

# Spillover effects between green bond markets and major financial markets

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**Abstract.** The study of spillover effects between the green bond market and major financial markets is of guiding significance for the development of a strong and sustainable green financial system to help realize the national goals of carbon peaking and carbon neutrality. This paper constructs the spillover index matrix through generalized vector autoregression and prediction error variance decomposition, studies the static and dynamic spillover between the green bond market and other major financial markets from the perspective of time and frequency domains, and further explores the mechanism and law of the spillover effect through the construction of the spillover network structure diagram. The conclusion is that there is a strong spillover effect between the green bond market and other major financial markets, which is asymmetric, and the spillover effect of negative return series is stronger than that of positive return series. In addition, the spillover effects among markets are strongest in the short term and gradually weaken in the medium and long term, and will be stronger in the case of high market uncertainty, such as the New Crown Pneumonia outbreak.

**Keywords:** green bond market; spillover effects; spillover index; spillover network.

## 1. Introduction

Green bonds are stable and sustainable investments that finance long-term social projects, such as wind and solar energy facilities, which often require significant financial support, and therefore raising funds through large bond markets that can provide financing over the long term may be a suitable option. At home and abroad, the development of green bonds can be traced back to 2007, when the World Bank first issued a financial instrument called "green bonds", which are used to support and finance environmentally friendly projects. With the increasing concern for environmental protection and sustainable development, the green bond market has experienced rapid development in the past few years. According to statistics from the Global Finance Alliance, new issuance in the global green bond market reached US\$257.1 billion in 2019, a 51 per cent increase from 2018. Currently, the main countries and regions issuing green bonds include Europe, the United States, China, etc. The United States has a large volume of green (sustainable) bond issuance, rich in variety, and a wide range of issuance subjects, and the cumulative issuance of green bonds by the United States has reached US\$372 billion since 2014 to the end of 2023, making it the world's largest issuer of green bonds. The foreign green bond market has formed a more mature system, compared to the rise of the global green bond market, China's green bond market started late, but the development momentum is fierce, as of the end of 2017, China has become the world's second largest issuer of green bonds. 2023, China's new green bond issuance scale of about 838.870 billion yuan, as of the end of the year, the cumulative issuance scale of about 3.62 trillion yuan, maintaining its position as the second largest issuance market for green bonds.

However, there were risk spillovers between China's green bond market and the equity markets of major financial markets. Given the uncertainty of international trade conflicts and the global trend towards interest rate cuts, concerns about the economic and political environment have had a noticeable impact on financial markets. When financial events hit a particular market, risk arises and accumulates as investors manipulate their money. Since China's opening to foreign investment, domestic and foreign investors have actively participated in this emerging market, enhancing the liquidity of funds and exacerbating the spillover effects between financial markets. Exploring the

spillover effects between the green bond market and major financial markets and revealing the internal mechanisms and laws at a deeper level are instructive as to whether green bonds help investors organise their portfolios. In addition, for regulators and policy makers, this study helps to understand the dependence between the green bond market and the stock market, as well as the resilience of the green bond market to stock market shocks, to further regulate the domestic green bond market, guide more funds to support green industries and projects, and develop a strong and sustainable green financial system, which will help to realise the national goals of carbon peaking and carbon neutrality. The following is a summary of the key points of the green bond market.

## **2. Literature review**

### **2.1. Spillovers between green bond markets and other markets**

With the rapid development of the green bond market, scholars at home and abroad have studied the spillover effect between the green bond market and other markets through various research models. Reboredo (2018) shows that the spillover effect of traditional bonds affects green bonds, which provide significant diversification benefits to the equity and energy markets. Reboredo and Ugolini (2020) examine price spillovers between the green bond market, the global government bond market, the global graded fixed-rate corporate bond, the global high-yield bond market, the global equity market, and the U.S. dollar currency market, and they find that the green bond market is a net recipient of price spillovers. Naeem et al. (2021) utilise the time-domain spillover framework of Diebold and Yilmaz (2014) and the frequency-domain spillover framework of Barunik and Krehlik (2018), reveals that there are asymmetric spillovers between green bonds and commodities across time and frequency cycles, and that the spillover effect is stronger in the short run. Elsayed et al. (2022) examined, through the spillover framework of Diebold and Yilmaz (2012) and a multivariate wavelet analysis approach, the interdependence between green bonds and financial markets, explaining that the direction and magnitude of spillovers differ across markets, with green bond markets receiving more spillovers but transmitting fewer. Yadav et al. (2023) use the DCC-GARCH model, Diebold and Yilmaz's (2012) time-domain spillover framework, and Barunik and Krehlik's (2017) frequency-domain spillover framework to examine the volatility spillovers between the green bond market and renewable energy and crypto markets, and found that there are linkages between them and the volatility spillovers are lower in the short run than in the medium and long run. Yousaf et al. (2024) used Barunik and Krehlik's (2018) methodology to investigate the dynamic frequency spillovers between the green bond market and the crude oil price. Yousaf et al. (2024) use Barunik and Krehlik's (2018) methodology to study the dynamic frequency spillovers between the green bond market and the crude oil price market, and find that spillovers between them are higher in the short-run than in the medium- to long-term.

### **2.2. Application of empirical modelling of inter-market spillovers**

Lin et al. (2019) investigates the dynamic linkages and spillovers among China's new energy market, coal market, and new energy companies' stock markets using the VAR (1)-DCC-GARCH (1,1) model and the VAR (1)-BEKK-AGARCH (1,1) model. Ji et al. (2019) apply Diebold and Yilmaz (2012, 2016) time-domain-based spillover framework to test the connectivity of return and volatility spillovers of six large cryptocurrencies. Deng et al. (2022) explored the dynamics between China's fossil energy market, the green finance market, and China's major traditional financial markets (stock, bond, and futures markets) based on Diebold and Yilmaz's [DY] (2012) time-domain spillover framework. spillovers and asymmetric linkages. Jiang et al. (2022) similarly apply the spillover framework of DY (2012) to measure the Granger causality and dynamic risk spillover effects of the international crude oil futures market on China's agricultural futures market from the perspective of return and volatility spillovers. Xie et al. (2023) explores the risk spillovers in China's financial and shipping markets, and in addition to applying the TVP-VAR model, the also involves the spillover framework of DY (2012) as well. Jin et al. (2024) constructed a multilayered frequency domain risk

spillover network containing short-, medium-, and long-run layers based on the methodology of Barunik and Krehlik (2018), and explored the extreme risk spillovers of the international energy market in different frequency bands.

Kocaarslan et al. (2024) used a TVP-VAR model to examine the dynamic network connectivity between the oil market, monetary policy, and exchange rate dynamics in the U.S. Chiappari et al. (2024) used the methods of Diebold and Yilmaz (2012, 2014) and Barunik and Krehlik (2018) to investigate how market spillovers are propagated in an integrated system of energy commodities. Elsayed et al. (2024) investigated dynamic returns and volatility spillovers in spot and futures markets in a binary financial system based on Diebold and Yilmaz's approach.

Taking a comprehensive view of the empirical models in recent years in the domestic and international literature on the study of inter-market spillovers, they mainly include the quantile analysis method, the DCC-GARCH model, the BEKK model, the TVP-VAR model, the time-domain spillover framework of Diebold and Yilmaz, and the frequency-domain spillover framework of Barunik and Krehlik, etc., of which the most widely used is the Diebold and Yilmaz's [DY] (2012) time-domain spillover framework. This model will also be used in this paper to investigate spillovers between the green bond market and major financial markets, and in combination with the use of Barunik and Krehlik's [BK] (2018) frequency-domain spillover framework to explore spillovers based on the entire time horizon and different time scales, respectively.

### 3. Methodology

#### 3.1. Time Domain Spillover Framework

To analyse the direction and strength of spillovers across different markets, this paper adopts the spillover index model of Diebold and Yilmaz (2012), which is based on the generalised vector autoregression (VAR) and forecast error variance decomposition (FEVD) processes. Compared to traditional models, the DY (2012) spillover index model not only removes the dependence of the results on lagged orders, but also captures the spillover results across the entire market and across markets, and further estimates the net risk spillover across markets over time.

Firstly, the smooth N-variable p-order vector autoregressive (VAR) model can be described mathematically as:

$$x_t = \sum_{i=1}^p \Phi_i x_{t-i} + \varepsilon_t, \quad (1)$$

Where  $x_t$  denotes the n-dimensional column vector of each market price return at time t, and  $\Phi_i$  denotes the  $N \times N$  matrix of autoregressive coefficients, and  $\varepsilon \sim (0, \Sigma)$  denotes the vector of independent and identically distributed disturbances consisting of zero and covariance matrices ( $\Sigma$ ) consisting of independent and identically distributed disturbance vectors.

