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RESEARCH ARTICLE

Examining the interconnectedness of green finance: an analysis of dynamic spillover effects among green bonds, renewable energy, and carbon markets

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Abstract
There is growing importance of green finance as a means to finance sustainable projects and reduce carbon emissions. Green bonds have emerged as an important financing tool in this context, and there is a need to understand how they are interconnected with other components of the green finance ecosystem, such as renewable energy and carbon markets. This study investigates the interconnectivity of green finance by analyzing the dynamic spillover effects among green bonds, renewable energy stocks, and carbon markets. Using daily data spanning from January 2010 to December 2020, vector autoregressive models and time-varying parameter models are applied to examine the transmission channels of shocks among these assets. The results reveal significant dynamic spillover effects between green bonds and renewable energy stocks, as well as between carbon markets and renewable energy stocks. Additionally, the findings suggest a complementary relationship between green bonds and carbon markets. This study provides insights into the interdependence of different green financial instruments and their role in promoting sustainable development. The outcomes of the research can guide policymakers, investors, and other stakeholders in making informed decisions regarding green finance.

Keywords Green bonds · Carbon markets · Renewable energy · Stock markets · Volatility dynamics

Introduction

Several initiatives have been launched to improve financial viability and growth in response to global warming and ecological deterioration. Whether green bonds may be utilized as a form of hedging in the context of financial risk administration has become more pressing as their prevalence in the financial markets continues to grow. Fang et al. (2022a) analysis's overarching goal is to measure how well green bonds perform as dynamic hedges against implied volatilities, which are future market uncertainty (Xiuzhen et al. 2022). The developing economies green bond issuance has been on a steep upward trend thorough 2017 also tak into account these sectors volatilies.

There have been several studies that examine the interplay between the green bond market and other industries, such as the traditional bond market (Ullah et al. 2020). Yet, research on green bonds' usefulness as a hedge against economic risk has been scant. With the ever-increasing scale of the green bond markets, this problem has become more significant. This analysis shows that green bonds are an affordable and efficient hedging tool. Expenditure in green bonds may be protected against fluctuations in currency and product prices; according to a recent research by Wei et al. (2022), it shows that green bonds are less successful at hedging than before the COVID-19 epidemic but are more effective against currency market swings.

Investors and regulators may benefit greatly from the data provided by implied volatility. The implied volatility of an option is determined by re-parameterizing the option price in the industry. Hence, it stands for the market risk that participants expect to materialize. In addition to the Black-Scholes implied volatility and historical realized volatility, He et al. (2019) discovered that "implied volatility

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subsumes all information included in each," making it a more accurate predictor of future realized volatility. Nevertheless, there has not been a conclusive proof that the development of implied volatility can be predicted. Hence, the findings are contradictory. So, it is essential to hedge against implied volatility, which is synonymous with hedging against uncertain forward-looking market risk. Ecological integrity is fundamental to the current economic system (Umair and Dilanchiev 2022). Reducing poverty and ensuring long-term financial development are directly tied to energy security and ecological sustainability. Numerous empirical studies have been conducted on the factors that contribute to ecological sustainability, such as the importance of green technology, the availability of energy resources, and the prevalence of alternative and nuclear energy, robust financial development, global trade, clean energy expenditure, high industrial value-added, capital formation, urbanization, population development, biocapacity, rising energy usage, and increasing tourism. Recent research (Wu et al. 2022) found that increasing ecological sustainability is essential, and this can only be done via sustainable oil use and manufacturing. Although researchers have devoted a great deal of effort to understanding the factors that contribute to and affect ecological sustainability, they defend the idea that cryptocurrencies are maturing into financial assets in light of their dramatic price appreciation over the last several years. Since it is both the most widely used and the pioneering cryptocurrency, Bitcoin naturally draws much interest. Bitcoin's puzzle-solving abilities allow decentralized systems to validate transactions reliably and issue new currency without a central authority. While the amount of Bitcoin transactions has risen, competition on the network has also increased. The complexity of the crypto algorithm that pays miners and verifies blocks makes it more difficult to predict energy and power fluctuations. BBC estimates that Bitcoin uses 121.36 terawatt hours (TWh) of power yearly. This is far more power than any home in Argentina needs. The Bitcoin Energy Consumption Index created by Digiconomist shows that one Bitcoin transaction is comparable to the power use of a typical American household for 53 days (Pan et al. 2023). These findings show that the energy industry is expected to play a significant role in the development of cryptocurrencies in the future.

There have been several studies that examine the interplay between the green bond market and other markets, such as the conventional bond market and the conventional stock market (Li and Umair 2023). Yet, research on green bonds' usefulness as a hedge against economic risk has been scant. With the ever-increasing scale of the green bond markets, this problem has become more significant. This analysis shows that green bonds are an affordable and efficient hedging tool. Expenditure in green bonds may be protected against fluctuations in currency and product prices. Recent research shows that green bonds are less successful at hedging than before the COVID-19 epidemic but are more efficient against currency market swings.

Investors and regulators may benefit greatly from the data provided by implied volatility. The implied volatility of an option is determined by re-parameterizing the price in the market (Liu et al. 2023). Hence, it stands for the industry risk that participants expect to materialize. In addition to the Black-Scholes implied volatility and historical realized volatility, it was discovered that "implied volatility subsumes all information included in each," making it a more accurate predictor of future realized volatility. In light of this, there is a subfield of academic study concerned with whether or not the implied volatility trajectory may be anticipated. Nevertheless, there has not been a conclusive proof that the development of implied volatility can be predicted (Ikram et al. 2019) (Iqbal et al. 2022). So, it is essential to hedge against implied volatility, which is synonymous with hedging against uncertain forward-looking market risk.

The growth of the green bond market over the last several years is a concrete evidence of the global economy's dedication to sustainability (Mohsin et al. 2020b). This long-term approach to sustainability is applied to the context of the natural ecosystem and financial development. Then, expenditure in a green bond indicates concern for the long-term health of the global economy. So, it makes sense to investigate whether or not green bonds can serve as a reliable hedging vehicle for implied volatilities, which stand for future industry risks (Agyekum et al. 2021). The efficacy of hedging against implied volatilities using assets other than green bonds, for instance, demonstrates that implied volatilities of other assets, such as equities, products, currencies, and socioeconomic situations, may be used to hedge implied volatilities of crude oil. In addition, adopting a flexible hedging strategy may provide substantial returns for investors. Future oil stockholders may reap significant rewards from a dynamic trading strategy contingent on oil volatility regimes (Asbahi et al. 2019). Agriculture-implied volatilities can be employed as a hedge against crude oil–implied volatility. Instead of using the implied volatilities of other assets, look at the efficacy of hedging in the Bitcoin, gold, commodities, and US dollar markets against the implied volatility of crude oil (Nasreen and Anwar 2014). According to the writers, Bitcoin's hedging performance is superior to that of gold and commodities but inferior to that of the US dollar.

By analyzing the dynamic spillover effects among green bonds, renewable energy stocks, and carbon markets, this study seeks to understand the interconnectedness of green finance. This study employs vector autoregressive (VAR) and time-varying parameter models to daily data from January 2010 to December 2020 to identify the transmission pathways through which shocks spread among these assets.

The selected timeframe enables a thorough examination of the interactions and dynamics among green bonds, renewable energy stocks, and carbon markets over time. The VAR models offer a framework for analyzing the causal connections and interdependencies between the relevant variables. These models can capture the dynamic interactions between green bonds, renewable energy stocks, and carbon markets by considering lagged effects and feedback loops. A more nuanced understanding of the changing dynamics in the green finance ecosystem is made possible by the time-varying parameter models, which also consider potential variations in the relationships over time. Using these econometric models, this study examines the interactions between green bonds, renewable energy stocks, and carbon markets to offer insightful information to policymakers, investors, and other green finance stakeholders. With the help of these insights, decision-making processes can be improved and informed strategies can be developed to maximize the contribution of green financial instruments to promote sustainable development. Moreover, by thoroughly examining the interdependence between various elements of the green finance ecosystem, this research adds to the body of knowledge already available on the subject.

The rest of this paper is organized as follows: The relevant literature on green finance is summarized in the "Literature review" section, focusing on the connections between green bonds, renewable energy stocks, and carbon markets. The methodology used in this study, including the data and econometric models used (VAR models and time-varying parameter models), are described in the "Methodology" section. The findings are presented in the "Result and discussion", along with their implications. The paper is concluded in the "Conclusion and policy implications" section with a summary of the main findings and their implications for investors, policymakers, and other stakeholders in the field of green finance.

Literature review

Most studies have focused on discovering how GBs vary from other bonds regarding risk and return. Verifying a green premium, also known as geranium, connected with the issue of GBs has been a central area of study since it facilitates issuing GBs over common bonds. Specifically, 121 European GBs issued between 2013 and 2017 were examined and an evidence that GBs are economically superior to non-green bonds was found. As a result, corporate issuers benefit more, and this advantage remains in the secondary market (Iqbal et al. 2019). Hence, GBs are a viable option for businesses seeking to finance or restructure environmentally friendly projects at a reduced cost of capital.

