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Contagion Effects in Financial Markets: Influence of Green Finance and Energy Sectors During Global Crises

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ABSTRACT

This study investigates the dynamic volatility interconnectedness between green bonds, renewable energy, fossil fuels, and the global sustainability index from September 01, 2014, to May 31, 2023. An overall volatility connectedness index of 46.77% is found through the use of an enhanced joint connectedness method in conjunction with a time-varying parameter vector autoregression (TVP-VAR) model. Marked increases in connectedness are observed through pivotal global events, like the oil shale shock, Coronavirus outbreak, and geopolitical turmoil following the Ukraine invasion, indicating contagion effects across the markets. Key findings reveal that the Green Bond Index, WTI Crude Oil, and Natural Gas indices from S&P GSCI are the leading net transmitters of volatility, while the DJ Sustainability World Index, Renewable Energy, and S&P GSCI Brent Crude primarily act as net receivers. Results offer valuable insights for environmentally focused investors, enabling them to mitigate risk through diversified portfolios of sustainable assets. Policymakers can also leverage these findings to recognize the impact of global events on financial stability and devise strategies that promote resilience and green finance adoption.

Keywords: Green Bonds, Sustainability Index, Renewable Energy, Fossil Fuels, Dynamic Connectedness, TVP-VAR

JEL classifications: G01, G12, O13, P18, P28

1. INTRODUCTION

The growing concerns surrounding climate change and the environmental impact of increasing fossil fuel consumption have raised alarms among regulators and environmentally conscious investors. The surge in energy consumption has heightened fears of ecological degradation, prompting regulatory bodies and eco-minded investors to prioritize a rapid and effective shift towards sustainable investments, particularly in clean energy (Mohammed and Mellit, 2023). As a result, green investments have gained considerable attention, allowing investors to reduce their carbon footprints, driven by rising carbon prices and the increasing urgency to decarbonize investment portfolios (Karkowska and Urjasz, 2023). The 2030 Agenda was introduced by the United Nations (UN) in 2015 to confront critical global challenges such as environmental degradation, climate change, and the exhaustion of natural resources. This agenda includes 17 global goals for sustainable development (SDGs), covering economic, social, and environmental aspects, with a particular focus on SDG 7 (Clean Energy) and 13 (Climate Action). These goals serve as a guiding framework for transitioning to sustainable energy and combating climate change, forming the basis for this study. The Paris Agreement, in tandem with the SDGs, has reinforced the significance of these objectives, fostering competition among investors eager to lead in the renewable energy sector (Sharif et al., 2022).

This research seeks to evaluate the impact of times of intense market stress, including events like the COVID-19 pandemic and geopolitical conflicts such as the Russia-Ukraine war, and shale oil revolution on the interactions between traditional energy and green investments. These extreme events can offer important perspectives on how the relationship between dirty energy (oil) and clean energy (renewable energy and green equities) changes as a result of increased uncertainty and market stress. The results of this study will enhance our understanding of green assets' potential for risk diversification and provide fresh insights into their significance in portfolio management. This is particularly valuable for investors seeking to minimize the carbon footprint of their investments while ensuring competitive returns and uncovering potential opportunities (Mercer, 2015; Batten et al., 2021).

