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Research article

Modelling the mean and volatility spillover between green bond market and renewable energy stock market

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Abstract: In this paper, we investigate the mean and volatility spillover between the price of green bonds and the price of renewable energy stocks using daily price series from 02/11/2011 to 31/08/2021. The unrestricted trivariate VAR-BEKK-GARCH model is employed to examine potential causality, mean, and volatility spillover effects from the green bond market to the renewable energy stock market and vice-versa. The results from the VAR-BEKK-GARCH model indicate that there exists a uni-directional Granger causality from renewable energy stock prices to green bond prices. While the price of green bonds is positively influenced by its own lagged values and the lagged values of renewable energy stock prices, only the past price value of renewable energy stocks has a positive effect on the current price value. We identified a uni-directional volatility spillover from renewable energy stock prices to green bond prices. However, there was no shock spillover from both sides of the market. This research shows that investors in the green bond market should always consider information from the renewable energy stock market because of the causal link between renewable energy stocks and green bonds.

Keywords: green bonds; clean energy stock; volatility spillover; climate change; VAR-BEKK-GARCH; climate finance

JEL Codes: B23, C22, C50

1. Introduction

In recent years, investors have made a concerted effort to include more environmentally friendly assets in their portfolios. As a result of these efforts, green bonds, a relatively new financial vehicle, have evolved. These bonds are growing and evolving rapidly, incorporating changes in the socio-economic environment. However, studies regarding the relationship with renewable energy stock are still limited. In the financial market, fluctuations in bond and stock prices might spread to different sectors and companies. Also, corporate investment can be influenced when bond and stock prices are aggregated (Chang et al., 2021).

Bonds have long been used to support large-scale low-carbon and climate-resilient (LCR) infrastructure or to fund loans. However, since 2007, there has been a special type of bond that is unique from conventional bonds and which is self-labeled or recognized as "green". A green bond is distinct from a conventional bond in that it represents a commitment to exclusively use the funds generated to solely finance or re-finance "green" projects, assets, or business operations. The green bond market is part of a larger effort to fund an economy-wide change to a low-carbon economy which is in tandem with the objectives of the Paris Agreement. Governments will therefore need to think about how they can help the global green bond markets evolve in order to fund the low-carbon transition. The market for green bonds has expanded quickly in recent years and holds the potential for advancing climate action. Global green bond issuance in 2014 was USD 36.6 billion, and the issuance of green bonds in 2020 was expected to reach USD 269.5 billion, according to the Climate Bonds Initiative (CBI). It should be noted that nineteen sovereigns have already issued green bonds totaling more than USD 130 billion to fund green initiatives in government budgets (OECD, 2021). Despite the challenges posed by the COVID epidemic, the issuance of green bonds in 2020 reached USD 297 billion, which is a record high (Boulle, 2021). Even though there has been a recent increase in the number of green bonds issued, the global market for green bonds is still a very small part of the over USD 100 trillion fixed income market as a whole. This may be a good sign for the growth of the green market.

Renewable energy, on the other hand, has emerged as a significant beneficiary of green bond proceeds. Between 2010 and 2017, green bond issuances targeted for clean or renewable energy initiatives increased from USD 4.3 billion to USD 97.8 billion (cbi, 2018). Hence, countries looking to expand renewable energy can turn to the green bond market, which now includes an increasing number of instruments dedicated to sustainable, environmentally friendly, climate-safe project financing. The good news is that clean, low-carbon energy sources are becoming increasingly cost-competitive. Renewables provided over half of the world's new electricity production capacity in 2014, according to the International Energy Agency's 2015 World Energy Outlook, and have now surpassed coal as the second-largest source of energy globally (IEA , 2015). According to Appavou et al. (2019), global investments in new renewable energy have increased in recent years, from less than USD 50 billion per year in 2004 to over USD 300 billion per year in 2019. This exceeds investments in new fossil fuel power by a factor of three. As indicated by C et al. (2021), the global renewable energy market is estimated to increase steadily from USD 881.7 billion in 2020 to about USD 1,977.6 billion by 2030. From Figure 1, green bond issuances are dominated by renewable energy, followed by energy efficiency initiatives and clean transportation.

