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Uncovering time and frequency co-movement among green bonds, energy commodities and stock market

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Abstract

Purpose – This paper aims to examine the comovement among green bonds, energy commodities and stock market to determine the advantages of adding green bonds to a diversified portfolio.

Design/methodology/approach – Generic 1 Natural Gas and Energy Select SPDR Fund are used as proxies to measure energy commodities, bonds index of S&P Dow Jones and Bloomberg Barclays MSCI are used to represent green bonds and the New York Stock Exchange is considered to measure the stock market. Granger causality test, wavelet analysis and network analysis are applied to daily price for the select markets from August 26, 2014, to March 30, 2021.

Findings – Results from the Granger causality test indicate no causality between any pair of variables, while cross wavelet transform and wavelet coherence analysis confirm strong coherence at a high scale during the pandemic, validating comovement among the three asset classes. In addition, network analysis further corroborates this connectedness, implying a strong association of the stock market with the energy commodity market.

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Originality/value – This study offers new evidence of the temporal association among the US stock market, energy commodities and green bonds during the COVID-19 crisis. It presents a novel approach that measures and evaluates comovement among the constituent series, simultaneously using both wavelet and network analysis.

Keywords Green bonds, Energy commodity, Comovement, Risk, Stock market, Diversification

Paper type Research paper

1. Introduction

> Climate change is the single greatest threat to a sustainable future but, at the same time, addressing climate challenges presents a golden opportunity to promote prosperity, security and a brighter future for all (United Nations, 2014).

Amidst growing concerns about a warming planet, wealth managers, pension funds and insurance companies are continually confronted with environmental risk, accountability and governance issues. With an intention to embrace a sustainable investing style, portfolio managers have widely recognized its potential and are inclined to invest in stocks with positive environmental effects. Numerous initiatives have been taken in the recent past to increase environmental awareness and promote the use of renewable energies (Ferrer *et al.*, 2021). The "green bond" market is one of the ecologically responsible financial products that has witnessed significant growth in terms of assets under management. Green bonds have gained wide acceptance over the past decade and emerged as a credible financial instrument for fostering an economy with low carbon footprints (Reboredo and Ugolini, 2020). The differentiating fact about a green bond is that the collected proceeds must be used for initiatives involving clean water management, energy efficiency, green architecture and sustainable sources (Reboredo, 2018; Flammer, 2020; Nguyen *et al.*, 2021; Yadav*et al.*, 2023). Apart from being an environment-friendly financial instrument, it builds a positive impact on the issuer's equity performance (Flammer, 2020) and outperforms returns relative to traditional corporate bonds (Lautsi, 2019). Since its first issuance in 2007, the volume of green bond has witnessed a consistent increase from $11bn in 2013 to $106.86bn in March 2021. It is projected to achieve $US2.36tn by 2023. Though Europe and the USA are leading the pack in green bond assets size, it is expected that China and India will soon have a major presence in the clean energy market.

The inclusion of green bonds in investment portfolios has generated substantial interest worldwide. There is an abundance of literature exploring the risk-return dynamics of traditional fixed income securities with green bonds (Pham, 2016; Goodell *et al.*, 2022). Studies have found a strong relationship between environmentally friendly bonds and conventional bonds. Simultaneously, including them in a portfolio can diversify and reduce the total portfolio risk (Reboredo, 2018). In comparison to the equity market and energy commodities, green bonds have delivered good returns with significantly lower volatility levels. Hence, comovement between these variables becomes essential to explore the advantage of portfolio diversification, especially when incorporating green bonds.

The integration of markets globally and the growing financialization of energy commodities have stimulated continuous research on the association between stock prices and energy markets (Yadav *et al.*, 2023; Malhotra *et al.*, 2023). Given the interrelationship between these asset classes, it becomes imperative for investors to understand the impact of comovement between stock markets, energy commodities and green bonds based on their risk appetite and the returns of their respective investment portfolios. This study selects green bonds, the stock market and energy commodities based on their relative historical returns and risk performance over the past five years (See Appendix Figures A1 and A2).

Data suggests significant variation in risk and return between these assets. This study attempts to establish connectedness among these variables by applying two multidimensional techniques: wavelet and network analyses. Wavelet and network analyses are used to analyze the dynamic movement among the three constituent asset classes over a range of time scales. Second, the discrete wavelet methods and causality tests are used to investigate the causation between the assets. Since wavelet analysis captures connectedness over different time-cycles, network analysis is applied to validate this connectedness among the constituent series for all observations in the sample.

This paper contributes to the existing literature in three ways: first, the results from the wavelet analysis might be of interest to investors, particularly those who prefer investment in low-risk products for diversification benefits. Second, the findings of this study can encourage investments in environmentally conscious businesses to encourage the mobilization of financial resources, promoting a climate-resilient economy. The preference for safer investment options assumes significance during times of economic upheaval, such as COVID-19. Third, this paper analyzes the interconnectedness among green bonds and financial assets over various time periods by using wavelet analysis. These results can benefit diverse investor groups, such as investment firms, intraday traders and pension funds (medium- to long-term) by uncovering viable investment possibilities.

The remainder of the paper is divided into the following sections. Section 2 provides a detailed literature review on the subject under discussion. Section 3 elaborates on the data and the econometric model used in the study. Section 4 discusses the empirical results. The study is concluded in Section 5, which also provides policy implications and outlines the future scope of the research.

2. Literature review

Green bond is used to raise funds from the financial market for financing "green" or "environment friendly" projects. In recent years, it has surfaced as a favorable investment choice (Flammer, 2020; Banga, 2019; Shishlov *et al.*, 2016). Documented data shows that green bond issuance has increased by approximately five times in the past five years and is projected to reach $1tn annually by 2030 (Fatin, 2019). Global entities and authorities are becoming increasingly conscious of the involvement of green bonds in developing a strong economy. The projection states that many countries will incorporate green bonds into their portfolios to tackle climate issues. As a result, there has been a surge in the investigation of green bonds and their applications. Existing literature highlights that green bonds are a valuable asset class in addressing climate change (Flaherty *et al.*, 2017). Several government agencies have started allocating funds from their budget to such green projects, which not only support climate issues but also contribute to the economy (Zhou and Cui, 2019). Many researchers have attempted to establish a link between green bonds and sustainability. Morana and Sbrana (2019) highlighted that green bond enables investment in climate-friendly projects and, hence, supports sustainability. A few researchers have related it to carbon emission reduction, sustainable development and green initiatives (Ng, 2018; Tolliver *et al.*, 2020). Collectively, there is sufficient evidence to support the fact that green bonds lead to sustainable development (Tang and Zhang, 2020).

