Hindawi
Discrete Dynamics in Nature and Society
Volume 2024, Article ID 9892400, 14 pages
https://doi.org/10.1155/2024/9892400

Research Article

Carbon Market Efficiency and Economic Policy Uncertainty: Evidence from a TVP-VAR Model

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Received 10 August 2023; Revised 21 November 2023; Accepted 21 January 2024; Published 15 April 2024

Academic Editor: Fabio Tramontana

This paper examines the dynamic linkages among economic policy uncertainty (EPU), the green bond market, the carbon market, and the macroeconomy using the time-varying parameter vector autoregressive (TVP-VAR) model with monthly data spanning from January 2016 to December 2021. Additionally, it assesses the robustness and accuracy of the empirical results through the Bayesian vector autoregressive (BVAR) model. The findings indicate that EPU negatively affects the green bond market in the short term but has a positive impact in the medium and long term. Conversely, EPU has a positive impact on the carbon market in the short term but a negative impact in the medium and long term. Furthermore, the green bond market negatively influences the carbon market in both the short and medium to long term. These results suggest that emerging markets, such as the green bond and carbon markets, are influenced by EPU. The adverse impact of the green bond market on the carbon market, however, contributes to expediting China's attainment of its low-carbon objectives. Appropriate economic policies can play a vital role in accelerating the transition to a low-carbon economy. The study also reveals that the US-China trade war has expedited the development of green capital markets in China, despite its impact on the green economic transition in the country. These findings provide insights for the government and investors to formulate suitable strategies for risk mitigation.

1. Introduction

Carbon emissions constitute one of the primary contributors to global warming, leading to a series of climate-related disasters that consistently jeopardize human life and property. In response to these challenges, nations worldwide have collaboratively endeavored to avert further climate-related catastrophes. In April 2016, one hundred and seventy-eight countries signed the Paris Agreement on Climate Change, establishing the development of a low-carbon economy with the principles of "low emissions, low energy consumption, and low pollution" as a shared global objective. Various low-carbon investment strategies have emerged as essential tools to combat climate change and reduce carbon emissions [1]. Presently, governments are proactively employing market mechanisms to innovate new market structures, facilitating the low-carbon transition of their economies.

China advocates a green and low-carbon economic approach, supporting innovative green financial instruments, with the carbon market and green bond market being the most crucial among them. These innovative green financial instruments serve as core policy tools to achieve China's low-carbon goals. The carbon market regulates carbon emissions through mechanisms such as the carbon asset price mechanism, market trading constraint mechanism, and administrative intervention mechanism. It accomplishes carbon emission targets through total control and allowance trading [2]. There is an urgent need to reduce energy consumption in China, as evident by the establishment of seven major carbon trading markets since 2011, including those in Beijing and Shanghai. It is noteworthy that, as of July 2021, a national carbon emissions trading market has been initiated, which comprises a cumulative carbon emission total exceeding 4 billion tons. This development is indicative of the rapid growth of the carbon trading market on a broader scale.

Simultaneously, the shift from the traditional crude and high-energy model of economic growth to a low-carbon model, characterized by new energy sources, high efficiency, and reduced carbon emissions, necessitates substantial capital investment. This transition underscores the importance of developing green finance, with the green bond market emerging as a particularly promising segment. Financing obtained through the green bond market stands as a critical pillar in facilitating the economy's low-carbon transformation [3–5]. The rapid advancement of the green bond market has played a positive role in expediting capital financing, optimizing resource allocation, enhancing environmental conditions, and fostering the development of a low-carbon economy. As of the end of 2021, China's cumulative green bond issuance has reached 199.2 billion USD (nearly 1.3 trillion CNY), propelling it to the position of the world's second-largest green bond market. China's green bond market is poised to become a key driver of the rapidly expanding global green bond market. The ongoing development of the green bond market is certain to fuel sustained economic growth [6] and contribute to the timely achievement of low-carbon goals.

The green bond market and the carbon market have emerged as innovative tools for mitigating greenhouse gas emissions and fostering the development of a green, low-carbon economy. With shared objectives, both markets are aligned with green and low-carbon policies and are notably influenced by EPU [7]. China's push towards establishing a large, unified national market and the integration of financial markets has created significant policy uncertainty that will impact the carbon neutrality process, while concurrently strengthening the linkage between the carbon market and the green bond market. A comprehensive understanding of the interactions and impacts between these two markets, coupled with the precise management of policy risks in both, holds significant theoretical and practical implications for promoting the synergistic development of policies in China's green bond market and carbon market. Such efforts are crucial for achieving emission and carbon reduction goals and for fostering a sustainable future.

Tiwari et al. [8] have provided empirical evidence of a linkage between the green bond market and the carbon market. However, research exploring the interaction between these two markets in China is still in its nascent stages. As it stands, the green bond market and the carbon market remain relatively isolated from each other. Further research is necessary to examine and understand the potential for synergy between these markets in promoting sustainable development and mitigating climate change. Moreover, China is characterized as a policy-oriented market, with scarce literature delving into the policy action mechanisms of the two markets. This paper investigates the connection between Economic Policy Uncertainty (EPU), the green bond market, and the carbon market. In addition, it introduces macroeconomic condition variables as control variables, aiming to align the research scenario more closely with the real environment of economic operation.

The study of financial markets has been a subject of great interest for scholars due to its inherent complexity, nonlinearity, and multi-fractal characteristics. In recent times, complexity theory and multifractals have emerged as effective approaches to analyze the correlation between variables in financial and economic systems. Scholars such as Gajardo and Kristjanpoller [9] have utilized various approaches, including detrended cross-correlation analysis (DCCA), to examine cross-correlation characteristics, asymmetric multifractality, and directionality among variables. Their work has highlighted the potential complexity of financial series, including non-linearity, asymmetry, and time-varying features. The time-varying parametric vector autoregressive (TVP-VAR) model is a highly effective tool for analyzing the time-varying characteristics of the relationship between economic variables. This model has the ability to capture changes in the system, identify nonlinear relationships between variables, and explore correlation characteristics and impact dynamics among variables. Therefore, this study adopts the TVP-VAR method to analyze the time-varying impact between the green bond market and the carbon market, which will provide valuable insights into the dynamic relationship between these two markets. The objective of this paper is to provide economic policymakers with a comprehensive review of past economic policies and their outcomes, with the aim of facilitating the formulation of targeted measures to mitigate economic fluctuations and minimize the risks associated with unforeseen shocks to economic operations in the future. The paper aims to contribute to the ongoing discourse on economic policy formulation and provide valuable insights for policymakers to make informed decisions that promote sustainable economic growth and stability.

In the development of green finance, the mutual influence of the carbon market and green bonds is progressively deepening. The linkage effect between these markets is intensifying, and the sustainable development of the green economy increasingly relies on the stability of both markets. Consequently, analyzing the linkage between green bonds and the carbon market and quantifying the interaction between the two has become a crucial focus in green finance research.