The moving average is expressed as:

$$x_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}, \quad (2)$$

Where the matrix of coefficients  $A_i$  ( $N \times N$ ) obeys recursion and is expressed in the following equation.

$$A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \dots + \Phi_p A_{i-p}, \quad (3)$$

Where  $A_0$  is the unit matrix of  $N \times N$  and when  $i < 0, A_i = 0$ .

Second, this paper will show the process of forecast error variance decomposition (FEVD). We define the own variance share as the proportion of the H-step forecast error variance due to the own shock at the forecasting  $x_i$  ( $i = 1, 2, \dots, N$ ) the share of the H-step forecast error variance due to the own shock at forecast time, and spillovers as the cross variance share, defined as the share of the forecast error variance due to the own shock at forecast time  $x_i$  at the time of forecasting, due to the  $x_j$  the proportion of the H-step forecast error variance that is due to shocks to the  $i = 1, 2, \dots, N, i \neq j$ .

In this paper, we use  $\theta_{ij}^g(H)$  to denote the estimated value of the spillover effect, the

$$\theta_{ij}^g(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \Sigma e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \Sigma A_h' e_i)}, \quad (4)$$

Where  $\sigma_{jj}$  is the standard deviation of the  $j$  standard deviation of the prediction error term for the first variable, and  $e_i$  is the selection vector, which is an N-dimensional column vector consisting of 0 and 1 with the first  $i$  element is 1 and all other elements are 0, and  $\Sigma$  denotes the error vector  $\varepsilon$  of the covariance matrix.

Since the shocks to each variable are not orthogonalized, the sum of the contributions to the variance of the prediction error (i.e. the row sum of the elements in the variance decomposition table) is not necessarily equal to one, i.e.  $\sum_{j=1}^N \theta_{ij}^g(H) \neq 1$ . Therefore, in calculating the spillover index, we normalise the matrix shown in Eqs. (1-4) as:

$$\tilde{\theta}_{ij}^g(H) = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^N \theta_{ij}^g(H)}, \quad (5)$$

Among them.  $\sum_{j=1}^N \tilde{\theta}_{ij}^g(H) = 1$ .  $\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H) = N$ .

The total spillover index is a measure of the overall connectivity of the variables of interest and is defined as follows:

$$S^g(H) = \frac{\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H)}{\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H)} \times 100 = \frac{\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H)}{N} \times 100, \quad (6)$$

The directional spillover index is a measure of the extent of spillovers between a market and other markets and is defined as follows:

$$\text{TO: } S_{j \leftarrow i}^g(H) = \frac{\sum_{j=1}^N \tilde{\theta}_{ji}^g(H)}{\sum_{j=1}^N \tilde{\theta}_{ji}^g(H)} \times 100 = \frac{\sum_{j=1}^N \tilde{\theta}_{ji}^g(H)}{N} \times 100, \quad (7)$$

$$\text{FROM: } S_{i \leftarrow j}^g(H) = \frac{\sum_{j=1}^N \tilde{\theta}_{ij}^g(H)}{\sum_{j=1}^N \tilde{\theta}_{ij}^g(H)} \times 100 = \frac{\sum_{j=1}^N \tilde{\theta}_{ij}^g(H)}{N} \times 100, \quad (8)$$

Where the TO spillover index and the FROM spillover index denote the spillover effect of market  $i$  on other markets and the spillover effect of other markets on market  $i$ , respectively.

The net spillover index is the difference between the TO spillover index and the FROM spillover index, defined as follows:

$$S_i^g(H) = S_{j \leftarrow i}^g(H) - S_{i \leftarrow j}^g(H) \quad (9)$$

### 3.2. Frequency domain overflow framework

To analyse the mean spillover between the green bond market and the relevant industry segments of the stock market in a more in-depth and multidimensional way, this paper also adopts Barunik and Krehlik's [BK] (2018) spillover index model, which is based on Diebold and Yilmaz's [DY] (2012) spillover framework that reveals different interaction effects between markets on different time scales (frequencies).

Time domain analysis usually focuses on the direct dependence in time, i.e. spillover effects in the whole-time dimension, and thus fails to capture spillovers in different time scales, whereas mean spillovers between the green bond market and the relevant industry segments of the stock market may behave differently in the short, medium and long term. Frequency domain analysis can be used to decompose the spillover index into different frequency bands by separating different frequency components (e.g., high-frequency component, low-frequency component, etc.), revealing the differences in spillovers between markets in the short-term (high-frequency) and long-term (low-frequency). Studying the mean spillover between the green bond market and the relevant industry sectors of the stock market from a frequency domain perspective helps investors and risk managers to optimise asset allocation. By understanding how the stock market interacts with the green bond market in different frequency bands, investors can more precisely formulate investment strategies to avoid risks in certain specific frequency bands. For example, the green bond market may be a haven for the equity market during certain low-frequency fluctuations, while the relationship between the two may be closer or synchronized during high-frequency fluctuations. Frequency domain analysis helps investors to identify subtle variations between these markets, and thus better diversify their risks.

Firstly, the frequency domain spillover index model of Barunik and Krehlik [BK] (2018) also requires the construction of a vector autoregressive model (VAR), which can then be converted from the time domain to the frequency domain by applying a Fourier transform to the moving average coefficients, and the frequency impulse response function can be defined as:

$$\Psi(e^{-\lambda\omega}) = \sum_{h=0}^N e^{-\lambda\omega h} \Psi_h, \quad (10)$$

$\Psi(e^{-\lambda\omega})$  is the impulse response coefficient  $\Psi_h$  the Fourier transform of the impulse response coefficients, and  $\lambda = \sqrt{-1}$ . The variable  $x_i$  at the frequency  $\omega$  The spectral density on is defined as:

$$S_x(\omega) = \sum_{h=-\infty}^{\infty} E(x_t x_{t-h}') e^{-\lambda\omega h} = \Psi(e^{-\lambda\omega}) \Sigma \Psi'(e^{\lambda\omega}), \quad (11)$$

$S_x(\omega)$  Describes the variable  $x_i$  at a frequency  $\omega$  How it is distributed on the frequency, so the frequency band  $\omega \in (-\pi, \pi)$  on the generalised causal spectrum is defined:

$$(f(\omega))_{i,j} \equiv \frac{\sigma_{jj}^{-1} |(\Psi(e^{-\lambda\omega}) \Sigma)_{i,j}|^2}{(\Psi(e^{-\lambda\omega}) \Sigma \Psi'(e^{+\lambda\omega}))_{i,i}}, \quad (12)$$

Denotes that at a given frequency  $\omega$  at a given frequency, the variable  $i$  is subjected to a variable  $j$  of the shock as a proportion of the spectrum. The frequency of the variable is determined by the frequency of the  $\omega$  of the variable at a given frequency  $i$  the frequency share of the variable is weighted to the equation  $(f(\omega))_{i,j}$  weighting, a generalised decomposition of the variance can be obtained, where the weighting function is expressed as:

$$\Gamma_i(\omega) = \frac{[\Psi(e^{-\lambda\omega})\Sigma\Psi'(e^{\lambda\omega})]_{i,i}}{\frac{1}{2\pi} \int_{-\pi}^{\pi} [\Psi(e^{-\lambda\mu})\Sigma\Psi'(e^{\lambda\mu})]_{i,i} d\mu}, \quad (13)$$

Therefore, the generalized variance decomposition in a particular frequency band  $d = (a, b)$ ;  $a, b \in (-\pi, \pi)$ . The generalised variance decomposition over a particular frequency band can be calculated as follows:

$$(\theta_d)_{i,j} = \frac{1}{2\pi} \int^d \Gamma_i(\omega)(f(\omega))_{i,j} d\omega, \quad (14)$$

When  $H \rightarrow \infty$  when  $(\theta_d)_{i,j}$  This can be further standardised as  $(\bar{\theta}_d)_{i,j}$ , which is expressed as:

$$(\bar{\theta}_d)_{i,j} = \frac{(\theta_d)_{i,j}}{\Sigma_j(\theta_\infty)_{i,j}}, \quad (15)$$

Define frequency-based connectivity over the frequency band as:

$$C_d^F = 100 \times \left( \frac{\Sigma_{i \neq j}(\bar{\theta}_d)_{i,j}}{\Sigma_j(\bar{\theta}_\infty)_{i,j}} - \frac{\text{Tr}\{\bar{\theta}_d\}}{\Sigma(\bar{\theta}_\infty)_{i,j}} \right), \quad (16)$$

Where  $\text{Tr}\{\cdot\}$  is the trace of the variance decomposition matrix, so the total spillover is calculated as:

$$C_d^W = 100 \times \left( 1 - \frac{\text{Tr}\{\bar{\theta}_d\}}{\Sigma(\bar{\theta}_d)_{i,j}} \right), \quad (17)$$

Like the time-domain spillover framework, directional spillover can be calculated at different frequencies. Therefore, in the frequency-domain spillover framework, the "TO", "FROM" and "Net" spillover effects can be expressed as follows.

