhance returns on investment (Maltais and Nykvist, 2020). By issuing green bonds, investors can create diversified portfolios that can not only stabilize assets in response to short-term shocks and economic volatility but also protect the environment and increase financial returns (Huynh *et al*., 2020). Since the introduction of green bonds, their market share has expanded significantly and received widespread attention. Therefore, the ongoing empirical investigation into the factors that influence green bonds is of utmost importance.

2.1. Green bond and economic policy uncertainty

It is evident that green bond prices are easily influenced significantly by macroeconomic indicators, such as geopolitical risk and economic policy uncertainty, among other factors (Broadstock and Cheng, 2019). The Economic Policy Uncertainty was initially introduced by Baker in the US, utilizing data derived from local newspapers, it is extensively employed as an indicator for depicting macroeconomic uncertainty in subsequent economic research. Subsequently, Huang & Luk, (2020) employed a similar approach by utilizing data derived from Chinese newspapers to compile a monthly Index of Economic Policy Uncertainty in China. Y. Zhang *et al*. (2023) conducted an analysis of both symmetric and asymmetric relationships among the BRICS economies utilizing panel ARDL and NARDL models. Their findings suggest that EPU leads BRICS countries to raise the consumption of internal resources. Specifically, the governments in these countries tend to utilize substantial natural resources to foster economic development and meet societal needs, which consequently exerts a significant adverse effect on the environment. Consequently, to effectively tackle the challenge of reconciling economic growth with environmental conservation, it is essential to promote the promotion of sustainable economic cycles, emphasizing investment in and attention to green bonds.

Concurrently, the examination of uncertainty indices can assist investors and policymakers in proactively implementing measures to mitigate the negative effects of uncertainty on stock markets and green finance. For instance, Doğan *et al*. (2023) underscored in their findings the critical function of uncertainty indices in highlighting the significance of green bonds as a safe-haven asset during times of economic uncertainty within the framework of the US economic market. Similarly, Bouri *et al*. (2024) found through their research that the green bond market is largely unaffected by the spillover effects of geopolitical risks. This also illustrates the hedging function and risk-averse characteristics of green bonds (Ejaz *et al*., 2022). Furthermore, during times of heightened volatility, green bonds demonstrate greater resilience, whereas traditional bonds may be adversely affected by geopolitical risks (Sheenan, 2023). Meanwhile, in the context of the discourse surrounding clean energy consumption and economic growth, Xue *et al*. (2022) implemented research of pertinent data from France and determined that the consumption of clean energy does not facilitate long-term reductions in emissions. However, Economic Policy Uncertainty (EPU) increases emission levels and poses a threat to environmental sustainability. By studying the impact of EPU on stock market returns in both developed and emerging economies, the results show that developed countries exhibit a greater sensitivity to global EPU than to domestic EPU. In contrast, emerging economies demonstrate a heightened vulnerability to local EPU (Hong *et al*., 2024).

In summary, this paper argues that economic policy uncertainty is usually accompanied by financial market volatility, which may directly affect the profitability of environmental protection and sustainable development projects, leading investors to more be fond of to short-term market volatility and interest rate changes, which in turn affects them to produce different investment behaviors, these alterations are expected to exert an asymmetric influence on the price of green bonds. Consequently, the hypotheses put forth in this study are as follows:

$\boldsymbol{H_1}$: *Economic policy uncertainty has a significant asymmetric impact on green bond prices.*

2.2. Geopolitical risk and stock markets

Geopolitical risk (GPR) is a potential risk due to political factors between different countries and regions, which is likely to make a certain impact on the global green economy, international financial, and commercial activities. For instance, companies facing significant geopolitical risks may safeguard their interests and business stability by increasing cash reserves and debt. While this strategy can help mitigate internal risks, it may also lead to a decline in the company's overall value (Pringpong *et al*., 2023). In addition, the frequent occurrence of geopolitical events often causes fluctuations in investor sentiment, thereby exacerbating the volatility of the stock market. For example, through empirical analysis conducted by Khraiche *et al*. (2023) revealed that geopolitical risks exert a more substantial negative impact in North America and Europe compared to Asia. The influence of variables such as GPR and EPU on the spillover effects associated with green bonds exhibits an asymmetric nature (Lucey and Ren, 2023). Alqahtani *et al*. (2020) investigated the in-sample and out-of-sample predictive power of global and Saudi GPR indices and crude oil returns on stock returns in six GCC countries and found that while global and Saudi GPR indices show weak in-sample predictability, the global GPR index demonstrates superior out-of-sample forecasting for Kuwaiti and Omani markets. The crude oil returns emerge as a more robust predictor across most GCC markets, both in-sample, and out-of-sample, suggesting their utility for active stock return prediction when econometric issues are addressed. Meanwhile, Zheng *et al*. (2023) pointed out that the risk spillover between geopolitical risks, global economic activities, and international financial markets exhibited significant asymmetry. In times of increased geopolitical turmoil, green bonds provide investors with an effective hedge; they are able to hedge geopolitical risk to some extent (Ali *et al*., 2023; Sohag *et al*., 2022). Hoque and Zaidi (2020) explored the impact of global and country-specific GPR on stock returns in emerging economies, and they argued that the two are characterized by nonlinearity, asymmetry, and heterogeneity. Concurrently, geopolitical uncertainty may lead to volatility in the pricing of green bonds, which provides effective advice and planning for bond practitioners and asset savers in optimizing ass*et al*location and portfolio strategies (Lee *et al*., 2021; B. Ren *et al*., 2023; Yadav *et al*., 2023; Bouri *et al*., 2023).

To sum up, this study argues that geopolitical risks will affect the government's role in supporting and promoting green bonds, which may increase the implementation risks of environmental protection and sustainable development projects, interfere with the market liquidity and pricing strategies of green bonds, and consequently cause asymmetric reactions from investors in the green bond market. Therefore, the following are the hypotheses put out in this paper:

***H*$_{2a}$**: *Geopolitical threats have a significant asymmetric impact on Chinese green bond prices.*

***H*$_{2b}$**: *Geopolitical acts have a significant asymmetric impact on Chinese green bond prices.*

2.3. Natural Gas Prices and the Green Bond Market

Previous research on the pricing of the green bond market has predominantly concentrated on issues such as economic policy uncertainty, geopolitical risk, as well as oil price volatility. However, the significance of natural gas, recognized as a clean energy source, is increasingly gaining prominence within the investment landscape (Halser *et al*., 2023; J. Li *et al*., 2022; T. Wang *et al*., 2020). Green bond as an important tool in the field of sustainable investment, its issuance and investment are favored by more and more investors and funds, and the association with traditional energy markets is also strengthened (H. Li *et al*., 2022; Z. Li *et al*., 2022). Abakah *et al*. (2023) by studying the U.S. bond market, found a significant two-way causal relationship between green bonds and natural gas prices under bearish market conditions. In addition, Akhtaruzzaman and Rahman (2024) compared the systemic risks and commonalities between the subsectors of the green and conventional energy markets in the U.S. They found that the green and conventional energy sectors are interconnected with significant systemic risk spillovers. Umar *et al*. (2024) posited that during periods of global economic market decline, policymakers must recognize the critical function of risk management strategies. They should be well-prepared and implement risk mitigation measures to deal with market volatility. This analysis provides a deeper insight into the interaction between energy price indices and their volatility, with a particular focus on natural gas prices and green bonds. By comprehensively considering the various complex factors affecting the green bond market, this meticulous approach is critical to accurately assessing the associated investment risks and opportunities, thus providing effective advice for environmentalists, bond investors and policymakers (X. Ren *et al*., 2022; T. Su *et al*., 2022; Tiwari *et al*., 2022).

In conclusion, this paper argues that the volatility of natural gas prices will affect the return on investment in clean energy projects, leading investors to be more cautious in choosing investment projects and possibly changing their portfolio strategies. In this context, investors may exhibit a preference for risk-averse assets or investment projects characterized by relative stability. This inclination is likely to exert an asymmetric influence on emerging markets, including green bonds. Consequently, the hypotheses put forth in this study are as follows:

***H_3**: Natural gas prices have a significant asymmetric impact on green bond prices in China.*

In conclusion, the preceding analysis and research outcomes regarding green bonds contribute to a deeper comprehension of their significant function in advancing the environmental protection sector and fostering sustainable development. Current researches also highlight the potential of green bonds to raise environmental awareness and tackle the challenge of climate change. Nevertheless, there is currently a lack of empirical research examining the interaction and impact of green bond prices on the China-related uncertainty index and natural gas. Besides, there is a notable deficiency in actionable recommendations and policy insights tailored for Chinese investors and financial managers. Few scholars generally consider natural gas as a key influencing factor in the field of green bond investment; therefore, including natural gas in green bond investment considerations may provide more diversified choices and risk management opportunities for portfolios, as well as furnish investors with valuable insights to mitigate exposure to market risks.