The main contributions of this paper are outlined as follows: (1) Pioneeringly, the study focuses on China's carbon market and green bond market to examine the correlation between them, incorporating Economic Policy Uncertainty (EPU) and macroeconomics into the analysis. This approach offers valuable insights for the advancement of both the carbon market and the green bond market in China. (2) The paper constructs an indicator system and innovatively employs the more transmissive and global time-varying parametric vector autoregressive (TVP-VAR) model for measurement. This methodology enables the analysis of shocks over time in terms of magnitude and direction, yielding conclusions that better align with the intricate reality of the economic environment, thereby complementing prior research. (3) The paper conducts a comprehensive analysis of the average transaction prices across five representative carbon trading markets in China, steering clear of the pitfalls of studying a single trading market in isolation.

In conclusion, this paper offers crucial insights into the interconnection between the carbon market and the green bond market, unveiling the mechanism of their synergistic development. These findings hold significant importance for effective policy implementation.

2. Literature Review

The carbon trading market is a system utilizing market mechanisms to attain emission reduction objectives. Numerous countries have been actively implementing carbon trading policies, with carbon cap schemes consistently recognized as a robust platform to achieve these targets [10]. Following years of exploration and development, the EU carbon emissions trading market and the California carbon cap-and-trade market [11–13] are flourishing. These markets effectively shape the behavior of enterprises through the price mechanism, ultimately realizing the goal of reducing carbon emissions [14].

Price volatility in one market is prone to affect another market [15]. Such volatility may sharply increase and spill over into other markets, especially during periods of economic policy uncertainty [16]. These intermarket spillovers offer valuable insights for investors and policymakers seeking investment opportunities and risk management strategies [17]. Carbon markets are increasingly influenced by commodities [18] and financial markets [19, 20]. In response to market uncertainty, investors employ portfolio diversification to minimize risks posed by other markets [21, 22]. The green bond market is considered an influential force in promoting climate-friendly and sustainable development [19]. Some evidence suggests that the emergence of green bonds can drive the development of new green technologies, contributing to the goal of transitioning the economy towards a low-carbon one [23].

The carbon market and the green bond market are two emerging financial markets with unique characteristics and interrelationships. While the carbon market is characterized by high volatility, the bond market is known to be less prone to fluctuations. The fluctuations in carbon returns may have a significant impact on the performance of green bonds, particularly during certain periods [24]. Rannou et al. [25] have identified complementarity and substitution relationships between the carbon market and the green bond market from the perspective of European power companies. In the short term, the green bond market complements the carbon market, while in the long term, it serves as a substitute. The occurrence of macroeconomic and financial "black swans" and "grey rhinos" since the subprime crisis in 2008 has led to a significant increase in Economic Policy Uncertainty (EPU). EPU is known to be a significant source of macroeconomic fluctuations, influencing various aspects of the economy, such as the stock market, bond market, commodity prices, and more [26, 27]. EPU can also contribute to cross-asset correlations through macro-fundamental channels [18, 28].

The development of the green bond market is inevitably subject to EPU shocks. According to recent empirical studies, it has been observed that there exists a time-varying and state-dependent relationship between green bonds and EPU. Specifically, during periods of low EPU, the correlation between green bonds and EPU is lower, suggesting that they may serve as an effective hedging tool against uncertainty in such periods. In the United States, it has been found that green bonds primarily serve as a hedge against EPU shocks rather than a safe haven [29]. Furthermore, Aamir et al. [30] confirm that positive shocks to EPU have a negative impact on the performance of green bonds, while negative shocks to EPU tend to improve their performance. These findings have important implications for investors who seek to manage their portfolio risk in the face of economic uncertainty. Green bond markets represent one potential avenue for hedging and mitigating systemic risks [22, 31]. The development of carbon markets is also influenced by EPU, indicating a relationship between EPU and carbon markets [32, 33].

Based on an autoregressive distributional lag model, Adams et al. [34] found that energy consumption and economic growth contribute to CO2 emissions, establishing a significant association between Economic Policy Uncertainty (EPU) and CO2 emissions in the long run. EPU typically exerts a direct impact on policy regulation and an indirect effect on economic demand, both influencing the willingness of economic agents to emit carbon and the intensity of emissions. As EPU increases, it accelerates the willingness and intensity of carbon emissions from economic agents [13, 35]. However, some scholars argue that a rise in EPU will suppress carbon emissions [36]. In the context of rapid global economic transformation, the COVID-19 pandemic and the Russian-Ukrainian conflict have pushed the already existing EPU to a more precarious edge. The increasing uncertainty in confronting China's economic development undoubtedly makes it more challenging to achieve the low-carbon target. Therefore, the inclusion of EPU as an influencing factor in our study significantly addresses the needs of the real economic environment and is thus highly necessary.

In terms of trading objectives, the two markets share the same intentions and goals in controlling greenhouse gas emissions and realizing low-carbon economic development. Regarding transaction costs, the carbon market increases current costs while promoting a low-carbon transition of the economy in the future. In contrast, the green bond market generates future debt costs while supporting green projects to effectively reduce current carbon emissions. Therefore, the two markets complement each other in promoting low-carbon development [37]. In terms of market demand, since the return on investment in green projects depends on the cost of carbon emissions, a stable carbon lattice will lead to relatively stable investment returns, thereby increasing the demand for green bonds. Consequently, there is a correlation between the carbon market and the green bond market, and the development of one market may have an impact on the other [38].

While studies on the correlation between the carbon market and the green bond market have been conducted in Europe and the US, there have been few studies on how these two markets influence each other in China, with a neglect of considerations for Economic Policy Uncertainty (EPU) factors. The Chinese carbon market and green bond market significantly differ from those in Europe and the US in terms of development scale, management mode, regulatory approach, price mechanism, and more. Therefore, we cannot directly apply the research results of studies on the European and US markets when managing risks in the two markets. Consequently, we chose to construct a time-varying parametric vector autoregressive (TVP-VAR) model to explore the dynamic linkage of EPU, the green bond market, and the carbon market. This aims to provide relevant policymakers and investors with a reference for decision-making and risk management.