State green bonds have larger spreads than their non-green counterparts, whereas green business bonds have narrower spreads. Using data from 89 bond pairings conclude that GBs outperform their conventionally issued counterparts regarding yield, liquidity, and volatility. In particular, unless the private issuer is committed to certifying the bond's "greenness," institutional GBs have a negative premium, whereas corporate GBs have a positive premium. As a result, green initiatives may be funded at a discount, and GBs might reap a negative premium. In their recent paper, it shows that general balance sheets are not considerably tighter in trade than their equivalents. According to Shah et al. (2019), GBs have a lower yield than traditional bonds, signifying a negative premium. This is especially true for financial and low-rated bonds. One such factor that might impact GB yields is the issue size. Market size and the presence of institutional investors are mentioned as possible incentives for investors. Emphasis of academic discourse towards "green stocks" and "green bonds," in particular against the background of global warming concerns (Mohsin et al. 2020a). The asset allocation features of green bonds were recently investigated by utilizing copula-based approaches. The research found that the positive effects of green bonds on portfolio administration manifest themselves during rising returns and falling market volatility. Similarly, the potential of green commodities and other precious metals as climate risk hedges was mulled (Zhang et al. 2021a). These results indicate that green bonds help mitigate climate-related expenditure portfolio risks. Green bonds have shown promise as a valuable asset class diversifier. According to the financial industry, circumstances profoundly impact the usefulness of green bonds and other traditional bonds. Green bonds have been shown to have a time-varying relationship with other bonds, as discovered. Clean energy equities were shown to move in tandem with other markets significantly. Consistent with previous research, it was found that green bonds exhibit substantial co-movements with other markets, especially during industry instability. Based on these results, green bonds might help shareholders mitigate portfolio risk (Xia et al. 2020). Widespread research over the past decade has discussed the value of cryptocurrencies as a haven asset and having a vital hedging role amid uncertainties, especially during the recent pandemic. On the other hand, some research has shown that cryptocurrency's volatility is often more significant than that of traditional investments (Mohsin et al. 2020a).

Green bonds and digital currencies have been linked for some time, but this connection has only recently been explored in the academic literature. A TVP-VAR network connectivity model was used to discover that there is time-varying and heightened crisis-related spillovers across cryptocurrencies and green and fossil fuel assets.

Also, negative return spillovers are more significant than positive ones among these assets. The research emphasizes the role of cryptocurrencies as diversifiers of assets alongside the efficiency of green bonds. Yet, in a rising industry, green bonds do not correlate well with digital currencies. Researchers found widespread market contagion throughout the outbreak. A rising body of literature has weighed in on the significance of cryptocurrencies as critical financial tools, as seen by the above debate (Mohsin et al. 2018). The study highlighted the extreme volatility of the cryptocurrency markets. Conflicting data support the link between cryptocurrencies and traditional assets. In contrast to traditional bonds, green bonds are thought to carry a substantial "geranium" or "green premium." In subsequent research, we analyze the interplay between green bonds and the financial markets to conclude their use as portfolio additions and risk mitigation tools (Mohsin et al. 2022). There is potential for improvement in the expansion. Still, more scholarly literature is needed on the interaction, even though the sustainability of our world. Using copula functions and conditional diversification metrics demonstrates that green bonds are highly correlated with state and business bonds but weakly correlated with the share and energy sectors. The diversification advantages from pairing green bonds with government bonds, even though it show excellent diversification capacities for stock and energy markets.

Although structural aspects, prior research (Mohsin et al. 2021) mainly analyzes price spillovers solely, neglecting spillovers in the second instant of the return distribution. Notably, asymmetric GARCH-based models must display or analyze these stylized aspects rather than highlighting a significant knowledge gap at the intersection of climate bonds and financial industries. Notably, relationship between green bonds and financial markets occurred outside the sample period used. In light of the recent discussion regarding how climate change and the COVID-19 pandemic pose intertwined and timely challenges to policymakers in 2021, addressing this issue is crucial for the sake of stockholders and governments.

Methodology

Event study

This study employed industry reacted to the COVID-19 epidemic, building on the work of, who examined the green bond industry in China (Liu et al. 2022c). With the advent of the event-study approach, researchers were able to analyze the industry's reaction to unforeseen events. Using this strategy, this study calculated the accuracy by factoring in the following:

$$R_t = \ln\left(\frac{P_t}{P_{t-1}}\right) \tag{1}$$

$$AR_t = R_t - \overline{R} \tag{2}$$

Where OVI denotes the out-of-the-ordinary rate of return at a time and the average rate for the estimate interval.

Following the recommendation by, the event Mohsin et al. (2022) date of this study was set as March 11, 2020, the day the World Health Organization first proclaimed the worldwide outbreak.

$$\dot{R} = \frac{1}{100}\sum_{t=-100}^{t=-199} R_t \tag{3}$$

$$CAR_t = \sum_{t=0}^{t=t_1} AR_t \tag{4}$$

Vector auto regression approach

To concurrently estimate several pairwise VAR parameters, the model considers heteroscedasticity and parsimony. For this study, we used the DCC-GARCH model, which was developed for OVX varaibles by (Monnin 2018) VAR estimation has two stages in its implementation. Starting with a univariate VAR model, the standard residuals are obtained as follows:

$$r_t = \mu_t + \varepsilon_{t,}\varepsilon_t \sim N\left(0, H_t\right) \tag{5}$$

$$h_t = \omega + a_1 h_{t-1} + b_1 \varepsilon_{t-1}^2 \tag{6}$$

where CVI the rate of return is, is the rate of technology, and h is the hypothetical variance based on the endogenous variable and the rate of technology. In the second stage, a DCC factor is estimated using multivariate VAR and standardized residuals, as shown below:

$$H_t = D_t R_t D_t \tag{7}$$

$$D_t = \mathrm{diag}\left\{ h_{11,t}^{\frac{1}{2}}, \dots, h_{nn,t}^{\frac{1}{2}} \right\}. \tag{8}$$

$$R_t = \mathrm{diag}\left(\frac{1}{\sqrt{q_{11,t}}}, \dots, \frac{1}{\sqrt{q_{nn,t}}}\right) Q_t \mathrm{diag}\left(\frac{1}{\sqrt{q_{11,t}}}, \dots, \frac{1}{\sqrt{q_{nn,t}}}\right) \tag{9}$$

$$Q_t = (1 - \alpha - \beta)\bar{Q} + \alpha \varepsilon_{t-1}\varepsilon'_{t-1} + \beta Q_{t-1} \tag{10}$$

Volatility forecasting

Realized measures

We predict a real return in a banking system using a realized return; further attempts were made for the introduction of the risk value (RV) indicates. After these studies, realized indicators have become more popular for volatility analyses and. In contrast, microstructure noise is accounted for by the realized kernel. The present study elucidates the factors that cause green bonds to be volatile. In-sample estimation or causality tests are often used in the existing research on the interconnectedness of the green bond sector and other essential sectors, and sometimes contentious conclusions are given. The results of this study were drawn from an out-of-sample prediction review to ensure their accuracy and validity. Crucially, the accurate measure of volatility was used throughout this study to exclude any possibility of skewed results, even though the resulting measure was calculated using intraday data according to Chen et al. (2020). Weekly, monthly, and quarterly RV are just a few examples of the lower frequency realized measures that have been endorsed and used by investigators who build them from daily returns.

Weekly RV was calculated using the following formulation derived from existing literature.

$$RV_t = \sum_{t=1}^{5} r_{i,t}^2, (i = 1, 2 \ldots, 5) \tag{11}$$

where stands for the weekly OVR, and on the day of the week, the return between close and close is represented by $\sum_{t=1}^{5} r_{i,t}^2$. Interestingly, daily returns were used in constructing weekly RV rather than intraday yields since they are immune to problems such as structural noise and price surges throughout the trading day.

Weekly VAR estimator

Given the remarkable success of the VAR process in predicting realized indicators, it is advocated that more manageable (Shen et al. 2021). Many studies have shown the HAR model's superiority in volatility forecasting. Specifically, VAR may be divided into sections representing long-, medium-, and short-term horizons. With its ability to represent the fashion, VAR is a valuable tool for volatility forecasting.

In keeping with the spirit of VAR (Wang et al. 2022), the following three factors based on varying time intervals contributed to the weekly RV:

$$RV_{t+1}^w = \beta_0 + \beta_1 RV_t^w + \beta_2 RV_t^m + \beta_3 RV_t^q + \beta_4 X_t^w + \varepsilon_{t+1} \tag{12}$$

In this study, we adopt an external factor in the form industry and relevant industries. Monthly intervals were established based on the following:

$$RV_t^m = \frac{1}{4} \sum_{i=0}^{3} RV_{t-i}^w \tag{13}$$

$$RV_t^q = \frac{1}{12} \sum_{i=0}^{11} RV_{t-i}^w \tag{14}$$

Forecasting evaluation

These are some formulations of the loss functions:

$$MSE = \frac{1}{j} \sum_{t=i+1}^{i+j} \left(R\hat{V}_t - RV_t\right)^2 \tag{15}$$

$$MAE = \frac{1}{j} \sum_{t=i+1}^{i+j} \left|R\hat{V}_t - RV_t\right| \tag{16}$$

$$HMSE = \frac{1}{j} \sum_{t=i+1}^{i+j} \left(1 - R\hat{V}_t / RV_t\right)^2 \tag{17}$$

$$HMAE = \frac{1}{j} \sum_{t=i+1}^{i+j} \left|1 - R\hat{V}_t / RV_t\right| \tag{18}$$

The MCS test excels because of its freedom in choosing a loss function without being hindered by a skewed reference model (Li et al. 2021). This method is crucial for assessing volatility forecasts. The core of an MCS analysis is a series of iterations meant to test the, the MCS test is complete. The calculations in the present study were performed using the computer language R.