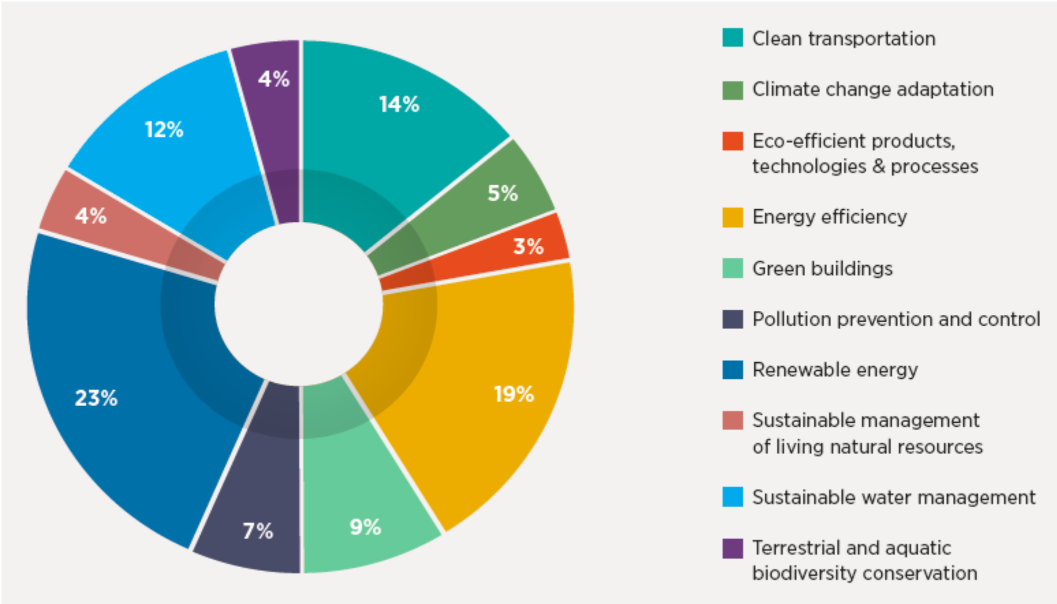

Figure 1. Green bond issuances by usage of proceeds and cumulative volume (USD) from 2010 to 2019*. Source: International Renewable Energy Agency (IRENA) analysis based on data from the Environmental Finance Bond Database (Appavou et al., 2019).
*Data for 2019 are available up to and including November 2019.

Figure 1 is consistent with the studies of Tolliver et al. (2020), who revealed that green bond markets are rapidly developing, but most of their proceeds are allocated to renewable energy. Their result indicates an interaction between the market for renewable energy stocks and green bonds. The interaction and influence between two financial markets have the propensity to increase investment, which can affect economic growth (Mishkin, 2007). The growing globalisation of financial markets, as well as the recent occurrence of financial crises and market crashes, such as the stock market crashes on the 19th of September 1998 and the 20th of February 2020, have reignited interest in how financial markets interact within and across, and how volatility spills over. Although the concept of financial markets influencing one another is long known (Engle III et al., 1988; Koutmos, 1996), the rising integration of financial markets has focused attention on stock market interaction and the processes through which stock return fluctuations are transmitted via different approaches (See Salisu and Oloko (2015); Guimarães-Filho and Hong (2016); Bala and Takimoto (2017)). From the foregoing, analyzing the interaction between different return series of financial markets will require taking into account the likelihood of volatility spillover effects between them. So, the estimation of multivariate volatility models are justified because a single autoregressive conditional heteroscedasticity (ARCH) or generalized autoregressive conditional heteroscedasticity (GARCH) model would ignore the likelihood of causality between the conditional variances of the markets.

Market players are naturally interested in how volatility moves between markets. Green bonds now make up a large part of the bond market. However, its dynamic risk and spillover to other financial markets, like the stock market and conventional bond market, play an important role in its understanding. This is because volatility is a typical stylized fact in financial markets. The nature of the spillover effect between the green bond market and the renewable energy stock market can help investors and regulators identify the nature of interaction between them and assess the implications of volatility spillovers, especially during periods of financial crisis. The objective of this study is two-fold. First, we evaluate the dependence between the price of green bonds and renewable energy stock prices. Thus, by using the Vector Autoregressive models and the Granger causality test, we can determine the dependence between these two assets. Secondly, to determine the mean and volatility spillover between the price of green bonds and renewable energy stock prices. Thirdly, to add to the scarce literature on the mean, shock, and volatility spillover between the renewable energy stock market and the green bond market. This study will thus help policymakers understand the behavior of the two markets (renewable energy stock market and green bond market) to implement regulations that ensure financial stability.

The paper is organized as follows. In section 2, we review literature that are related to the study and the methodology used for the study. The data and methods for constructing the VAR-BEKK-GARCH model for the study are described in Section 3. The empirical analysis is presented in Section 4. Section 5 presents the conclusion and policy implications of the study.

2. Literature review

The popularity of finance in environmental sustainability has caught the world's attention to explore the volatility spillover between green bonds and renewable energy. In addition, studying the dynamic dependency between the return and volatility of green bond prices and the prices of renewable energy equities has emerged as an important field of research. Because of their importance to environmental sustainability, studies examining the connection between green bonds and renewable energy have recently risen to the forefront of their respective fields of study. For instance, the work of Pham (2016) employed a multivariate GARCH model to evaluate the volatile behaviour in the green bond market, which serves as a basis for most research on the relationship of the green bond market to other financial markets. Using the DCC multivariate GARCH model, Shbib (2020) studied the volatility dependencies and the dynamic conditional correlations between the markets for green bonds and traditional bonds. The study revealed that there is a strong positive volatility and conditional correlation between the two markets. In furtherance of the study of Shbib (2020), Rannou et al. (2020) noted that there is significant persistence of shocks to the conditional correlation between the European green bond and carbon markets. The study also revealed significant bi-directional shock transmission and no significant spillover effects between the two markets. Liu et al. (2021) used different time-invariant and time-varying copula techniques to evaluate the dynamic dependency structure between green bonds and key global and sectoral clean (renewable) energy markets from July 5th, 2011 to February 24th, 2020. Their findings showed that the green bond and renewable energy stock markets have a positive time-varying average and tail dependence. Furthermore, significant downward or positive movements in the green bond market have a spillover effect on the stock market, and vice versa. Park et al. (2020) examined the relationship between the green bond and equity markets using a bivariate-GARCH model and found that, while the two markets have some volatility spillover effects, neither market responds to negative shocks in the other. By employing the framework of Diebold and Yılmaz (2014) and Baruník and Křehlík (2018), Naeem et al. (2021) concluded that there was asymmetric spillover among green bonds and commodities across time and frequency. Recently, Tsoukala and Tsiotas (2021) used a DCC model specification with alternative distributional assumptions to analyze the volatility and correlation dynamics between conventional bond and green bond assets. There have also been studies on green bonds and commodities (Tsagkanos et al., 2022).