3. Econometric Models

The TVP-VAR model equation is defined as follows:

$$\mathrm{A}y_t = F_1 y_{t-1} + F_2 y_{t-2} + \cdots + F_s y_{t-s} + \mu t, \quad t = s+1, \cdots, n \tag{1}$$

In equation (1), y_t is the $k \times 1$ vector of observed variables, t is a variable vector of degree $k \times 1$; A and $F_1, \cdots F_s$ are all $k \times k$ matrices of coefficients, is used to measure structural effect, $\mu_t \sim N(0, \sum\sum 1)$.

$$\sum = \begin{pmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_k \end{pmatrix}. \tag{2}$$

Then, we suppose that the A matrix is a lower triangular matrix.

$$A = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ a_{21} & 1 & \ddots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ a_{k1} & a_{k2} & \cdots & 1 \end{pmatrix}. \tag{3}$$

Next, we reformulate the following VAR model using equation (1)

$$\begin{aligned} y_t &= B_1 y_{t-1} + B_2 y_{t-2} + \cdots + B_s y_{t-s} \\ &\quad + A^{-1} \sum \varepsilon_t, \varepsilon_t \sim N\left(0, I_k\right). \end{aligned} \tag{4}$$

In equation (4), $B_i = A^{-1} F_i$, $i = 1, 2, \cdots, s, X_T = I_t \odot (y'_{t-1}, \cdots y'_{t-s})$, where $\odot$ expressed as Kronecker product. Equation (4) can be formulated as follows:

$$y_t = X_t \beta + A^{-1} \sum \varepsilon_t. \tag{5}$$

Next, we consider the time-varying and stochastic volatility of the model.

$$y_t = X_t \beta_t + A_t^{-1} \sum_t \varepsilon_t, \quad t = s+1, \cdots, n. \tag{6}$$

In equation (6) β_t, $A_t \sum_t \varepsilon$ are time-varying. Let $\alpha_t = (\alpha_{21}, \alpha_{31}, \alpha_{32}, \alpha_{41}, \cdots \alpha_{k,k-1})'$, and $h_t = (h_{1t}, h_{2t}, \cdots, h_{\mathrm{kt}})'$, $h_{\mathrm{jt}} = \ln \delta_{1t}^2$, $j = 1, 2, \cdots k, t = s+1, \cdots, n$. Then, we assume that the parameters in equation (6) follow a random walk process.

$$\beta_{t+1} = \beta_t + \mu_{\beta t}, \tag{7}$$

$$\alpha_{t+1} = \alpha_t + \mu_{\alpha t}, \tag{8}$$

$$h_{t+1} = h_t + \mu_{ht}, \tag{9}$$

$$\begin{pmatrix} \varepsilon_t \\ \mu_{\beta t} \\ \mu_{\alpha t} \\ \mu_{ht} \end{pmatrix} \sim N \left\{ 0, \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & \sum \beta & 0 & 0 \\ 0 & 0 & \sum \alpha & 0 \\ 0 & 0 & 0 & \sum h \end{bmatrix} \right\}, \quad t = s+1, \cdots, n. \tag{10}$$

In equation (10) $\beta_{p+1} \sim N(\mu_{\beta_0} \sum_{\beta_0} \beta)$, $\alpha_0 \sim N(\mu_{\alpha_0} \sum_{\alpha_0} \alpha)$, $h_{p+1} \sim N(\mu_{h_0} \sum_{h_0} h)$. According to Nakajima [39], we can use MCMC simulation sampling method to estimate the parameters and determine the number of simulation samples. In this paper, MCMC algorithm performs 1000 presamplings and 10000 samplings.

4. Empirical Research

The data sources for the variables are as follows: Economic Policy Uncertainty (EPU) Index, Green Bond Index, average trading prices of the five major carbon emission markets (carbon price), and Producer Price Index (PPI). The dataset consists of monthly data from January 2016 to December 2021. The China Economic Policy Uncertainty (EPU) index is a widely used measure of economic and policy uncertainty in China. The index is compiled by Shangqin Lu and Yun Huang, who collect relevant word frequencies from news articles and statistically calculate the index based on these word frequencies. The primary purpose of the EPU index is to reflect the degree of uncertainty that exists in the Chinese economy and policy environment. To ensure that the analysis results are not affected by excessive values, the EPU index is treated as a logarithm. In addition, the China Green Bond Index is published by China Bond Financial Valuation Center Co., Ltd. This index is designed to serve as a performance benchmark and underlying index for investing in green bonds. It selects green bonds with certain stock sizes and credit levels that meet specific requirements and provides a measure for the development of China's green bond market. Furthermore, China has initiated local pilot programs for carbon emission trading in several major cities since October 2011. The average trading prices of the five major carbon emission markets in Beijing, Shanghai, Hubei, Guangdong, and Shenzhen are selected to indicate changes in the carbon market. However, the Chongqing and Tianjin markets were excluded due to their low turnover. These measures reflect China's ongoing efforts to address climate change and promote sustainable economic development. The Producer Price Index (PPI) measures the trend and degree of change in the ex-factory prices of industrial enterprises. The Chinese economy, being an industrial powerhouse, is currently undergoing a process of economic transformation and upgrading which places significant emphasis on the industrial transformation. The structural changes occurring in the secondary sector have a strong correlation effect on other industries and, as such are expected to have a considerable impact on the overall economic development of China. One way to assess the macroeconomic situation is by utilizing the PPI which can provide valuable insights into the economic trends and performance of the country.

Table 1 shows the descriptive statistics of the main variables of the paper. The results show that Epu Index has a mean of 274.6 and a standard deviation of 121.3; the Green Bond Index has a mean of 157.5 and a standard deviation of 12.52; carbon price has a mean of 32.79 and a standard deviation of 6.28; and PPI index has a mean of 102.4 and a standard deviation of 4.45. (See Table 2).

The Augmented Dickey-Fuller (ADF) test can be employed to determine whether the original data are smooth. The table below presents the ADF test values for the four datasets after first-order differencing. P values less than 0.05 indicate that the original hypothesis of smooth time series data cannot be rejected at the 5% significance level. This confirms the stability of the data after first-order differencing.

Table 1: Values of descriptive statistics.

Variable	N	Mean	SD	Min	Max
Epu index	72	274.6	121.3	106.8	661.8
Green bond index	72	157.5	12.52	141.9	180.2
Carbon price	72	32.79	6.280	22.88	45.50
PPI index	72	102.4	4.450	94.70	113.5

Table 2: Unit root test results.

Variable (the first-order difference)	ADF
EPU	-13.94433^{***}
Green bond	-5.806012^{***}
Carbon price	-7.080471^{***}
PPI	-4.492268^{***}

4.1. Estimation Results of the TVP-VAR Model. We simulated and estimated a four-variable time-varying parametric vector autoregressive (TVP-VAR) model using Markov Chain Monte Carlo (MCMC): Economic Policy Uncertainty (EPU) Index, Green Bond Index (Green Bond), average trading prices of the five major carbon emission markets (Carbon Price), and Producer Price Index (PPI). The TVP-VAR model involves Bayesian estimation through the Markov Chain Monte Carlo (MCMC) method. The lag order was determined to be 1 based on the Akaike Information Criterion (AIC). Ten thousand iterations of simulations were performed using Oxmetrics 6.0.