Growing recognition of climate change-related risks has also led to increased volatility in financial markets, particularly in industries tied to fossil fuels. Extreme weather events and long-term environmental shifts are becoming significant factors in market performance. As a result, the financial community has adapted by incorporating climate-related factors into investment strategies, reflecting the rising importance of sustainable investing, especially during heightened uncertainty like the COVID-19 pandemic. Moreover, various initiatives have emphasized strategies for addressing and adjusting to the impacts of climate change. These approaches involve promoting renewable energy, introducing green bonds, and enforcing carbon pricing mechanisms. Renewable energy serves as a sustainable substitute for fossil fuels, offering significant potential to lower greenhouse gas emissions and support the transition to an eco-friendly economic system, as emphasized in the 2015 Paris Climate Agreement. The renewable energy market has increasingly captured the interest of investors. Following the introduction of the first green bond by the European Investment Bank in 2007, these instruments have become widely recognized as a valuable fixed-income asset, particularly appealing to environmentally conscious investors aiming to act as Responsible Investors. Green bonds serve a dual purpose: on the one hand, they contribute to combating climate change by funding ecologically sustainable projects, while on the other, they provide investors with an opportunity to diversify their portfolios and mitigate risk effectively. The study of Nguyen et al. (2021) highlight that green bonds are characterized by a consistently weak and inverse relationship with stocks and commodities, irrespective of the time period. This characteristic underscore their potential as a valuable diversification tool, particularly as a hedge within portfolios containing renewable energy stocks. Notably, their study also that the connection between stocks and commodities became stronger during the Subprime Crisis, further emphasizing the distinct behavior of green bonds in periods of financial instability. Amid the Coronavirus crisis, it becomes particularly relevant to explore the interconnectedness between green bonds, renewable energy, Sustainability, and Fossil Fuels markets in these circumstances. The energy sector, significantly impacted by the pandemic, offers a unique backdrop for analyzing how green bonds may influence or stabilize the relationship within this market during such challenging times. Hosseini (2020) highlights that the remarkable expansion of the global renewable energy sector has encountered substantial obstacles due to the pandemic crisis, which poses a risk of hindering and potentially reversing the progress achieved in recent years. In this line, the uncertainties triggered by the COVID-19 pandemic have had a more substantial effect on the returns and fluctuations of renewable energy stocks, in contrast to the spillover effects observed during the 2008 recession (Liu et al., 2021). Recent research on green bonds has explored their role within various financial contexts, such as their correlation with traditional bonds, commodities (Nguyen et al., 2021; Chatziantoniou et al., 2022), their links to financial systems (Reboredo and Ugolini, 2020), and their effectiveness as a safeguard against carbon dioxide market turbulences (Jin et al., 2020). Green bonds, by contributing to the fight against climate change, can serve as a protective measure for renewable energy stocks, particularly during global disruptions like the Corona pandemic that adversely affect these assets. This potential to hedge is strengthened by the fact that many green bond investors are driven by a sense of purpose, aiming to contribute to environmental preservation. However, the effectiveness of sustainable bonds in supporting clean energy equities could be diminished if continued investments in fossil fuels persist, making clean energy stocks less appealing and competitive to market participants. Grasping the interrelationship between these financial markets is crucial, particularly during periods of heightened volatility triggered by global events like economic downturns and international conflicts. Despite the increasing recognition of these dynamics, a significant gap persists in the literature regarding how these markets interact and affect each other during times of crisis.

Our findings reveal two critical aspects: first, a pronounced interdependence among the green bond, renewable energy, and fossil fuel markets, with their connections becoming more prominent during major geopolitical events and crises. This underscores the contagion effects that can cascade through these markets during periods of turbulence. Second, the research identifies specific assets as key transmitters and receivers of volatility shocks, offering actionable insights for market participants. Although the interconnected nature of financial markets is well-recognized, limited research addresses how these markets behave during crises. By focusing on the role of global events in shaping the volatility dynamics of these asset classes, this study contributes to filling this gap and provides essential insights to investors for navigating these complex interdependencies. Our results underscore the resilience of green bonds, highlighting their safe-haven properties and ability to stabilize investment portfolios during market turbulences. Unlike traditional bonds, green bonds exhibit lower volatility and maintain a weak correlation with conventional equities and commodities, making them effective tools for portfolio diversification and risk reduction. Indeed, the identification of key assets as transmitters and receivers of volatility shocks provides actionable insights for designing targeted interventions to minimize spillover effects and protect market stability.

The paper is organized as follows: Section 2 provides a concise literature review, establishing the background for the research. Section 3 explains the methodology adopted for the analysis. Section 4 introduces the dataset and includes preliminary analyses. Section 5 presents the empirical findings. Lastly, Section 6 concludes the paper and underscores important policy implications.

2. REVIEW OF RELATED STUDIES

Recent research continues to explore the linkage between sustainable investments and energy sectors, especially during crises and periods of heightened market volatility. As financial globalization expands and commodity markets become increasingly financialized, the fossil fuel sector has undergone substantial price volatility, often driven by the global political events such as armed clashes, commercial tensions, and economic sanctions. Liu et al. (2023) note that recent events, such as the trade tensions between China and the U.S., along with the ongoing conflicts in Ukraine and the Middle East, have disrupted financial markets. These disruptions, driven by supply chain issues, have contributed to energy price volatility, negatively affecting global economic performance. During the 2017-2018 U.S.-China trade war, for example, crude oil prices saw increased volatility (Mignon and Saadaoui, 2024), along with a decline in the U.S. Treasury yields and S&P 500 index, while gold prices rose (Chen et al., 2022). Furthermore, geopolitical tensions, such as the Russia-Ukraine conflict, have intensified instability in oil prices, with significant spillover effects on the clean energy sector. Liu et al. (2025) reported that the conflict between Russia and Ukraine caused significant disruptions in the energy market, leading to significant surges in the prices of crude oil, coal, and natural gas.