As demonstrated above, the green bond market has been empirically linked to other financial markets, but less is known about its connectedness with renewable energy stock markets. That is, research on the causality and spillover relationship between green bonds and the broader class of renewable energy is still lacking. This work adds to the field by focusing on causality, mean, shock, and volatility spillovers between the green bond market and renewable energy stocks. Studies on shock and volatility spillover between these two markets are very important since they are very much connected, as indicated by Tolliver et al. (2020).

At the same time, the literature on the methodology used to explore the dependence and spillover among asset classes are diverse. Different researchers have explored price volatility using multivariate GARCH models to facilitate analysis of multi-dimensional relationships among different markets (Sadorsky, 2012; Salisu and Mobolaji, 2013; Pham, 2016; Gyamerah, 2019; Shbib, 2020; Yu et al., 2020; Özdurak, 2021).

Özdurak (2021) used a DCC-GARCH model to explore the spillover effect of market sentiments, oil prices, and technology company stock returns on clean energy investments. By employing the VAR-BEKK-GARCH model, Yu et al. (2020) examined the dependence between the crude oil market (WTI) and the stock markets of the US and China, and volatility spillovers between them during 1991-2016. The results from the study showed that the VAR-BEKK-GARCH model was able to capture distinctive volatility spillovers across those periods under study, with varying directionality, in the presence of structural changes. Salisu and Mobolaji (2013) and Yu et al. (2020) used the VAR-BEKK-GARCH model to examine the volatility spillover between different financial markets. They argued that the VAR-BEKK-GARCH model gives a more accurate forecast than the conventional multivariate GARCH models, while some of the conventional GARCH models, such as the GED-GARCH model, are restricted to modelling extreme cases of risk spillover (Fan et al., 2008); or need a lot of parameters for estimation, such as the DCC-MECGARCH model (Tsuji, 2018). Further studies revealed that the VAR-BEKK-GARCH is more effective since it needs fewer parameters when examining spillover effects in multi-markets (Stelzer, 2008; Schreiber et al., 2012). It is evident that the VAR-BEKK-GARCH performs better than other competing models when capturing the dependence and spillover among financial assets.

3. Data and methodology

This section presents the data and econometric model used to study the shock transmission and volatility spillovers between renewable energy stocks and green bond markets.

3.1. Data

To eliminate the effect of exchange rates on the spillover, all prices are expressed in the same currency, the United States Dollar (USD). Daily data from January 02, 2012, to August 31, 2021, yielding a total of 2508 observations, is used for this study. The S&P Green Bond index is a weighted average of 10120 constituent indices based on market value. The S&P Green Bond index market value outstanding as of September 20, 2021 is 1047361.96 million USD. The S&P Global Clean Energy Index, which has a target constituent count of 100, is meant to estimate the performance of firms in global renewable energy-related sectors from both developed and emerging economies, and its weighting method is the modified market capitalization weighted average. The S&P Green Bond Index and S&P

Global Clean Energy Index are used as proxies for the green bond market and renewable energy stock market, respectively. The plots of the daily closing prices of the renewable energy stock market (RES) and green bond market (GB) are presented in Figure 2. A visual examination of Figure 2 demonstrates considerable upward movement throughout the period under study (30/12/2012-31/08/2021), with the exception of a sharp negative dip in the early months of 2020. This can be attributed to the effect of the pandemic in both indices. However, there was a significant plunge after the dip, indicating the propensity of the two indices to withstand the effects of the pandemic.

Table 1. Descriptive statistics of the changes in price.

	Minimum	Maximum	Mean	Std. Dev.	Skewness	Kurtosis	JB test
RES	-0.1249	0.1103	4.7320e-04	0.0138	-0.6668	10.3422	11363***
GB	-0.0242	0.0201	7.9260e-05	0.0033	-0.3817	5.7642	3533.1***

*, **, *** denotes significance at 10%, 5%, and 1% respectively

Table 1 contains summary statistics for the changes in prices for the renewable energy stock and green bond markets. The mean of the change for both indices is positive, with renewable energy stocks giving the maximum mean price change. The volatility in the prices is significantly small (the standard deviation for renewable energy stocks is 0.0132 and 0.0033 for the green bond). However, the renewable energy stock market is more volatile than the green bond market. The distributions of both markets are skewed to the left, indicating that both markets have a longer left tail and more large negative price changes than large positive price changes. Also, the distribution in both markets exhibits excess kurtosis. These indicate that both indices deviate from the normal distribution, as proven by the Jarque-Bera statistics at a 1% significance level.

Figure 2. Daily closing price of renewable energy and green bond.