The parameter estimation results of the Time-Varying Parametric Vector Autoregressive (TVP-VAR) model are presented in Table 3. At the 95% confidence level, all Geweke convergence test results are below 1, well under the critical value of 1.96. Therefore, we cannot reject the null hypothesis that the sampling parameters cluster within the 95% confidence interval for the parameters of the TVP-VAR model. This implies that MCMC sampling converges very well. In addition, the coefficients for all parameters show a zero effect less than 100, indicating that the sample size is sufficient for further inference of the model. In conclusion, the parameter estimation of the TVP-VAR model is effective, and the dynamic relationship between variables can be further investigated.

Figure 1 depicts the estimated results of the model after 1000 presamples and 10,000 samples using the MCMC algorithm. The three rows in the diagram display the estimated results of the sample autocorrelation coefficient, sample paths, and posterior distributions, respectively, from top to bottom. As shown in Figure 1, the sample autocorrelation coefficient sharply drops and fluctuates around 0 after the removal of the initial 1000 samples, indicating that the sampling method can generate uncorrelated sample information. The sample paths in the second row generally exhibit steady fluctuations, signifying that the MCMC algorithm provides an effective simulation of the parameter distribution. The posterior distribution estimation in the third row resembles a normal distribution, confirming the effectiveness of the value sampling.

4.2. Impulse Response Analysis

4.2.1. Time-Varying Impulse Response Analysis. To investigate the dynamic relationship between EPU, the green bond market, the carbon market, and the macroeconomy, we examine the situation under various time delays using time-varying impulse response functions. In this study, we employed one lag (one month) for the short term, two lags (two months) for the medium term, and four lags (four months) for the long term.

Figure 2 illustrates that both short-term and medium-to-long-term EPU have impacts on the green bond market, aligning with the perspective of Haq et al. [29]. In the short term, the influence of EPU on green bonds manifests as a continuous negative shock, while in the medium and long term, the impact transforms into a continuous positive shock. The short-term impact is more substantial and time-varying, whereas the medium- and long-term impacts are relatively moderate. In China, both the green bond market and the stock market are influenced by EPU. However, due to the high volatility of the stock market, the effect of EPU on the stock market surpasses its impact on the green bond

Table 3: Estimation result.

Parameter	Mean	SteDev	95% *L*	95% *U*	Geweke	Inef
sb1	0.0227	0.0025	0.0184	0.0284	0.941	3.73
sb2	0.0225	0.0026	0.0181	0.0282	0.907	3.34
sa1	0.0797	0.0312	0.0417	0.1561	0.853	30.13
sa2	0.0749	0.0233	0.0418	0.1316	0.464	21.41
sh1	0.2050	0.1051	0.0738	0.4837	0.061	65.25
sh2	0.2208	0.0852	0.1039	0.4267	0.428	34.42

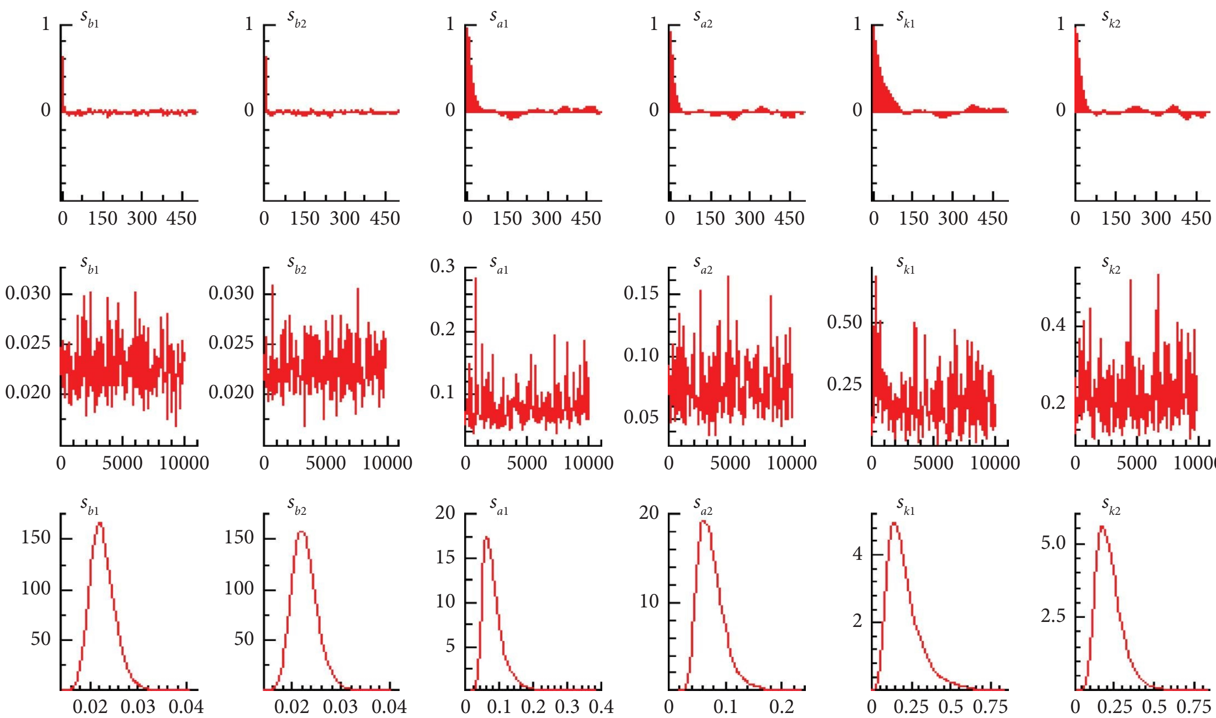

Figure 1: Estimation results of the TVP-VAR model.

market. In the short term, an escalation in EPU prompts investors to become more risk-averse, leading to reduced investments in both the stock and green bond markets as they shift towards lower-risk assets like treasury bonds. Consequently, an increase in short-term EPU results in a decline in green bond market prices, consistent with the findings of Aamir et al. [30]. Nevertheless, in the medium and long term, the green bond market remains an investment avenue with relatively stable and higher returns compared to treasury bonds and other risky instruments like the stock market. Thus, when EPU increases, green bonds appreciate and serve as an effective hedge, contrasting with the observations of Inzamam [29].

The visual representation presented in Figure 3 highlights the enduring influence of the EPU shock on the carbon trading market. This outcome lends credence to the conclusions reached by Adedoyin and Zakari [33], Adams et al. [34], and other academic researchers who have explored the topic. Notably, green bonds respond to EPU with a positive effect in the short term and a negative effect in the medium and long term. Specifically, the largest impact is identified in the short term, with a relatively mild impact in the medium and long term. As the carbon market is policy-driven [40], an increase in EPU leads to a short-term rise in the carbon market price, aligning with the study by Bel and Joseph [35]. In China, elevated EPU introduces investment uncertainty for the future economy. Given the certain policy goal of transitioning to a green, low-carbon economy, the carbon market becomes a relatively secure investment and a preferred market for investors. From the medium to the long term, an increase in EPU heightens investors' expectations of transition risks. This results in decreased confidence in future investment and heightened concerns about emerging markets such as the carbon market. Consequently, investors increasingly revert to traditional financial markets and conventional investment instruments, leading to a decline in carbon market prices. This aligns with the observations of Koch et al. [36] and Yang [13].