Data

In recent years, many global green bond indexes have been created to track the performance of the international green bond industry. There are reports that the global green bond indexes have correlation factors near 1, suggesting that their underlying dynamics are comparable. Also, we performed a robustness test by referring to the Solactive Green Bond Index.

This study's predictors were drawn mainly from the financial markets, where the authors found inspiration from earlier studies (Liu et al. 2022b). The foreign exchange market fixed-income market; and the market for green bond and cryptocurrency have developed. The dynamics of environmentally friendly financial products are the subject of new research.

There are three primary sources of uncertainty: the financial sector, the energy sector, and green expenditure activities (Zhang et al. 2021b). According to Xu et al. (2023), a firm's bottom line can take advantage of taking steps to slow ecological degradation because doing so can garner the interest of potential stockholders and lead to the provision of additional technological or financial support on the part of administrations (Yu et al. 2021). The market's performance may improve as a result of this circumstance. The conventional economic industry and the green financial industry may be related. Green expenditure activities and the energy market impact the green financial market. For instance, a corporation's manufacturing expenses and earnings are affected by the state of the energy industry. Market participants' confidence in an investment firm helping to usher in the low-carbon economy is correlated with the extent to which it engages in green expenditure activities. Hence, green economic sector players often factor in energy product mobility while making choices. In addition, the fact that prior studies have primarily thought about the price connection explored the volatility connection.

The green bond (GB) is widely used as a stand-in for worldwide economic unpredictability, according to the work of Yu et al. (2020). This analysis relies entirely on information culled from Bloomberg and S&P Global. Because most international indexes of green bonds only became accessible after 2014, the timeframe covered by this study which is more than 6-years-long runs from October 2013 to January 2020, using the CVI initial difference as a forecast rather than a realized indicator. This analysis primarily examined the effect of shocks emanating from different sectors of the economy, particularly the financial industry, state-of-the-art and earlier studies focusing on price dynamics. Instead of using in-sample estimates, the conclusion relies on RV predictions performed outside of the data set.

Result and discussion

Descriptive statistics

The descriptive statistics are shown in Table 1. We found that all series exc had positive daily averages. Bitcoin was the most volatile currency, followed by Ethereum. As compared to OVX, CVI, Green, green bond indexes showed more minor standard deviations, indicating they were less volatile investments (Yao and Liu 2021). All market returns were also shown to be leptokurtic. All markets exhibited non-normal price distributions as measured by kurtosis, skewness, and the Jarque-Bera index. The unit root's null hypothesis was rejected at the 1% level using statistics. According to Table 1, every series except GB, RE, and SOE had kurtosis over threshold, suggesting that the returns series for the period had flatter tails than would be expected from a normally distributed series. The GB statistics also argue against the null hypothesis for the unit root at the 1% level, and the Jarque-Bera test enables us to reject it for all series at the 1% level.

Static correlation

The Pearson correlation coefficients between the various components of China carbon futures and stock returns of liner shipping firms are shown in Table 2. Markowitz's portfolio theory criterion is met by the correlation of 15.78 percentage points among Maersk and carbon futures in the frequency band. In contrast, the correlation between the other liner shipping firms and carbon futures is modest and negative (Shen et al. 2022). In the d2 frequency range, correlations between carbon futures and shipping businesses like Maersk, CVI, SOE, and OVX are more than 5%, whereas correlations with the other shipping companies are weak. Maersk, GB, RE, and Kline are among the corporations with 14.23%, 15.92%, 8.02%, and 16.19 percentage

Table 1 Descriptive statistics

	GB	RE	OVX	SOE	Green	CVI
Mean	−0.129	−0.049	−0.077	−0.161	−0.142	−0.088
Max	21.470	15.407	14.647	18.950	11.543	41.139
Min	−17.614	−12.218	−14.088	−32.719	−16.014	−17.877
Std. dev	4.088	3.280	4.141	4.208	3.750	4.119
Skewness	0.321	0.321	−0.129	−0.166	−0.202	0.671
Kurtosis	6.480	5.450	5.171	11.870	6.704	19.655
Jarque-Bera	1280	780	629	3881	1388	21930
ADF	−39.39	−41.19	−41.77	−41.19	−43.50	−42.58
ARCH (10)	11.19	12.752	12.71	13.47	70.18	7.17
$Q\ (30)^2$	162.90	288.60	655.31	500.66	3572	114.04

Table 2 Static correlation

Static correlation	*GB*	*RE*	*OVX*	*SOE*	*Green*	*CVI*
GB	1					
RE	−0.80	1				
OVX	0.41	−0.49	1			
SOE	0.29	−0.50	0.81	1		
Green	0.14	−0.29	0.39	0.39	1	
CVI	−0.03	−0.06	0.15	0.14	0.10	1

correlations with carbon futures on the d3 frequency band. There is little to no association between carbon futures and stock returns across all three-time scales, suggesting that risk may be successfully mitigated via portfolio methods, as presented in Table 2.

Using the static spillover transmission method, we begin by investigating the COVID-19 pandemic's impact on green bond markets, cryptocurrencies, and uncertainty. By this method, we can see how the degree to which market expectations shift in response to occurrences in other markets and the degree to which connection across markets changes over time (Lv et al. 2022). We looked at bear market conditions to determine the spillover impacts of cryptocurrencies and COVID-19 pandemic–related uncertainty on the green bonds market. The data demonstrated that static spillover effects were more pronounced at the lower and higher quantiles than at the median. Static spillovers from all indices topped 81.41% for both green bond and cryptocurrency systems during bear and bull market states but were only 54.75 percentage points under stable market conditions in Fig. 1.

Base model analysis

It is also noteworthy that in the significantly lower and higher industry states, the uncertainty associated with green bond indexes and cryptocurrencies. Finally, Tables 3 shows that crypto assets were the most significant net contributors to volatility shocks. In the case of environmentally friendly bonds, these investments often provide a positive return. Our results verify that both OVX and green bonds are shock transmitters. Similarly, a study of the interplay between Fintech, green bonds, and cryptocurrencies found that Bitcoin was a net contributor to volatility shocks during the period from November 2018 to June 2020, while green bonds and green bond selections were net beneficiaries of the ensuing market fluctuations. This table presents the preliminary analysis of six different return series denoted by the index names, namely, GB, RE, OVX, SOE, Green, and CVI.

The analysis includes various statistical measures, such as the mean, standard deviation, median, minimum, maximum, range, skewness, and kurtosis. These measures give us an understanding of the central tendency, variability, and shape of the return series. The mean values for all series are relatively small, indicating that on average, the returns are close to zero. The standard deviation values are small for GB and RE but higher for OVX, SOE, Green, and CVI, suggesting that the latter series have higher variability. The median values are also close to zero for all series except Green, which has a median of 0.004. The minimum and maximum values show the range of returns observed in each series. The highest range is observed in the Green series, with a value of 0.597. The skewness values provide insight into the symmetry of the return distributions. Negative skewness values for GB, OVX, and SOE indicate that these series have more negative returns. Conversely, positive skewness values for RE and Green imply that these series have more positive returns. The CVI series has a skewness value close to zero, indicating a more symmetrical distribution. The kurtosis values provide information on the shape of the return distributions. High kurtosis values indicate that the distribution has a sharper peak and heavier tails than a normal distribution. All series have kurtosis values higher than three, except for CVI. The OVX series has the highest kurtosis value of 8.739, indicating a more peaked and fat-tailed distribution.

The JB test, ADF test, and PP test are statistical tests that provide evidence of the normality and stationarity of the return series. All series have statistically significant JB, ADF, and PP test values, indicating that they are not normally distributed and are non-stationary. Finally, the LB (20) test measures the autocorrelation of the return series up to 20 lags. The Green series has a statistically significant LB (20) value of 70.04, indicating the presence of autocorrelation in the series.