3. Data and Methodology

3.1. Data

This study investigates the asymmetric relationship between the uncertainty index and green bond prices in China, covering the period from August 2012 to July 2022. Taking into account the availability of data and the necessity to incorporate a comprehensive range of observations, this study identifies four pertinent uncertainty indices based on the existing literature. Firstly, we selected the China Bond Green Bond Index from the Wind database as the representative data for the green bond market in China. Secondly, we selected the geopolitical risk index, recently developed by Caldara and Iacoviello, (2022), as an indicator of geopolitical instability. The index is calculated each month by assessing the proportion of total articles and news stories related to adverse geopolitical events, thus providing a comprehensive measure of geopolitical risk. It is subdivided into two sub-indices: geopolitical threats and geopolitical acts. Finally, we employ the average price of China's imported LNG as a representative indicator of the level of domestic natural gas prices (Ferrari *et al.*, 2021; H. Li *et al.*, 2017; T. Wang *et al.*, 2024). Given that all the aforementioned data are expressed as indices, logarithmic transformations are applied to all variables. Table 1 presents variables' definitions and their sources.

Table 1: Variable definitions and sources

Symbol	Definition	Source
GB	China Green Bond Index	Wind Database
EPU	China's Economic Policy Uncertainty Index	Davis *et al*. (2019)
GPRT	Geopolitical Threats	Caldara and Iacoviello, (2022)
GPRA	Geopolitical Acts	Caldara and Iacoviello, (2022)
LNG	China's Liquefied Natural Gas Price Index	Wang *et al*. (2024)

Source: Authors' own elaboration

3.2. Methodology

This study examines the influence of EPU, GPR, and LNG on the pricing of green bonds in China, employing a variety of methodological approaches. In the context of model selection, this research examines the application of the Quantile-on-Quantile Regression (QQR) methodology as introduced by Sim and Zhou (2015). There are several reasons for choosing this approach:(1) Traditional linear methods such as OLS, assume uniform effects across quartiles, which may not capture the asymmetric features of face changes. In contrast, the QQR method allows us to model specific quartiles of the variable, thus revealing tail dependence. (2) QQR is an improvement of the traditional quantile regression method, combining it with nonparametric estimation, which is more conducive to revealing the effects and relationships between independent and dependent variables of different quantiles (Urom *et al.*, 2022). (3) The QQR method performs better in dealing with outliers and heteroscedasticity problems. Especially when dealing with complex economic and financial data, the empirical results from this method tend to be more thorough and nuanced (Duan *et al.*, 2021). In addition, we utilized the quantile Granger causality test developed by Troster (2018), combined with wavelet analysis method to enrich the empirical results, which is of great practical significance and policy implications for the study and understanding of causality between uncertainty indices, natural gas prices on green bond returns.

3.2.1. Quantile-on-quantile Regression (QQR)

This study employs quantile on quantile regression to examine the effect of various quantiles of the variable X (EPU, $GPRT$, $GPRA$, and LNG) on different quantiles of Y (GB) between different quantiles, a procedure that can be characterized by the subsequent nonparametric quantile regression model:

$$Y_t = \beta^{\theta}(X_t) + \varepsilon_t^{\theta} \tag{1}$$

In Eq. (1), Y_t denotes the price index of GB in period t. Similarly, X_t denotes the uncertainty index or price index of *EPU*, *GPRT*, *GPRA*, and *LNG* in period t; θ denotes θ-th quantile of the conditional distribution of X. ε_t^{θ} represents an error term whose θ the quantile of the conditional distribution is equal to zero. $\beta^{\theta}(.)$ is an unknown parameter. Due to the lack of information about the past between Y_t and X_t then can linearize $\beta^{\theta}(.)$ by performing a first-order Taylor expansion on X_t. Then the equation can be rewritten as:

$$\beta^{\theta}(X) \approx \beta^{\theta}(X^{\tau}) + \beta^{\theta'}(X^{\tau})(X_t - X^{\tau}) \tag{2}$$

In Eq. (2), $\beta^{\theta'}$ is the partial derivative of $\beta^{\theta}(X^{\tau})$. Alternatively, in conjunction with that mentioned by Sim and Zhou (2015), Eq. (1) can be reformulated as follows:

$$Y_t = \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(X_t - X^{\tau}) + \varepsilon_t^{\theta} \tag{3}$$

In detail, bandwidth selection is a critical aspect of non-parametric analyses, as it plays a significant role in refining the target points and influencing the rate of results. An increase in the bandwidth parameter leads to a reduction in variance and a corresponding decrease in estimation bias, and conversely, a smaller bandwidth yields the opposite effects. Therefore, a bandwidth value of $h = 0.05$ was employed in this research, in accordance with the recommendations put forth by Sim and Zhou (2015).

3.2.2. Quantile Granger causality

This paper employs the quantile granger causality methodology developed by Troster (2018) to examine the causal relationships among EPU, GPRT, GPRA, LNG and green bond prices. This method not only provides a robustness test for the initial data estimates but also helps to uncover the causal relationship between the predicted variable and the outcome variable across different quantiles. This approach effectively captures tail dependence within the data series, a feature that is overlooked by conventional Granger causality methods. Simultaneously, the reliance on medians for linear Granger causality estimates introduces a potential bias in the findings, as this approach fails to consider causal relationships that may manifest across different quantiles. Therefore, quantile Granger causality is more effective compared to traditional causality tests due to its ability to more accurately test for non-linear causality between the variables being tested, while not being affected by the size of the data.

3.2.3. Wavelet Coherent Transform

In this study, we integrate QQR with wavelet coherence variation to enhance our findings. The choice of the WTC method is based on the following considerations: (1) Wavelet analysis decomposes the signal into time and scale components, enabling us to observe the relationships between variables in the short, medium and long term. (2) When examining time-series data, vector autoregression (VAR), while focusing on time-domain interactions, cannot highlight frequency-specific dynamics. However, WTC can capture localized dependencies in the time and frequency domains through the series. (3) WTC is a robust method. It can solve nonsmoothness problems when the data exhibit time-varying volatility and structural breaks under consideration of both the time and frequency domains. The cross-wavelet transform of two time series, denoted as $x(t)$ and $y(t)$, can be expressed as follows:

$$W_n^{XY}(u,s) = W_n^X(s,\tau)W_n^{Y*}(s,\tau) \tag{4}$$

In equation (4), u represents the position, s denotes the scale, and the symbol * indicates the complex conjugate. The computation of the WTC is performed in the following manner:

$$R_n^2(s,\tau) = \frac{|S(s^{-1}W_n^{XY}(s,\tau))|^2}{S(s^{-1}|W_X(s,\tau)|^2)S(s^{-1}|W_Y(s,\tau)|^2)} \tag{5}$$

In Eq. (5), S denotes the simultaneous smoothing of time and frequency, and the range of values of $R_n^2(s,t)$ is in the range $0 \le R_n^2(s,t) \le 1$.

4. Results and discussion

Table 2 presents the descriptive statistics for all variables discussed in this paper, and GB has a negative skewness. EPU and GPRT show a positive skewness, suggesting that investors may expect EPU and GRPT to change slightly more often, but hardly ever significantly. With a relatively high standard deviation is EPU, which may be due to the fact that the variable is affected by market factors and policy news, and therefore exhibits a high degree of volatility. LNG and GPRT show a higher kurtosis, which may imply that the data distribution is relatively concentrated. The Jarque–Bera test results reveal that most variables, GB, EPU, GPRT, and LNG exhibit non-normal distributions, as indicated by their statistically significant test statistics. In contrast, GPRA shows no significant deviation from normality, suggesting that it may follow a normal distribution.

Table 2: Descriptive Statistics

Variable	Mean	Max	Min	Std. dev.	Skewness	Kurtosis	Jarque–Bera	*p*-value
GB	4.980	5.223	4.724	0.150	−0.198	1.901	6.818**	0.033
EPU	5.212	6.495	4.076	0.594	0.053	1.895	6.164**	0.046
GPRT	4.570	5.578	4.014	0.255	0.793	4.213	19.94***	0.000
GPRA	4.064	5.121	3.051	0.393	−0.104	2.990	0.215	0.898
LNG	4.606	4.987	4.244	0.106	−0.323	5.945	45.46***	0.000

Note: *, ** and *** denote significance at 10%, 5% and 1% levels, respectively.
Source: Authors' own calculations

Table 3 presents the results of the correlation analysis. It is evident that the strongest correlation with GB is observed with EPU, followed by GPRT and LNG. Before conducting the QQR analysis, we employed the quantile autoregressive unit root test to mitigate potential biases in the results and to enhance the robustness of our assessment regarding the continuity of the pertinent indicators (Çıtak *et al.*, 2021).

Table 3: Correlation matrix

	GB	EPU	GPRT	GPRA	LNG
GB	1.00				
EPU	0.79	1.00			
GPRT	0.28	0.15	1.00		
GPRA	−0.39	−0.55	0.28	1.00	
LNG	0.07	0.09	−0.19	−0.10	1.00

Source: Authors' own calculations

Table 4 presents the findings of the quantile autoregressive unit root test. The estimated persistence and *t*-statistic for 19 quantiles, ranging from 0.05 to 0.95, are provided, allowing for the determination of the presence or absence of quantile unit root. If the critical value exceeds the estimated *t*-statistic, the null hypothesis that $\alpha(\tau) = 1$ cannot be rejected at the 5% significance level for each quantile. The test results showed that none of the selected indexes showed quantile smoothness at the significance level of 5%.