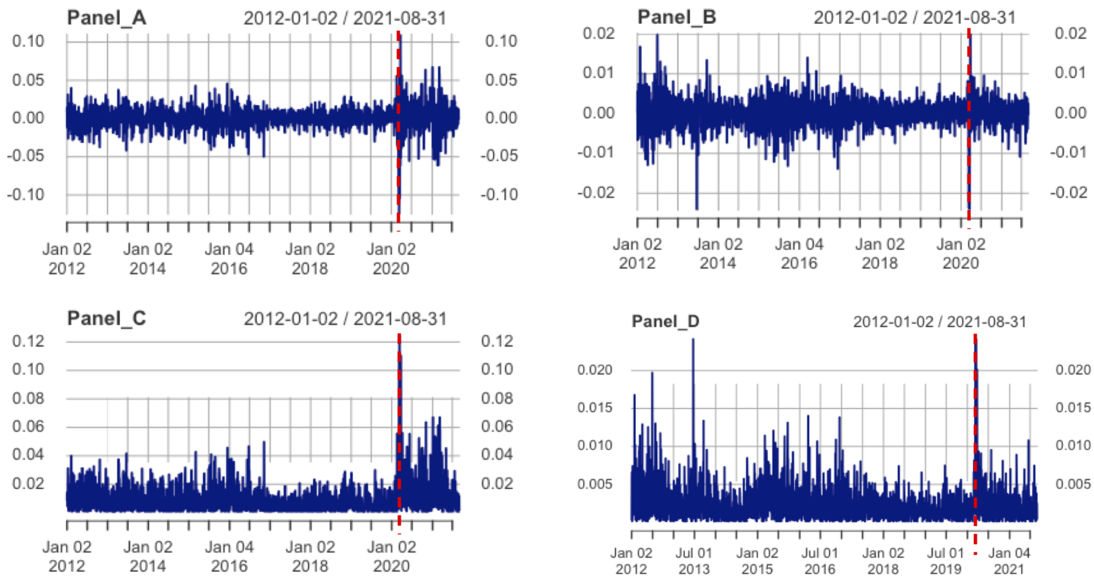

Figure 3. Price changes in the market.
Note: Panel A and B show the time series of price change of series of renewable energy (RE) and green bond (GB) markets respectively

Figure 3 shows the daily price change for renewable energy stock markets and green bond markets, respectively. Both graphs (Panel A and B) seem to follow a white noise process even though they exhibit volatility clustering effects. The graphs show how volatility has changed across time. Panels A and B show that both markets have some common peaks and troughs in their volatility, with the most apparent peaks occurring during the financial crisis in early 2020 (as indicated by the red dotted vertical lines).

3.2. Empirical methodology

In this paper, we employ the VAR-BEKK-GARCH to model volatility spillover between the two markets (renewable energy stock and green bond markets). The VAR-BEKK-GARCH model is employed for the empirical analysis of mean, shock, and volatility spillover because, by its definition, it ensures that the covariance matrix is positive definite.

3.3. The vector autoregressive (VAR) models

The "spillover effect between two markets" refers to the fact that the return or volatility in one market is influenced not only by its own prior movements but also by previous movements in other markets. A VAR model represents the evolution of a collection of K endogenous variables as a linear function of only their past values throughout the same sample period ($t = 1, \cdots, T$), thereby explaining the impact of various economic shocks on the economic variables. The VAR models are estimated for each of the two markets as in Equation 1,

$$
\begin{aligned}
R_t &= \kappa_0 + \sum_{i=1}^{s} \kappa_1 R_{t-1} + \sum_{i=1}^{s} m_j B_{t-1} + \epsilon_t \\
B_t &= \kappa_0 + \sum_{i=1}^{s} \kappa_1 B_{t-1} + \sum_{i=1}^{s} m_j R_{t-1} + \epsilon_t,
\end{aligned} \tag{1}
$$

where R_t and B_t represent the renewable energy and green bond markets respectively at a given time t.

3.3.1. GARCH(1,1) model

The standard GARCH model is a generalization of the ARCH model where it allows the conditional volatility to be dependent upon its own lags. Suppose p and q are the number of lagged squared returns included and the number of lagged volatilities, then the GARCH (p, q) model is defined as:

$$
\begin{aligned}
u_t &= \alpha_t \epsilon_t \\
\sigma_t^2 &= \omega^2 + \sum_{m=1}^{p} \alpha_m u_{t-m}^2 + \sum_{n=1}^{q} \beta_n \sigma_{t-n}^2,
\end{aligned} \tag{2}
$$

where $\omega > 0$, $\alpha_n > 0, \beta_n \geq 0$, $\sum_{m=1}^{p} \alpha_m \leq 1$, $\sum_{n=1}^{q} \beta_n \leq 1$ and for $\alpha_m + \beta_n < 0$, GARCH(1,1) is covariance stationary.
To begin, GARCH(1,1) models are constructed for each variable (stock and bonds) in both the crisis and post-crisis periods.