Figure 4 illustrates the influence of the green bond market on the carbon emissions trading market. In both the short and medium-to-long term, carbon emissions trading prices are susceptible to shocks from the green bond market, resulting in negative effects. The most substantial impact occurs in the short term, exhibiting a significant time-

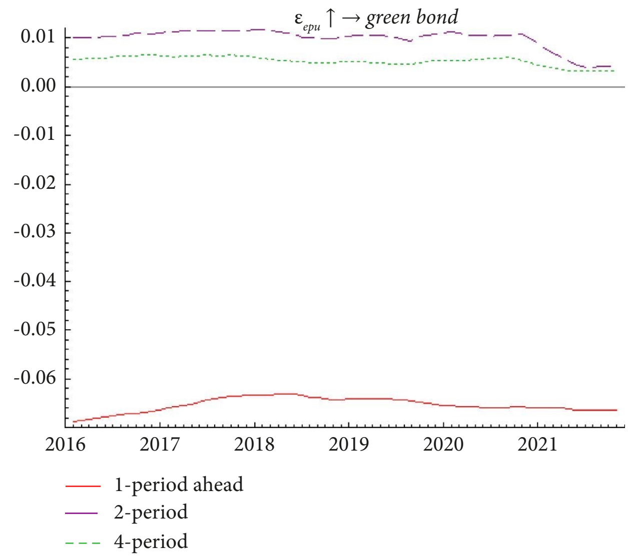

Figure 2: The impact from EPU on the green bond market with Time-varying.

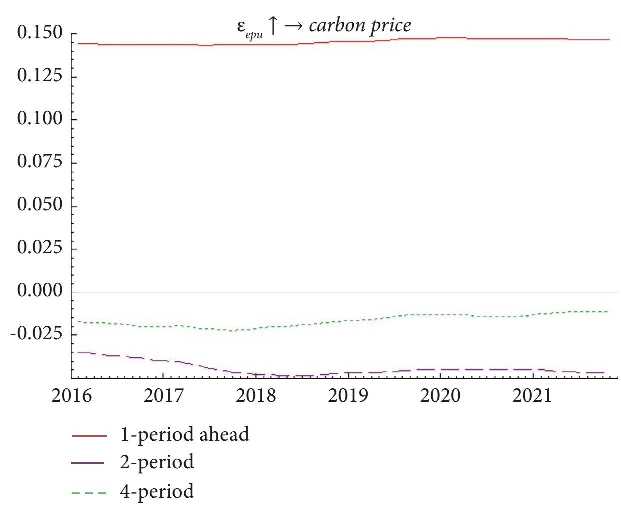

Figure 3: The impact from EPU on the carbon market with Time-varying.

varying effect, which aligns with the findings of Yang [27] and Hammoudeh et al. [24]. This phenomenon may be attributed to the complementarity between the green bond market and the carbon market. When the price of the green bond market rises, investor enthusiasm increases, fostering a relatively prosperous market. Bond issuers can secure the funds necessary for transitioning to a green, low-carbon enterprise through debt financing.

For newly established green and low-carbon enterprises lacking remaining carbon trading resources, the green bond market can comprehensively fulfill their capital requirements for green development. Subsequently, the carbon market assumes a supplementary role for green capital needs, serving as a replenishment station to support struggling enterprises in the transition phase, albeit with limited dynamism that contributes to a decline in carbon market prices. Conversely, a decrease in the market price of green bonds prompts a rise in carbon market prices, incentivizing more enterprises to undertake energy-saving and emission reduction initiatives. This, in turn, generates additional surplus carbon emission rights, allowing enterprises to accrue more revenue in the carbon market. The increased carbon market prices result in higher costs for acquiring carbon emission rights and diminished profits for entities exceeding emission limits. Consequently, these enterprises resort to raising funds through the issuance of green bonds and other means to undertake technological and process innovations, reduce carbon emissions, and expedite the transformation into green, low-carbon entities. As a result, a negative interaction process between the green bond market and the carbon market ensues, aligning with the short-term findings and contrasting with the long-term observations of Rannou et al. [25]. Both markets contribute to the green low-carbon transition of firms, and the turbulence in EPU may strengthen the linkage between the green bond market and the carbon market [27, 28].

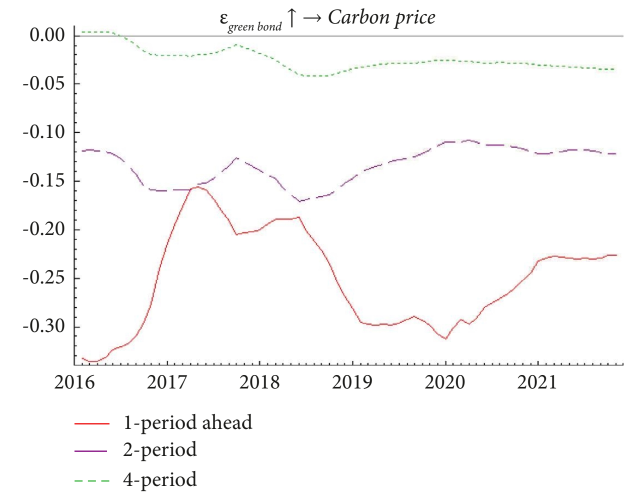

FIGURE 4: The impact from green bond market on carbon market with Time-varying.

However, a higher price in the carbon market and a lower price in the green bond market widen the range of participants engaged in carbon trading, enhancing the benefits associated with the low-carbon transition of the economy.

In addition to assessing the impact of EPU, this paper delves into the macroeconomic ramifications of the green bond market, unraveling the dynamic relationship between the green bond market and the producer price index. Figure 5 elucidates the influence of the green bond market on the producer price. Initially, until March 2018, the green bond market exerted a positive shock on the producer price. Post-March 2018, coinciding with the commencement of US-China trade friction, this impact undergoes a transformation into a negative shock. One plausible rationale is rooted in the advent of the trade tensions between the US and China in March 2018. Prior to this, amidst the domestic drive to boost green GDP and implement supply-side reforms, China actively fostered the development of the green bond market to substantially curtail high inputs, high consumption, and high pollution while augmenting efficiency [5]. This initiative led to increased investments in the green industry and green technology, triggering initial manifestations of scale benefits and spillover effects, contributing to the overall growth in industrial output. Following the onset of the US-China trade friction, the green bond market began to exert a negative impact on the PPI. A plausible explanation lies in the substantial impact of the trade friction on export trade, a foundational element of China's macroeconomy. With export trade taking a hit, the domestic economic development faced impediments, making it challenging for nascent green industries and green R&D enterprises to flourish independently. Enterprises embarking on their green transformation witnessed reduced profits and diminished output due to a lack of international market influence. In such an environment, the ongoing promotion of supply-side structural reforms persisted. While the green bond market continued to propel the green transformation of enterprises, the associated transformation costs escalated. Consequently, enterprise output decreased, and the macroeconomy experienced a decline. This aligns with the perspective presented by Pham [41]. The findings underscore that the green bond market fosters macroeconomic development during periods of smooth economic operations in China. However, when China's economy grapples with external shocks such as trade frictions, the green bond market decelerates macroeconomic development.