Table 4: Quantile autoregressive unit root test

T	GB_t		EPU_t		$GPRT_t$		$GPRA_t$		LNG_t	
	α	*t*-statistic	α	*t*-statistic	α	*t*-statistic	α	*t*-statistic	α	*t*-statistic
0.05	0.836	3.029	0.471	2.683	0.542	2.157	0.719	1.584	−0.377	6.147
0.10	0.939	−0.719	0.403	−2.522	0.424	−3.595	0.737	−1.784	−0.082	−2.925
0.15	0.969	−0.583	0.464	−3.259	0.347	−4.830	0.713	−1.983	−0.077	−4.420
0.20	0.948	−1.064	0.522	−4.522	0.348	−6.130	0.711	−2.297	0.013	−4.951
0.25	0.959	−1.045	0.486	−4.357	0.382	−5.276	0.772	−2.132	0.044	−5.927
0.30	0.975	−0.860	0.409	−5.297	0.385	−5.564	0.720	−2.727	0.045	−7.600
0.35	0.979	−0.664	0.539	−4.168	0.523	−4.976	0.707	−2.799	0.077	−7.723
0.40	0.986	−0.494	0.480	−4.972	0.546	−4.593	0.666	−3.315	0.081	−10.303
0.45	0.989	−0.351	0.442	−5.554	0.536	−4.263	0.621	−3.740	0.096	−11.160
0.50	0.985	−0.534	0.450	−5.032	0.500	−4.589	0.631	−3.853	0.000	−13.231
0.55	0.981	−0.650	0.450	−4.985	0.491	−4.510	0.599	−4.473	−0.007	−12.449
0.60	0.988	−0.362	0.441	−5.396	0.503	−4.519	0.626	−4.923	−0.023	−11.783
0.65	0.988	−0.363	0.446	−4.957	0.539	−4.543	0.615	−4.900	−0.043	−11.737
0.70	0.972	−0.864	0.494	−4.515	0.552	−4.238	0.634	−4.255	−0.019	−11.343
0.75	0.989	−0.335	0.531	−3.680	0.593	−3.393	0.593	−4.266	0.009	−8.594
0.80	0.998	−0.055	0.509	−3.452	0.621	−2.899	0.594	−3.759	−0.046	−8.091
0.85	0.973	−0.837	0.527	−3.302	0.574	−2.317	0.594	−3.266	0.002	−6.683
0.90	0.965	−0.734	0.570	−2.052	0.562	−1.969	0.692	−1.771	−0.160	−3.224
0.95	0.937	0.958	0.739	1.210	0.753	1.265	0.888	0.623	−0.095	5.224

Note: T denotes quantile point, $\hat{\alpha}$ denotes point estimate, *t*-statistic denotes *t*-statistic value.
Source: Authors' calculations.

As presented in Table 5. This study adopted the quantile cointegration test established by Xiao (2009) to conduct a more comprehensive analysis and to determine whether a cointegration relationship exists among the variables. The coefficients associated with β and γ represent the maximum canonical values, while the critical values are designated as CV1, CV5, and CV10, corresponding to significance levels of 1%, 5%, and 10%, respectively. The findings from the quantile cointegration analysis suggest that the research variables exhibit cointegration, indicating a nonlinear long-term relationship between green bond prices and above four variables. This relationship provides a foundation for further empirical investigations.

Table 5: Quantile cointegration test

Models	Coefficient	$sup_\tau\|V_n(\tau)\|$	CV1	CV5	CV10
a. GB	β	50.3194	31.0728	18.8775	14.1049
vs.					
EPU	γ	4.5547	3.0256	1.7524	1.3115
b. GB	β	281.0616	89.1986	49.6035	37.8001
vs.					
GPRT	γ	32.4279	11.3461	5.7978	4.2615
c. GB	β	162.0308	74.3084	37.6578	29.5133
vs.					
GPRA	γ	20.0905	7.5004	3.9989	2.9172
d. GB	β	4322.8579	365.6671	181.3756	126.7127
vs.					
LNG	γ	474.6236	45.2206	18.8349	12.0530

Notes: β and γ denote the coefficients in the quantile cointegration model, $sup_\tau|V_n(\tau)|$ denotes the maximum value of the test statistic, and CV1, CV5, CV10 denote the critical values of statistical significance for 1%, 5% and 10% levels, respectively.

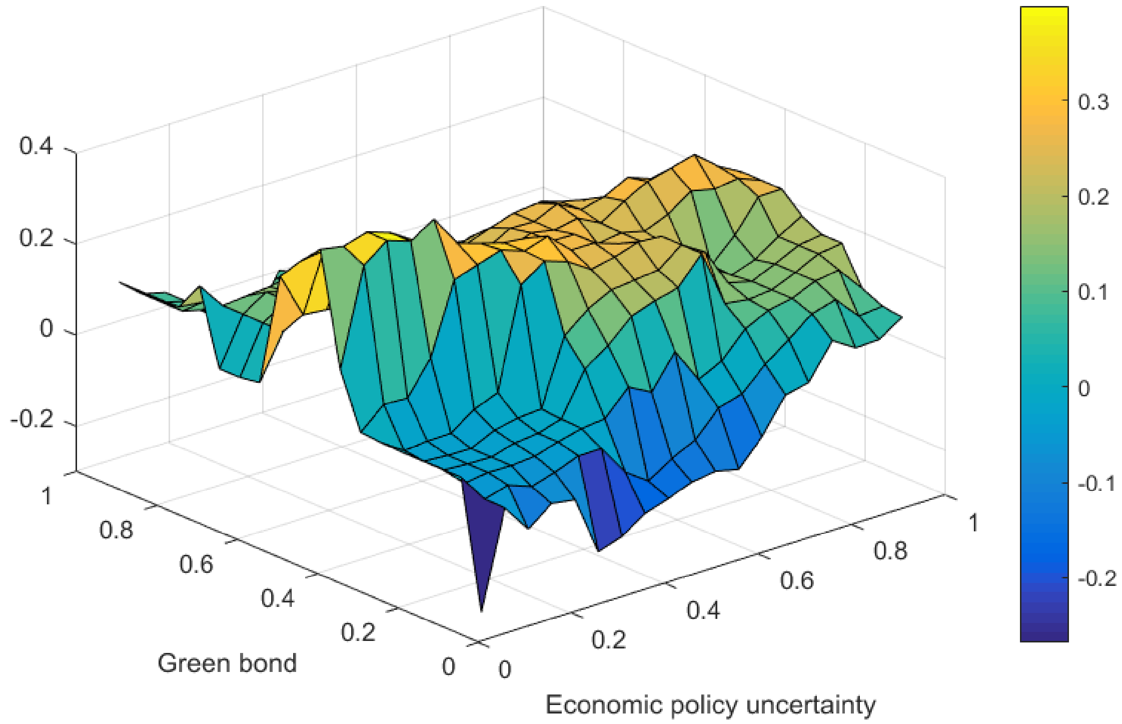
Source: Authors' own calculations

4.1. Results of quantile-on-quantile regression analyses

This section presents an empirical analysis of the asymmetric effects and influences of EPU, GPRT, GPRA, and LNG on China's green bonds. As shown in Figures 1, 2, 3 and 4, the coefficients of the slope $\beta_1(\sigma, \tau)$ are presented, demonstrating the impact of the chosen indices on the σ-th quantile of green bonds. The plot of the relationship between the two gives the results related to the hypotheses. Specifically, the paper finds that EPU, GPRT, GPRA and LNG have an overall positive impact on green bond prices, suggesting that these four independent variables are important factors affecting green bonds, particularly in different economic conditions and intricate geopolitical circumstances. Within each group, there are notable differences in the quantiles of the selected indicator and the slope coefficients of the green bond prices. This observation shows that the relationship between these two variables exhibits asymmetry in their quantiles.

Figure 1 illustrates the impact of varying quantiles of EPU on distinct quantiles of green bond prices. The empirical findings align with Hypothesis 1. The findings from the quantile estimation indicate that EPU and GB are negatively correlated at lower quantiles. At the median and higher quantiles of these two indicators, a more pronounced positive correlation is observed between EPU and GB. The findings indicate that fluctuations in EPU will have a substantial influence on the green bond price. When EPU rises, investors' risk appetite may decrease. Green bonds usually have higher credit ratings and stable funding compared to traditional bonds (Sheenan, 2023). Therefore, investors may prefer green bonds as a safe-haven asset, driving up green bond prices. This is consistent with the view of Gök *et al*. (2025). In addition, it should also be noted that when the EPU increases, the government part of the great extent of the introduction of green transition policies, such as carbon tax or subsidies. This will increase the attractiveness of green bonds. On the other hand, in the low EPU quartile, traditional asset returns rebound. Investors, affected by the macroeconomic situation, may shift their funds from green projects to high-yield assets, leading to a decrease in green bond returns. Therefore, there is an asymmetric impact of EPU changes on GB returns in both long- and short-term time frames (Tang *et al*., 2023). This phenomenon is closely related to policy support and investors' demand for risk avoidance.