Table 4 presents an overview of the dynamic conditional correlations (DCCs) between the six return series, namely, GB, RE, OVX, SOE, Green, and CVI. The DCCs measure the extent to which the correlation between two return series varies over time. Specifically, they provide information on the conditional correlation between the series at time t, given the information available up to time t-1. The table shows the mean, standard deviation, minimum, and maximum values of the DCCs for each pair of return series. The mean values of the DCCs range from −0.6715 to 0.1266. The negative value for GB indicates an inverse relationship between GB and the other return series. Positive values for RE, OVX, and CVI suggest a positive relationship between these series and

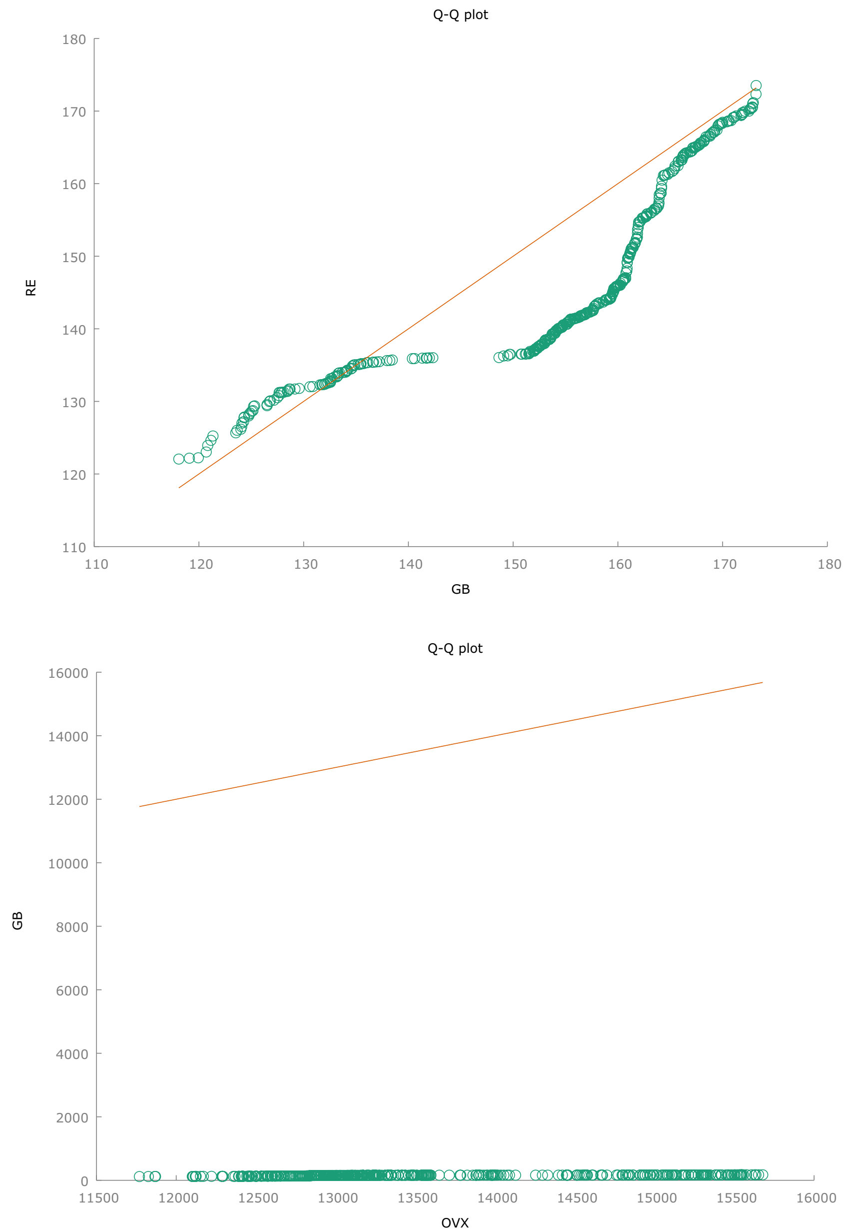

Fig. 1 Q-Q plot of OVX and GB

Table 3 Preliminary analysis of the return series.

Index	*GB*	*RE*	*OVX*	*SOE*	*Green*	*CVI*
Mean	0.001	0.000	0.003	0.005	−0.001	−0.001
Std. dev.	0.008	0.007	0.019	0.041	0.059	0.059
Median	0.001	0.001	0.004	0.005	0.004	0.001
Min	−0.061	−0.019	−0.129	−0.250	−0.350	−0.180
Max	0.041	0.041	0.105	0.170	0.260	0.229
Range	0.088	0.061	0.242	0.414	0.597	0.404
Skewness	−1.181	0.490	−1.218	−0.666	−0.442	0.077
Kurtosis	6.877	1.988	8.739	7.459	4.142	0.566
JB test	929***	70.7***	1388***	1014***	380***	4.62*
ADF test	−5.7***	−5.1***	−6.4***	−7.4***	−7.5***	−6.1***
PP test	-331***	-351***	-388***	-341***	-259***	-331***
LB (20)	30.81	22.29	14.60	24.30	70.04***	30.50

Table 4 An overview of DCCs

DCC	*Mean*	*Std. dev.*	*Min*	*Max*
GB	−0.6715	0.0621	−0.7908	−0.4377
RE	0.0500	0.1015	−0.2505	0.3731
OVX	0.0977	0.0888	−0.2251	0.3549
SOE	−0.0251	0.0670	−0.2990	0.2190
Green	−0.0105	0.0546	−0.1950	0.1287
CVI	0.1266	0.0988	−0.2008	0.4480

the other return series. The SOE and Green series have mean DCC values close to zero, indicating a weaker relationship with the other series. The standard deviation values range from 0.0546 to 0.1015, with the RE series having the highest value. The higher standard deviation values suggest that the correlation between the return series varies significantly over time. The minimum and maximum values show the range of the DCCs observed for each pair of return series. The range for GB is the highest, with a minimum value of -0.7908 and a maximum value of −0.4377, indicating a wide variation in the correlation between GB and the other series over time. Overall, the DCCs provide important information on the relationships between the return series and how these relationships vary over time. Understanding these dynamics is crucial for portfolio management and risk assessment. No matter the economic climate, the most beneficial spillover effects were shown in the six COVID-19-related indices. This suggests that the fear of a global corona virus outbreak was the most significant influence on the green bond and cryptocurrency sectors. This result demonstrates that the published COVID-19 data exacerbate market volatility. Cameron and Trivedi (1990) found similar findings, namely, those official releases of the COVID-19 new case infection and mortality ratio favorably impact the volatility of financial markets in the China. High-frequency patterns in the implied volatility of S&P 500 index options and the OVX are affected by macroeconomic pronouncements.

As for the relationship between green bonds and cryptocurrencies, under extremely adverse market conditions and highly favorable market conditions, volatility spillovers from cryptocurrency markets are statistically produced to green bonds. Bullish cryptocurrency markets have transferred 27.96 percentage points to the MSCI green bond index worldwide, 28.03 percentage points to the MSCI green bond index in China, and 27.78% to the S&P green bond index. Liu et al. (2022a) and Chang et al. (2022) suggest that cryptocurrency markets had a significant impact during bull markets for green bonds. When the market was bearish, everyone acted the same way (Table 5).

The net pairwise information connectivity displayed in reveals, on the other hand, that shocks in cryptocurrency's markets have been communicated to all green bond markets under all market conditions, with CVI dominance notable during negative market periods. Based on these results, Bitcoin may have a more significant overall impact on green bonds than Ethereum, OVX, or SOE. Hence, growing trends in CVI investments by investors and decision-makers worldwide may account for CVI market domination. Overall, we assume that the four cryptocurrency markets causing us to worry are heavily connected with green bonds regarding the return transfer mechanism, especially in unfavorable market occurrences. In light of the COVID-19 health crisis, investors and policymakers need to assess the impact of cryptocurrency's shock spillovers on green bonds when markets are bearish and bullish to formulate optimal crypto-green bond portfolios that maximize benefits and minimize risks, as presented in Table 6.

The static interconnectedness of market-to-market volatility spillovers in the form of a heatmap. The height of the colored bar indicates the magnitude of the spillovers in volatility between the market pairs. Cells with lighter colors

Table 5 Base model results

	GB	*T statistic*	*RE*	*T statistic*	*OVX*	*T statistic*	*SOE*	*T statistic*
AR (0)	−0.0055***	−3.07	−0.0061***	−3.00	−0.0117***	−3.47	−0.0143***	−6.16
AR (1)	−0.0261***	−5.80	−0.0170***	−4.70	−0.0241***	−7.90	−0.0388***	−18.77
AR (2)	−0.0118***	−4.88	−0.0141***	−3.71	−0.0117***	−3.50	−0.0031	−1.31
AR (3)	−0.0070**	−3.31	0.0050	1.51	−0.0039*	−1.69	−0.0315***	−14.66
AR (4)	−0.0203***	−5.79	−0.0190***	−5.28	−0.0261***	−11.80	−0.0177***	−7.17
AR (5)	−0.0305***	−11.28	−0.0204***	−7.88	−0.0366***	−14.61	−0.0381***	−18.12
AR (6)	−0.0103***	−4.50	−0.0050	−1.61	−0.0180	−6.50	−0.0270	−14.47
AR (7)	0.0080***	3.61	0.0080**	3.60	−0.0014	−0.60	0.0002	0.04
AR (8)	0.0040	1.03	0.0051	1.58	0.0019	0.77	−0.0166***	−8.21
AR (9)	−0.0017	−0.70	0.0007	0.31	0.0061***	3.39	0.0080***	4.81
AR (10)	0.0014	0.50	−0.0004	−0.21	0.0105***	3.41	0.0218***	12.07
AR (11)	0.0216***	6.28	0.0180***	4.88	0.0166***	6.19	0.0277***	13.11

Table 6 Cumulative abnormal returns.