Several scholars have also studied the yield of green bonds. Green bonds are significantly less expensive than conventional bonds, as noted by Agliardi and Agliardi (2019), who emphasized the presence of "green premium" in green bonds. Several studies have compared the green bond to traditional bonds (Zerbib, 2019) with varying results. Investors prefer green bonds due to their higher yields (Lautsi, 2019) and lower risk of loss compared to traditional bonds (Nanayakkara and Colombage, 2019). In addition, Kuchin *et al.* (2019) found that the issue of green bonds has been met with favorable market reception and can raise a company's worth. Studies also show that the issuance of green bonds affects the share price of a company, and its value and liquidity (Flammer, 2020; Banga, 2019) examined whether green bonds solely attract environmentally aware investors. He concluded that the epidemic had heightened the interest in green bonds, even among conventional investors. A small number of studies indicate that the nature of projects funded by green bonds makes them a riskier investment option than other types of bonds. The green premium, as discovered by Hachenberg and Schiereck (2018), causes green bonds to yield more. Uddin *et al.* (2013) examined German and some other international stock markets and came to identical conclusions, proving that comovement could also create financial crises. However, green bond returns are vulnerable to price volatility, geopolitical risk (Tang *et al.*, 2023; Singh *et al.*, 2023) and global economic policy uncertainty.

The modern portfolio theory considers portfolio optimization as combining assets of multiple classes to offset portfolio risks. Portfolio optimization requires uncorrelated asset classes due to the heterogeneous and changing cross-market interactions. A safe-haven asset can minimize risk and comovement for a particular outcome (Kinateder *et al.*, 2021). In an effort to find a safe haven that can counterbalance investors' falling returns, researchers are exploring a wide variety of assets, including gold (Hassan *et al.*, 2022), sovereign bonds (Hassan *et al.*, 2021; Yarovaya *et al.*, 2021) and cryptocurrency (Corbet *et al.*, 2020). Moreover, it has been observed that gold acts as a comparatively weaker safe haven than sovereign bonds during the financial turmoil created due to the health crisis over the past several decades (Choudhury *et al.*, 2022). Green bonds also have a unique return-risk profile distinct from other asset classes and can act as a safe haven or hedger for investors, wealth managers, hedge funds and pension funds (Tiwari *et al.*, 2023). The COVID-19 pandemic outbreak triggered academia's thirst to analyze the impact of current market conditions on market comovements. The literature provides evidence of the profound impact of the COVID-19 pandemic on equity markets that highlights the need for sustainable solutions. It is found that green bonds act as a possible risk mitigator against the volatility and its spillover among examined markets (Naeem *et al.*, 2022; Chopra and Mehta, 2023).

There is a growing body of academic research demonstrating the interconnectedness of green bonds and other financial markets. In both rising and falling markets, researchers have looked at how green bonds compare to various asset classes, for instance, government bonds, corporate bonds, equities, oil, commodities and clean energy. The literature of interconnection with green bonds and conventional bonds yields mixed results. The initial line of research in the literature found no benefits to incorporating green bonds into conventional bond portfolios. However, Reboredo (2018), Broadstock and Cheng (2019), Ferrer *et al.* (2021) and Kocaarslan (2021) discovered a significant comovement and strong dynamic correlations. In addition, Pham and Nguyen (2021) observed tail dependence between green bonds and conventional bonds, suggesting the transmission of risk between these markets and a limited potential for diversification or hedging advantages for investors, especially in bearish market situations. Reboredo and Ugolini (2020) and Huynh (2022) found similar outcomes when comparing green bonds to treasury bonds.

Green bonds are emerging as a strategic asset that can shield price and risk linkage from the equity market to other markets. Green bonds can help diversify investors' portfolios due to their minimal comovement (Dutta *et al.*, 2021). It was also noticed that the effectiveness of green bonds' diversification was restricted to markets in bullish conditions, and the correlation reduced in normal market conditions; however, the comovement significantly strengthened post-COVID-19 outbreak (Pham and Nguyen, 2021). When combined with commodities, such as gold (Dutta *et al.*, 2021), aluminum, copper, nickel and zinc, green bonds provided hedging benefits (Naeem *et al.*, 2021b). However, Naeem *et al.* (2021a) discovered conflicting results and reported a significant association of green bonds with gold and silver in short as well as the long term.

As time scales increased, the interconnectedness between stocks and commodities progressively strengthened and the spillover surged momentarily during times of crisis. In times of crisis, investment diversification is aided by the evidence of bidirectional causality between green bonds and commodities markets. The pass-through implications of the uncertainty index emphasize the relevance of green bonds as a safe haven option to invest.

The association of renewable energy with green bonds has been the subject of recent scholarly investigation. Green bonds have exhibited a high degree of correlation with clean energy sources (Reboredo, 2018; Reboredo and Ugolini, 2020). A few studies have also established an association of green bonds with sustainable development goals (Le *et al.*, 2020; Taghizadeh-Hesary and Yoshino, 2019, 2020), investment in green bonds is regarded as the most effective method to achieve the 2030 SDGs. Despite this increase, green bonds continue to represent less than 1% of the overall bond market. As per the green bonds are primarily issued to fund projects that are green, such as renewable energy projects (45%), energy efficient projects (20%), energy efficient transportation (13%) and water, refuse and pollution control projects (15% each). With approximately 80% of green bond issuances denominated in USD and EUR, these two currencies dominate the green bond market. Countries that have issued green bonds include China, the USA and France (London: Climate Bonds Initiative, 2019). Numerous green bonds have been issued by central and local governments, significant corporations and banks (London: Climate Bonds Initiative, 2019). As we enter the "decade of action," there is an urgent need to invest in climate-related initiatives, resulting in substantial green bond investments.

Considering contradictory findings, it is necessary to investigate the connectedness of green bonds with other commercial assets. This paper bridges a void by investigating the correlation between green bonds and energy commodities. The study contributes in multiple ways: first, it provides an in-depth analysis of green bonds and presents evidence that green bonds are a prospective portfolio diversifier. The paper uses wavelet analysis, which goes a step further in assessing the interconnectedness among the variables. It takes into account the possibility that various investors may have distinct investment strategies and preferences (Polanco-Martínez *et al.*, 2018; Ranta, 2013). Wavelet analysis enabled us to assess the frequencies over different time horizons, which provides a better understanding of the association and allows for the management of nonstationary in the time series.

3. Data and methodologies

3.1 Data description

We investigate the comovement and lead-lag association among green bonds, energy commodities and the stock market, considering time and various frequencies. On this note, the daily data of two global green bond indices, two energy commodity indices and one stock market index are considered. Referring to the study of Reboredo (2018), this study considers two global green bond indices as a proxy, two energy commodity indices to represent the global energy commodity market and the US stock exchange to signify the equity market. S&P Dow Jones Green Bonds Index (hereafter RSPDJGB) and Barclays MSCI Green Bond Index (hereafter RBMSCIGB) are selected as proxies for green bond indices, Generic 1 Natural Gas and Energy Select (hereafter RG1NG) and Energy select SPDR fund (hereafter RESPDR) are proxies of energy commodities and New York stock exchange (hereafter RNYSE) is proxy for the stock markets.