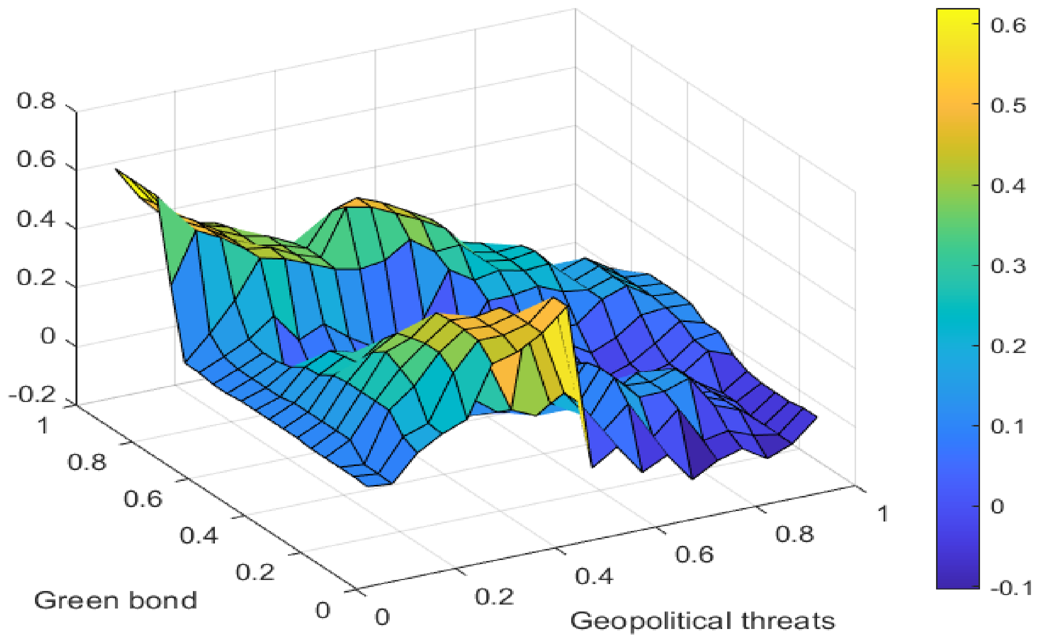
Figure 1: Impact of Economic Policy Uncertainty on Green Bonds: A QQR Regression Estimates



Note: The QQR graph illustrates the slope coefficient estimates β (θ, τ) in the *z*-axis against the quantiles of economic policy uncertainty in the *x*-axis and the quantiles of green bond in the *y*-axis.
Source: Authors' own calculations

As presented in Figure 2, GPRT and green bond returns exhibit an asymmetric relationship throughout the observed sample period, which is consistent with Hypothesis 2a. The two indicators show a significant positive correlation at the GB quantile (0.8–0.95) and the GPRT quantile (0.3–0.45). However, there exists an inverse relationship between the lower quantile of GB (0.05–0.8) and the range of quantiles from low to high of GPRT. Specifically, the analysis suggests that uncertainty in the green bond market is likely to be lower at low to moderate levels of geo threats. This would gain the attention of investors to prioritize green bonds as an investment product. This paper also notes that when faced with extreme geopolitical threats, investors view green bonds as a "geopolitical safe haven". This is because green bonds are decoupled from traditional fossil energy sources and are characterized by policy support. An increase in GPRT is likely to expose the risk of dependence on traditional energy sources and lead countries to invest more in renewable energy. This will increase the demand for green bonds and improve their returns. However, a rise in GPRT could also exacerbate green bond market volatility. If investors are too pessimistic about the market outlook, they may reduce their investment in green bonds, leading to a decline in their prices. Overall, GPRT has a significant asymmetric impact on green bond prices. This is closely related to traditional energy markets, policy stability, and the sustainability of green projects. This volatility has implications for investment behavior and investor sentiment changes in the energy and economic sectors. These findings support previous studies by Akhtaruzzaman and Rahman (2024), Tian *et al.* (2022) and Agoraki *et al.* (2022).

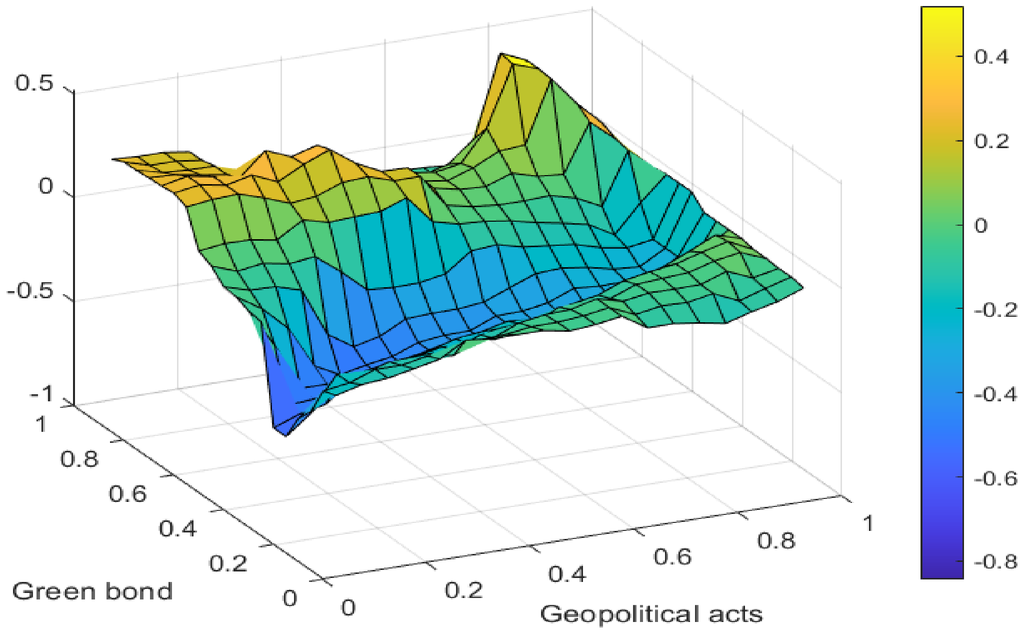
Figure 2: Impact of Geopolitical Threats on Green Bonds: A QQR Approach



Note: The QQR graph illustrates the slope coefficient estimates *β* (*θ*, *τ*) in the *z*-axis against the quantiles of geopolitical threats in the *x*-axis and the quantiles of green bond in the *y*-axis.
Source: Authors' own calculations

Figure 3 illustrates the influence of GPRA on green bond prices. The findings presented in the figure indicate that geopolitical acts exert a detrimental effect on the prices of green bonds throughout the sample period, thereby supporting hypothesis 2b. There is a positive relationship between the lower quantile of GPRA (ranging from 0.05 to 0.3) and the higher quantile of GB (spanning from 0.6 to 0.95). However, the effect of GPRA becomes weak as the slope parameter of the higher quantile of GPRA decreases in steepness across all scatters of GB. In general, the impact of GPRA on green bond prices exhibits an asymmetric pattern. Specifically, under low or median quartile GPRA, multiple countries may jointly promote carbon neutral targets, form green international cooperation or reduce carbon tariffs (Tolliver *et al.*, 2020). As a result, the amount of investment in green projects is enhanced, capital inflows are attracted, and green bond returns show a solid increase. However, when GPRA decreases, the economic market environment will also stabilize. Relatively optimistic investors may increase their risk appetite for the market and shift their attention to traditional markets, reducing the demand for green bonds and leading to a decline in their returns (Ejaz *et al.*, 2022). On the other hand, when encountering high-risk geopolitical behavior, the implementation of green projects will face some obstacles. First, the supply of key resources for green technologies may be limited, leading to increased costs and longer project cycles for green projects. Ultimately, this results in an increase in the credit risk of green bonds and a possible decline in returns. Second, global economic market panic leads to the withdrawal of funds from risky assets, resulting in significant selling pressure on green bonds in the short term (Zheng *et al.*, 2023). For example, at the beginning of the Russia-Ukraine war, European green bonds rose rapidly as the energy transition accelerated. However, as the conflict intensified and gas supplies were cut off, some green projects were delayed or halted, leading to a fall in returns. In addition, stringent ESG disclosure requirements by regulators have helped to enhance the credibility of green bonds and boost their returns. Therefore, the effect of GPRA on green bond returns is asymmetric, and the above findings support the study by Tang *et al*. (2023), Lee *et al*. (2022) and Khraiche *et al*. (2023).