	GB	*T statistic*	*RE*	*T statistic*	*OVX*	*T statistic*	*SOE*	*T statistic*
CAR (0, +2)	−0.050***	−7.518	−0.041***	−6.104	−0.051***	−11.907	−0.062***	−17.310
CAR (0, +5)	−0.102***	−14.939	−0.068***	−8.830	−0.112***	−18.141	−0.150***	−31.530
CAR (0, +8)	−0.102***	−12.331	−0.070***	−6.171	−0.130***	−16.889	−0.190***	−29.650
CAR (0, +11)	−0.077***	−6.770	−0.052***	−3.471	−0.088***	−12.505	−0.129***	−18.061

Table 7 In-sample estimation outputs

		GB	*RE*	*OVX*	*SOE*	*Green*
GB	0.000*** (2.415)	0.000 (0.888)	0.000*** (4.758)	0.000*** (3.561)	0.000*** (4.590)	0.000** (3.622)
RE	0.712*** (21.680)	0.39*** (6.566)	0.239*** (4.159)	0.166*** (4.396)	0.697*** (12.741)	0.692*** (12.680)
OVX	−0.181* (−1.870)	−0.260*** (−4.144)	−0.216*** (−4.148)	−0.090 (−1.306)	−0.177** (−3.038)	−0.181* (−1.901)
SOE	0.090 (0.761)	0.080 (0.766)	0.151* (1.841)	0.05 (0.990)	0.062 (0.471)	0.080 (0.70)
Green	——	0.918*** (12.303)	——	——	——	——
CVI	——	——	0.051***(17.931)	——	——	——
R square	0.388	0.571	0.717	0.702	0.377	0.366

imply less volatility spillover connections, whereas darker cells suggest stronger ones (Barbier 2020). Many darker-colored cells demonstrated that pairwise volatility spillover connectedness was larger in bearish and bullish states than in standard settings. The substantial volatility spillover transmission is associated with green bonds in the media. In addition, the SSM combination has a sizable connection under excessive market risk, as measured by the volatility connectedness coefficient. Normal circumstances were characterized by low volatility spillover connectivity, as shown by a lighter-colored heatmap matrix. This may show that while the market was calm, the impact of COVID-19 uncertainties and cryptocurrencies on green bonds was minimal. Many cells with deeper colors imply higher volatility spillover connectivity between market pairings, as presented in Table 7.

Table 8 displays some intriguing results for the model using climate bond and gold indices. According to the return formulae, climate bond returns greatly impact gold returns, while bond returns do not respond to gold. As a result, the performance of gold may be predicted by the performance of climate bonds. In this situation, volatility is linked on both sides. The effects of news shocks in one market might be felt in the other. Thus, traders may use data from one market to forecast the other.

Table 9 displays findings for the model using climate bonds and crude oil indices, which are strikingly comparable to those obtained using the stock-bond model. As a result, the climate bond and oil markets are impacted by the shocks and lagged volatility experienced in their respective sectors in the past. There is considerable evidence of bidirectional volatility transmission between the climate bond and crude oil markets but no return spillovers. Oil price volatility is affected by news shocks from the climate bond market, but not vice versa.

Table 8 Ranking of Barclays MSCI Green Bond Index forecasts given by weekly TP VAR

Predictor				
Forecasting length = 80				
No predictor	7	11	6	6
GB	*6*	*7*	*4*	*4*
RE	*5*	*4*	*4*	*5*
OVX	5	5	11	11
SOE	13	13	12	12
Green	11	8	8	7
CVI	12	6	13	13
Forecasting length = 160				
No predictor	11	11	6	11
GB	*6*	*7*	*4*	*4*
RE	*4*	*6*	*5*	*5*
OVX	*5*	*5*	*7*	*6*
SOE	13	13	12	12
Green	12	8	11	5
CVI	7	4	13	14

There are a lot of fascinating discoveries about the link between climate bonds and major economic sectors and their volatility transmission. We first discovered a correlation between climate bonds and share price market volatility

Table 9 Results of the MCS test in Barclays MSCI Green Bond Index volatility forecasting given by weekly TP VAR

Predictor					
No predictor	0.00	0.66	0.00	0.00	1
GB	0.00	0.71	0.00	0.00	1
RE	0.00	0.77	0.00	0.00	1
OVX	0.00	0.80	0.00	0.00	1
SOE	0.00	0.71	0.00	0.00	1
Green	0.00	0.66	0.00	0.00	1
CVI	0.00	0.00	0.00	0.00	0

Table 10 Output of forecasting the encompassing test

Predictor	*Coefficient*	*T value*	*Predictor*	*Coefficient*	*T value*
Intercept	0.00**	3.028	*Intercept*	0.00	1.331
No predictor	−1.12	−1.108	*No predictor*	−0.31	−0.460
GB	0.61***	4.815	*GB*	0.29***	4.031
RE	−0.17	−1.472	*RE*	−0.19*	−1.750
OVX	−0.05	−0.417	*OVX*	0.04	0.339
SOE	−0.03	−1.508	*SOE*	−0.06***	−4.108
Green	0.70*	1.766	*Green*	0.31*	1.680
CVI	0.05	1.161	*CVI*	0.06	1.303
Adj. R squared	0.77		*Adj. R squared*	0.88	

that works both ways. Consequently, the bond market may be predicted using data from are a reliable predictor of future gold yields within the framework of the gold-bond model in Fig. 2. Finally, the magnitude levels of shocks and volatilities in the cross-market news are shown to be significantly less than the impacts of own one-period delayed shocks and volatilities (Ding et al. 2014). Our findings show that the last news and volatility shocks are more important in determining future price changes in each sector, as presented in Table 10.

According to Table 11, the average connection between bonds and gold or oil is positive. As a result, a rise in the cost of gold or crude oil is mirrored in the market for climate bonds. Considering finance environmentally favorable initiatives like renewable energy projects, this discovery is not shocking for the RE oil market (Maddala and Wu 1999). While renewable energy firms aim to provide a replacement for crude oil, a spike in crude oil costs would drive financial agents to switch to other energy sources in Fig. 3. One may thus anticipate that the price of renewable energy would climb once the price of crude oil did so due to demand-side forces. This suggests that the oil industry and the climate bond market will be positively correlated.

Moreover, it indicates that oil market players may have chances for hedging. In contrast, environment bonds tend to have the most significant association with the gold market, suggesting that gold is not a valuable hedge for ethical expenditures (Alola et al. 2022). There may be a positive correlation between gold and climate bonds since both are attractive options for investors seeking safety amid financial downturns. According to the research of Fang et al. (2022b), gold is not a reliable hedging tool for the bond markets in China, as presented in Table 12.

The data show counterintuitiveness considering the generally good correlation between stock and traditional bond sectors. For instance, it provides evidence that share and bond sectors are generally positively associated. They

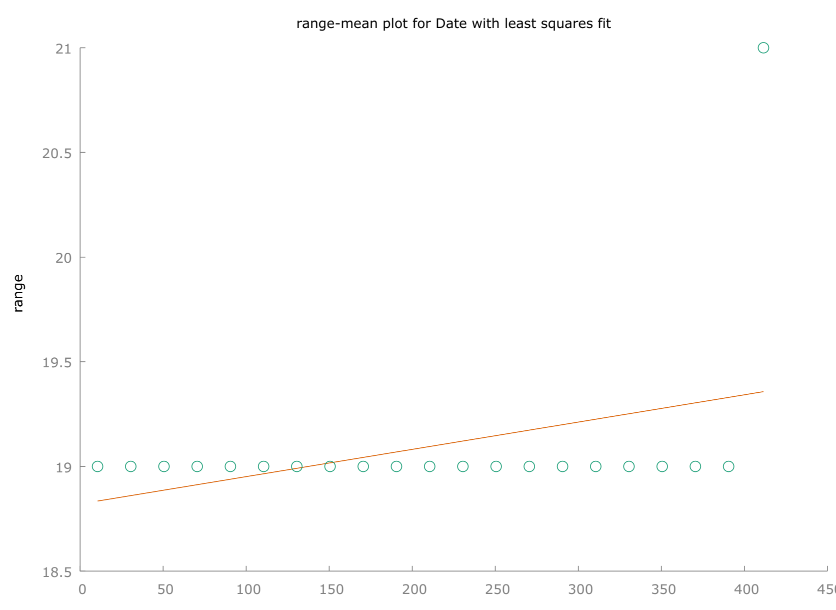

Fig. 2 Range mean plot with least square fit

Table 11 Ranking of Solactive Green Bond Index forecasts given by weekly RV HAR

Predictor				
Forecasting length = 80				
No predictor	7	11	6	8
GB	5	7	3	3
RE	4	5	4	3
OVX	6	4	11	6
SOE	13	13	12	12
Green	8	8	8	7
CVI	11	5	13	13
Forecasting length = 160				
No predictor	7	11	8	8
GB	5	7	5	3
RE	4	4	5	6
OVX	6	6	6	7
SOE	13	14	12	12
Green	12	8	11	8
CVI	7	8	13	13

claim that stockholders only go towards secure fixed-income instruments like business expenditure and treasury bonds during equities market volatility. The same is true of the findings of Halkos and Managi (2023). Yet our research shows that climate bonds and the S&P 500 index do not move in tandem, suggesting that climate bonds may be used to protect against losses in the S&P 500 in Fig. 4. Our research has significant ramifications for moral investors seeking to spread out the dangers inherent in asset holdings, as presented in Table 13.