S&P Green Bond Index tracks the global green bond market maintaining rigorous standards. It is a weighted index that is issued to raise funds for environmentally friendly projects. RBMSCIGB is a multicurrency global index that consists of fixed income securities issued to fund only environmentally friendly projects. It effectively encompasses the energy sector of the S&P 500 Index. Generic 1st Natural Gas is a natural gas futures contract traded on the New York Mercantile Exchange. It is considered as the national benchmark price for natural gas. RESPDR emphasizes the energy sector of the S&P 500 Index and offers exposure to the firms dealing with consumable fuel, oil, gas and energy equipment. We collect the data of these constituent markets spanning from August 26, 2014 to March 30, 2021. Further, these daily prices are converted into log returns to remove the deviation. We furnish the description of the constituent series as follows in Table 1.

3.2 Econometric models

We analyze the time and frequency comovement among green bonds, energy commodities and the stock market. For empirical estimation, Granger causality and wavelet and network analysis are used, which are described as follows.

3.2.1 Granger causality model. In existing literature, Granger causality (Granger, 1969) is considered as one of the models used to investigate the causal association among examined series. Granger causality is applied in time series data analysis to determine whether a shift in one variable may influence another variable. Using this model, it can be determined whether the examined markets or series exhibit unidirectional/bidirectional/none. This model estimates variations in the model error when new series are included to intensify the estimation of the dependent signal (Granger, 1969). The model allows for investigation without the requirement of any priori hypothesis. It is based on the cause takes place before its effect, and the cause leads to distinctive knowledge about future values. This method is applied to stationary series only. If series are not stationary, it is important to convert them into stationary series, either by detrending or differencing, and then apply the test. The Granger causality equation can be presented as follows:

$$X_{(t)} = \sum_{j=1}^{p} A_{11,j}; X_{(t-j)} + \sum_{j=1}^{p} A_{12,j}; Y_{(t-j)} + \varepsilon_{1(t)} \tag{1}$$

$$Y_{(t)} = \sum_{j=1}^{p} A_{21,j}; X_{(t-j)} + \sum_{j=1}^{p} A_{22,j}; Y_{(t-j)} + \varepsilon_{2(t)} \tag{2}$$

where *p* signifies the lag of the examined markets used in this study.

Table 1. Examined assets class and their description

Market	Asset	Acronyms	Source
Green Bond	S&P Dow Jones Green Bonds Index	RSPDJGB	Bloomberg
	Barclays MSCI Green Bond Index	RBMSCIGB	Bloomberg
Energy commodity	Generic 1 Natural Gas	RG1NG	Bloomberg
	Energy Select Energy select SPDR fund	RESPDR	Bloomberg
Stock	New York Stock Exchange	RNYSE	Bloomberg

Source: Authors' own presentation

3.2.2 Wavelet analysis. In simple terms, wavelet implies "mini waves" that display a wavering pattern of extension and deterioration within a small period. It helps to examine the frequency connectedness among variables. It is classified into three categories: continuous wavelet transforms (CWT), cross wavelet transforms (CWT) and wavelet coherence (WC). Under continuous wavelet transform (CWT), the function that carries out wavelet transformation results in the formation of some fundamental functions called daughter wavelets $\psi\iota$, s(t) out of a mother wavelet and ψ(t) by the process of disintegration of a time series. It is shown to be a representation of time and scale, where the scale is represented by a dilation parameter related to the frequency-based information *t*, and the translation parameter is a function of time. The wavelets can be precisely stated as λs, ι(t) = 1s$\sqrt{}\lambda$(t − ιs).

The factor of normalization is denoted by 1 s$\sqrt{}$, which assures that the transformation of wavelet across timescales can be compared.

Further, the CWT is mathematically shown as below:

$$T_z(s,i) = \int_{-\infty}^{\infty} z(t)\frac{1}{\sqrt{s}}\lambda^s\left(\frac{t-i}{s}\right)dt \tag{3}$$

To calculate the wavelet power spectra, the spectral density of the time series on a two-dimensional scale is used. Torrence and Compo (1998) calculated the white and red noise WPS at each and every time *n* and scale *s*, as demonstrated:

$$\left(\frac{|T_n^z(s)|^2}{\sigma_p^2} \prec p\right) = \frac{1}{2}pf\chi_v^2 \tag{4}$$

where ν equals 1 and 2 for real and complex wavelets, respectively.

Another form of wavelet analysis is the cross-wavelet transforms (XWT). The XWT of two time series (X_n and Y_n) is denoted as $W^{XY} = W^X W^Y *$, where * indicates complex conjugation. In this equation, $|W^{XY}|$ shows the cross-wavelet power. In time frequency space, the local relative phase of xn with yn can be accepted as the complex argument (W^{xy}). For the P^X and P^Y, the XWT is mathematically presented as below:

$$\mathrm{D}\left(\frac{|W_n^X(s)W_n^Y*(s)|}{\sigma_X\sigma_Y} < p\right) = \frac{Z_v(p)}{v}\sqrt{P_k^X P_k^Y} \tag{5}$$

where $Z_\nu(p)$ is confidence level, p is the probability of a probability density function specified by the square root of the product of two χ^2 distributions.

WC is the third form of wavelet analysis, which is applied for assessing the association between two procedures by looking for frequency time intervals and bands. This approach is related to linear correlation analysis that aids in disclosing irregular relationships between two trends and their notable linear cohesion correlation. Mathematically, it is expressed as below:

$$R_t^2(\Omega_s) = \frac{\left|\varepsilon\left(\Omega_s^{-1}W_t^{eo}(\Omega_s)\right)\right|^2}{\varepsilon\left|\left(\Omega_s^{-1}\left|W_t^e(\Omega_s)\right|^2\right)\right| . \varepsilon\left|\left(\Omega_s^{-1}\left|W_t^0(\Omega_s)\right|^2\right)\right|} \tag{6}$$

where R_t^2 (Ω_s) is the value of wavelet squared coherency and ε denotes the smoothing operator. To quantify the phase association, the circular mean of the phase over regions is shown in this paper with 5% statistical significance. The statistical significance of the WC is computed using the Monte Carlo techniques.

3.3 Network analysis

A network refers to diverse structures containing variables represented by nodes and the connection among these nodes. Networks are also known as graphs, with nodes and edges referred to as vertices and links, respectively. Network analysis is conducted at both the individual and group level. It signifies a range of analytical techniques that assess various network models. It provides the capacity to evaluate complex relationship behaviors.

Network analysis is a three-step procedure:

(1) Assess the network structure on the basis of statistical tool, which considers the actual relationship behavior among the variables.

(2) Examine the network structure.

(3) Evaluate the correctness of the network parameters and procedures.