4.2.2. Impulse Response Analysis at Different Time Points. In addition to time-varying impulse response functions, the TVP-VAR model can also generate impulse response functions at specific time points, showcasing the impact at distinct moments. To achieve this objective, we have selected three pivotal observation points that align with significant events. The first observation point is March 2018 ($t = 27$), which marked the official commencement of the US-China trade friction and a subsequent rise in international EPU. The second observation point is September 2020 ($t = 39$), which coincides with the 75th UN General Assembly. During this period, major global concerns were addressed, including the 2019 coronavirus disease, the 2030 Agenda for Sustainable Development, and climate change. In addition, China proposed the goal of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. The third observation point is April 2021, when various departments of the People's Bank of China (PBOC) jointly issued the "Green Bond Support Project Catalogue (2021 Edition)," which standardized the criteria for defining green bond projects. By analyzing these observation points, we aim to shed light on the complex interplay between EPU, green bonds, carbon markets, and the macroeconomy, and contribute to the existing literature on sustainable finance and environmental economics.

Figure 6 illustrates the impact of EPU on the green bond market. The effect of EPU on the green bond market remains consistent across all three time points, manifesting as negative shocks that reach a minimum negativity within the lag 1 period and subsequently taper off to zero. The shock's impact was most pronounced in March 2018, signifying that the heightened EPU resulting from the U.S.-China trade friction exacerbates the volatility of the green bond market.

Figure 7 depicts the impact of EPU shocks on the carbon market at three distinct time points. The impact trends are nearly identical across all three instances. EPU exhibits a positive effect on the carbon market, reaching its peak in the lagged period and gradually diminishing until the impact recedes to zero. The escalation in EPU leads to a rise in prices in the carbon trading market, signaling increased investor attention to the carbon trading market and investment in carbon financial instruments as a hedging strategy amid heightened EPU.

Figure 8 illustrates the impact of the green bond market shock on the carbon market, primarily exhibiting a negative trend. It attains its peak in the lagged period and then gradually diminishes until reaching zero. This outcome aligns with the aforementioned time-varying impulse response. In Figure 9, the impact of the green bond market

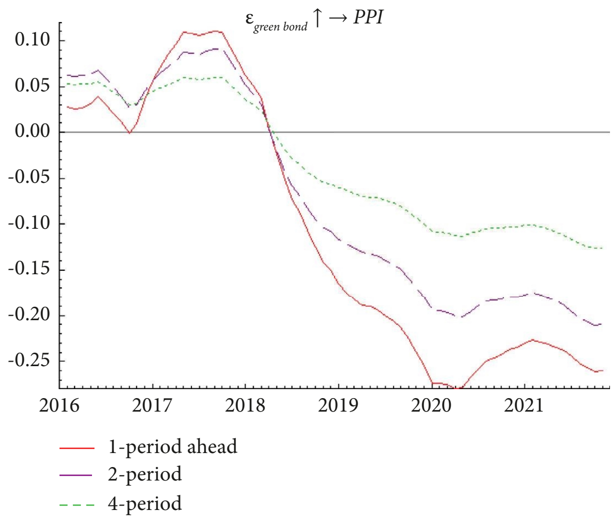

Figure 5: The impact from green bond market on producer price index with Time-varying.

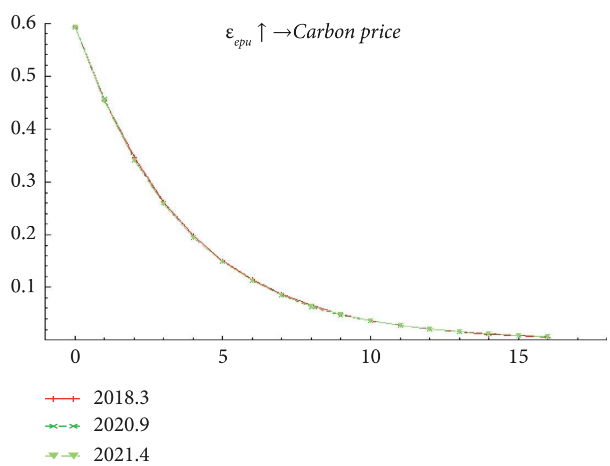

Figure 6: The impact from EPU on the green bond market at different time points.

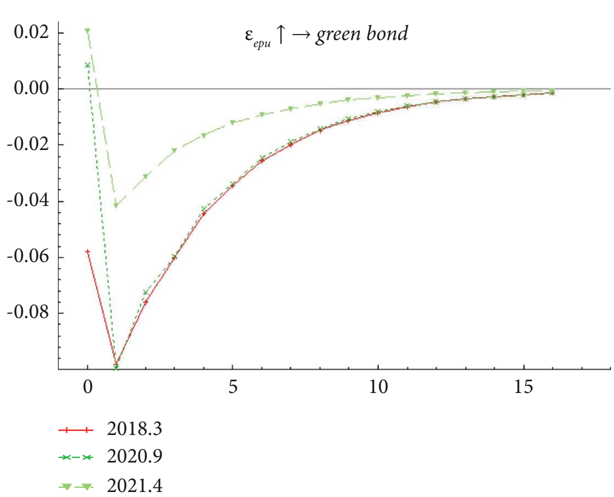

Figure 7: The impact from EPU on the carbon market at different time points.

shock on the PPI is presented. There is a substantial contrast between the March 2018 shock and the shocks in September 2020 and April 2021. The March 2018 shock yields a positive effect on the PPI, while the shocks in September 2020 and April 2021 result in a negative impact on the PPI—a finding consistent with the time-varying impulse responses. The U.S.-China trade war has exerted a significant influence, and China's low-carbon economic transition confronts challenges both domestically and internationally.

Therefore, to facilitate the seamless transition to a green economy, China should adopt a new paradigm in response to climate change and carbon neutrality. This paradigm should center around the domestic grand cycle, with the domestic and international double cycles mutually reinforcing each other. Embracing a system-based approach to openness, the fundamental concept should involve proactively aligning with international carbon emission standards. Furthermore, it is imperative to enhance the investment and regulatory systems, fostering a newfound advantage in international cooperation and competition amid evolving circumstances. Given the current surge in global risk factors, the financial market must bolster its resilience against risks stemming from external uncertainties [42]. The government's role extends beyond formulating preferential policies for green projects and providing a conducive development platform. It should broaden the spectrum of entities participating in green financial development, emit positive market signals, and, critically, diversify green products. In addition, a coordinated linkage mechanism between the green bond market and the carbon market should be introduced in due course. This will maximize the synergistic development function of the two markets.