3.3.2. BEKK-GARCH model

The multivariate GARCH (MGARCH) model has been widely used in modeling volatility transmission among market indices. In this paper, the volatility spillover effects in the green bond and renewable energy stock markets are studied using the GARCH (1,1) model with BEKK representation. The BEKK-GARCH model is an extension of the Bollerslev (1986) GARCH model. The bivariate BEKK-GARCH(1,1) model is chosen among the family of MGARCH models. There are many ways to describe the parameters of the conditional variance-covariance matrix. One way is to model it as a bivariate BEKK-GARCH process.
The mean equation based on the VAR model is given in Equation 3,

$$
r_t = \mu_t + \epsilon_t, \tag{3}
$$

where $r_t = (r_{1t}, r_{2t})$ is the change rate of variable 1 and variable 2 respectively. Also, it is assumed that μ_t satisfies the mean function and ϵ_t is the corresponding error terms.
The BEKK formulation helps in detecting the existence of any volatility transmission from one market to another (Engle and Kroner, 1995). The general structure of a BEKK model (**?**) is

$$
H_t = C'C + \sum_{i=1}^{q} \sum_{j=1}^{J} A'_{ji} \epsilon_{t-i} \epsilon'_{t-i} A_{ji} + \sum_{i=1}^{q} \sum_{j=1}^{J} G'_{ji} H_{t-i} G_{ji} \tag{4}
$$

From the Equation 4, the first order BEKK model is given as in Equation 5,

$$H_t = C'C + A'\epsilon_{t-1}\epsilon'_{t-1}A + G'H_{t-1}G \tag{5}$$

where C is a 2×2 lower triangular matrix, A and G are 2×2 unrestricted square matrix which captures the ARCH and GARCH effects respectively. The elements of A measure the effect of shocks or news on the conditional variances and show how they are linked with prior squared errors, and the elements of G depict how historical conditional variances influence current levels of conditional variance (i.e., the degree of volatility persistence in market conditional volatility). The BEKK parameterization for systematic GARCH could be written as:

$$H_t = C'C + \begin{bmatrix} a_{11} & a_{1,2} \\ a_{21} & a_{2,2} \end{bmatrix}' \begin{bmatrix} \epsilon^2_{1,t-1} & \epsilon_{1,t-1}\epsilon_{2,t-1} \\ \epsilon_{2,t-1}\epsilon_{1,t-1} & \epsilon^2_{2,t-1} \end{bmatrix} \begin{bmatrix} a_{11} & a_{1,2} \\ a_{21} & a_{2,2} \end{bmatrix} + \begin{bmatrix} g_{11} & g_{1,2} \\ g_{21} & g_{2,2} \end{bmatrix}' H_{t-1} \begin{bmatrix} g_{11} & g_{1,2} \\ g_{21} & g_{2,2} \end{bmatrix} \tag{6}$$

where

$$H_t = \begin{bmatrix} h_{11} & h_{1,2} \\ h_{21} & h_{2,2} \end{bmatrix} \tag{7}$$

By assuming that matrices A and G are diagonal, Equation 6 will have a diagonal form. The diagonal elements in matrices A and G measure the impact of a market i's own past shocks and volatility on its conditional variance. The off-diagonal components of $A(a_{ij})$ and $G(g_{ij})$ quantify the cross-market impacts of shock and volatility (i.e. volatility spillover). Equation 6 can be expanded as follows:

$$\begin{aligned} h_{11,t} =& c^2_{11} + a^2_{11}\epsilon^2_{1,t-1} + 2a_{11}a_{22}\epsilon_{1,t-1}\epsilon_{2,t-1} + a^2_{21}\epsilon^2_{2,t-1} + g^2_{11}h_{11,t-1} + 2g_{11}g_{22}h_{12,t-1} \\ &+ g^2_{21}h_{22,t-1} \end{aligned} \tag{8}$$

$$\begin{aligned} h_{22,t} =& c^2_{21}c^2_{22} + a^2_{12}\epsilon^2_{1,t-1} + 2a_{12}a_{22}\epsilon_{1,t-1}\epsilon_{2,t-1} + a^2_{22}\epsilon^2_{2,t-1} + g^2_{12}h_{11,t-1} + 2g_{12}g_{22}h_{12,t-1} \\ &+ g^2_{22}h_{22,t-1} \end{aligned} \tag{9}$$

$$\begin{aligned} h_{12,t} =& c_{11}c_{21} + a_{11}a_{12}\epsilon^2_{1,t-1} + (a_{21}a_{12} + a_{11}a_{22})\epsilon_{1,t-1}\epsilon_{2,t-1} + a_{21}a_{22}\epsilon^2_{2,t-1} + g_{11}g_{12}h_{11,t-1} \\ &+ (g_{21}g_{12} + g_{11}g_{22})h_{12,t-1} + g_{21}g_{22}h_{22,t-1}, \end{aligned} \tag{10}$$

where $h_{21,t} = h_{12,t}$, $h_{11,t}$ represents the conditional variance of change at time t in renewable energy market returns, $h_{22,t}$ represents the conditional variance of green bond market returns at time t, and $h_{12,t}$ is the conditional covariance between change in renewable energy and green bond market returns at time t. Suppose $a_{21} = g_{21} = 0$, then the volatility of variable 2 is influenced by its own lagged volatility and residual (this means that variable 1 has no volatility spillover effect on variable 2). And when $a_{21} = b_{21} = a_{12} = g_{12} = 0$, then there is no volatility spillover between the two variables.

Assuming normally distributed errors, the parameters of the bivariate models can be calculated by maximizing the log likelihood function. The log likelihood function may be expressed as in Equation 11.

$$\log L = -\frac{TN}{2}\log(2\pi) - \frac{1}{2}\sum_{t=1}^{N}(\log|H_t| + \epsilon'_t H_t^{-1}\epsilon_t), \tag{11}$$

where θ and N are vector of parameters that can be estimated and the total number of observations respectively.