The node indicates the specific component of a scale, sub-scale or a composite scale. The selection of a node depends on the type of data that offers the best and most insightful understanding of the problems that need to be solved. In this analysis, edges denote a variety of relationships. One may categorize networks as directed or undirected. The directed edge states that all the edges are directed, while undirected refers to the absence of direction of edge.

In a nutshell, Granger causality is used to determine the direction of causality among energy commodities, stock markets and green bonds, while wavelet and network analyses are applied to examine the comovement among the constituent markets. For a deeper understanding, wavelet analysis examines the frequency connectedness consisting of continuous wavelet, cross-wavelet transforms, and WC, while network analysis unravels the connectedness with the help of the network structure, centrality indices and accuracy of edge weights.

4. Empirical results and estimation

This section of the paper documents the results derived from descriptive statistics, Granger causality test and the wavelet analysis.

4.1 Summary statistics and Granger causality result

The summary statistics of green bond, energy commodities and the US stock market is presented in Table 2. Results from return on RG1NG display both minimum and maximum daily returns. Furthermore, the mean return of RSPDJGB is negative; however, the rest of the series have positive mean returns. Among the values of standard deviation ad return on RG1NG are the most volatile, followed by return of RSPDJGB and return on RNYSE. Considering the skewness, it reveals that except for natural gas, each series is left-skewed, indicating an asymmetric tail. Kurtosis results display right skewness in each series, indicating leptokurtic distributions, having more peaked and fatter tails. On this note, it can be inferred that both kurtosis and skewness reject normality in return; the same is verified by the Jarque–Bera test. Further, to check the stationarity of the constituent return series, an augmented Dickey–Fuller test (ADF) is used, which shows that the *p*-value of each series is

Statistics	RBMSCIGB	RSPDJGB	RG1NG	RESPDR	RNYSE
Min. value	−0.02	−0.02	−0.17	−0.22	−0.13
Max. value	0.02	0.02	0.34	0.15	0.10
Mean	0.00	0.00	0.00	0.00	0.00
Stdev	0.00	0.00	0.03	0.02	0.01
Skewness	−0.32	−0.06	1.05	−0.98	−1.36
Kurtosis	11.82	6.01	10.61	17.88	23.03
Jarque–Bera test	10,024***	2,671***	8,363***	25,358***	38,428***
ADF test	−12.509**	−12.531**	−11.011***	−10.893**	−11.481**

Source: Authors' own presentation

Table 2.
Descriptive statistics

less than 5%, implying that the stationarity is at I (0). Next, the study applies Granger causality to analyze the cause-and-effect among the markets.

Table 3 depicts the Granger causality result of the constituent series. This study investigates the comovement effect from two types of green bonds (MSCI Green Bond Index and S&P Dow Jones Green Bond index) to energy commodities (natural gas, SPDR fund) and the stock market (NYSE). Granger causality test examines the direction or the diffusion of information from one variable to another variable (Huang *et al.*, 2023). Table 2 shows that BMSCIGB) does not Granger cause RG1NG, RESPDR and RNYSE. RG1NG, RESPDR and RNYSE also do not Granger cause BMSCIGB. Similarly, there is no Granger causality between RSPDJGB and RG1NG, RESPDR and RNYSE, nor is there any Granger causality from RG1NG, RESPDR and RNYSE to RSPDJGB. It can be summarized that none of the variables whether green bonds, energy commodities or the stock exchange show unidirectional or bidirectional causality with either each other.

4.2 Wavelet analysis on green bond, energy commodity and the US stock market

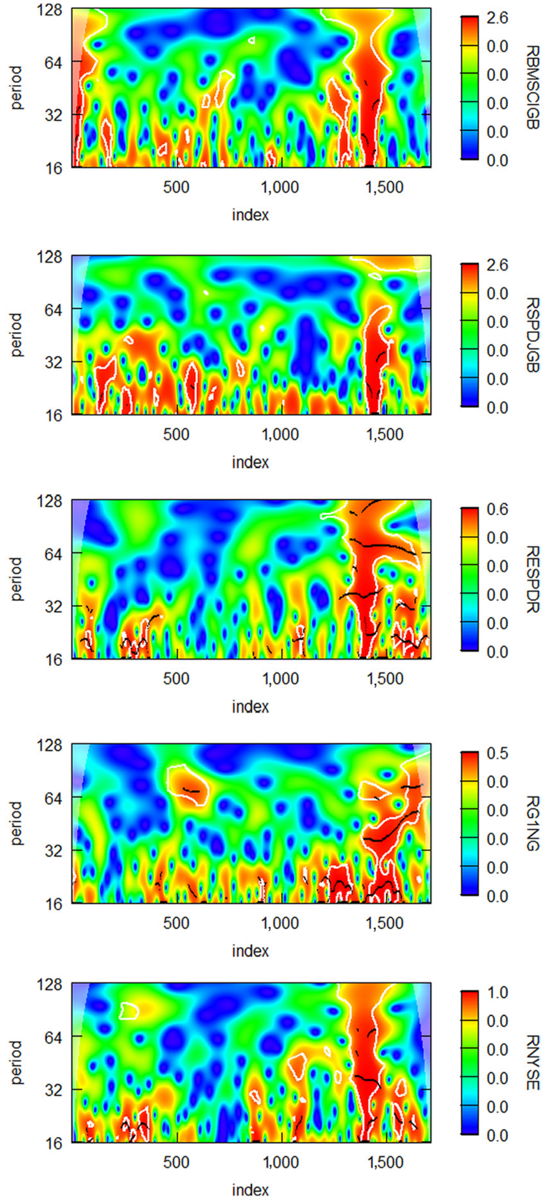
Wavelet analysis is applied to analyze the time-frequency dynamic comovement of the green bond, with energy commodity and RNYSE. The result obtained from wavelet analysis is presented in the form of continuous wavelet transform, cross-wavelet transform and WC. Figure 1 presents a graphical representation of the green bond (RBMSCIGB, RSPDJG),

H0	*F*-value	*p*-value
No → from RBMSCIGB to RG1NG	0.45	0.77
No → from RG1NG to RBMSCIGB	1.51	0.20
No → from RBMSCIGB to RESPDR	1.85	0.12
No → from RESPDR to RBMSCIGB	0.96	0.43
No → RBMSCIGB to RNYSE	1.20	0.31
No → RNYSE to RBMSCIGB	0.56	0.69
No → RSPDJGB to RG1NG	1.74	0.14
No → RG1NG to RSPDJGB	1.58	0.18
No → RSPDJGB to RESPDR	1.44	0.22
No → RESPDR to RSPDJGB	0.95	0.44
No → RSPDJGB to RNYSE	0.71	0.58
No → RNYSE to RSPDJGB	0.81	0.52

Source: Authors' own presentation, → indicates for the Granger causes, H0 stands for null hypothesis

Table 3.
Granger causality test

Daily observation	Time
500	26-08-2014
1000	05-07-2018
1500	08-06-2020
1711	30-03-2021