Table 14 shows the ranking of the Solactive Green Bond Index forecasts given by the ARFIMAX model for two different forecasting lengths of 80 and 160. The rankings are based on the mean squared error (MSE) of the forecasts, with lower MSE values indicating better forecasts. The table presents the rankings for each of the six predictors considered, including the index itself (GB), as well as five additional variables: RE, OVX, SOE, Green, and CVI. The first column of each set of rankings shows the results with no predictor. For the forecasting length of 80, the rankings suggest that using the GB predictor produces the most accurate forecasts, followed by the OVX predictor. The RE, SOE, Green, and CVI predictors perform less well, with higher MSE values. When no predictor is used, the model performs similarly to using the RE, SOE, Green, or CVI predictors. For the forecasting length of 160, the rankings remain similar, with the GB predictor producing the most accurate forecasts. The OVX predictor remains in second place, followed by the RE predictor, which performs better than in the previous case. The rankings for SOE, Green, and CVI remain the same as in the previous case. Again, when no predictor is used, the model performs similarly to using the Green or CVI predictors. Overall, the rankings suggest that the GB and OVX predictors are the most useful for forecasting the Solactive Green Bond Index, with the RE predictor also providing some value. The other predictors, including the index itself, do not appear to be as useful for forecasting the index.

After that, we provide a best guess at the cross-quantilogram findings during the current COVID-19 pandemic. As the green bond market was established only after the global financial crisis, its potential as a haven investment during widespread industry turmoil may be tested. Recent research shows that a haven spread, yet cryptocurrency's exchanges offered few refugee-friendly options throughout the epidemic (Ofori et al. 2023). Nonetheless, gold's status as a traditional haven asset provided some refuge. Thus, we make an effort to investigate how the market contagion may impact the diversifier and safe-haven potential of green bond investors.

As shown in the first column of Table 14, the short-term relationship between the green bond index and traditional expenditure exhibits an amplified lead-lag association in the lower-left returns quantiles, suggesting that green bonds did not offer any safe-haven opportunities during the market contagion. We also find a stronger lead-lag relationship between the green bond index and traditional investing in the middle quantiles of returns (Gossel 2018). This suggests that the green bond's diversification ability for short-term shareholders is diminished during the outbreak. All the graphs demonstrate a dynamic pattern of connection, confirming the time-varying lead-lag relationship between the green bond index and traditional expenditures. Quantiles of traditional expenditure returns and the green bond index's lower quantiles exhibit a dynamic link, as seen in the first column of. For instance, there is a dynamically decreasing relationship between the lowest quantiles of all stock investors and the green bond index. Our finding suggests that green bond returns continue to have a limited correlation with traditional stock investments amid broad market volatility, making them a potential hedge for equity shareholders. In addition, a more in-depth examination of the epidemic reveals a discernible drop in the lead-lag correlation, indicating that green bonds may be an alternative investor during a financial crisis. During the epidemic, the disconnection between the green bond index and more traditional assets like Green, SOE (Shahbaz et al. 2018), and commodities investments is less prominent. Moreover, we find evidence of a decoupling impact between green bond returns and traditional expenditure in the form of a rising correlation between inverse quantiles of the green bond index and traditional equities assets (Anu et al. 2023). The median and maximum quantile returns of the green bonds index are less correlated with those of traditional investors, except for the CVI and the RE (Delacámara 2008). As the lead-lag relationship weakens more for sample stock investors and GB in the parallel medium returns quantiles, green bonds are an excellent diversification option for holders of these instruments.

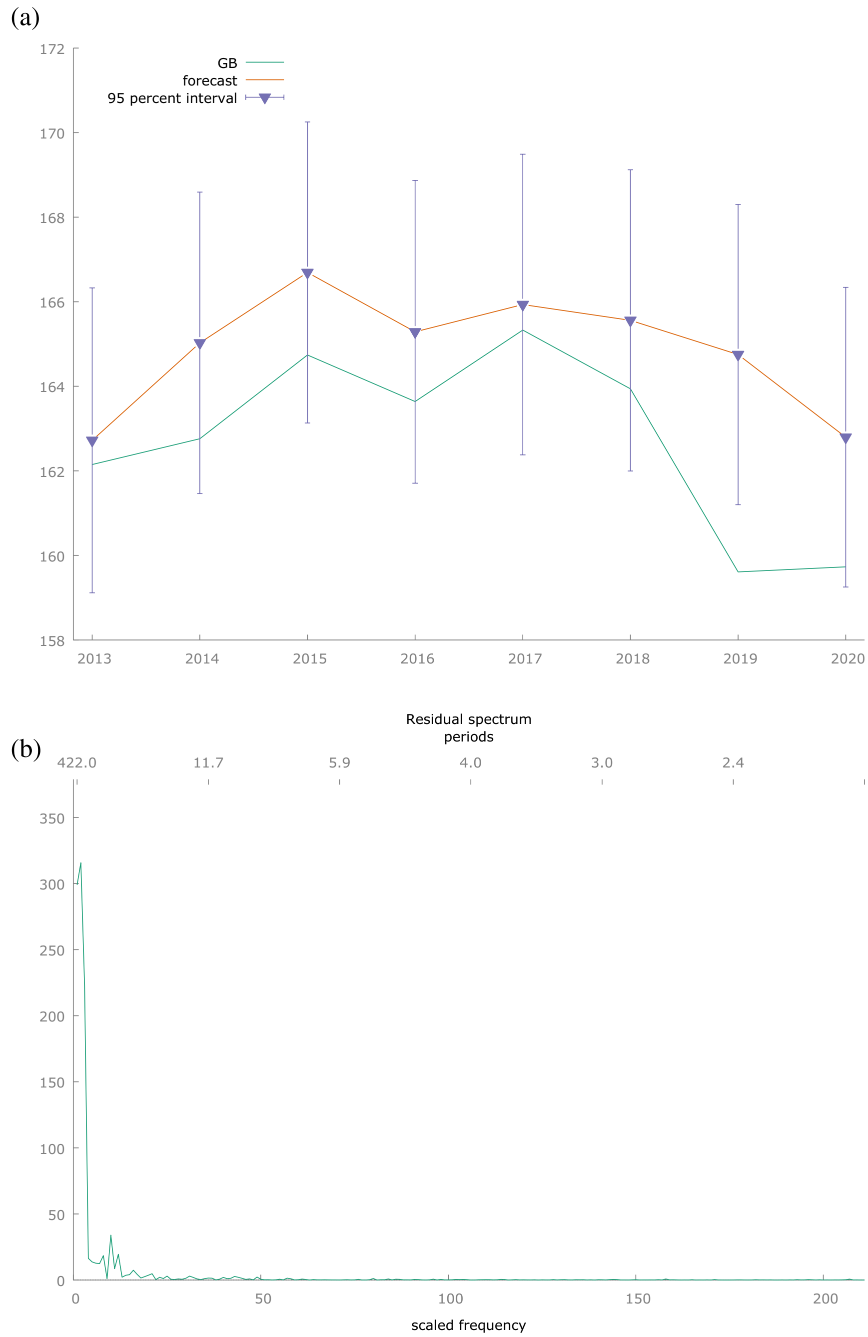

Fig. 3 **a** Forecast term. **b** Residual spectrum period

Table 12 Results of the MCS test in Solactive Green Bond Index forecasting given by weekly TP VAR

No predictor	0.00	0.81	0.00	0.00	1
GB	0.00	0.77	0.00	0.00	1
RE	0.00	0.77	0.00	0.00	1
OVX	0.00	0.71	0.00	0.00	1
SOE	0.00	0.80	0.00	0.00	1
Green	0.00	0.81	0.00	0.00	1
CVI	0.00	0.00	0.00	0.00	0

Conclusion and policy implications

By considering the impact of the carbon price, this research analyzes the transmission patterns of risk between green bonds and renewable energy equities. This research, motivated by the growing popularity of sustainable investing strategies, uses daily data from 2010 to 2020, to analyze how green bonds, carbon pricing, and renewable energy equities transmit their respective returns to one another. This study examined the precarious side of the green economic industry by first investigating how the green bond industry reacts to severe negative