The frequency spillover Market  $i$  transmitted to other markets is:

$$\text{TO: } (C_d^F)_{i \rightarrow j} = 100 \times \left( \Sigma_{j,i \neq j} \bar{\theta}_{ji}(d) \right) \frac{\Sigma \bar{\theta}(d)}{\Sigma \bar{\theta}(\infty)}, \quad (18)$$

Market  $i$  Subject to frequency spillovers from other markets for:

$$\text{FROM: } (C_d^F)_{j \leftarrow i} = 100 \times \left( \Sigma_{j,i \neq j} \bar{\theta}_{ij}(d) \right) \frac{\Sigma \bar{\theta}(d)}{\Sigma \bar{\theta}(\infty)}, \quad (19)$$

Net spillover:

$$\text{Net: } (C_d^F)_{\text{net}} = (C_d^F)_{i \rightarrow j} - (C_d^F)_{j \leftarrow i} \quad (20)$$

As in the time-domain spillover framework, a  $(C_d^F)_{\text{net}}$  A positive value indicates that the market is a net transmitter of spillovers, while a negative value indicates that the market is a net recipient.

#### 4. Sample and data

Table 1 shows the research variables used in this paper. In order to study the spillover effects between the green bond market and other major financial markets, the green bond market, stock market, treasury bond market, gold futures market, RMB foreign exchange market, and coal market are

selected as the main research objects in this paper, and the CSI-Chinese Green Bonds Net Price Index, the CSI 300 Index, the CSI-Total Treasury Bonds Net Price Index, and the Shanghai Futures Exchange Gold Futures Price Index are also chosen as proxies for each market, USD-RMB exchange rate mid-price, and CSI Coal Index as proxies for each market. The daily closing prices of the above six markets from the first trading day of 2016 to the last trading day of 2022 are selected as observations, excluding legal holidays and other non-trading days, and the data used are from the Wind database and Rexchip database.

**Table 1.** Relevant variables

Primary Markets	Proxy indicators	Indicator code
Green Bond Market	China Bond-China Green Bond Net Price Index	CGBI
stock exchange	CSI 300 index	CSI300
treasury bond market	China Bond - Treasury Total Net Price Index	CTBI
gold futures market	Shanghai Futures Exchange Gold Futures Price Index	Gold
Renminbi Foreign Exchange Market	Median exchange rate of the United States dollar against the renminbi (daily frequency)	USDCNY
coal market	CSI Coal Index	Coal

In addition, the time series of all price indices are converted into a sequence of returns by means of a logarithmic percentage difference, as defined below:

$$r_t = 100 \times \ln(P_t/P_{t-1}),$$

Meanwhile, to quantify the asymmetric spillovers, this paper divides the return series into positive and negative return series, denoted as:

$$r(+)=\begin{cases} r_t, & r_t > 0, \\ 0, & r_t \leq 0. \end{cases}$$

$$r(-)=\begin{cases} 0, & r_t \geq 0, \\ r_t, & r_t < 0. \end{cases}$$

**Table 2.** Descriptive statistics

Primary Markets	CGBI	CSI300	CTBI	Gold	USDCNY	Coal
average value	0.0020	0.0065	0.0007	0.0347	0.0040	0.0245
maximum values	0.8078	5.7774	0.9103	5.3989	1.0437	8.4667
minimum value	-0.8416	-8.2087	-0.9707	-4.8086	-1.4117	-9.6471
standard deviation	0.0811	1.2377	0.1238	0.8188	0.2439	2.0504
skewness	-0.8182	-0.6004	-0.0665	-0.0817	-0.1176	-0.2490
kurtosis	19.3105	4.2961	8.0673	4.8841	2.5648	1.8878
ADF test	-9.55***	-11.93***	-10.67***	-11.86***	-10.78***	-12.11***

Table 2 presents descriptive statistics about the log returns of each market. As shown in Table 2, the mean value of the return series of all markets is close to zero, and the mean value of the returns of the gold futures market and the coal market is larger compared to the other markets. Among them, the coal market has the largest maximum value and the smallest minimum value of return, while the green bond market has the smallest maximum value and the largest minimum value of return. Meanwhile, the volatility of the yield in the coal market is the largest and the volatility of the yield in the green bond market is the smallest, which is in line with the previous analysis about the maximum and minimum values of the yields. In addition, the yields obey the left-skewed distribution and the kurtosis coefficients of all yields are greater than 0, which indicates that the distribution of the yield series in all markets is steeper and spiky compared to the normal distribution. Except for the RMB

foreign exchange market and the coal market, the kurtosis of all other markets is greater than 3, which is a thick-tailed distribution. In general, the more prominent the characteristics of the spiked fat-tailed distribution, the more extreme events and the greater the tail risk. The ADF test shows that all yield series are smooth at the 1% significance level.

## 5. Empirical results

### 5.1. Total spillover based on the time domain

Table 3 depicts the time-domain based static aggregate spillover index matrices for the green bond market, stock market, treasury bond market, gold futures market, RMB foreign exchange market and coal market. Following DY (2012), the row non-diagonal lines indicate the spillovers from other markets to which each market is exposed, and similarly, the column non-diagonal lines indicate the impact of each market on the spillovers from other markets. The off-diagonal row sums (i.e., FROM columns) and the off-diagonal column sums (i.e., TO rows) indicate the connectivity of a market with other markets in the entire direction. The All rows are the total spillover indices that contain a market's own spillovers, i.e., column sums that contain the values on the diagonal. The Net rows are the sums of the spillovers that each market is subjected to from the other markets and the effect of spillovers to other markets, which is numerically expressed as the difference between TO spillovers and FROM spillovers, with negative values indicating that the market is a net recipient of spillovers and positive values a net transmitter.

In terms of directed connectivity, the focus of this paper is on spillover effects between the green bond market and other markets. Firstly, as can be seen in Table 3, the green bond market has a strong spillover effect and is more connected to other markets. The green bond market is subject to 38.92 per cent of spillover shocks from other markets, while causing 31.83 per cent of spillover shocks to other markets, and the green bond market has a net spillover effect of -7.09 per cent, making it a net recipient of spillovers and the largest net recipient of spillovers in the market. This may be since the green bond market, as an emerging market, is more unstable in its development compared to other markets and is more susceptible to spillover effects from other markets.

In particular, the green bond market is affected by the equity market and has a spillover impact of 0.12 per cent on the equity market. Notably, the green bond market is affected by 37.13 per cent of spillovers from the treasury market and 30.45 per cent of spillovers to the treasury market. Numerically, the green bond market is more closely linked to the treasury bond market and is also subject to more spillover impacts from that market, which is because green bonds are a special bond instrument with the general characteristics of ordinary bonds, and different from ordinary bonds, green bonds are used to use the proceeds exclusively to finance green projects that meet the prescribed conditions or to refinance these projects, and the green bond market is essentially the same as the The green bond market essentially belongs to the bond market with the treasury bond market. In addition, the green bond market is also more closely linked to the gold futures market, which is affected by a 0.75 per cent spillover from the gold futures market and has a 0.93 per cent spillover impact on it. Compared with other markets, the spillover effect between the green bond market and the RMB foreign exchange market and the coal market is weaker, only affected by the spillover impact from the RMB foreign exchange market and the coal market by 0.02% and 0.31%, and generating a spillover impact on them by 0.09% and 0.24% respectively. Therefore, green bonds can be used as a diversified portfolio instrument in energy futures.

Therefore, we can conclude that there is a strong connectivity between the green bond market and other markets, that it is most closely linked to the treasury market, and that green bonds are better suited to serve as a risk diversification tool in the fossil energy market than traditional financial assets.

**Table 3.** Aggregate spillover indices based on the time domain

	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	61.08	0.71	37.13	0.75	0.02	0.31	38.92
CSI300	0.12	75.55	1.20	0.15	0.78	22.21	24.45
CTBI	30.45	1.21	66.20	1.05	0.03	1.06	33.80
Gold	0.93	0.24	1.59	95.87	1.28	0.08	4.13
USDCNY	0.09	5.42	0.24	1.22	91.88	1.15	8.12
Coal	0.24	21.87	1.20	0.10	0.34	76.25	23.75
TO	31.83	29.44	41.37	3.27	2.45	24.80	133.16
All	92.91	104.99	107.56	99.14	94.33	101.06	22.19
NET	-7.09	4.99	7.56	-0.86	-5.67	1.06	

## 5.2. Time-domain based asymmetric spillover

In this subsection, asymmetric spillover analysis is performed by decomposing the return series into positive and negative return series. As shown in Tables 4 and 5, the total spillover index based on the positive return series is 17.5 per cent (104.98/600), while the total spillover index for the negative return series is 20.65 per cent (123.89/600), which leads to the conclusion that there is an asymmetric spillover effect in the time domain for the positive and negative return series, and that the spillover effect under the positive return series is smaller than that under the negative return series.