Source: Authors' own creation

Figure 1.
Continuous wavelet transform of examined markets

energy commodity (RG1NG and RESPDR) and US Stock Market (RNYSE) based on the continuous wavelet transform, where the continuous wavelet transform includes three cycles, i.e. monthly scale (16–32 days), monthly to quarterly scale (32–64 days) and quarterly to annual scale (64–128 days). The figure presents the scale in the Y-axis and time in the X-axis. Further, blue color depicts lower power while red shows higher power. The white contour represents the significance level (at 5%); there is a great role of cone of influence to examine the region affected by edge effects. The graphical representation of return on RBMSCIGB, displays high power or strong variation in small scale (16–32 days) and low power in a large scale (64–128 days). However, during the beginning of 2020, there was high power in all these scales. Similarly, RESPDR is witnessed with high power in small scale and high power in large scales only during 2020. In rest of the periods, there is no high power. Furthermore, the rest of the series, such as RSPDJGB, RG1NG and RYNSE, exhibit a similar pictorial representation. During 2020, they all have high power and significant contour in all the scales (16–32 days, 32–64 days and 64–128 days). It is observed that all the series have high power in small scale with a significance level above 5%. This signifies a relatively high variation during a financial crisis like COVID-19.

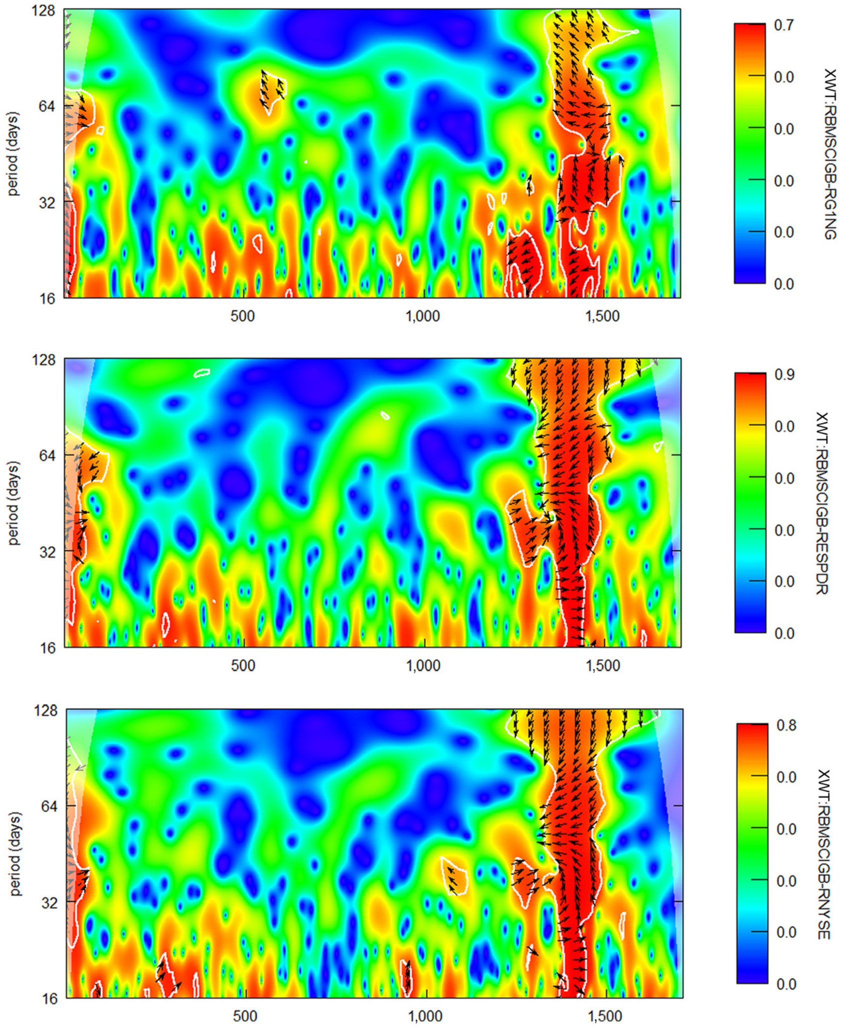
For further analysis of comovement from green bonds to energy commodity and the US stock market, the cross-wavelet transform (XWT) is applied. Figure 2 presents comovement from RBMSCIGB to energy commodity (RG1NG and RESPDR) and the US stock market (RNYSE), while Figure 3 shows the comovement from RSPDJG energy commodity to the US stock market. An arrow signifies the phase difference, which is also known as the cyclical effect among variables. The majority of the arrows are left and up to the XWT between RBMSCIGB and RGING, which indicates that RG1NG is lagging. Surprisingly, the XWT between RBMSCIGB, RESPDR and RNYSE is different, as a majority of the arrows are left but down signifying, that RESPDR and RNYSE are leading RBMSCIGB. Further, the result from RSPDJG to energy commodity and the US stock market is on similar lines. Referring to the graphical representation shown in Figure 2, it is evident that there is anti-phase during 2020 in each scale (small, medium and large). Similar evidence of anti-phase is witnessed because of the global turmoil caused by COVID-19 (Figure 3).

Finally, wavelet coherency is applied to check the association of green bond with energy commodity and the US stock market. Figure 4 depicts the wavelet coherency graph between constituent markets, examining frequency bands and time intervals. Coherence is strong at short-scale and medium-scale (16–32 days, 32–64 days and 64–128 days) as several islands are identified in these scales. In the short scale (16–32 days), mostly the directions of the arrows are right and down, indicating that RBMSCIGB and RSPDJGB are leading energy commodity in the US market.

In comparison to equity markets, the size of green bond markets is expanding enormously, indicating significant investor interest in this category of investment. Hence, there is a need to examine the financial contagion or comovement among green bonds, energy commodity and the stock market. Exploring the results derived from wavelet analysis, strong coherence is identified in high scale during 2020, pointing to the prevalence and impact of the COVID-19 crisis. Since there is no evidence of coherence before this global turmoil, this phenomenon can be suitably attributed to the crisis, indicating its impact during this tenure. On similar lines, financial comovement among these markets is established during the pandemic; however, this comovement is in anti-phase, indicating diversification opportunities..

4.3 Evidence of correlation and network analysis

Figure 5 illustrates the overall distribution of data in form of pairwise degree of relationship among the constituent series considered in this study. It indicates that the data used in this paper does not follow the normal distribution pattern. It is observed that the high correlation



Source: Authors' own creation

Figure 2.
XWT between RBMSCIGB, energy commodity and the US stock market

between return on the US stock market (RYNSE) and the return of RSPDJGB (RESPDR) is followed by return on RG1NG and RYNSE. A negative correlation (−0.021) is found between RBMSCIGB and RESPDR, RESPDR and RBMSCIGB (−0.043) and RG1NG and RSPDJGB (−0.039). The lowest correlation is noted between RNYSE and RSPDJGB (−0.043). It is surprising to observe that there is a negative correlation between two categories of green bond, i.e. RESPDR and RBMSCIGB. Furthermore, the degree of association with network analysis is validated.