Along with geopolitical challenges, the rising frequency of climate-related events is increasingly disrupting global markets and impeding economic growth (Shahrour et al., 2023). The escalating urgency to tackle climate change has added a new dimension of uncertainty, driven by changing climate policies (Bouri et al., 2023). Changes in regulations, legislative reforms, and international accords such as the Paris Accord have created a more unpredictable environment for fossil fuel markets. The uncertainty surrounding climate policies has had a profound effect on financial markets and sparked extensive discussions on the nexus between the commodity sector and green bonds, making it a crucial area of study. According to Pham and Nguyen (2021), the effectiveness of green bonds as a hedging tool is highly dependent on prevailing market conditions. Moreover, green bonds have been recognized as effective tools for hedging against fluctuations in traditional financial markets (Lee et al., 2021) and have demonstrated resilience as long-term investments, during periods of crisis (Arif et al., 2021). Studies highlight their significant contribution to stabilizing price volatility in agricultural commodities, natural gas, and certain industrial metals (Naeem et al., 2021a). Additionally, they demonstrate strong potential for risk mitigation across a range of other commodities, with the exception of precious metals (Naeem et al., 2021b). As uncertainty grows, it not only affects the hedging capacity of green bonds but also alters their relationships with both renewable energy markets and traditional assets, particularly during periods of market turbulence. Karim et al. (2022) observed a significant positive relationship involving green bonds, commodity indices, and the wider financial markets, potentially exacerbating systemic volatility during and after major global occurrences, like Corona pandemic. Lin and Su (2021) found that the effect of the pandemic crisis on energy market connectedness was most significant during the initial outbreak, but it decreased in the subsequent period. Benlagha and El Omari (2022) and Akyildirim et al. (2022) highlight the heightened interconnectedness of energy markets during crises, emphasizing the difficulties this creates for portfolio diversification. They note that gold and oil serve different functions, with each playing a unique role in the transmission and reception of shocks. Ferrer et al. (2018) employed time-frequency connectedness techniques to demonstrate that that the association of clean energy stocks with oil prices intensifies during periods of financial turbulence. These results align with the findings of Lundgren et al. (2018), demonstrating significant spillover effects between oil prices and green energy in periods of crisis, with uncertainty acting as a catalyst for volatility. Furthermore, Attarzadeh and Balcilar (2022) and Umar et al. (2022) demonstrated that the transmission of volatility between clean energy assets and fossil fuel markets intensify notably during periods of economic turmoil, like the subprime mortgage crisis and the most recent global health crisis. In a similar vein, Dutta et al. (2021) explored the dynamic associations between green bonds, climate bonds, US equities, crude oil, and gold during the COVID-19 pandemic. Their analysis revealed a negative correlation between climate bonds and US equities, while green bonds showed a positive relationship with both gold and crude oil. Previous research has extensively investigated the dynamics involving green bonds and various financial sectors. For example, Reboredo (2018) used the threshold GARCH model to illustrate that green bonds are notably affected by price fluctuations originating from corporate and treasury fixed-income markets. Likewise, Reboredo and Ugolini (2020) employed a structural vector autoregression (SVAR) method to highlight the robust connections relating to the fixed-income, currency markets, and green bond markets, while observing weaker associations with energy markets.

Besides, Zhang et al. (2023) and Zhang and Umair (2023) examined the interrelationships between ESG indicators, sustainability stocks, green bonds, carbon emission futures, and renewable energy stocks. Their findings highlighted carbon emission futures as key transmitters of volatility, with green bonds also serving a transmitting role, albeit with a minimal contribution to the overall interconnectedness. Although the shift toward renewable energy resources, like biomass, wind, solar, and wave energy, the energy sector continues to face significant challenges in achieving sustainable development and reducing CO_2 emissions (Yadav et al., 2023; Chen et al., 2022).