4. Empirical results

4.1. Stationarity and autocorrelation test of price series

The Augmented Dickey-Fuller (ADF) and Phillips and Perron (PP) unit root tests are used to test for stationaity in the price series for both markets. The results of the augmented Dicker Fuller (ADF)Dickey and Fuller (1979) and Phillips-Perron (PP) Phillips (1988) unit root tests are presented in Table 2. It is evident from both tests that, at level I(0), both the renewable energy stock and green bond market prices are not stationary since the null hypothesis of unit root is not rejected at the 1% significance level. However, both series only become stationary after the first difference, I(1). Thus, it can be concluded that the level values of both series are stationary at I(1).

Table 2. Augmented Dicker Fuller (ADF) and Phillips-Perron (PP) unit root test.

	Level I(0)		**First Difference I(1)**	
Test Statistics	ADF	PP	ADF	PP
RES	-0.9370	-3.0266	-25.639***	-2199.7***
GB	-1.4079	0.8216	-32.953***	-2469.4***

*, **, *** denotes significance at 10%, 5%, and 1% respectively

Table 3 confirms the presence of serial correlation and heteroskedasticity in the price series of the renewable energy and green bond markets using the Lagrange Multiplier (LM) test, hence the GARCH specifications can be employed.

Table 3. Lagrange Multiplier (LM) test for ARCH effects.

Test Statistics	Renewable Energy	Green Bond
LM Test (5)	654.38*	160.27***
LM Test (10)	681.84*	215.87***

*, **, *** denotes significance at 10%, 5%, and 1% respectively

4.2. Vector autoregressive (VAR) models

The optimum lag order is obtained by utilizing the lag length criteria. This allows the test to capture all the changes in the market prices. A VAR model is developed, including an I(1) series with a constant term. A constant term was selected because it had the maximum log-likelihood value of the model. The optimal lag using the Schwarz Criterion (SC) and Hannan Quinn (HQ) Criterion is lag 2. VAR(2) models are developed for the period under study.

4.3. Granger-Causality

The Granger causality test is used to explore the causal relationship between the price of green bonds and the price of renewable energy. The findings from Table 4 indicate that at a 1% significance level, the price of renewable energy stocks is the Granger cause of the green bond price. Since most of the proceeds from the green bond market are invested in renewable energy, the changes in the price of renewable energy will have an effect on the green bond price. For instance, an increase in the share price of renewable energy stocks will influence investors in renewable energy to purchase green bonds on the market. Demand for green bonds will thus cause a price increase in green bonds. Thus, confirming that green bond issuances by usage of proceeds and cumulative volume from 2010 to 2019 as presented in Figure 1 where green bond issuances are dominated by renewable energy. This is consistent with the study of Tolliver et al. (2020). However, at a 1% significance level, the price of green bonds is not the Granger cause of the price of renewable energy stocks. That is, an increase in the price of green bonds does not affect the price of renewable energy. Therefore, there exists a uni-directional Granger causality from renewable energy to the price of green bonds.

Table 4. Granger causality.

Null Hypothesis	F-Statistics	Prob.	Reject/fail to reject
H1: GB does not Granger cause RES	1.6478	0.1926	fail to reject
H2: RES does not Granger cause GB	10.999	1.712e-05	reject

* denotes rejection of the hypothesis

4.4. Mean spillover effect

The final results from the VAR model are presented in Table 5. The price of renewable energy stocks is only influenced by its own lagged values. However, the price of green bonds is influenced by its own lagged values and the lagged values of renewable energy stock prices. Specifically, in the regression equation with RES as the predicted variable, the coefficient of RES_{t-1} and RES_{t-2} are significant at a 1% level and positive. This indicates that the past price values of renewable energy stocks have a positive effect on the current price of renewable energy stocks. For the regression equation with GB as the predictor variable, the coefficients of GB_{t-2} and RES_{t-2} are positive and statistically significant at 5%. In comparison the coefficient of RES_{t-1} is statistically significant and positive at 1%. This shows that the past price values of both renewable energy stocks and green bonds positively influence the current price of green bonds. The results are consistent with the results obtained from the Granger causality test. In both instances, the constant term is not significant in predicting either the price series of the renewable energy market or the green bond market. With respect to the mean spillover effect, there is a uni-directional linkage between the price of green bonds and the price of renewable energy stocks. In the face of market risk, stakeholders may use this finding to determine the direction of the correlation between them and adapt hedging plans in advance.

Table 5. Parameter estimates of VAR model

	RES	GB
GB_{t-1}	-1.2153	0.0187
	[0.0201]	[0.0202]
GB_{t-2}	0.7140	0.0456**
	[0.7665]	[0.0201]
RES_{t-1}	0.1450***	0.0020***
	[0.0201]	[0.0005]
RES_{t-2}	0.0916***	0.0012**
	[0.0202]	[0.0005]
C	0.4305	0.0083
	[0.3345]	[0.0088]
R-Squared	0.0334	0.0128
Adj. R-squared	0.0318	0.0113
S.E. equation	16.72	0.4396
F-Statistics	21.58***	8.123***

*, **, *** denotes significance at 10%, 5%, and 1% respectively. [ ] denotes the T-statistic.