Firstly, the connectivity of the individual markets in both positive and negative return subsamples is observed. It can be observed that the identity of the green bond market as a net recipient does not change under either the positive or negative return series. Under the negative returns sequence, the identity of all markets is consistent with that under the gross returns sequence, and in general, spillovers in the market are dominated by negative returns. Observation of Table 4 reveals that under the positive return series, the identities of the gold futures market and the coal market are the opposite of those under the total return series, which further suggests that the spillover effect of negative returns is stronger than that of positive returns, i.e., investors are more averse to the risk of price declines, and the spillover effect of negative sentiment in the market is stronger.

Second, the paper compares the spillover effects among markets in both the positive and negative return series subsamples. Observing Tables 4 and 5, the spillover shock to the green bond market from other markets is 35.21% under the negative return series, which is smaller than the 35.85% under the positive return series, whereas the spillover effect is weaker under the positive return series for all other markets, which can indicate that the green bond market is less affected by the downside price risk and may be more likely to be favored by investors compared to other markets. It is interesting to note that the green bond market's exposure to spillovers from the treasury market is stronger under the negative return series, suggesting that the green bond market is vulnerable to downside price risk in the treasury market, which is inconsistent with the overall results, and may be explained by the fact that green bonds, along with traditional treasury bonds, are both investment instruments in the bond market, and price declines in treasury bonds are more likely to be a downward trend in the prices of the bond market as a whole, and therefore green bonds are also would be subject to downward price risk. For other markets, the green bond market is less affected by the negative return series, especially the stock market and coal market, the green bond market is affected by 0.19% and 0.06% respectively, which shows that the green bond market is almost not affected by the risk of price decline in the stock market and coal market, and that the green bond has a certain hedging characteristics, and can be used as a tool to diversify the risk in the stock market and coal market. risk diversification tool in the stock market and coal market.

Therefore, we can conclude that negative return spillovers across markets in the time domain are stronger and investors are more averse to downside price risk, while green bonds are less susceptible

to downside price risk and can be used as a risk diversification tool, possessing a certain risk aversion nature.

**Table 4.** Positive spillover indices based on the time domain

	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	64.15	0.33	34.10	0.83	0.11	0.48	35.85
CSI300	0.31	83.47	0.51	0.55	0.61	14.54	16.53
CTBI	29.15	0.13	69.38	0.76	0.13	0.46	30.62
Gold	0.57	0.27	1.01	97.39	0.53	0.22	2.61
USDCNY	0.15	1.46	0.18	0.66	97.16	0.38	2.84
Coal	0.40	14.63	0.55	0.48	0.47	83.47	16.53
TO	30.59	16.83	36.35	3.28	1.85	16.08	104.98
All	94.73	100.31	105.73	100.67	99.01	99.55	17.50
NET	-5.27	0.31	5.73	0.67	-0.99	-0.45	

**Table 5.** Negative spillover indices based on the time domain

	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	64.79	0.19	34.56	0.34	0.07	0.06	35.21
CSI300	0.12	75.18	0.27	0.18	0.72	23.52	24.82
CTBI	30.29	0.35	68.07	0.79	0.22	0.30	31.93
Gold	0.81	0.89	1.20	96.04	0.64	0.41	3.96
USDCNY	0.34	1.68	0.50	0.55	96.57	0.36	3.43
Coal	0.10	23.78	0.31	0.18	0.18	75.46	24.54
TO	31.66	26.89	36.85	2.03	1.82	24.65	123.89
All	96.45	102.07	104.92	98.07	98.39	100.11	20.65
NET	-3.55	2.07	4.92	-1.93	-1.61	0.11	

### 5.3. Total spillover based on frequency domain

Following the practice of BK2018, this section sets three frequency bands of high frequency ( $\pi$ ,  $\pi/5$ ), medium frequency ( $\pi/5$ ,  $\pi/30$ ), and low frequency ( $\pi/30$ , 0), which correspond to the short-term 1-5 days, medium-term 5-30 days, and long-term more than 30 days to observe the frequency-domain-based spillover effects among markets. Table 6 shows the matrix of total spillover indices based on the frequency domain for the green bond market, stock market, treasury bond market, gold futures market, RMB foreign exchange market and coal market.

First, we observe that the total spillover indices across markets in the high, medium and low frequency subsamples are 19.89 per cent, 6.72 per cent and 1.33 per cent, respectively. This suggests that spillovers across markets are strongest in the high-frequency band, but further weakened as frequency decreases, i.e., spillovers across markets are stronger in the short term, have weakened significantly in the medium term, and are barely noticeable in the long term.

Second, we observe spillovers across markets. Panel A reports spillovers across markets in the high-frequency band (1-5 days), with the green bond market, the stock market, the treasury bond market, and the coal market all suffering large spillover shocks from other markets, with spillover indices exceeding 20 per cent. Among them, the gold futures market suffers the weakest spillover shock from other markets, only 9.56 per cent, indicating that gold futures have a certain degree of stability compared with other investment instruments and are not easily affected by price fluctuations in other markets. Panel B reports the spillovers across markets in the mid-frequency band (5-30 days), where the overall level of spillovers has declined considerably, and the spillover shocks to each market from other markets have also weakened. In particular, the equity and treasury markets experienced a nearly 20 per cent weakening of shocks from other markets, suggesting that these two markets are more

affected in the short term, with more liquid trading and more volatile volatility that is dominated by short-term factors. The green bond market, on the other hand, is only hit by shocks from 22.88 per cent to 16.80 per cent from the short to medium term, a decline close to that of the gold futures market, suggesting that green bonds are a more stable investment vehicle compared to equities and treasury bonds. Panel C reports spillovers across markets in the low frequency band (above 30 days), and the overall level of spillovers has continued to decline, with the exception of the green bond market and the treasury market, where spillover shocks to other markets have fallen to less than 1 per cent, suggesting that in the long run these markets have become virtually immune to spillovers from other markets. The exposure of the green bond market to other market shocks has also declined more significantly in the long term, from 16.80 per cent to 3.52 per cent, but is still higher than in other markets, further suggesting that green bonds are a more suitable risk-hedging instrument for medium- to long-term investments.

**Table 6.** Total spillover index based on frequency domain

Panel A: HF band 3.14 to 0.63, corresponding to a period of 1 to 5 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	34.72	1.41	19.42	0.81	0.23	1.02	22.88
CSI300	0.89	56.69	2.06	1.26	1.30	19.03	24.54
CTBI	22.25	1.83	46.12	1.32	0.34	1.58	27.32
Gold	1.13	2.04	1.70	70.76	2.93	1.76	9.56
USDCNY	0.74	4.74	0.98	3.18	66.41	2.11	11.75
Coal	0.99	18.59	1.91	1.16	0.61	57.90	23.27
TO	26.01	28.61	26.05	7.74	5.42	25.50	119.32
All	60.73	85.30	72.17	78.49	71.83	83.39	19.89
NET	3.13	4.07	-1.27	-1.83	-6.32	2.23	
Panel B: MFB 0.63 to 0.10, corresponding to a period of 5 to 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	18.32	0.91	14.56	0.57	0.14	0.62	16.80
CSI300	0.20	11.24	0.48	0.33	0.34	3.21	4.56
CTBI	6.02	0.70	14.51	0.41	0.11	0.54	7.77
Gold	0.38	0.33	0.54	14.50	0.53	0.26	2.05
USDCNY	0.34	1.72	0.39	0.80	14.35	0.64	3.97
Coal	0.22	4.03	0.50	0.24	0.17	10.71	5.16
TO	7.15	7.68	16.46	2.45	1.29	5.28	40.31
All	25.47	18.92	30.97	16.94	15.65	15.99	6.72
NET	-9.65	3.12	8.69	0.40	-2.68	0.12	
Panel C: low frequency band 0.10-0.00, corresponding to a period of more than 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	3.75	0.19	3.06	0.12	0.03	0.13	3.52
CSI300	0.04	2.12	0.09	0.06	0.07	0.60	0.85
CTBI	1.14	0.14	2.79	0.08	0.02	0.10	1.48
Gold	0.08	0.06	0.11	2.74	0.10	0.05	0.39
USDCNY	0.07	0.34	0.08	0.17	2.74	0.13	0.78
Coal	0.04	0.76	0.09	0.05	0.03	2.00	0.97
TO	1.36	1.48	3.42	0.48	0.25	1.01	8.00
All	5.11	3.60	6.22	3.22	2.98	3.01	1.33
NET	-2.16	0.63	1.94	0.09	-0.54	0.04	