4.3. Robustness Check. Robustness testing is crucial for ensuring the stability of study findings amid model transformations [43]. In order to validate the robustness and accuracy of the time-varying parametric vector autoregressive (TVP-VAR) model results and mitigate the potential influence of chance, we employed a Bayesian VAR (BVAR) model for robustness testing. The BVAR model incorporates prior distributions of coefficients in the VAR model. Unlike the traditional VAR model, it can constrain the range of coefficient values, address the information limitations of small samples, mitigate the overparameterization issue, and enhance the precision of parameter estimation. Hence, it is well-suited for the robustness testing in this study. The results are depicted in Figure 10. The impact of Economic Policy Uncertainty (EPU) is negative on the green bond market and positive on the carbon market. Conversely, the impact of a green bond is negative on the carbon market and negative on the macroeconomy. Upon comparing the trend of each impulse response function, it is evident that the trend of the impulse response results from the BVAR aligns closely with that of the TVP-VAR model presented earlier in this paper. Consequently, the results demonstrate reliability.

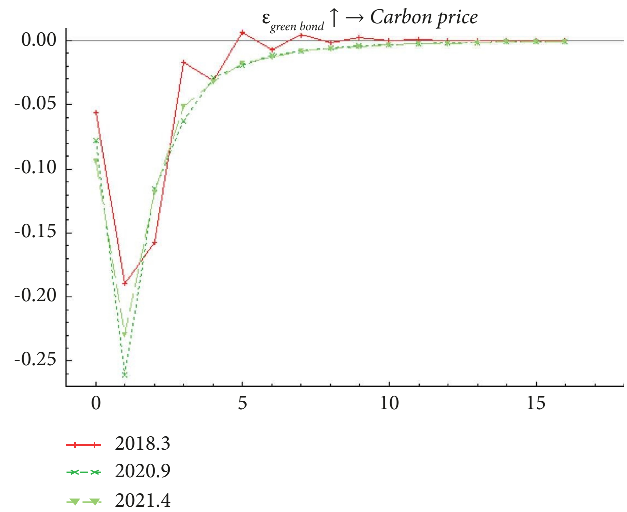

Figure 8: The impact from green bond market on the carbon market at different time points.

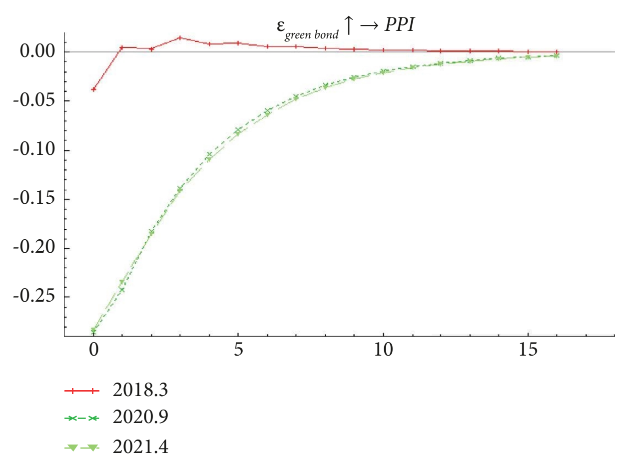

Figure 9: The impact from green bond market on producer price index at different time points.

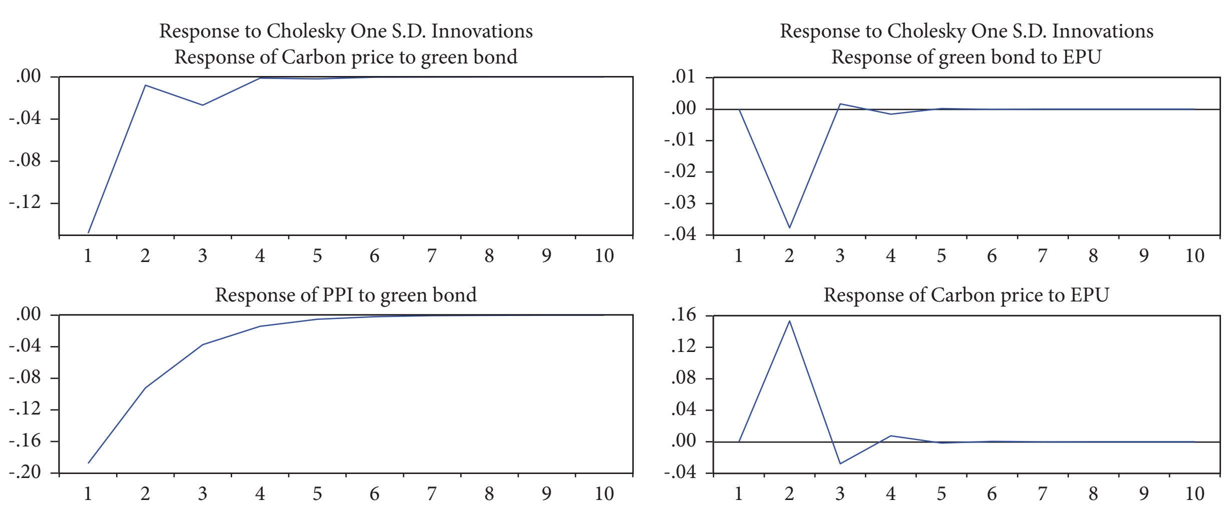

Figure 10: The robustness test based on BVAR model.

5. Discussion

5.1. Implications for Theory. To address climate change and actively engage in global governance, China has consistently advanced carbon peaking and carbon neutrality, implementing effective measures to promote low-carbon economic transformation. The scholarly discourse within this particular context has been predominantly focused on conducting in-depth research into the development of both the carbon market and the green bond market. A substantial body of literature exists that has individually shed light on the respective roles and significance of these two markets in facilitating the low-carbon transition [44–48]; there exists a relative isolation in the examination of these markets collectively. This study, taking China as an example, delves into the dynamic linkages between Economic Policy Uncertainty (EPU), the green bond market, and the carbon market. It enhances the conventional VAR model by employing a more transmissive and global time-varying parameter VAR (TVP-VAR) model for measurement, providing insights into the propagation of shocks over time in terms of magnitude and direction. This complements previous studies, offering a nuanced understanding of the time-varying relationship between the green bond market and the carbon market. The empirical results contribute to the literature on the linkage development of these two markets and the mechanisms of policy effects, enriching the theory of risk management in new financial markets. Moreover, the study equips investors with an analytical foundation for formulating effective portfolio strategies amidst complex changes in EPU.