Finally, network analysis examines the relationship among green bonds, energy commodity and the US stock market. In this paper, network analysis includes network structure, centrality indices and accuracy of edge weights. Figure 6 illustrates the network

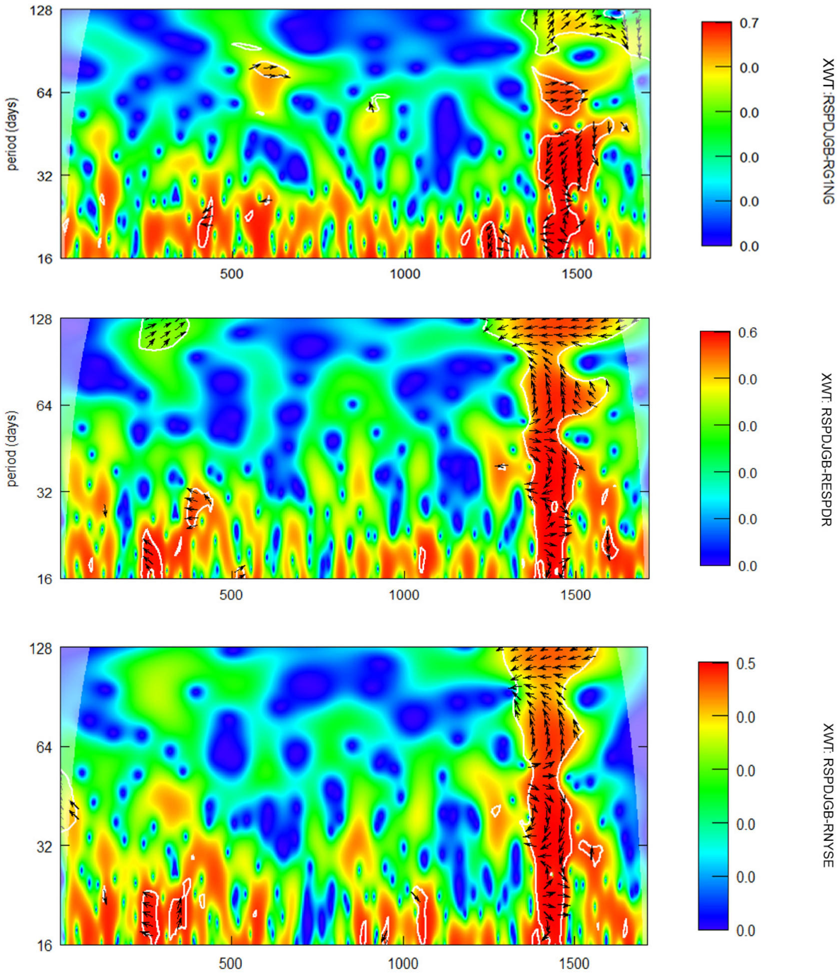
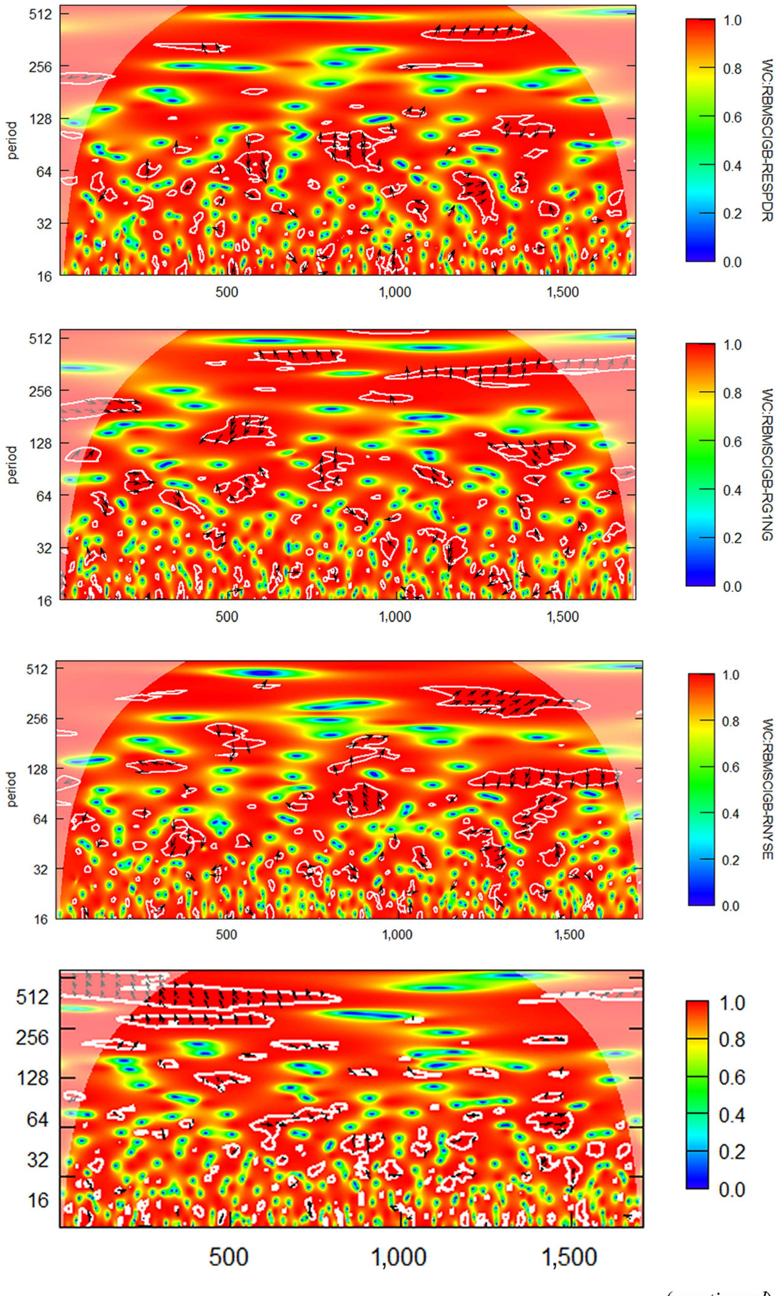


Figure 3.
XWT between RSPDR, energy commodity and the US stock market

Source: Authors' own creation

structures among the constituent variables. The connected node indicates the power of relationship, which is found only between return on RSPDJGB (RESPDR) and return on the US stock market (return on RNYSE). The rest of the variables show weak correlation as the nodes are not connected; the same is confirmed from the the unconditional correlation figure shown above. Centrality indices in terms of strength of association are shown in Figure 7. The strength of the association and different constituent series are displayed on the horizontal and vertical axes, respectively. Centrality indices highlight the relative importance of a node to the other nodes in the network. In Figure 7, a high strength value in RESPDR and RNYSE is observed, hence, it can be said that RESPDR and RNYSE have a strong connection to the nearby nodes.