Fig. 4 Ellipse of marginal interval

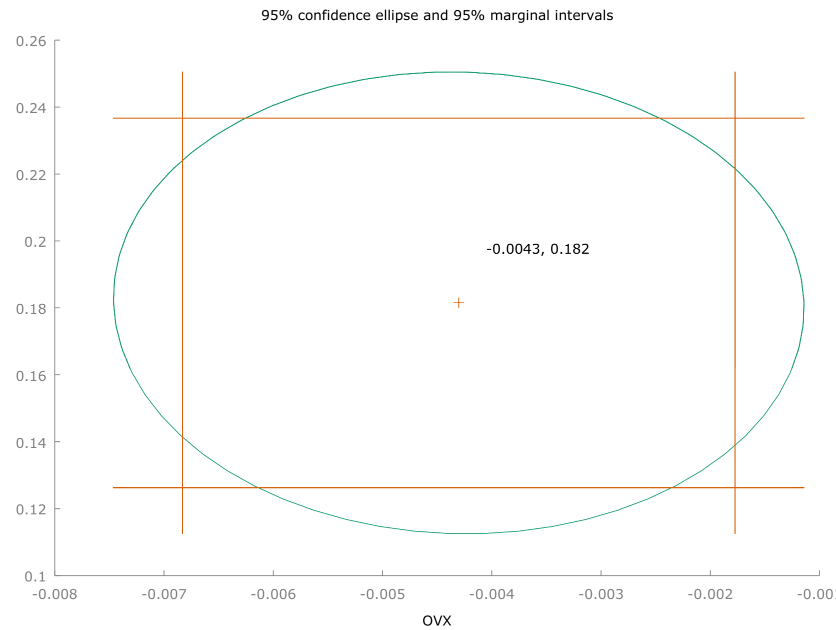

Table 13 Ranking of Barclays MSCI Green Bond Index forecasts given by ARFIMAX

Predictor				
Forecasting length = 80				
No predictor	7	12	4	8
GB	6	7	3	4
RE	4	4	7	5
OVX	5	5	11	11
SOE	13	13	12	12
Green	8	11	7	6
CVI	12	6	13	14
Forecasting length = 160				
No predictor	8	11	8	4
GB	7	7	5	6
RE	4	5	5	6
OVX	6	4	11	11
SOE	14	13	12	12
Green	11	12	6	6
CVI	12	6	14	13

Table 14 Ranking of Solactive Green Bond Index forecasts given by ARFIMAX

Forecasting length = 80				
No predictor	6	12	7	7
GB	5	7	4	7
RE	4	4	4	5
OVX	5	3	11	7
SOE	13	13	12	12
Green	11	11	6	6
CVI	7	7	13	13
Forecasting length = 160				
No predictor	6	8	7	6
GB	5	7	4	3
RE	4	7	5	5
OVX	6	4	11	11
SOE	13	13	12	12
Green	12	12	8	8
CVI	11	6	13	13

shocks and then delving into and analyzing in great detail the factors that contribute to the volatility dynamics of the market. These are some ways in which this study adds to the existing body of knowledge: Via illuminating a case study that looked at how the green bond industry reacted to the COVID-19 pandemic's shock, extending volatility forecasting to the green bond market, and illuminating the underlying causes that cause volatility in the green finance market. Global solar receives the most considerable amount of spillovers from the renewable energy sector (27.509%). The clean energy sector is the primary transmitter of shocks to green bonds in the event of return transmission from renewable energy equities. So, the amount of shock sent from green bonds to renewable energy stocks is less than the amount transmitted from renewable energy stocks to green bonds. Specifically, 39.795% of total solar GB and 34.212% of wind OVX are communicated to other markets, while 56.577% of clean energy's GB is spilled to these other assets. Moreover, several permutations have shown a greater return to volatility ratio than green bonds. We determine that VAR dynamic portfolio weights heavily emphasize green bonds, whereas VAR only vary by small margins. Lastly, we demonstrate that the investment risk of all assets, except green bonds, has been decreased in the multivariate portfolio setting. Our results suggest that the SSM portfolio had the highest performance overall.

The results of this study have significant policy ramifications for numerous green finance stakeholders. Policymakers can use these insights to design and improve their initiatives to advance sustainable development. The following are significant policy ramifications:

Increasing the incorporation of green bonds and stocks of renewable energy sources: Green bonds and renewable energy stocks were found to have significant dynamic spillover effects, which points to a close relationship between these two elements of the green finance ecosystem. The combination of green bond financing and stock investments in renewable energy sources is something that policymakers can support and facilitate. This can be done by enacting legislation that offers incentives for renewable energy projects financed by green bonds or by setting up unique trading and investment platforms for green bonds and renewable energy stocks.

Strengthening the complementary relationship between carbon markets and green bonds: The research points to a positive relationship between carbon markets and green bonds. Policymakers can take advantage of this relationship by creating regulations that encourage the concurrent use of green bonds and carbon markets. The effectiveness of both instruments in promoting sustainable development can be improved, for instance, by developing mechanisms that enable green bond issuers to access carbon credits or by offering incentives to investors to support green bonds linked to carbon reduction projects.

Increasing investor awareness and education: The findings of this study demonstrate the dynamics and interdependence of the green finance ecosystem. Policymakers can significantly aid the promotion of investor awareness and education about these connections. This can be done by setting up workshops, seminars, and educational campaigns to inform investors about the risks and rewards associated with investing in green bonds, renewable energy stocks, and carbon markets. By increasing investor knowledge, policymakers can encourage more informed decision-making and greater participation in green finance initiatives.

Promoting data transparency and standardized reporting: Given the study's findings about the study's complex interdependencies, policymakers should stress the significance of data transparency and standardized reporting in the field of green finance. Increase transparency and enable more precise risk and performance assessments by establishing clear reporting guidelines and disclosure requirements for green bond issuers, renewable energy producers, and participants in carbon markets. To ensure consistency and comparability across the industry, policymakers can also support the development of standardized metrics and methodologies for measuring and reporting the environmental impact of green finance projects.

International cooperation and knowledge exchange should be encouraged because green finance operates globally, allowing policymakers to benefit from best practices and experiences. This can entail joint initiatives to address global sustainability challenges, sharing of research and data, and collaboration in developing regulatory frameworks. Policymakers can foster an environment favorable to the successful implementation and global scaling-up of green finance initiatives by encouraging collaboration and knowledge sharing.

Overall, the study's policy implications highlight the necessity of a thorough and well-rounded approach to green finance. Policymakers can maximize the benefits of green finance in advancing sustainable development goals by recognizing and taking advantage of the connections among green bonds, renewable energy stocks, and carbon markets.

This investigation into the connections between renewable energy stocks, carbon markets, and green bonds offers insightful information. However, some restrictions must be understood. Because the study only considered the period from January 2010 to December 2020, it may need to reflect how the green finance ecosystem changes over time adequately. Although instructive, the modeling approach may need to be more concise in how complex the relationships are. The study also fails to establish a causal relationship, fails to account for market-specific variables, and may not be broadly applicable due to regional and contextual differences. Future research should consider these limitations by incorporating more recent data, considering external factors and systemic risks, and examining causal relationships to provide a more thorough understanding of the interconnections within green finance. The results should be interpreted with caution.

Data availability The data that support the findings of this study are openly available on request.

Author contribution Conceptualization, methodology: YaFei Zhang. Writing (original draft), data curation, data Analysis: Muhammad Umair.

Declarations

Ethical approval and consent to participate We declare that we have no human participants, human data or human issues.

Consent for publication We do not have any individual person's data in any form.

Competing interest The authors declare no competing interests.

References

Agyekum EB, Amjad F, Mohsin M, Ansah MNS (2021) A bird's eye view of Ghana's renewable energy sector environment: a multi-criteria decision-making approach. Util Policy. https://doi.org/10.1016/j.jup.2021.101219

Al Asbahi AAMH, Gang FZ, Iqbal W et al (2019) Novel approach of Principal Component Analysis method to assess the national energy performance via Energy Trilemma Index. Energy Rep. https://doi.org/10.1016/j.egyr.2019.06.009

Alola AA, Adebayo TS, Onifade ST (2022) Examining the dynamics of ecological footprint in China with spectral Granger causality and quantile-on-quantile approaches. Int J Sustain Dev World Ecol 29:263–276. https://doi.org/10.1080/13504509.2021.1990158

Anu SAK, Raza SA et al (2023) Role of financial inclusion, green innovation, and energy efficiency for environmental performance? Evidence from developed and emerging economies in the lens of sustainable development. Struct Chang Econ Dyn 64:213–224. https://doi.org/10.1016/j.strueco.2022.12.008

Barbier EB (2020) Greening the Post-pandemic Recovery in the G20. Environ Resour Econ. https://doi.org/10.1007/s10640-020-00437-w

Cameron AC, Trivedi PK (1990) Regression-based tests for overdispersion in the Poisson model. J Econom 46:347–364

Chang L, Zhang Q, Liu H (2022) Digital finance innovation in green manufacturing: a bibliometric approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-18016-x

Chen X, Xu Q, Li X et al (2020) Molecular and phenotypic characterization of nine patients with STAT1 GOF mutations in China. J Clin Immunol 40:82–95

Delacámara G (2008) Guía para decisores Análisis económico de externalidades ambientales. Cepal 82

Ding H, He M, Deng C (2014) Lifecycle approach to assessing environmental friendly product project with internalizing environmental externality. J Clean Prod 66:128–138. https://doi.org/10.1016/j.jclepro.2013.10.018