$$\begin{aligned} \mathrm{RES} &= -1.2153\,\mathrm{GB}_{t-1} + 0.7140\,\mathrm{GB}_{t-2} + 0.1450\,\mathrm{RES}_{t-1} + 0.0916\,\mathrm{RES}_{t-2} + 0.4305 \\ \mathrm{GB} &= 0.0187\,\mathrm{GB}_{t-1} + 0.0456\,\mathrm{GB}_{t-2} + 0.0020\,\mathrm{RES}_{t-1} + 0.0012\,\mathrm{RES}_{t-2} + 0.0083 \end{aligned} \tag{12}$$

Equation 12 is the vector autoregressive model for renewable energy stocks and green bonds, respectively, which takes into account the lags of both variables. In Table 6, the invertible roots of the VAR model of the AR characteristic polynomial associated with the different lags of the variables in the model specification are summarized. The VAR model is stationary since all of its lambdas (roots) are within the unit circle (i.e. $\lambda < 1$). The cumulative sum of the recursive residuals (Rec-CUSUM) test is performed to test whether the estimated parameters of the short-run and long-run dynamics of the equations in the VAR models are stable over time. For stability of models, the Rec-CUSUM statistics must stay within the 5% critical bound (represented by two straight lines). Figure 4 clearly shows that all equations in the VAR model are stable over time.

Table 6. Roots of the VAR model

λ_1	λ_2	λ_3	λ_4
0.3912	0.272	0.1996	0.1551

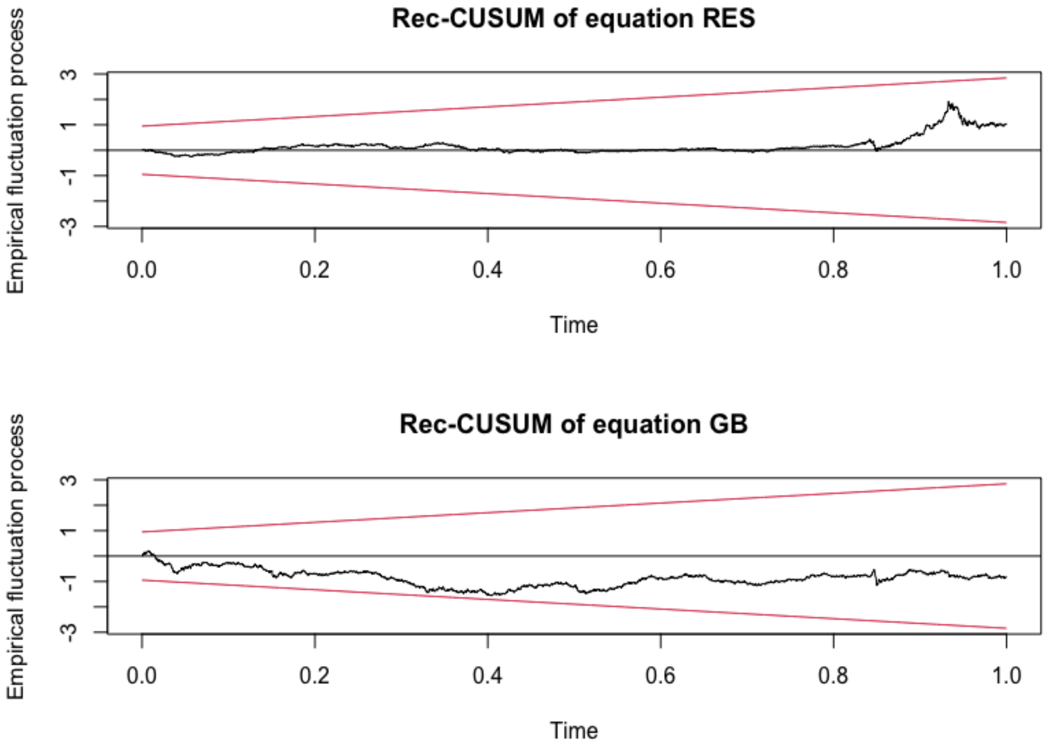

Figure 4. Rec-CUSUM of equations in the VAR model.

4.5. *Impulse response analysis*

The spillover effect between the green bond and renewable energy prices is demonstrated through the results obtained from the impulse response analysis presented in Figure 5. In the impulse response graph of GB to RES, renewable energy stock prices have a negative impact on green bond prices in the short term and reach their maximum value in Period 2. However, the negative response weakens sharply in Period 3, followed by weakly negative and positive. It then converges to zero after Period 6. This indicates that sudden changes in the price of renewable energy stocks will lower green bond prices in the short term, and the latter will rise and fall depending on the changes in renewable energy stock prices. This result is in tandem with the realities of the market since the majority of the proceeds from Green Bonds are invested in renewable energy. The green bond graph shows a sharp jump in green bond prices.