Finally, the bootstrapped confidence interval is used to check the robustness of the edge. The bootstrapped confidence interval plot provides a visual representation of the estimates



(*continued*)

Figure 4.
Wavelet coherence among green bond, energy commodity and the US stock market

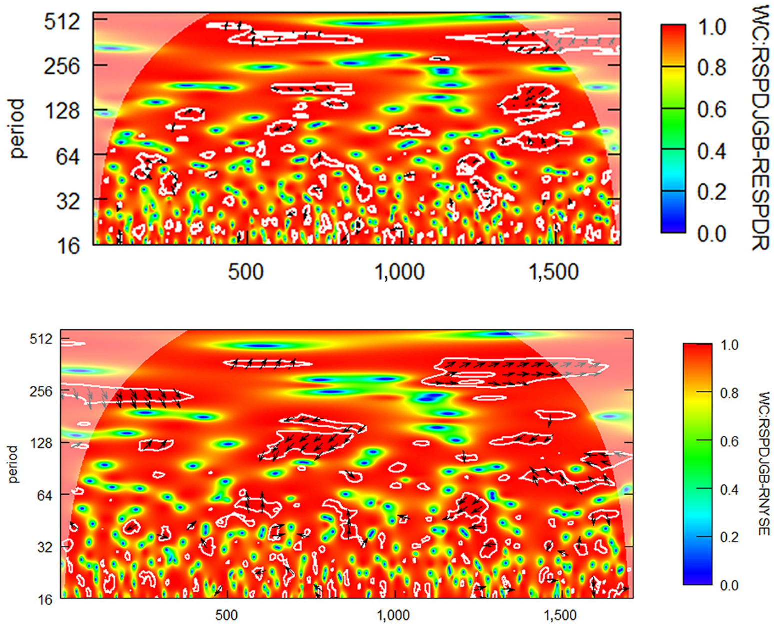


Figure 4.

Source: Authors' own creation

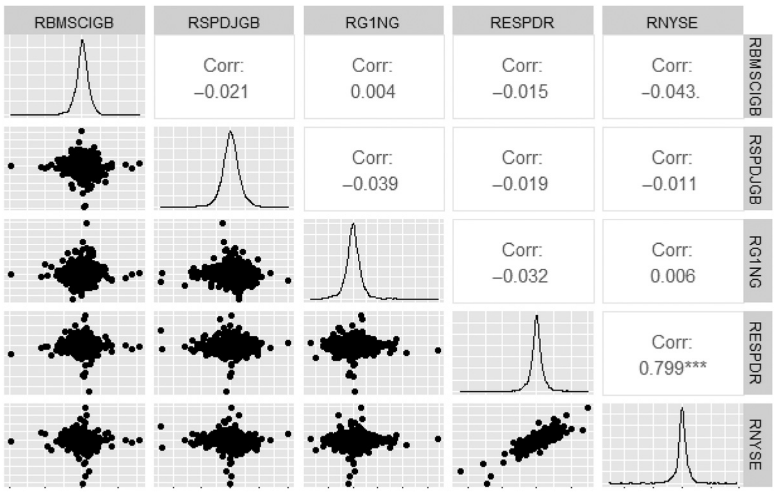


Figure 5. Pairwise correlation and distribution plot of constituent variables

Source: Authors' own creation

shown in Figure 8, in which the red line indicates the edge value while the grey bars surrounding this red line show the width of the bootstrapped confidence intervals. Considering the figure, it is observed that all the edges are estimated at zero except RESPDR-RNYSE. This is confirmed by the bootstrapped confidence as these estimated values are under the grey line.

Based on the network analysis, we find a strong connection between RESPDR and RNYSE, signifying that there is no possibility of diversification between RESPDR and RNYSE.

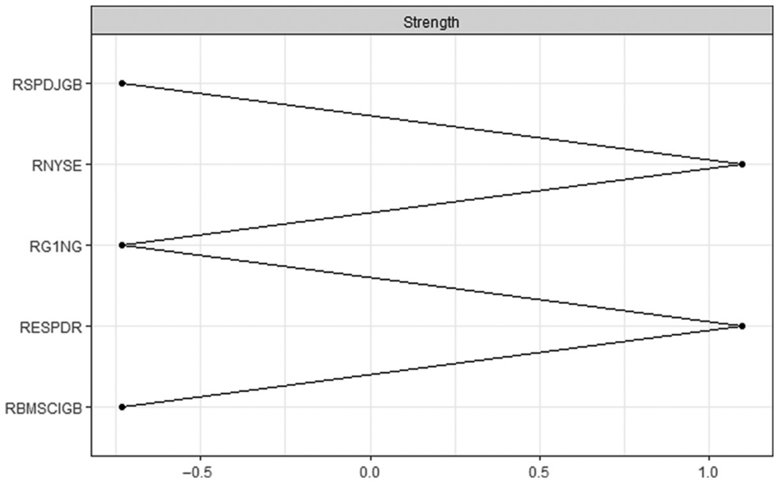
5. Conclusions and policy implications

An examination of the comovement or dynamic linkage among green bonds, commodities and stock markets is emerging as a pertinent topic that explores the role of green bonds in risk mitigation, especially during times of crisis. This paper furnishes fresh evidence of the time and frequency comovement of green bonds with energy commodity and the US stock market using Granger causality, wavelet analysis and network analysis.

The results of Granger causality test reveal an absence of causality among the selected green bonds, energy commodities and the US stock market. Green bonds, energy commodities and the US stock market display similar patterns based on the wavelet power spectrum, indicating the presence of high price volatility, especially during the period of