Furthermore, interconnectedness in global energy markets is vital in influencing the dynamics between traditional and sustainable energy investments. Price shifts in conventional energy markets, like oil and gas, frequently result in spillover effects that influence investment trends in the green energy sector. Research indicates that during periods of uncertainty, investors often engage in herd behavior, which amplifies volatility in both green and fossil fuel markets. This behavior can be linked to psychological factors influencing sustainable investment decisions. For example, negative oil shocks, particularly during crises, may lead to increased pessimism toward sustainable assets, affecting capital allocation decisions (Olasehinde-Williams et al., 2023). These patterns become more pronounced during major disruptions, such as the 2014-2016 oil crisis, the negative oil price event of 2020, and the pandemic crisis. Additionally, studies highlight significant and uneven spillover effects from oil price shocks to sustainable investments, with demand disruptions having the greatest effect (Lu et al., 2024). Moreover, green bonds have been shown to provide diversification benefits, suggesting that investors may seek refuge in sustainable assets during periods of uncertainty Elsayed et al. (2024). Similarly, Dutta et al. (2020) discovered that during periods of crisis, volatility in the oil market has a substantial effect on the prices of green assets. As oil price volatility increases, investors tend to redirect their investments towards sustainable assets, highlighting the link between oil market fluctuations and eco-friendly investments. This emphasizes the critical role of volatility in influencing investment choices in the renewable asset market. According to the research by Yaya et al. (2022) and Lee et al. (2022), fluctuations in sustainable investments are notably affected by different forms of oil price shocks. From a global perspective, Baumeister and Hamilton (2019) examine the global connection between green investments and oil shocks by utilizing a dataset that categorizes oil shocks into four types: Supply, demand, precautionary demand, and economic growth. They use wavelet coherence to analyze market fluctuations and causality during key events like the financial crisis, the oil crisis of 2014-2016, and the recent pandemic crisis. This approach provides crucial insights for informing regulations and guiding investment choices in both fossil fuel and renewable energy sectors.

3. METHODOLOGY

The transmission mechanism among green bonds, global sustainability, renewable energy, and fossil fuels in a time-varying context was analyzed using the Time-Varying Parameter Vector Autoregressive (TVP-VAR) connectivity method introduced by Antonakakis et al. (2020). This approach provides benefits over Diebold and Yilmaz's (2014) connectedness framework, which depends on a rolling window VAR approach. Unlike the later, this method does not require the selection of a potentially bias window size and prevents the loss of observations by utilizing the Kalman filter for estimation, as inspired by the work of Koop and Korobilis (2014).

TVP-VAR model is estimated with a lag length (p) set to one, and the Bayesian Information Criterion (BIC) guides its selection.

$$Y_T = \beta_t z_{t-1} + \varepsilon_t;\ \varepsilon_t | F_{t-1} \sim 0, S_t \quad (1)$$

$$\text{vec}(\beta_t) = \text{vec}(\beta_{t-1}) + v_t\ v_t | F_{t-1} \sim (0, R_t) \quad (2)$$

Y_T represents m × 1 vector endogenous variables, z_{t-1} represents m × 1 vector of lagged Y_T from t-p to t-1. ε_t and v_t are vectors of error terms. F_{t-1} denotes all known information until t-1. S_t and R_t Variance-covariance matrices that vary over time.

To perform the Generalized Forecast Error Variance Decomposition, the TVP-VAR model is converted into the TVP-VMA (time-varying parametric moving average) model, in accordance with the methods described by Koop et al. (1996) and Pesaran and Shin (1998), utilizing the specified function:

$$Y_T = \sum_{i=1}^{p} \beta_{it} Y_{t-i} + \varepsilon_t = \sum_{j=0}^{\infty} A_{jt} \varepsilon_{t-j} \quad (3)$$

The H-step ahead Generalized Forecast Error Variance Decomposition "GFEVD" assesses the influence of a shock in series j on series i and is computed as illustrated in equation (4):

$$d_{ij}^{gH} = \frac{\sigma_{ij}^{-1} \sum_{h=0}^{H-1} (e'\theta_h \sum ej)^2}{\sum_{h=0}^{H-1} (e'\theta_h \sum \theta'_h ei)}, \sum_{J=1}^{N} \tilde{\theta}_{i=1}^{g}(\text{H}) = 1 \text{ and}$$

$$\sum_{i,j=1}^{N} \theta_{ij,t}^{g}(\text{H}) = N \quad (4)$$

Here, "σjj" denotes j^th equation's standard deviation, and *e'* is the selection vector set to 1 in the i^th element unity and 0 elsewhere. It is important to note that the sum of the elements in each row of the variance decomposition table may not equal $\sum_{J=1}^{N} \theta_{ij,t}^{g}(\text{H}) \neq 1$.

$$\tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H}) = \frac{\theta_{ij,t}^{g}(\text{H})}{\sum_{J=1}^{N} \theta_{ij,t}^{g}(\text{H})} \quad (5)$$