Finally, we look at the net spillover indices across markets. It is interesting to note that the green bond market is a net transmitter of spillovers in the high-frequency band (1-5 days), contrary to the conclusions drawn from the spillover index based on the time domain, but in the medium-frequency

band (5-30 days) and in the low-frequency band (more than 30 days), it reverts back to its status as a net receiver, which is caused by the fact that, in the high-frequency band, it changes from being a net receiver in the treasury bond market to a net transmitter. This is a further indication that in the short-term price fluctuations across markets are very sharp and cause stronger shocks to other markets. Treasury rates, as risk-free rates, are the safest investment product, so in the ultra-short term there is less risk of price volatility compared to green bonds, and instead it is the Treasury market that is more susceptible to spillovers from the green bond market. However, in the longer term, this effect gradually diminishes, especially in the medium term, when the net spillover index of the green bond market is -9.65 per cent, which is closest to the time-domain-based net spillover index of -7.09 per cent, indicating that the price of green bonds has gradually become more stable in the medium to long term and that it is a medium- to long-term investment tool.

Therefore, we can conclude that spillover effects between markets are strongest in the short term and gradually weaken in the medium to long term. Compared to other investment products, green bonds are a more stable and more suitable instrument for medium- and long-term investment.

#### **5.4. Frequency domain based asymmetric spillover**

Table 7 and 8 report the frequency-domain based positive spillover index matrices and frequency-domain based negative spillover index matrices for the green bond market, stock market, treasury bond market, gold futures market, RMB foreign exchange market, and coal market, respectively. First, we observe the total spillover indices in Table 7 and 8. The total spillover indices for the positive return series are 17.31%, 6.06%, and 1.39% for the high frequency (1-5 days), mid-frequency (5-30 days), and low frequency (more than 30 days), and the total spillover indices for the negative return series are 18.01% for the high frequency (1-5 days), mid-frequency (5-30 days), and low frequency (more than 30 days), respectively, 6.85% and 1.61% in all three frequency bands, the total spillover index of positive return series is smaller than the total spillover index of the corresponding negative return series, providing evidence of the existence of asymmetric spillovers in the frequency domain, and the spillover effect of negative return series is stronger than that of positive return series, and the result is in line with the time-domain based asymmetric spillover index.

Second, we observe the net spillover indices across markets. Panel A of Table 7 and 8 depicts the spillover indices for the positive and negative return series under the high frequency band (1-5 days), respectively. Under the positive return series, the green bond market and the coal market are net transmitters, and the equity market, the traditional bond market, the gold futures market and the RMB foreign exchange market are net receivers. Under the negative return series, the green bond market, the stock market and the coal market are net transmitters and the other markets are net receivers, which is also consistent with the results under the total return series, suggesting that in the short run, spillovers in the market are dominated by negative returns and investors react more to downside price risks. Panel B of Table 7 and 8 depicts the spillover indices for the positive and negative return series under the mid-frequency band (5-30 days), respectively, with the green bond market, the RMB foreign exchange market, and the coal market being net receivers and the rest of the markets being net transmitters under the positive return series. Under the negative return series, the green bond market, the gold futures market, the RMB foreign exchange market and the coal market are net receivers and the rest of the markets are net transmitters. Under the total return series, the green bond market and the RMB foreign exchange market are net receivers and the rest of the markets are pick-up transmitters. The results of the positive return series are more consistent with the total return series under the mid-frequency band, so the finding that in the medium term, spillovers in the market are more affected by positive returns and investors are more concerned with bringing in returns as well as maximizing benefits is acceptable. Panel C of Table 7 and 8 depicts the spillover indices for the positive and negative return series under the low frequency band (30 days or more), respectively. Under the positive return series, the green bond market, the RMB foreign exchange market, and the coal market are net receivers, and the rest of the markets are net transmitters. Under the negative return series, the green bond market and the RMB foreign exchange market are net receivers and the

rest of the markets are net transmitters, consistent with the total return series. It shows that in the long run, the spillover effect of the negative return series is stronger than that of the positive returns, and investors' negative sentiment is stronger. Thus overall, spillovers in the market are dominated by negative returns.

It can therefore be concluded that asymmetric spillovers still exist in the frequency domain and that spillovers in the market are dominated by negative returns.

**Table 7.** Positive spillover indices based on the frequency domain

Panel A: HF band 3.14 to 0.63, corresponding to a period of 1 to 5 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	35.55	0.84	18.28	1.02	0.88	0.72	21.74
CSI300	1.41	60.57	1.50	1.50	1.71	14.82	20.95
CTBI	19.94	1.09	49.34	1.28	0.94	1.02	24.26
Gold	1.26	1.09	1.55	71.36	2.55	1.53	7.99
USDCNY	1.74	2.38	1.82	2.34	66.74	1.50	9.78
Coal	1.16	14.21	1.09	1.15	1.55	59.91	19.15
TO	25.51	19.61	24.25	7.29	7.62	19.59	103.87
All	61.05	80.17	73.59	78.65	74.37	79.50	17.31
NET	3.76	-1.34	-0.01	-0.70	-2.16	0.44	
Panel B: MFB 0.63 to 0.10, corresponding to a period of 5 to 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	18.92	0.48	12.94	0.83	0.67	0.37	15.29
CSI300	0.24	11.59	0.38	0.35	0.37	2.63	3.96
CTBI	5.48	0.28	14.97	0.55	0.43	0.18	6.92
Gold	0.35	0.22	0.66	15.28	0.45	0.27	1.95
USDCNY	0.77	0.49	0.75	0.96	15.76	0.55	3.52
Coal	0.31	3.47	0.34	0.32	0.26	12.83	4.71
TO	7.15	4.94	15.07	3.01	2.18	4.00	36.35
All	26.07	16.54	30.04	18.28	17.94	16.83	6.06
NET	-8.14	0.98	8.16	1.05	-1.34	-0.71	
Panel C: low frequency band 0.10-0.00, corresponding to a period of more than 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	4.71	0.11	3.17	0.22	0.18	0.10	3.79
CSI300	0.05	2.19	0.07	0.07	0.08	0.47	0.74
CTBI	1.17	0.05	3.02	0.12	0.11	0.04	1.49
Gold	0.09	0.04	0.15	2.99	0.10	0.05	0.44
USDCNY	0.24	0.10	0.23	0.23	3.27	0.12	0.92
Coal	0.08	0.66	0.08	0.06	0.04	2.47	0.93
TO	1.64	0.97	3.70	0.70	0.51	0.78	8.31
All	6.35	3.16	6.72	3.69	3.79	3.25	1.39
NET	-2.15	0.23	2.21	0.26	-0.41	-0.14	

**Table 8.** Negative spillover index based on frequency domain

Panel A: HF band 3.14 to 0.63, corresponding to a period of 1 to 5 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	32.33	0.65	16.19	1.06	0.52	0.59	19.02
CSI300	0.84	55.50	1.07	1.11	0.89	19.81	23.72
CTBI	18.83	1.22	47.40	1.68	0.66	0.84	23.24
Gold	1.73	2.30	1.90	68.93	1.90	2.24	10.07
USDCNY	1.61	1.94	2.03	1.94	70.31	1.23	8.75
Coal	0.91	19.22	1.51	0.98	0.63	57.78	23.25
TO	23.92	25.34	22.70	6.77	4.60	24.71	108.05
All	56.24	80.84	70.10	75.70	74.91	82.50	18.01
NET	4.90	1.62	-0.53	-3.30	-4.15	1.46	
Panel B: MFB 0.63 to 0.10, corresponding to a period of 5 to 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	21.82	0.61	14.60	0.71	0.44	0.64	16.99
CSI300	0.39	12.18	0.46	0.42	0.33	3.48	5.08
CTBI	7.15	0.45	15.17	0.49	0.25	0.37	8.71
Gold	0.59	0.66	0.38	15.06	0.41	0.42	2.47
USDCNY	0.45	0.74	0.45	0.59	14.99	0.33	2.56
Coal	0.33	4.14	0.44	0.22	0.17	10.55	5.31
TO	8.92	6.61	16.33	2.43	1.59	5.25	41.12
All	30.74	18.79	31.51	17.49	16.59	15.80	6.85
NET	-8.08	1.53	7.62	-0.44	-0.96	-0.07	
Panel C: low frequency band 0.10-0.00, corresponding to a period of more than 30 days							
	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	5.49	0.16	3.73	0.18	0.11	0.17	4.35
CSI300	0.11	2.44	0.12	0.10	0.07	0.69	1.08
CTBI	1.74	0.10	3.39	0.11	0.05	0.10	2.09
Gold	0.14	0.15	0.08	2.95	0.07	0.09	0.52
USDCNY	0.10	0.15	0.10	0.11	2.86	0.07	0.53
Coal	0.07	0.82	0.09	0.05	0.03	2.03	1.07
TO	2.16	1.38	4.13	0.54	0.34	1.11	9.65
All	7.65	3.82	7.52	3.49	3.21	3.14	1.61
NET	-2.19	0.30	2.03	0.01	-0.19	0.04	