Figure 3: Impact of Geopolitical Acts on Green Bonds: A QQR Approach



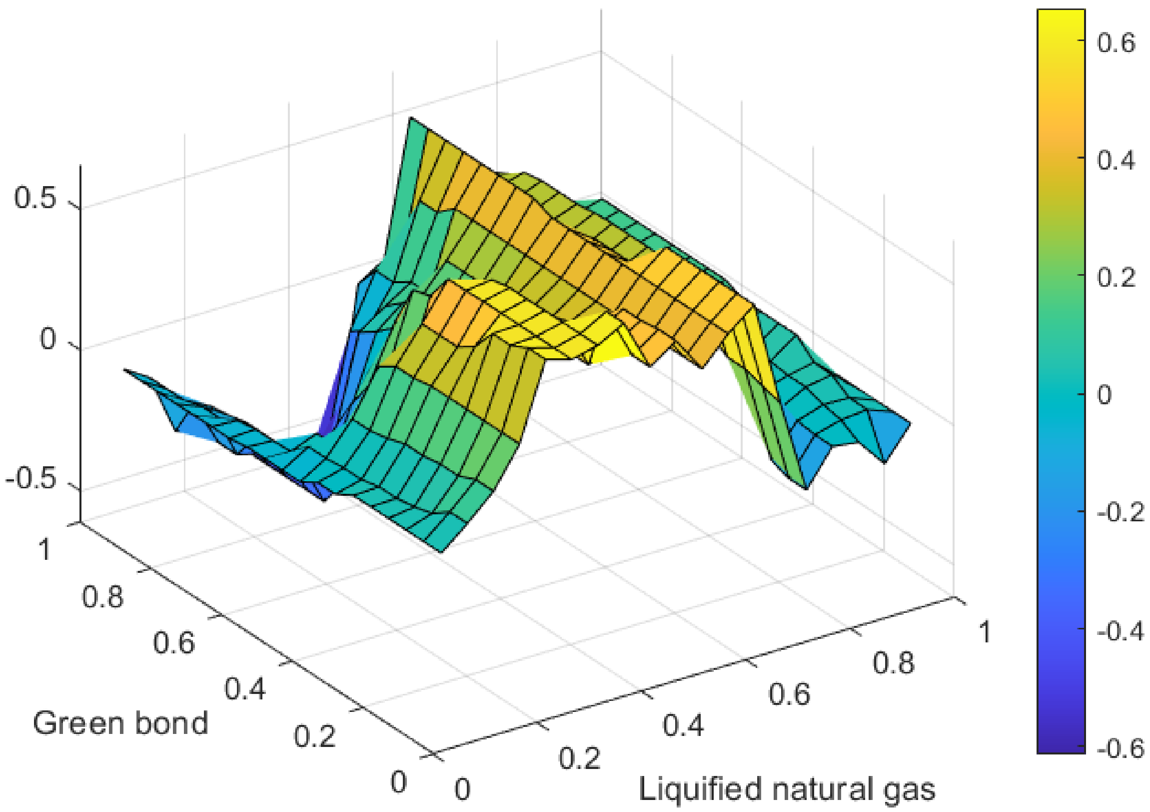
Note: The QQR graph illustrates the slope coefficient estimates $\beta(\theta, \tau)$ in the *z*-axis against the quantiles of geopolitical acts in the *x*-axis and the quantiles of green bond in the *y*-axis.

Source: Authors' own calculations

As can be seen from Figure 4, there exists a certain asymmetric relationship between LNG and green bond prices, which is consistent with Hypothesis 3. In most quartiles of LNG (0.3–0.7), LNG shows a strong positive relationship with GB. Similarly, in the middle and lower quartiles of GB (0–0.4), the two are positively related. However, in the higher quartile of GB (0.7–0.9), there is a significant negative relationship between the two variables. Specifically analyzed, there is a substitution effect between LNG and green bonds when LNG prices fall. Lower prices of traditional energy sources may force countries to accelerate their green transformation, such as China's "dual carbon" goal. This could lead to increased investment in green projects and higher returns on green bonds (Wang *et al*., 2024). In addition, lower LNG prices are good for energy companies that use natural gas, helping them to reduce energy costs and improve their resilience to risk. On the other hand, this paper finds that in the short term, when LNG prices rise, energy companies face inflationary pressure, which leads to an increase in their financing costs. Then the green projects concerned will experience delay risk, which affects the bond returns. In the long term, if the market faces a sustained increase in LNG prices. Then the government, considering energy security, may increase the amount of coal-powered energy, causing green bonds to become less attractive. However, if the carbon tax policy is introduced at the same time, it may reduce the negative impact. Meanwhile, renewable energy sources are becoming more competitive as technology advances and related costs fall. If these alternative energy sources dominate the market, it may reduce the demand for investment in natural gas-related projects, leading to volatility in green bond prices. Therefore, natural gas price and green bonds show an asymmetric effect in general. The above findings support the study of Yadav *et al*., (2023), Maltais and Nykvist (2020) and Mensi *et al*. (2024).

Based on the above research findings, this paper comes through the existing studies on green bonds versus traditional bonds. This paper argues that green bonds are more susceptible to geopolitical risks compared to traditional bonds, which is consistent with the study of Sheenan, 2023). Meanwhile, green bonds possess better risk aversion than traditional assets and are more likely to be favored by investors when facing high uncertainty, which is similar to Dong *et al*. (2023). Next, this study employs granger causality across various quantiles to examine the bidirectional relationships among EPU, GPRT, GPRA, and LNG in relation to green bond prices in China. Table 6 summarizes the test results. We observe that the impacts of EPU, GPRT, GPRA and LNG on green bonds are heterogeneous, suggesting that they do not have a homogeneous effect on green bonds. The results of the granger causality method based on quantiles show that the four aforementioned variables, along with green bonds, exhibit a bivariate relationship across the majority of pertinent quantile indicators. The results are consistent within the framework of the QQR model. Thus, significant fluctuations – whether positive or negative – in EPU, GPRT, GPRA and LNG are associated with variations in green bond prices.

Figure 4: Impact of Liquefied Natural Gas on Green Bonds: A QQR Approach



Note: The QQR graph illustrates the slope coefficient estimates β (θ, τ) in the *z*-axis against the quantiles of liquefied natural gas in the *x*-axis and the quantiles of green bond in the *y*-axis.

Source: Author's own calculations

Table 6: Granger causality in quantile test results

Quantiles	EPU → GB	GB → EPU	GPRT → GB	GB → GPRT	GPRA → GB	GB → GPRA	LNG → GB	GB → LNG
0.05	1.000	0.464	1.000	1.000	1.000	0.500	1.000	0.560
0.10	0.012**	1.000	0.012**	1.000	0.012**	1.000	0.012**	0.476
0.15	0.036**	0.619	0.036**	0.702	0.036**	0.321	0.036**	0.226
0.20	0.012**	0.464	0.012**	0.524	0.012**	0.500	0.012**	0.012**
0.25	0.012**	0.012**	0.012**	0.024**	0.012**	0.452	0.012**	0.012**
0.30	0.321	0.143	0.321	0.083***	0.321	0.845	0.321	0.012**
0.35	0.238	0.464	0.238	0.381	0.238	0.869	0.238	0.012**
0.40	0.274	0.274	0.274	0.774	0.274	0.798	0.274	0.012**
0.45	0.286	0.417	0.286	0.762	0.286	0.810	0.286	0.036**
0.50	0.155	0.702	0.155	0.619	0.155	0.381	0.155	0.036**
0.55	0.679	0.333	0.679	0.429	0.679	0.631	0.679	0.012**
0.60	1.000	0.476	1.000	0.131	0.917	0.536	1.000	0.024**
0.65	0.798	0.333	0.798	0.310	0.714	0.714	0.798	0.012**
0.70	0.083***	0.619	0.083***	0.774	0.083***	0.095***	0.083***	0.024**
0.75	0.012**	1.000	0.012**	0.095***	0.012**	0.500	0.012**	0.060***
0.80	0.012**	1.000	0.012**	0.071***	0.012**	0.702	0.012**	0.012**
0.85	0.036**	0.821	0.036**	0.655	0.036**	0.714	0.036**	0.107
0.90	0.274	1.000	0.274	1.000	0.274	1.000	0.274	1.000
0.95	0.655	0.512	0.655	0.095***	0.655	0.464	0.655	0.631