Source: Authors' own creation

Figure 6. Network structure among the constituent variables



Source: Authors' own creation

Figure 7. Centrality indices among the constituent series

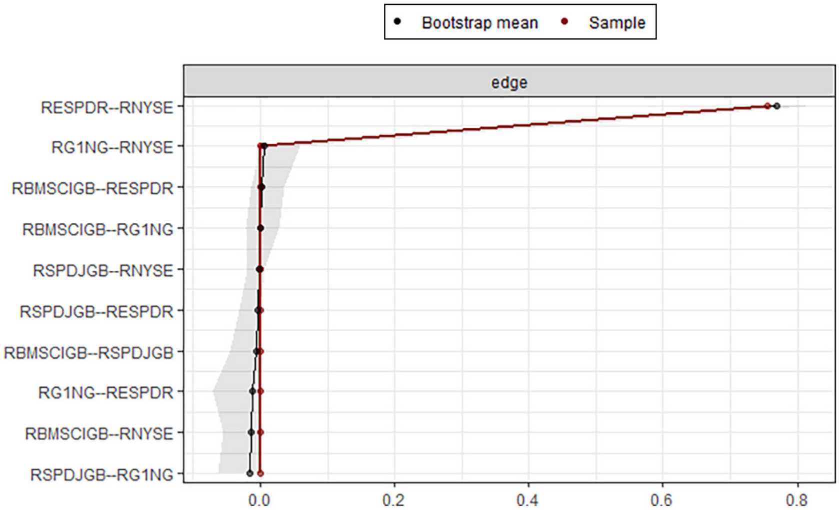


Figure 8.
Accuracy of the edge weight

Source: Authors' own creation

crisis and instability. Each series exhibits high power on a small-scale and is significant at the 5% level, indicating a significant impact of COVID-19 in 2020 during the selected time-frequency. These results are further strengthened by the cross-wavelet transform and network analyses. The WC analysis displays similar movement between pairs of return sequences and is significantly affected by the financial crisis, which cannot be identified by traditional time series techniques. This study confirms the presence of strong coherence in high scale during 2020, both at short scale and the medium scale (16–32 days, 32–64 days and 64–128 days). Since there is no evidence of coherence before the global turmoil, this phenomenon can be suitably attributed to the COVID-19 crisis, indicating its impact on the examined markets during this period. Even though financial comovement is established between these markets during the pandemic; since these are in anti-phase, they indicate suitable diversification opportunities. Results of the WC show right, and down arrows, suggesting a lead-lag relationship of green bonds with energy commodity and the US stock market (RBMSCIGB and RSPDJGB). This relationship, however, varies over various time scales. Further, network analysis validates the connectedness and strength between the nodes of RESPDR and RNYSE, implying strong correlation between these two asset classes.

The results derived from this paper have implications for market regulators, portfolio managers and investors. First, given that the green bonds are less volatile than energy commodities and provide better long-term returns (See Appendix Figures A1 and A2), investors should consider investing in them to diversify their portfolios. Institutional investors should also consider investing in green bonds to improve their corporate governance, and social and environmental rating. These results recommend the inclusion of green bonds in a market portfolio of energy commodities to obtain benefits of diversification. A strong unidirectional relationship between green bonds and the stock market implies that investors aiming to reduce risk through diversification should avoid holding both assets simultaneously in their portfolios. Similarly, the existence of high correlation between energy commodities and the stock market established through the network analysis indicates that investors should not have these assets concurrently in their portfolio. The continuous wavelet results indicate that green bonds, energy commodities and the US stock market have high power during 2020 both in small and large scales. Significant variation in these series can be attributed to a financial crisis such as COVID-19, implying that investors should invest in these assets during such crises. The CWT results indicate suitable diversification opportunities, since variables depict being in anti-phase during the COVID-19 crisis in 2020. Since these assets move in opposite directions during such financial crises, investors should invest in green bonds, energy commodity and stock markets to mitigate risk through diversification. This study further establishes that the relationship of green bonds with energy commodities and the stock market varies over time periods. Hence, it is suggested that investors use these asset classes in varying proportions over different time periods to take advantage of hedging and diversification opportunities.

This paper has some limitations that offer opportunity for further research. Future studies can combine dynamic hedging models and wavelet correlation to examine the dynamic relationship and volatility linkages between green bonds, energy commodities and stock markets. The results from such studies would help in identifying optimal portfolio weights and suitable hedge ratios, particularly during crisis and unforeseen market conditions.

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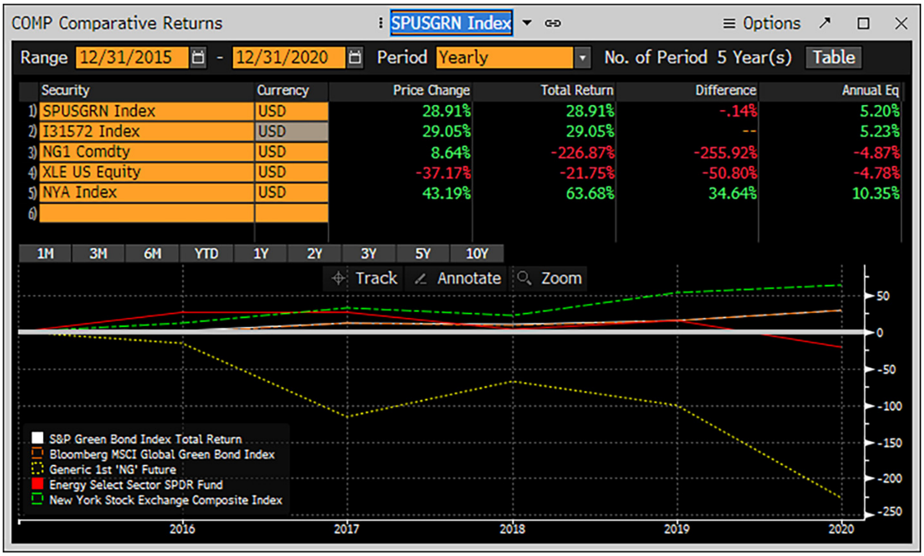
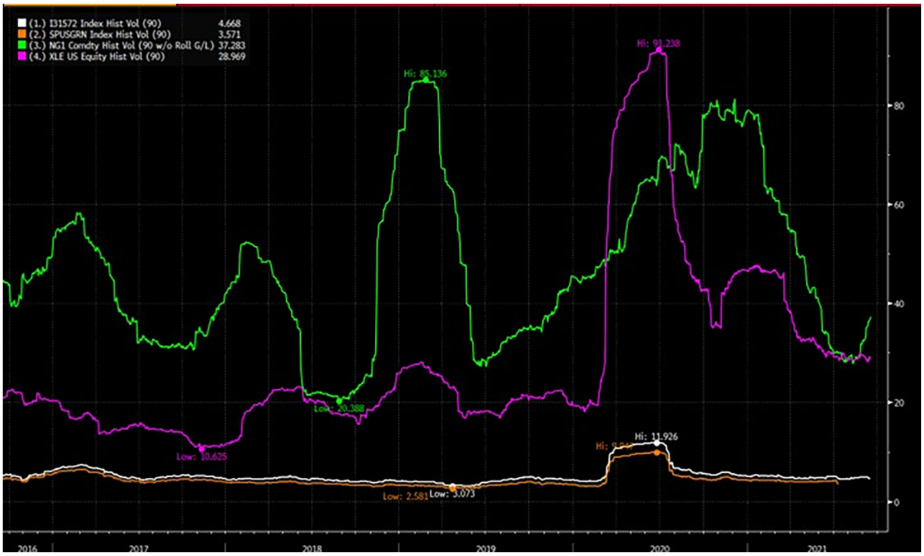
Appendix



Source: Bloomberg

Figure A1.
Historical annualized returns for selected proxies from 2016 to 2020



Source: Bloomberg

Figure A2.
90-Days historical volatility for selected proxies from 2016 to 2020