### 5.5. Dynamic spillover index

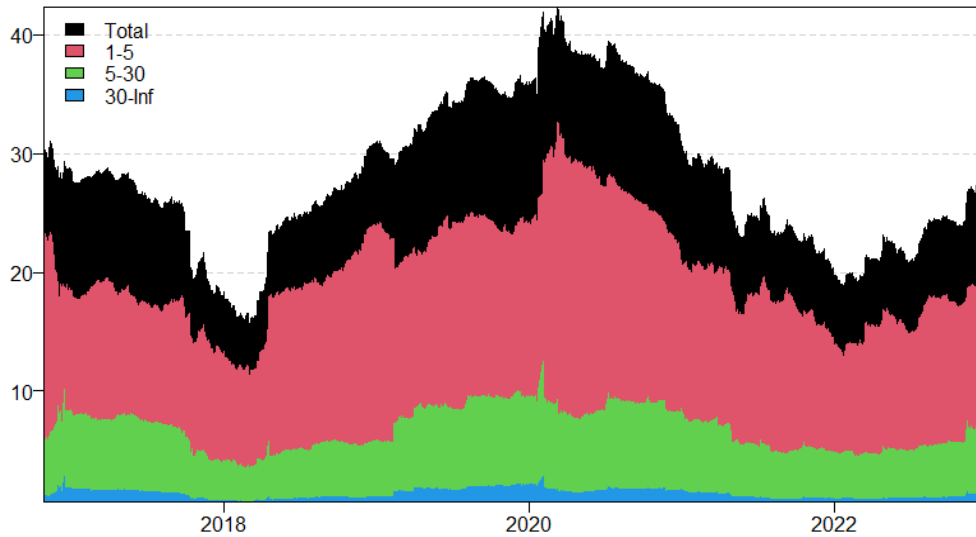
In this paper, we choose the rolling window approach with a length of 200 trading days to study the dynamic spillover index, which helps us to visualize more intuitively the relationship between specific events occurring in the period 2016-2022 and spillover effects.

Figure 1 depicts the dynamic total spillover indices between markets based on the time and frequency domains for the entire sample period, and there are three more important time periods. The first period is before 2018, when the total spillover index between markets shows a decreasing trend, the second period is 2018-2022, during which the total spillover index between markets experiences an increase and then a decrease, but the average spillover index is larger than the other two periods and reaches a peak of more than 40% in 2020, and the third period is after 2022, when the total spillover index between markets starts to slowly pick up. The 2018-2022 period is characterized by several major events in domestic and international financial markets. Firstly, there was more and more news about the trade conflict between China and the U.S. In 2018, the U.S. announced that it would impose high tariffs on steel and aluminium products from several countries, and then it announced that it would

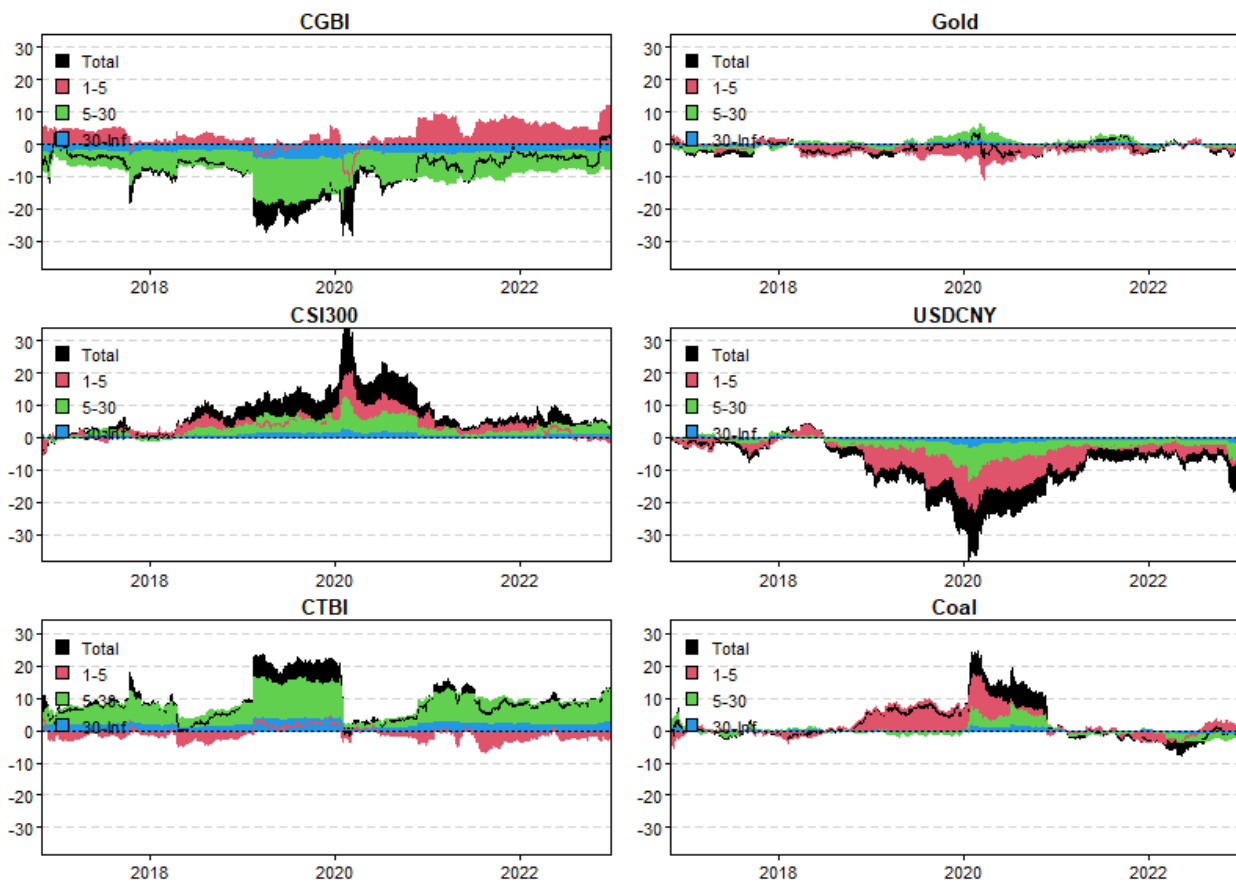
impose tariffs on some of the commodities imported from China, stirring up a trade conflict on a wide scale, increasing uncertainty in the market, undermining investor confidence, and intensifying the turbulence in the global stock market, bond market, foreign exchange market, commodities market, and other markets. Secondly, the Federal Reserve has raised interest rates four times, driving the global financial environment to tighten, triggering a general fall in asset prices. Affected by multiple factors such as the Fed's interest rate hike, some emerging economies suffered capital outflows. In addition, the P2P thunderstorm also occurred in 2018, as the intermediary platform of the borrowing and lending parties, but ultimately it was overdue and unable to pay, investors suffered heavy losses, and the industry suffered a crisis of confidence. The outbreak of the new coronary pneumonia epidemic at the end of 2019, and the year 2020 is the most serious time for the global new coronary pneumonia epidemic, this world-class crisis has brought about serious consequences, and the global economy suffered a heavy blow, and once shut down. In 2022, the Federal Reserve continued to raise interest rates, by the recurrence of the epidemic, external liquidity tightening and geopolitical risk impact, China's A-share three major stock indexes all closed down, the Shanghai index, the Shenzhen Composite Index and the GEM index fell by 15.13%, 25.85%, and 29.37% during the year, respectively. Overall, therefore, inter-market connectivity was stronger during the crisis than in the absence of the crisis.