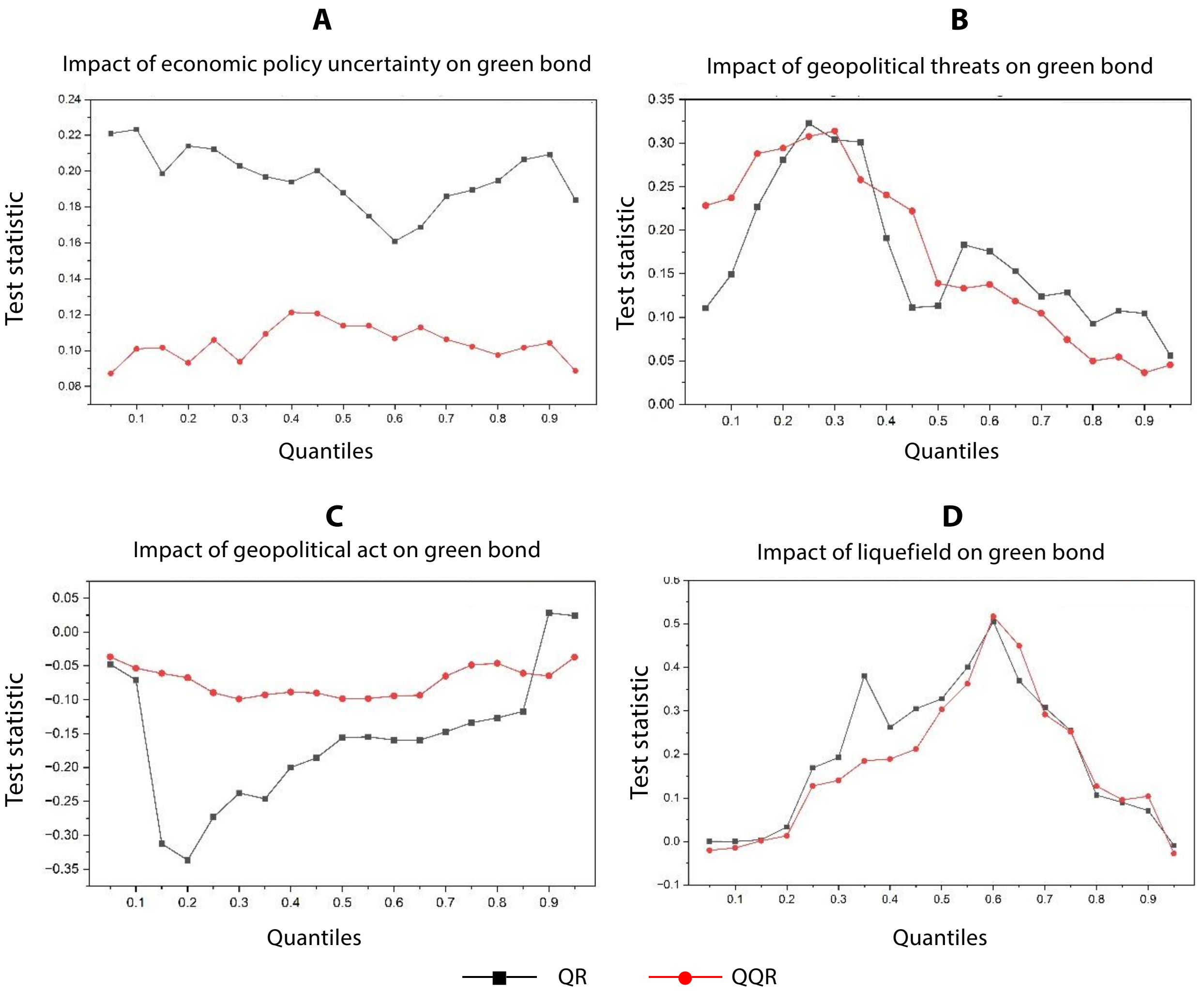
Notes: **, and *** denote the significance level at 5% and 10% levels, respectively. → denotes the causality direction.

Source: Authors' own calculations

4.2. Validity analysis of the QQR model

This study employs the QQR methodology to examine the asymmetric effects of the quantiles of chosen indicators on the price of green bonds in China. To assess the validity of the QQR methodology, we conduct a comparative analysis of the mean slope coefficients obtained from QQR with those obtained from conventional quantile regression. Figure 5 presents a comparative analysis of QQR in relation to standard quantile regression methodologies. The comparison results verify our findings and show that the mean of QQR coefficients trend in the same direction as the mean of QR coefficients. The four sets of images illustrate that the average coefficients of the two methods exhibit parallel alignment, demonstrating a synchronous movement. Consequently, the methodology employed offers a more thorough examination of the asymmetric effects of EPU, GPRT, GPR, and LNG on green bonds across various quantiles of τ and θ.

Figure 5: Comparison of QR and QQR estimates: Impact of macroeconomic and geopolitical factors on Green Bonds



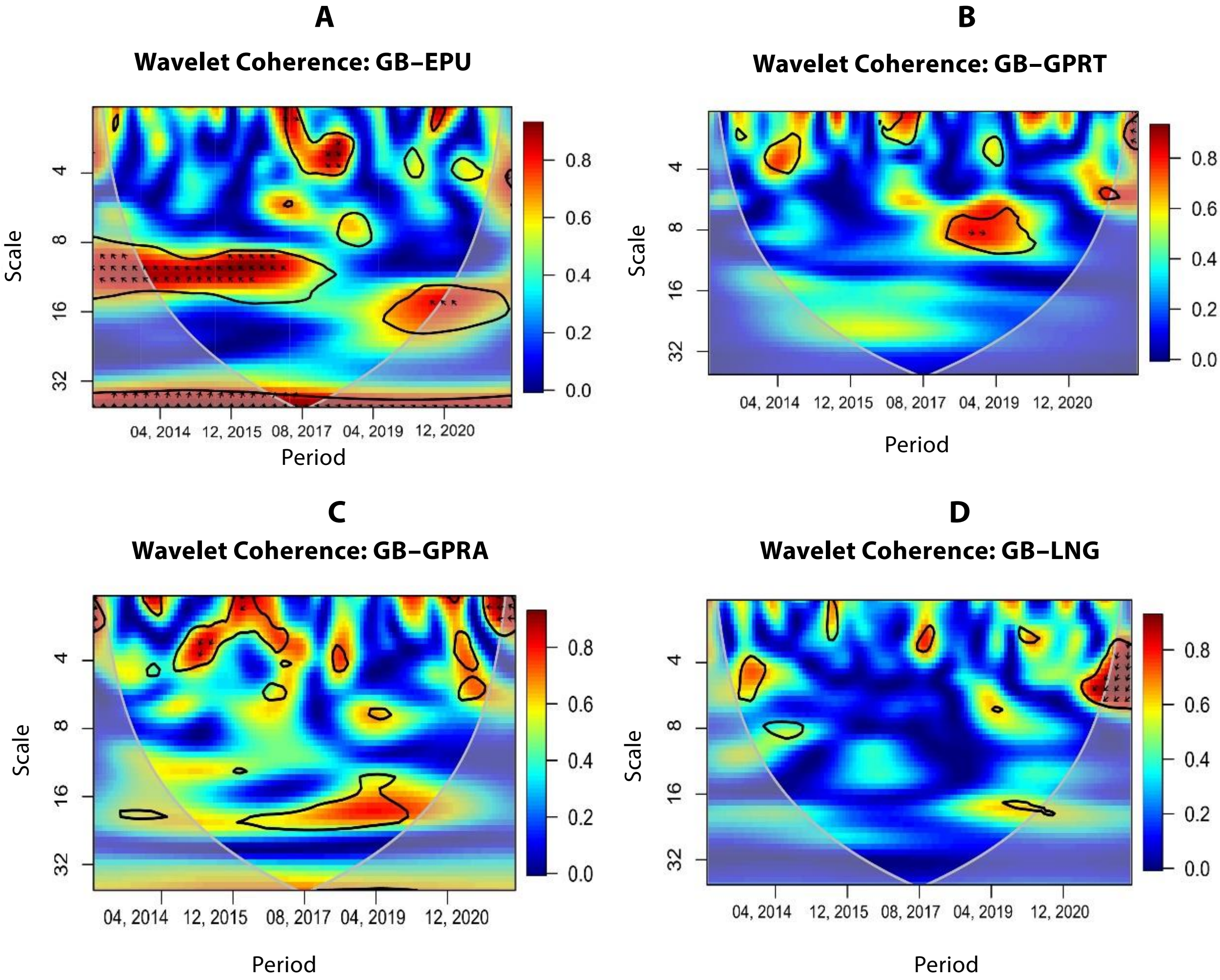
Note: The graphs demonstrate the parameter estimates of standard Quantile Regression (QR) and Quantile-on -Quantile Regression (QQR) for: (A) Economic policy uncertainty and green bond, (B) Geopolitical threats and green bond, (C) Geopolitical acts and green bond, (D) Liquified natural gas and green bond.

Source: Authors' own calculations

4.3 Wavelet coherence transform analysis results

This section further explores the time-frequency covariance and causality between EPU, GPRT, GPRA, LNG and green bond prices. The temporal and frequency co-shifting of the causal influences exerted by above variables on the price of green bonds in China is comprehensively analyzed through the application of the wavelet coherence method (WTC). Figure 6 shows the wavelet coherence transformation results. In the analysis of GB-EPU, it is observed that there are directional indicators pointing both upward to the right and upward to the left during the period from 2012 to 2022, which indicates a significant asymmetric effect between EPU and green bonds. Therefore, it would be advisable for policymakers to prioritize regional collaboration and the standardization of green bonds in order to alleviate the risks associated with uncertainty. Similarly, Figure 6 shows the WTC between GPRT, GPRA, and GB from 2012 to 2022. The majority of the arrows associated with GPRT are oriented upwards to the right, indicating a robust correlation across various frequencies from 2017 to 2022. The directional arrows for GPRA are oriented downward to the left, signifying a robust correlation across various frequencies from 2014 to 2017. The results indicate that GPRT and GB are positively correlated, whereas GPRA and GB exhibit negatively correlated. Similarly, the relationship between LNG and GB in the context of the WTC is illustrated in Figure 6, and it can be observed that there are fewer or weaker links between the two from 2012 to 2020, and after 2020, most of the arrows are down to the left, indicating a negative link at high and medium frequency. Overall, it is clear that EPU, GPRT, GPRA and LNG indicators are important indicators.