5.2. Implications for Policy. The empirical results demonstrate that EUP has the opposite effect on the carbon and green bond markets in the short-, medium-, and long term. Previous studies have recommended that policymakers strengthen incentives to reduce low-carbon emissions in a single market [49–52], but they have not often considered the connections between the two markets. This study examines the ultimate outcomes of policies from the perspective of market linkages, presenting policymakers with a more extensive analytical viewpoint. This means that policymakers must take into account not only the policy impacts of a single market but also the linkage effects of related markets when making decisions. Furthermore, the research findings reveal that when we approach environmental issues from a financial perspective, the economy and the environment can both develop in a win-win situation.

Achieving environmental friendliness is greatly aided by strong economic development. China has yet to fully tackle its low-carbon goals, but in addition to utilizing market mechanisms to control carbon emissions, policymakers should prioritize the development of a robust green financial market. This will provide ample financial support for enterprises seeking to transform their practices to be more energy-efficient and reduce emissions. Ultimately, the pursuit of environmentally-friendly economic development hinges on the wise decision-making of government officials.

5.3. Limitations and Future Research Directions. Similar to prior research, this paper possesses certain limitations, prompting the need for subsequent in-depth investigations. Firstly, our examination has focused on the linkage mechanisms and policy implications between China's green bond market and the carbon market. A parallel inquiry could be conducted in other nations, leveraging the wealth of economic data available in the digital age. Secondly, beyond the models employed in this study, exploring the impact of changes in China's green bond market on carbon market development could benefit from the integration of various models. Utilizing novel forecasting and machine learning models (Li et al., 2018) holds the potential to offer predictive insights, providing practical guidance for policymakers and governments.

6. Conclusion

In recent years, China has been actively addressing climate change and striving to achieve its low-carbon targets. Numerous studies have presented evidence supporting the positive impact of low-carbon assets on carbon emission reduction. Despite the growing interest in sustainable finance, there has been a paucity of research on the synergies between the green bond market and the carbon market in driving low-carbon initiatives. This gap in knowledge highlights the need for further investigation into the combined contribution of these two markets, which could potentially unlock new opportunities for financing the transition towards a low-carbon economy.

This research utilizes monthly data spanning from January 2016 to December 2021. A Time-Varying Parameter Vector Autoregression (TVP-VAR) model is employed to investigate the dynamic interplay between EPU, the green bond market, the carbon market, and the macroeconomic environment. The robustness and accuracy of the empirical results are tested through the BVAR model. The analysis reveals that EPU exerts a negative short-term impact on the green bond market and a positive medium-to-long-term impact. Conversely, EPU has a positive short-term impact on the carbon market but a negative medium-to-long-term impact. The green bond market negatively influences the carbon market in both the short and medium-to-long term. In periods of smooth economic activity, the green bond market fosters macroeconomic development; however, during external shocks like trade frictions, it hampers macroeconomic progress.

The results of this study contribute to the ongoing discourse surrounding the correlation between the green bond market and the carbon market, and provide novel insights for advancing China's green and low-carbon economic growth. The proposals outlined in this paper are as follows:

(1) The global economy is currently facing challenges, and the world situation is complex and volatile. With rising inflation in the US and the Federal Reserve implementing interest rate hikes to curb inflation, tightening monetary policy may have negative

spillover effects. Economic Policy Uncertainty (EPU) could experience significant fluctuations due to turbulent events in financial markets and macroeconomics [53]. As economic policy uncertainty worsens, policymakers should be particularly vigilant regarding the potential contagion of EPU volatility on green bonds and carbon markets. Strengthening risk regulation is essential to prevent risks from materializing. Chinese regulators should standardize the information disclosure system to enhance the accuracy of information in the market, thereby improving market efficiency. A robust information disclosure mechanism forms the basis for effective market information. Accurate and efficient information collection, release, and transmission are fundamental for investors to make rational decisions. Building upon the existing information disclosure framework, it is crucial to further categorize and refine disclosure guidelines based on the characteristics of green financial products. Establishing and enhancing unified information disclosure guidelines, creating a centralized platform to streamline the information disclosure process, and optimizing efficiency will contribute to introducing international management standards. Strengthening certification management and regulating fund usage will enhance market credibility and international recognition of these products.

(2) In the low-carbon transformation of the economy, the green bond market provides effective financial support, while the carbon market controls and restrains the total amount of carbon emissions. Favorable conditions for the low-carbon transformation of the economy occur when the price of the carbon trading market is higher and the price of the green bond market is lower, and China's two markets are currently at such a stage. The Chinese government could adopt an inverse price strategy for the two markets in a moderate manner when formulating development policies, while also strengthening risk regulation to address the root causes of risk contagion. When developing risk management strategies for a single market, consideration should be given to the risk status of that market in relation to other markets. Regulators in the regulatory process should acknowledge the uniqueness of the market's risk and simultaneously account for the linkage between different markets. While emphasizing the market's own risk, they should also consider risks emanating from external factors. The goal is not only to ensure the market's orderly operation but also to maintain a market-oriented bidding process. Striking a balance is essential–protecting the rights and interests of investors while respecting the market's game mechanism. Investor rights and interests should be safeguarded in a manner that also respects the dynamics of the market game mechanism.

(3) The Chinese government is actively promoting the development of green finance, and both the carbon market and the green bond market have started to play roles. However, these markets are closely interacting with each other, and due to the small size and low market activity, policies still need further optimization. To address this, the government can take several steps. Firstly, it can offer more incentives to attract additional market players to engage in green production and operations. Secondly, the government can provide increased support for green research and development (R&D) to mitigate the risks associated with enterprises investing in such initiatives. Thirdly, there is an opportunity to establish a linkage mechanism within the green financial market. This involves innovating the combination of green financial products by integrating the relevance of the carbon market and the green bond market. By breaking down barriers between markets, a diverse portfolio of green products can be created, fostering a new mode of coordinated development. This approach is expected to contribute to the realization of low-carbon goals and facilitate the high-quality development of China's economy.

(4) Market participants should promptly adjust their portfolios based on the linkage mechanisms of the two markets to hedge their investment risks. Investors can leverage portfolio theory, which suggests a negative correlation between different asset types and overall asset risk. Consequently, when crafting investment portfolios, investors must take into account the correlation of various asset types. In the case of a portfolio that includes both carbon and green bond products, it is crucial for investors to comprehend the correlation between the two markets. This understanding is vital to assessing the overall risk profile comprehensively, enabling investors to make informed and rational decisions.

Data Availability

The data that support the findings of this study can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was financially supported by the Humanities and Social Sciences Research Project of Chongqing Municipal Education Commission: Study on Economic Policy Uncertainty, Green Bond Market and Carbon Market Dynamics (Grant no. 23SKGH389); Key Research Project of School of Business and Industry, Chongqing College of

Humanities, Science & Technology: Study on the Linkage Development of Carbon Market and Green Bond Market to Promote Low-Carbon Economic Transition Path (Grant no. CRKGS202301), and Research Center for the Development of Small and Medium-Sized Cities in the Chengdu-Chongqing Economic Circle.

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