Figure 2 depicts the dynamic net spillover indices for each market based on the time and frequency domains for the entire sample period. Firstly, we can observe that the green bond market and the RMB FX market are net recipients in general. In connection with the previous analysis, both the US-China trade friction and the Fed's interest rate hike are prone to have a serious impact on the RMB FX market, and in fact, in the second half of 2018, the RMB exchange rate continued to weaken against the US dollar, and the RMB FX market was hit by huge spillovers from other markets. At that time, China's green bond market was still in the emerging stage, and its development was still unstable, which made it susceptible to influences from other markets. However, it is worth paying attention to the fact that the green bond market will briefly have a spillover effect on other markets at the two points in time of high uncertainty in 2018 and 2020. The possible explanation is that when financial market uncertainty is high, most investors are risk-averse, and funds will flow into the less risky green bond market. Second, equity markets and traditional bond markets are net transmitters in general. The stock market has strong spillover characteristics and is more likely to generate spillover shocks to other markets. The traditional bond market, on the other hand, is always favoured by investors due to the high security of treasury bonds. With respect to the coal market, during the NKP epidemic around 2020, the coal market exhibited a complete net transmitter role. This was since the New Crown Pneumonia epidemic disrupted the equilibrium between the supply and demand sides of the coal market, productivity declined during the epidemic and coal production was reduced, demand outstripped supply, and the price of coal increased, which led to spillovers from the coal market to the rest of the market. Finally, the role of net transmitters and net receivers in the gold futures market is not well defined and is generally more balanced, with the gold-based precious metals serving as a stable investment vehicle for risk diversification.

Therefore, we can conclude that inter-market connectivity is stronger in situations of higher market uncertainty, such as the New Crown Pneumonia outbreak. During this period, green bonds can briefly fulfil their safe-haven nature, while gold futures possess stable safe-haven qualities, both of which can be considered as risk diversification tools by investors.



**Figure 1.** Rolling window estimation of total spillover index based on frequency domain



**Figure 2.** Rolling window estimation of net spillover index based on frequency domain

### 5.6. Network structure analysis

In this subsection, spillover network analysis through Gephi software further demonstrates the linkages between the green bond market and the major financial markets based on the time and frequency domains, which can reveal more specifically the role of different markets in the risk transfer process and the strength of risk transmission. Each node in the figure represents each market, the size of the node indicates the number of net transmissions of spillover effects between the market and other markets, the larger the node, the more often, the direction of the arrow indicates the direction

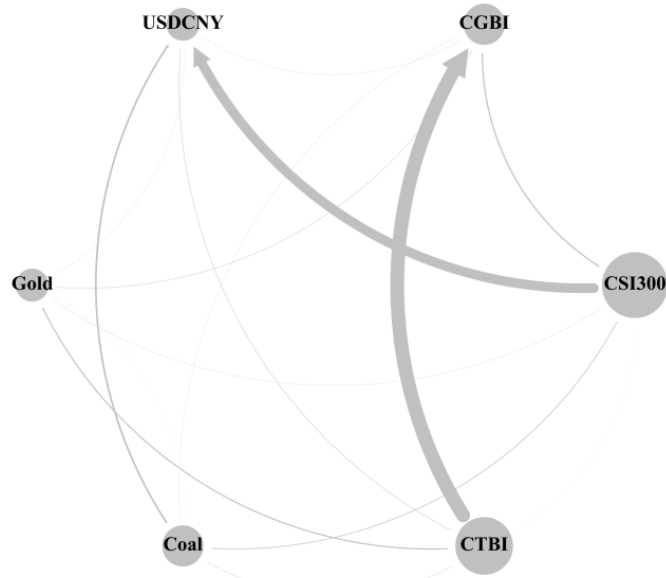
of transmission of spillover effects between the two, the thickness of the line indicates the strength of pairwise spillover effects between the two, the thicker the line, the stronger the spillover effects.

### 5.6.1. Time-domain based overflow networks.

Figure 3 depicts the time-domain-based spillover network connectivity of the green bond market, stock market, treasury bond market, gold futures market, RMB foreign exchange market and coal market, which shows that there are network lines connecting any two markets, i.e., there are linkages between all the markets, and no market is independent of the spillover network. The linkage between the green bond market and the treasury market is the strongest, with the green bond market being a net recipient of the treasury market and subject to its spillover shocks, followed by the stock market and the RMB foreign exchange market. There is also some degree of linkage between the green bond market and the equity market, while linkages between the green bond market and the RMB foreign exchange market, the gold futures market and the coal market are weak.

Table 9 describes the structural characteristics of the time-domain based spillover network, it can be seen that: (1) the network density is 0.5, the value of the network density ranges from 0 to 1, the higher the density, it means that the connection between the nodes in the network is more tightly connected, the general network density is difficult to reach 1, and the density in this paper is the same as the maximum density that can be found in the actual network, which means that the correlation of the spillover effect between the markets is relatively high. (2) The clustering coefficient is 0.5, the clustering coefficient is usually also used to measure the degree of closeness between the nodes in the network, especially the interconnection between the nodes and their neighboring points, which indicates that the degree of spillover in this network is high and the spillover surface is wide. (3), The network diameter is the maximum value of the shortest path length between all pairs of nodes in the network, while the average path length is the average value of the shortest path length between all pairs of nodes in the network, the average path length is 1.33, which is closer to 1, and the network diameter is 3, which indicates that there is a direct spillover effect between most of the markets, and that there are a small number of markets where there are not direct spillovers but rather, the spillovers are transmitted through other markets as a medium. transmission of spillovers.

Table 10 further describes the centrality of each market. It can be seen that (1) the largest point out degree is the stock market and it has a point out degree of 5 and a point in degree of 0, indicating that the stock market is a net transmitter in all pairwise spillovers with other markets and has a radiating effect on the other markets, with more spillovers. The Treasury bond market has the second highest point-out degree and has a strong spillover effect on other markets. The green bond market and the coal market both have a point out degree of 2 and a point in degree of 3, suggesting that they have some degree of spillover impact on other markets, but are more susceptible to spillover shocks from other markets than transmitting spillovers to other markets. The gold futures market and the RMB foreign exchange market have a point out degree of 1 and a point in degree of 4. Changes in their own asset prices do not have a relatively significant impact on other markets, but are instead subject to a high degree of spillover impacts from changes in asset prices in other markets. (2) The intermediate centrality of stock market and treasury bond market is 0. The intermediate centrality is used to measure the ability of nodes to act as information intermediaries in the network, indicating that the stock market and the treasury bond market can directly influence each other with other markets without any other market as a medium, which indicates that they have a greater influence in the financial system, and this is also in line with the analyses of the point out degree and the point in degree in the previous section. The gold futures market and the coal market, on the other hand, both have an intermediate centrality degree of 3, which is a strong intermediary that fuels spillovers and strengthens the closeness and relevance of the spillover network. The green bond market and the RMB foreign exchange market have an intermediation centrality of 0.5, which also has a certain degree of intermediation, though it is weaker.



**Figure 3.** Time domain-based spillover network

**Table 9.** Structural characteristics of the spillover network based on the time domain

network density	clustering factor	network diameter	Average path length
0.5	0.5	3	1.33

**Table 10.** Node centrality analysis

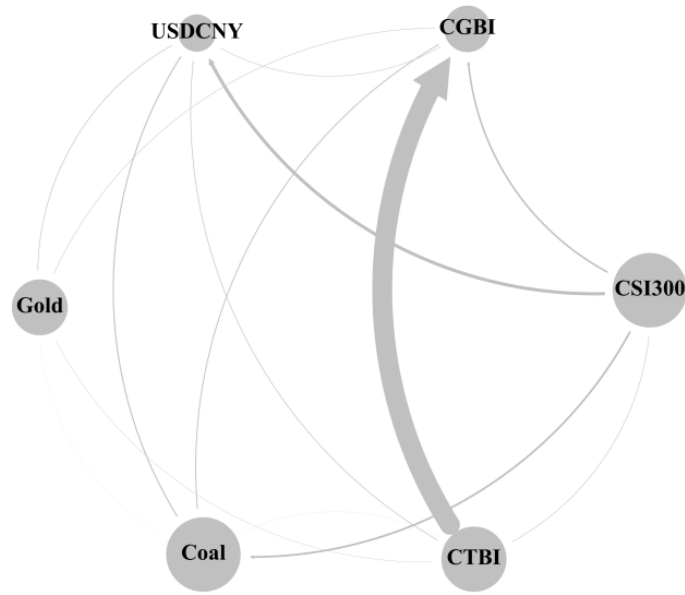
market	out-degree	into-degree	Centricity
Green Bond Market	2	3	0.5
stock exchange	5	0	0
treasury bond market	4	1	0
gold futures market	1	4	3
Renminbi Foreign Exchange Market	1	4	0.5
coal market	2	3	3