Figure 6: Wavelet Coherence Power Spectra: Green Bond vs. Uncertainty and Energy Factors



Notes: Wavelet Coherence power spectra of (A) green bond and economic policy uncertainty, (B) green bond and geopolitical threats, (C) green bond and geopolitical acts (D), green bond and liquified natural gas. The thick black contour indicates the 5% significance level relative to the red noise. Power levels are color-coded, transitioning from blue (low power) to red (high power). The white cone of influence represents the region where edge effects may distort the results.

Source: Authors' own elaboration

5. Conclusion

This paper uses the dataset from August 2012 to July 2022 and adopts non-parametric methods such as QQR, Granger causality, and WTC are employed to investigate the interrelationships among different quantiles of EPU, GPRT, GPRA and LNG in relation to varying quantiles of green bonds. This study makes an important contribution to the existing literature on the interaction of EPU, GPRT, GPRA, LNG and green bonds. The main conclusion of this paper is that EPU, GPRT and LNG show a strong positive effect on green bonds in most quartiles and frequencies. While GPRA is mostly negatively related to green bond returns. All the above four variables have asymmetric relationship with green bonds. Based on the above results, this paper suggests that in the Chinese market environment, policy makers need to calibrate dynamic policies and formulate contingency plans in advance. At the same time, the resilience of the energy supply chain should be strengthened, and the government's risk response capability should be improved to guarantee the implementation of green projects. For investors and fund managers, this paper provides them with quantile and wavelet analysis results, which help them capture policy dividends. In addition, given the asset hedging advantages of green bonds, it is important for relevant government agencies and portfolio investors to actively advocate investment in environmentally sustainable financial instruments such as green bonds.

This study has some limitations. First, the study focuses exclusively on China's green bond market, and the findings may not be generalizable to other regions. Future research could explore more developed green bond markets, such as the US and Europe, to evaluate the impact of similar variables. Second, this study used a few variables (EPU, GPR, and LNG prices) to check their impact on green bond returns. Future research could incorporate additional factors, such as regulatory changes, technological advancements, or investor sentiment, to provide a more comprehensive understanding of green bond dynamics

Disclosures and declarations

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Data availability: The datasets used and/or analyzed in this study are accessible from the corresponding author on demand.

Authors' contributions:

Xiaohui Qu: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing-Original Draft

Chaokai Xue: Writing-Original Draft, Visualization, Supervision, Project Administration

Mahmood Ahmad: Writing review and editing

Qun Gao: Writing review and editing, validation

Yuxi Wu: Writing review and editing

Nomenclature

EPU	Economic Policy Uncertainty
GPR	Geopolitical Risk
LNG	Liquefied Natural Gas
QQR	Quantile-on-Quantile Regression
GPRT	Geopolitical Threats
GPRA	Geopolitical Acts
SDGs	Sustainable Development Goals
WTC	Wavelet Coherence Analysis

References

Abakah, E. J. A., Tiwari, A. K., Adekoya, O. B., & Oteng-Abayie, E. F. (2023). An analysis of the time-varying causality and dynamic correlation between green bonds and US gas prices. *Technological Forecasting and Social Change,* 186, 122134. https://doi.org/10.1016/j.techfore.2022.122134

Agoraki, M.-E. K., Kouretas, G. P., & Laopodis, N. T. (2022). Geopolitical risks, uncertainty, and stock market performance. *Economic and Political Studies*, 10(3), 253–265. https://doi.org/10.1080/20954816.2022.2095749

Akhtaruzzaman, M., Banerjee, A. K., Boubaker, S., & Moussa, F. (2023). Does green improve portfolio optimisation? *Energy Economics*, 124, 106831. https://doi.org/10.1016/j.eneco.2023.106831

Akhtaruzzaman, M., Banerjee, A. K., Ghardallou, W., & Umar, Z. (2022). Is greenness an optimal hedge for sectoral stock indices? *Economic Modelling*, 117, 106030. https://doi.org/10.1016/j.econmod.2022.106030

Akhtaruzzaman, M., & Rahman, M. R. (2024). Commonality in systemic risk from green and conventional energy. *Energy Economics*, 107404. https://doi.org/10.1016/j.eneco.2024.107404

Ali, S. R. M., Anik, K. I., Hasan, M. N., & Kamal, M. R. (2023). Geopolitical threats, equity returns, and optimal hedging. *International Review of Financial Analysis*, 90, 102835. https://doi.org/10.1016/j.irfa.2023.102835

Alqahtani, A., Bouri, E., & Vo, X. V. (2020). Predictability of GCC stock returns: The role of geopolitical risk and crude oil returns. *Economic Analysis and Policy*, 68, 239–249. https://doi.org/10.1016/j.eap.2020.09.017

Bhutta, U. S., Tariq, A., Farrukh, M., Raza, A., & Iqbal, M. K. (2022). Green bonds for sustainable development: Review of literature on development and impact of green bonds. *Technological Forecasting and Social Change*, 175, 121378. https://doi.org/10.1016/j.techfore.2021.121378

Bouri, E., Gök, R., Gemici, E., & Kara, E. (2024). Do geopolitical risk, economic policy uncertainty, and oil implied volatility drive assets across quantiles and time-horizons? *The Quarterly Review of Economics and Finance*, 93, 137–154. https://doi.org/10.1016/j.qref.2023.12.004

Bouri, E., Hammoud, R., & Kassm, C. A. (2023). The effect of oil implied volatility and geopolitical risk on GCC stock sectors under various market conditions. *Energy Economics*, 120, 106617. https://doi.org/10.1016/j.eneco.2023.106617

Broadstock, D. C., & Cheng, L. T. W. (2019). Time-varying relation between black and green bond price benchmarks: Macroeconomic determinants for the first decade. *Finance Research Letters*, 29, 17–22. https://doi.org/10.1016/j.frl.2019.02.006

Caldara, D., & Iacoviello, M. (2022). Measuring Geopolitical Risk. *American Economic Review*, 112(4), 1194–1225. https://doi.org/10.1257/aer.20191823

Çıtak, F., Şişman, M. Y., & Bağcı, B. (2021). Nexus between disaggregated electricity consumption and CO2 emissions in Turkey: new evidence from quantile-on-quantile approach. *Environmental and Ecological Statistics*, 28(4), 843–860. https://doi.org/10.1007/s10651-021-00504-5

Davis, S.J., Liu, D., Sheng, X.S., 2019. Economic policy uncertainty in China since 1949: The view from mainland newspapers. Fourth Annual IMF-Atlanta Fed Research Workshop on China's Economy Atlanta 1–35.

Doğan, B., Trabelsi, N., Tiwari, A. K., & Ghosh, S. (2023). Dynamic dependence and causality between crude oil, green bonds, commodities, geopolitical risks, and policy uncertainty. *The Quarterly Review of Economics and Finance*, 89, 36–62. https://doi.org/10.1016/j.qref.2023.02.006

Dong, X., Xiong, Y., Nie, S., & Yoon, S.-M. (2023). Can bonds hedge stock market risks? Green bonds vs conventional bonds. *Finance Research Letters*, 52, 103367. https://doi.org/10.1016/j.frl.2022.103367

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. https://doi.org/10.1016/j.eneco.2021.105131

Ejaz, R., Ashraf, S., Hassan, A., & Gupta, A. (2022). An empirical investigation of market risk, dependence structure, and portfolio management between green bonds and international financial markets. *Journal of Cleaner Production*, 365, 132666. https://doi.org/10.1016/j.jclepro.2022.132666

Ferrari, D., Ravazzolo, F., & Vespignani, J. (2021). Forecasting energy commodity prices: A large global dataset sparse approach. *Energy Economics*, 98, 105268. https://doi.org/10.1016/j.eneco.2021.105268

Gök, R., Şenol, Z., Durgun, B., & Bouri, E. (2025). Green bonds and financial markets: Interdependence across different market situations. *Journal of Environmental Management*, 373, 123408. https://doi.org/10.1016/j.jenvman.2024.123408

Halser, C., Paraschiv, F., & Russo, M. (2023). Oil–gas price relationships on three continents: Disruptions and equilibria. *Journal of Commodity Markets*, 31, 100347. https://doi.org/10.1016/j.jcomm.2023.100347

Hong, Y., Zhang, R., & Zhang, F. (2024). Time-varying causality impact of economic policy uncertainty on stock market returns: Global evidence from developed and emerging countries. *International Review of Financial Analysis*, 91, 102991. https://doi.org/10.1016/j.irfa.2023.102991

Hoque, M. E., & Zaidi, M. A. S. (2020). Global and country-specific geopolitical risk uncertainty and stock return of fragile emerging economies. *Borsa Istanbul Review*, 20(3), 197–213. https://doi.org/10.1016/j.bir.2020.05.001

Huang, Y., & Luk, P. (2020). Measuring economic policy uncertainty in China. *China Economic Review*, 59, 101367. https://doi.org/10.1016/j.chieco.2019.101367

Huynh, T. L. D., Hille, E., & Nasir, M. A. (2020). Diversification in the age of the 4th industrial revolution: The role of artificial intelligence, green bonds and cryptocurrencies. *Technological Forecasting and Social Change*, 159, 120188. https://doi.org/10.1016/j.techfore.2020.120188