Fang W, Liu Z, Surya Putra AR (2022a) Role of research and development in green economic growth through renewable energy development: Empirical evidence from South Asia. Renew Energy 194:1142–1152. https://doi.org/10.1016/j.renene.2022.04.125

Fang Z, Razzaq A, Mohsin M, Irfan M (2022b) Spatial spillovers and threshold effects of internet development and entrepreneurship on green innovation efficiency in China. Technol Soc 68:101844. https://doi.org/10.1016/j.techsoc.2021.101844

Gossel SJ (2018) FDI, democracy and corruption in Sub-Saharan Africa. J Policy Model 40:647–662. https://doi.org/10.1016/j.jpolmod.2018.04.001

Halkos G, Managi S (2023) New developments in the disciplines of environmental and resource economics. Econ Anal Policy 77:513–522. https://doi.org/10.1016/j.eap.2022.12.008

He L, Liu R, Zhong Z et al (2019) Can green financial development promote renewable energy investment efficiency? A consideration of bank credit. Renew Energy 143:974–984. https://doi.org/10.1016/j.renene.2019.05.059

Ikram M, Mahmoudi A, Shah SZA, Mohsin M (2019) Forecasting number of ISO 14001 certifications of selected countries: application of even GM (1,1), DGM, and NDGM models. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-04534-2

Iqbal N, Tufail MS, Mohsin M, Sandhu MA (2022) Assessing Social and Financial Efficiency: The Evidence from Microfinance Institutions in Pakistan. Pakistan J Soc Sci 39:149–161

Iqbal W, Yumei H, Abbas Q et al (2019) Assessment of wind energy potential for the production of renewable hydrogen in Sindh Province of Pakistan. Processes. https://doi.org/10.3390/pr7040196

Li C, Umair M (2023) Does green finance development goals affects renewable energy in China. Renew Energy 203:898–905. https://doi.org/10.1016/j.renene.2022.12.066

Li Z, Shi H, Liu H (2021) Research on the concentration, potential and mission of science and technology innovation in China. PLoS One 16:e0257636

Liu F, Umair M, Gao J (2023) Assessing oil price volatility co-movement with stock market volatility through quantile regression approach. Resour Policy 81:103375. https://doi.org/10.1016/j.resourpol.2023.103375

Liu H, Wu W, Yao P (2022a) A study on the efficiency of pediatric healthcare services and its influencing factors in China ——estimation of a three-stage DEA model based on provincial-level data. Socioecon Plann Sci 84:101315. https://doi.org/10.1016/j.seps.2022.101315

Liu H, Yao P, Latif S et al (2022b) Impact of Green financing, FinTech, and financial inclusion on energy efficiency. Environ Sci Pollut Res 29:18955–18966. https://doi.org/10.1007/s11356-021-16949-x

Liu H, Zhou R, Yao P, Zhang J (2022c) Assessing Chinese governance low-carbon economic peer effects in local government and under sustainable environmental regulation. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17901-9

Lv S, Zhao S, Liu H (2022) Research on the coupling between the double cycle mode and technological innovation systems: empirical evidence from data envelopment analysis and coupled coordination. Systems 10

Maddala GS, Wu S (1999) A comparative study of unit root tests with panel data and a new simple test. Oxf Bull Econ Stat 61:631–652. https://doi.org/10.1111/1468-0084.0610s1631

Mohsin M, Zhou P, Iqbal N, Shah SAA (2018) Assessing oil supply security of South Asia. Energy 155:438–447. https://doi.org/10.1016/j.energy.2018.04.116

Mohsin M, Nurunnabi M, Zhang J et al (2020a) The evaluation of efficiency and value addition of IFRS endorsement towards earnings timeliness disclosure. Int J Financ Econ. https://doi.org/10.1002/ijfe.1878

Mohsin M, Zaidi U, Abbas Q et al (2020b) Relationship Between Multi-Factor Pricing And Equity Price Fragility: Evidence From Pakistan. Int J Sci Technol Res 8

Mohsin M, Hanif I, Taghizadeh-Hesary F et al (2021) Nexus between energy efficiency and electricity reforms: A DEA-Based way forward for clean power development. Energy Policy. https://doi.org/10.1016/j.enpol.2020.112052

Mohsin M, Taghizadeh-Hesary F, Shahbaz M (2022) Nexus between financial development and energy poverty in Latin America. Energy Policy 165:112925. https://doi.org/10.1016/j.enpol.2022.112925

Monnin P (2018) Central banks should reflect climate risks in monetary policy operations. SUERF Policy Note, Issue

Nasreen S, Anwar S (2014) Causal relationship between trade openness, economic growth and energy consumption: A panel data analysis of Asian countries. Energy Policy 69:82–91. https://doi.org/10.1016/j.enpol.2014.02.009

Ofori EK, Onifade ST, Ali EB et al (2023) Achieving carbon neutrality in post COP26 in BRICS, MINT, and G7 economies: The role of financial development and governance indicators. J Clean Prod 387:135853. https://doi.org/10.1016/j.jclepro.2023.135853

Pan W, Cao H, Liu Y (2023) "Green" innovation, privacy regulation and environmental policy. Renew Energy 203:245–254. https://doi.org/10.1016/j.renene.2022.12.025

Shah SAA, Zhou P, Walasai GD, Mohsin M (2019) Energy security and environmental sustainability index of South Asian countries: A composite index approach. Ecol Indic 106:105507. https://doi.org/10.1016/j.ecolind.2019.105507

Shahbaz M, Nasir MA, Roubaud D (2018) Environmental degradation in France: The effects of FDI, financial development, and energy innovations. Energy Econ 74:843–857. https://doi.org/10.1016/j.eneco.2018.07.020

Shen L, Zhang X, Liu H (2022) Digital technology adoption, digital dynamic capability, and digital transformation performance of textile industry: Moderating role of digital innovation orientation.

Manag Decis Econ 43:2038–2054. https://doi.org/10.1002/mde.3507
Shen L, Zhang X, Liu H, Yao P (2021) Research on the Economic Development Threshold Effect of the Employment Density of the Shanghai Consumer Goods Industry in the Context of New Manufacturing, Based on the Experience Comparison with International Metropolis. Mathematics 9
Ullah K, Rashid I, Afzal H et al (2020) SS7 Vulnerabilities—A Survey and Implementation of Machine Learning vs Rule Based Filtering for Detection of SS7 Network Attacks. IEEE Commun Surv Tutorials 22:1337–1371. https://doi.org/10.1109/COMST.2020.2971757
Umair M, Dilanchiev A (2022) Economic Recovery by Developing Business Starategies: Mediating Role of Financing and Organizational Culture in Small and Medium Businesses. Proc B 683
Wang X, Huang J, Liu H (2022) Can China's carbon trading policy help achieve Carbon Neutrality? — A study of policy effects from the Five-sphere Integrated Plan perspective. J Environ Manage 305:114357. https://doi.org/10.1016/j.jenvman.2021.114357
Wei X, Mohsin M, Zhang Q (2022) Role of foreign direct investment and economic growth in renewable energy development. Renew Energy 192:828–837. https://doi.org/10.1016/J.RENENE.2022.04.062
Wu Q, Yan D, Umair M (2022) Assessing the role of competitive intelligence and practices of dynamic capabilities in business accommodation of SMEs. Econ Anal Policy. https://doi.org/10.1016/j.eap.2022.11.024
Xia Z, Abbas Q, Mohsin M, Song G (2020) Trilemma among energy, economic and environmental efficiency: Can dilemma of EEE address simultaneously in era of COP 21? J Environ Manage. https://doi.org/10.1016/j.jenvman.2020.111322
Xiuzhen X, Zheng W, Umair M (2022) Testing the fluctuations of oil resource price volatility: A hurdle for economic recovery. Resour Policy 79:102982. https://doi.org/10.1016/j.resourpol.2022.102982
Xu Z, Mohsin M, Ullah K, Ma X (2023) Using econometric and machine learning models to forecast crude oil prices: Insights from economic history. Resour Policy 83:103614. https://doi.org/10.1016/j.resourpol.2023.103614
Yao P, Liu H (2021) Research on Behavior Incentives of Prefabricated Building Component Manufacturers. Information 12
Yu L, Chen Z, Yao P, Liu H (2021) A Study on the Factors Influencing Users' Online Knowledge Paying-Behavior Based on the UTAUT Model. J Theor Appl Electron Commer Res 16:1768–1790
Yu L, Liu H, Diabate A et al (2020) Assessing Influence Mechanism of Green Utilization of Agricultural Wastes in Five Provinces of China through Farmers' Motivation-Cognition-Behavior. Int J Environ Res Public Health 17
Zhang D, Mohsin M, Rasheed AK et al (2021a) Public spending and green economic growth in BRI region: Mediating role of green finance. Energy Policy. https://doi.org/10.1016/j.enpol.2021.112256
Zhang X, Liu H, Yao P (2021b) Research jungle on online consumer behaviour in the context of web 2.0: traceability, frontiers and perspectives in the post-pandemic era. J Theor Appl Electron Commer Res 16:1740–1767