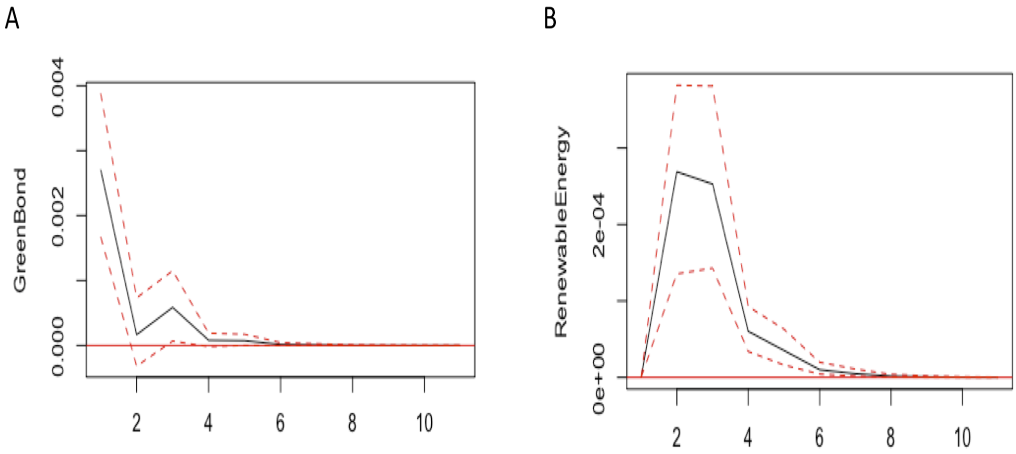

Figure 5. Impulse responses of equations in the VAR model.

4.6. BEKK-GARCH

The BEKK-GARCH model captures own and cross-volatility spillovers between the price of renewable energy stocks and the green bond market. From Table 7, a_{11} and a_{22} (the ARCH terms) are statistically significant at 1%, which indicate the existence of ARCH effects. The statistically significant values also indicate that the current volatility for the price series of green bonds and renewable energy stocks is significantly influenced by their own lagged innovations, and that the impact is rather high at 0.2383 and 0.5272. The GARCH terms (g_{11} and g_{22}) are significant at 1% and larger than the ARCH terms (a_{11} and a_{22}), indicating that the behaviour of the present covariance and variance is not so much influenced by the size of historical innovations as by the value of lagged covariances and variances. Furthermore, the statistically significant GARCH parameters g_{11} and g_{22} reveal the degree to which volatility clustering exists. For instance, the g_{11} value implies that 95.09% of the volatility in the price of the previous day's green bond persists in the following day.

The off-diagonal components of matrices $A(a_{ij})$ and $G(g_{ij})$, $i \neq j$ capture the shock and volatility spillovers respectively between the two markets. The results from Table 7 show that a_{12} and a_{21} are not significant. Hence, there is no shock spillover from both sides of the market. The significant g_{21} coefficient estimate and insignificant g_{12} parameter estimates indicate the presence of a uni-directional volatility spillover from renewable energy stock prices to green bond prices. This indicates that the volatility in renewable energy prices influences the market price of green bonds. Contrary, the insignificant g_{12} coefficient estimate reveals that volatility in the price of green bonds does not affect the volatility of renewable energy stock prices. These results are in congruence with the results obtained from the Granger causality test in Table 4.

Table 7. Estimates of the BEKK-GARCH(1,1) model for renewable energy and green bond returns series.

Parameter	Estimate	Std. Error	t value	Pr(> |*t*|)
Mean(GB)	0.0105	0.0079	1.3216	0.1863
Mean(RES)	0.3696	0.1636	2.2588	0.023895**
c_{11}	0.0884	0.0198	4.4647	8.0165e-06***
c_{21}	0.5573	0.2360	2.3613	0.0182*
c_{22}	3.3524	0.3804	8.8116	< 2.22e-16***
a_{11}	0.2383	0.0255	9.3412	< 2.22e-16***
a_{21}	-0.5000	0.5257	-0.9512	0.3415
a_{12}	0.0006	0.0007	0.8669	0.3860
a_{22}	0.5272	0.0377	13.9979	<2.22e-16 ***
g_{11}	0.9509	0.0155	61.5174	< 2.22e-16 ***
g_{21}	0.3756	0.2262	1.6608	0.0968*
g_{12}	-0.0004	0.0005	-0.7337	0.4631
g_{22}	0.8120	0.0277	29.3068	< 2.22e-16 ***

*, **, *** denotes significance at 10%, 5%, and 1% respectively; Stock and Bond represent renewable energy stock and green bond indices respectively

5. Conclusions and policy implications

This study employed the VAR-BEKK-GARCH model to investigate the mean, shock, and volatility spillover between the price of green bonds and the price of renewable energy stocks over the period January 02, 2011 to August 31, 2021. Using the Granger causality test, it was revealed that the change in prices of renewable energy stocks is the Granger cause of the green bond price, while the changes in the price of green bonds are not the Granger cause of the price of renewable energy stocks. From the constructed VAR model, there was a mean spillover effect between the green bond price and the renewable energy price, implying that they would both be influenced by their past variations. We identified a uni-directional volatility spillover from renewable energy stock prices to green bond prices. However, there was no shock spillover from both sides of the market.

The findings are critical for understanding the interaction between the green bond market and the renewable energy market. The results have important ramifications for practitioners, such as traders and environmentally friendly investors, portfolio managers, as well as policymakers to mitigate their risks in their international investments. The results are crucial for developing hedging and diversification strategies for investors and decision-makers in both the renewable energy stock and green bond markets. The fact that there is a spillover effect from the renewable energy stock market suggests that there are few chances for diversification. For future research, shock and volatility spillover between carbon prices, green bond prices, and renewable energy stock prices can be investigated. Future studies should focus on analyzing the structural links that underlie the volatility relationship between the green bond market and renewable energy stock markets. It could be beneficial to compare the theoretical and empirical spillover indices to multivariate GARCH models theoretically and empirically.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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