Khraiche, M., Boudreau, J. W., & Chowdhury, M. S. R. (2023). Geopolitical risk and stock market development. *Journal of International Financial Markets, Institutions and Money*, 88, 101847. https://doi.org/10.1016/j.intfin.2023.101847

Lee, C.-C., Lee, C.-C., & Li, Y.-Y. (2021). Oil price shocks, geopolitical risks, and green bond market dynamics. *The North American Journal of Economics and Finance*, 55, 101309. https://doi.org/10.1016/j.najef.2020.101309

Lee, C.-C., Tang, H., & Li, D. (2022). The roles of oil shocks and geopolitical uncertainties on China's green bond returns. *Economic Analysis and Policy*, 74, 494–505. https://doi.org/10.1016/j.eap.2022.03.008

Li, H., Chen, L., Wang, D., & Zhang, H. (2017). Analysis of the Price Correlation between the International Natural Gas and Coal. *Energy Procedia*, 142, 3141–3146. https://doi.org/10.1016/j.egypro.2017.12.376

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. https://doi.org/10.1016/j.egyr.2022.08.230

Li, J., Dong, X., & Dong, K. (2022). Green efficiency of natural gas and driving factors analysis: the role of the natural gas price in China. *Energy Efficiency*, 15(5), 24. https://doi.org/10.1007/s12053-022-10033-0

Li, Z., Kuo, T.-H., Siao-Yun, W., & The Vinh, L. (2022). Role of green finance, volatility and risk in promoting the investments in Renewable Energy Resources in the post-covid-19. *Resources Policy*, 76, 102563. https://doi.org/10.1016/j.resourpol.2022.102563

Lucey, B., & Ren, B. (2023). Time-varying tail risk connectedness among sustainability-related products and fossil energy investments. *Energy Economics*, 126, 106812. https://doi.org/10.1016/j.eneco.2023.106812

Maltais, A., & Nykvist, B. (2020). Understanding the role of green bonds in advancing sustainability. *Journal of Sustainable Finance & Investment*, 1–20. https://doi.org/10.1080/20430795.2020.1724864

Mensi, W., Selmi, R., Al-Kharusi, S., Belghouthi, H. E., & Kang, S. H. (2024). Connectedness between green bonds, conventional bonds, oil, heating oil, natural gas, and petrol: new evidence during bear and bull market scenarios. *Resources Policy*, 91, 104888. https://doi.org/10.1016/j.resourpol.2024.104888

Monasterolo, I., & Raberto, M. (2018). The EIRIN Flow-of-funds Behavioural Model of Green Fiscal Policies and Green Sovereign Bonds. *Ecological Economics*, 144, 228–243. https://doi.org/10.1016/j.ecolecon.2017.07.029

Pham, L., & Nguyen, C. P. (2022). How do stock, oil, and economic policy uncertainty influence the green bond market? *Finance Research Letters*, 45, 102128. https://doi.org/10.1016/j.frl.2021.102128

Pringpong, S., Maneenop, S., & Jaroenjitrkam, A. (2023). Geopolitical risk and firm value: Evidence from emerging markets. *The North American Journal of Economics and Finance*, 68, 101951. https://doi.org/10.1016/j.najef.2023.101951

Ren, B., Lucey, B., & Luo, Q. (2023). An examination of green bonds as a hedge and safe haven for international equity markets. *Global Finance Journal*, 58, 100894. https://doi.org/10.1016/j.gfj.2023.100894

Ren, X., Li, Y., yan, C., Wen, F., & Lu, Z. (2022). The interrelationship between the carbon market and the green bonds market: Evidence from wavelet quantile-on-quantile method. *Technological Forecasting and Social Change*, 179, 121611. https://doi.org/10.1016/j.techfore.2022.121611

Sheenan, L. (2023). Green bonds, conventional bonds and geopolitical risk. *Finance Research Letters*, 58, 104587. https://doi.org/10.1016/j.frl.2023.104587

Sim, N., & Zhou, H. (2015). Oil prices, US stock return, and the dependence between their quantiles. *Journal of Banking & Finance*, 55, 1–8. https://doi.org/10.1016/j.jbankfin.2015.01.013

Sohag, K., Hammoudeh, S., Elsayed, A. H., Mariev, O., & Safonova, Y. (2022). Do geopolitical events transmit opportunity or threat to green markets? Decomposed measures of geopolitical risks. *Energy Economics*, 111, 106068. https://doi.org/10.1016/j.eneco.2022.106068

Su, T., Zhang, Z. (Justin), & Lin, B. (2022). Green bonds and conventional financial markets in China: A tale of three transmission modes. *Energy Economics*, 113, 106200. https://doi.org/10.1016/j.eneco.2022.106200

Tang, Y., Chen, X. H., Sarker, P. K., & Baroudi, S. (2023). Asymmetric effects of geopolitical risks and uncertainties on green bond markets. *Technological Forecasting and Social Change*, 189, 122348. https://doi.org/10.1016/j.techfore.2023.122348

Tian, H., Long, S., & Li, Z. (2022). Asymmetric effects of climate policy uncertainty, infectious diseases-related uncertainty, crude oil volatility, and geopolitical risks on green bond prices. *Finance Research Letters*, 48, 103008. https://doi.org/10.1016/j.frl.2022.103008

Tiwari, A. K., Aikins Abakah, E. J., Gabauer, D., & Dwumfour, R. A. (2022). Dynamic spillover effects among green bond, renewable energy stocks and carbon markets during COVID-19 pandemic: Implications for hedging and investments strategies. *Global Finance Journal*, 51, 100692. https://doi.org/10.1016/j.gfj.2021.100692

Tolliver, C., Keeley, A. R., & Managi, S. (2020). Drivers of green bond market growth: The importance of Nationally Determined Contributions to the Paris Agreement and implications for sustainability. *Journal of Cleaner Production*, 244, 118643. https://doi.org/10.1016/j.jclepro.2019.118643

Troster, V. (2018). Testing for Granger-causality in quantiles. *Econometric Reviews*, 37(8), 850–866. https://doi.org/10.1080/07474938.2016.1172400

Umar, Z., Hadhri, S., Abakah, E. J. A., Usman, M., & Umar, M. (2024). Return and volatility spillovers among oil price shocks and international green bond markets. *Research in International Business and Finance*, 69, 102254. https://doi.org/10.1016/j.ribaf.2024.102254

Urom, C., Ndubuisi, G., Guesmi, K., & Benkraien, R. (2022). Quantile co-movement and dependence between energy-focused sectors and artificial intelligence. *Technological Forecasting and Social Change*, 183, 121842. https://doi.org/10.1016/j.techfore.2022.121842

Wang, J., Ma, F., Bouri, E., & Zhong, J. (2022). Volatility of clean energy and natural gas, uncertainty indices, and global economic conditions. *Energy Economics*, 108, 105904. https://doi.org/10.1016/j.eneco.2022.105904

Wang, T., Wu, F., Dickinson, D., & Zhao, W. (2024). Energy price bubbles and extreme price movements: Evidence from China's coal market. *Energy Economics*, 129, 107253. https://doi.org/10.1016/j.eneco.2023.107253

Wang, T., Zhang, D., Ji, Q., & Shi, X. (2020). Market reforms and determinants of import natural gas prices in China. *Energy*, 196, 117105. https://doi.org/10.1016/j.energy.2020.117105

Wang, Y., Bouri, E., Fareed, Z., & Dai, Y. (2022). Geopolitical risk and the systemic risk in the commodity markets under the war in Ukraine. *Finance Research Letters*, 49, 103066. https://doi.org/10.1016/j.frl.2022.103066

Xiao, Z. (2009). Quantile cointegrating regression. *Journal of Econometrics*, 150(2), 248–260. https://doi.org/10.1016/j.jeconom.2008.12.005

Xue, C., Shahbaz, M., Ahmed, Z., Ahmad, M., & Sinha, A. (2022). Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? *Renewable Energy*, 184, 899–907. https://doi.org/10.1016/j.renene.2021.12.006

Yadav, M. P., Pandey, A., Taghizadeh-Hesary, F., Arya, V., & Mishra, N. (2023). Volatility spillover of green bond with renewable energy and crypto market. *Renewable Energy*, 212, 928–939. https://doi.org/10.1016/j.renene.2023.05.056

Zhang, J., Zeng, Q., Bouri, E., & Gozgor, G. (2025). Newly-constructed Chinese geopolitical risk index and trade stock returns. *Research in International Business and Finance*, 74, 102705. https://doi.org/10.1016/j.ribaf.2024.102705

Zhang, Y., Huang, Y., & Wang, X. (2023). Impact of economic policy uncertainty, oil prices, and technological innovations on natural resources footprint in BRICS economies. *Resources Policy*, 86, 104082. https://doi.org/10.1016/j.resourpol.2023.104082

Zheng, J., Wen, B., Jiang, Y., Wang, X., & Shen, Y. (2023). Risk spillovers across geopolitical risk and global financial markets. *Energy Economics*, 127, 107051. https://doi.org/10.1016/j.eneco.2023.107051