### 5.6.2. Frequency domain based spillover networks.

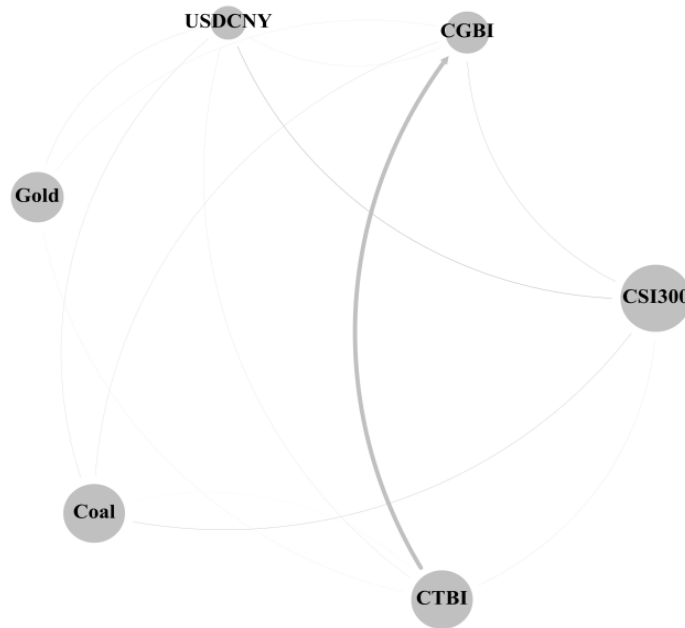
Looking at Figure 4-6 reveals that there are direct or indirect linkages between all markets, whether in the high-frequency band (1-5 days), the medium-frequency band (5-30 days), or the low-frequency band (more than 30 days), and no market is independent of the spillover network, but that the overall linkages between markets diminish as the maturity period lengthens.

Table 11 describes the structural characteristics of the spillover network based on the frequency domain, further confirming these findings. (1) The network density decreases with maturity, from 0.5 to 0.467 in the medium term and 0.433 in the long term, which is a significant weakening, although the degree of inter-market tightness remains high. (2) The clustering coefficients show similar changes, once again supporting the conclusion that inter-market linkages gradually weaken in the medium and long term. (3) In the short term, the network diameter is 3 and the average path length is 1.333, which differs from the network diameter and is closer to 1, suggesting that risk is a direct spillover in most of the markets, and among a few markets it is a spillover through other markets as an intermediary channel. In the medium term the network diameter is 2 and the average path length is 1.067, whereas in the long term the network diameter is still 2 and the average path length is 1.133, suggesting that in the long term there are more inter-market spillovers than in the medium term that are not direct spillovers.





**Figure 5.** Mid-term spillover network based on frequency domain (5-30 days)



**Figure 6.** Long-term spillover network based on frequency domain (30 days or more)

**Table 11.** Structural features of spillover networks based on frequency domains

frequency range	network density	clustering factor	network diameter	Average path length
HFB (1-5 days)	0.5	0.5	3	1.333
Medium band (5-30 days)	0.467	0.467	2	1.067
Low-frequency band (more than 30 days)	0.433	0.45	2	1.133

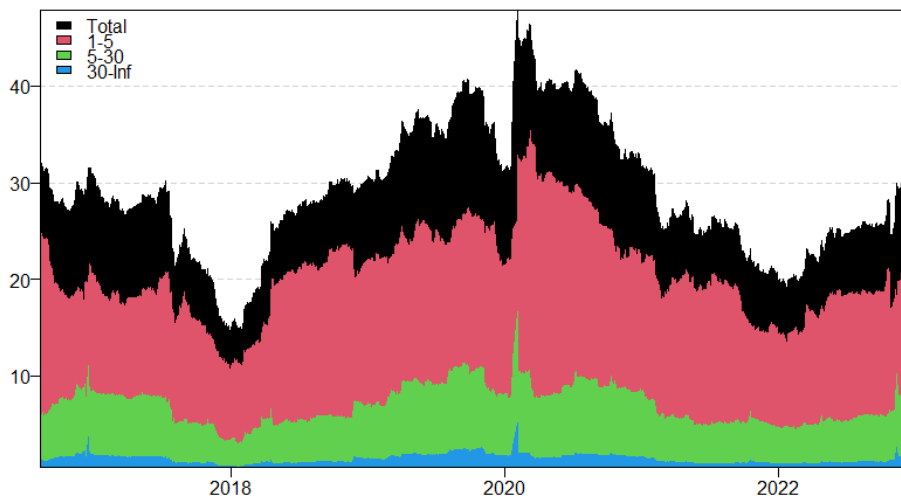
**Table 12.** Node centrality analysis

frequency range	market	out-degree	into-degree	Centricity
High-frequency (1-5 days)	Green Bond Market	3	2	3
	stock exchange	3	2	0.5
	treasury bond market	4	1	3
	gold futures market	1	4	0
	Renminbi Foreign Exchange Market	0	5	0
	coal market	4	1	0.5
Medium band (5-30 days)	Green Bond Market	1	4	0
	stock exchange	4	0	0
	treasury bond market	3	2	0.5
	gold futures market	2	2	0
	Renminbi Foreign Exchange Market	0	5	0
	coal market	4	1	0.5
Low-frequency band (more than 30 days)	Green Bond Market	1	4	0
	stock exchange	4	0	0
	treasury bond market	3	2	2
	gold futures market	2	1	0
	Renminbi Foreign Exchange Market	0	5	0
	coal market	3	1	0

## 5.7. Robustness Tests

### 5.7.1. Changing the scrolling window.

To verify the robustness of the empirical results, the size of the rolling window is adjusted to 150 in this paper to compare with the total spillover index plots under the rolling window 200. Figure 7 depicts the total spillover index plots based on the time and frequency domains under the rolling window of 150, and the total spillover index shows the same trend as that under the rolling window of 200, and the change of the total spillover index is still manifested in three major phases, and there is no significant change in the overall trend characteristics of each phase. It can be concluded that the empirical results of this paper are relatively robust.



**Figure 7.** Rolling window estimation of total spillover index based on frequency domain (150)

### 5.7.2. Changing the forecast period and lag order.

To verify the robustness of the empirical results, this paper adjusts the number of forecast steps to 100 and the lag order to 4, and compares it with the table of static total spillover indices with 10 forecast steps and 1 lag order. Table 13 demonstrates the adjusted static total spillover index, and the

results are basically the same as the results of the static spillover index before the adjustment, which indicates that changing the forecast period has almost no effect on the results, and the conclusions of this paper are robust.

**Table 13.** Adjusted total spillover indices based on time domains

	CGBI	CSI300	CTBI	Gold	USDCNY	Coal	FROM
CGBI	59.94	1.21	37.57	0.87	0.02	0.40	40.06
CSI300	0.19	75.61	1.35	0.12	0.93	21.80	24.39
CTBI	29.83	1.76	65.80	1.21	0.20	1.20	34.20
Gold	1.04	0.31	1.78	95.07	1.61	0.18	4.93
USDCNY	0.24	6.05	0.39	1.41	90.49	1.41	9.51
Coal	0.29	21.54	1.38	0.25	0.40	76.14	23.86
TO	31.59	30.88	42.48	3.86	3.16	24.99	136.96
All	91.53	106.49	108.28	98.93	93.65	101.13	22.83
NET	-8.47	6.49	8.28	-1.07	-6.35	1.13	

## 6. Conclusions and suggestions

This paper takes the green bond market, the stock market, the treasury bond market, the gold futures market, the RMB foreign exchange market and the coal market as the main objects of research, and studies the mechanism and law of the spillover effect between the green bond market and other markets, and finds that: (1) there is a strong connectivity between the green bond market and other markets, and its connection with the traditional financial market is closer, and compared with traditional financial assets, green bonds are more suitable as a risk diversification tool in the fossil energy market; (2) there is asymmetric spillover between markets, and the spillover effect of the negative return series is stronger, green bonds are not easily affected by the downside price risk, and can be used as an investment tool for risk diversification; (3) the spillover effect between markets is strongest in the short term, and gradually weakened in the medium and long term, compared with other investment products, green bonds are more suitable for medium- to long-term investments; (4) inter-market connectivity will be stronger in the event of high market uncertainty, such as the new Crown Pneumonia epidemic. During this period, green bonds can briefly act as a hedge, and therefore can be considered as a risk diversification tool by investors.

Based on the above conclusions, this paper draws the following recommendations: (1) For policy makers, they need to understand the dependence between the green bond market and various markets, as well as the resilience of the green bond market to risky shocks, and they should pay attention to the role played by the green bond market in stabilizing the energy market, and implement environmental policies to support the development of the green financial market, and at the same time, encourage the enterprises concerned to flow more capital into the green bond market, promote energy transformation, and make correct guidance during the crisis. (2) For investors, green bonds have a certain risk aversion nature, compared with other financial instruments such as stocks, is a more stable investment tool, investors can add it to the diversified investment portfolio for risk diversification.

Overall, it is meaningful to study the spillover effects between the green bond market and other markets to build a more complete green financial system.

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