The GFEVD technique allows us to design four connectivity procedures: The total connectedness TC (H), The transmission of directional "TO others" $C_{i\to j,t}(H)$, The reception of directional connectedness "FROM others" $C_{i\to j,t}(H)$, net directional connectedness (NET) $C_{i,t}(H)$, are calculated as the following:

$$\text{TC (H)} == \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{\sum_{\text{i,j}=1}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})} \times 100 = \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{N} \times 100 \quad (6)$$

$$C_{\text{i}\to\text{j,t}}(H) = \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{\sum_{\text{i,j}=1}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})} \times 100 = \frac{\sum_{j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{N} \times 100 \quad (7)$$

$$C_{\text{i}\leftarrow\text{j,t}}(H) = \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{\sum_{\text{i,j}=1}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})} \times 100 = \frac{\sum_{j=1, i\neq j}^{N} \tilde{\text{d}}_{ij,t}^{\text{g}}(\text{H})}{N} \times 100 \quad (8)$$

$$\text{C}_{\text{i,t}}(H) = \text{C}_{\text{i}\to\text{j,t}}(H) - \text{C}_{\text{i}\leftarrow\text{j,t}}(H) \quad (9)$$

4. DATA

This research examines the dynamic interplay between green bonds, global sustainability, renewable energy, and fossil fuels through the lens of volatility. It relies on daily closing prices from four prominent indices: the S&P GSCI Green Bonds, the Dow Jones Sustainability World Index, the Global Renewables Index (RENIXX), and the S&P GSCI Fossil Fuels, encompassing WTI crude oil, Brent crude, and natural gas. Using a comprehensive dataset from DataStream spanning September 01, 2014, to May 31, 2023, the study analyzes the impact of notable worldwide occurrences like Shale oil boom, COVID-19 outbreak, and Russia-Ukraine conflict on the interconnections amid these assets.

Adopting the approach suggested by Antonakakis et al. (2018), volatility for each series is measured through the absolute return formula: Vt = |lnPt − lnPt−1|. This method offers a robust estimation of volatility, enabling a deeper understanding of the evolving relationships within these markets.

Table 1 provides a summary of the descriptive statistics for the daily volatility of the selected assets from September 01, 2014, to May 31, 2023. Green Bonds demonstrate remarkable stability, with a mean daily volatility and variance of 0.003, reflecting minimal price fluctuations. In comparison, WTI Crude Oil and Natural Gas show significantly greater variances, at 0.025 and 0.023 respectively, highlighting their susceptibility to larger daily price changes.

The other assets fall within a moderate range, with average daily volatilities between 0.006 and 0.025 and variances from 0.007 to 0.023. Although these assets are less stable than Green Bonds, they are notably less volatile than WTI Crude Oil. The Green Bond and Sustainability Indexes maintain the lowest variances, at 0.003 and 0.006, respectively, signaling their relatively stable and low-risk profiles.

The skewness and kurtosis metrics suggest that the daily volatilities among each asset deviate significantly from a normal distribution. Notably, WTI Crude Oil exhibits the most pronounced skewness and excess kurtosis, pointing to highly asymmetric returns and extreme price fluctuations. The Jarque-Bera test verifies the non-normality of these distributions, while the Elliott-Rothenberg-Stock test proves that every time series is stationary, with no evidence of a unit root. Moreover, the Q (10) and Q2 (10) test results highlight significant serial correlation in the daily returns of all assets, indicating that the returns are neither independent nor identically distributed.

Table 2 offers insights from the correlation analysis, where Green Bonds exhibit moderate positive correlations with Sustainability (0.121) and Renewable Energy (0.125), suggesting a tendency for these variables to move in tandem.

The correlation analysis reveals several noteworthy relationships among the variables under study. A particularly strong correlation is observed between Sustainability and Renewable Energy (0.367), indicating a significant level of interdependence between these factors. Conversely, energy assets, like WTI Crude Oil, Brent Crude, and Natural Gas, generally exhibit weak correlations with the other variables. An exception is the very strong positive correlation (0.853) between WTI Crude Oil and Brent Crude, reflecting their substantial co-movement within the energy market.

Interestingly, Natural Gas demonstrates moderate positive correlations with Green Bonds (0.150) and Renewable Energy (0.099), suggesting some degree of linkage with these green and sustainable investments.

Overall, the correlation matrix illustrates a complex network of interactions among energy-related variables. While traditional energy sources tend to operate independently from other assets, notable exceptions, such as the relationship amid WTI Crude Oil and Brent Crude, also the moderate association of Natural Gas with green assets, underscore the nuanced dynamics inside the energy market. These results highlight the value of understanding these intricate relationships for a thorough examination of energy market dynamics.

5. EMPIRICAL RESULTS AND ANALYSIS

5. 1. Average Dynamic Connectedness

This subsection analyzes the volatility interconnectedness among green bonds, global sustainability, renewable energy, and fossil fuels. The findings, summarized in Table 3, demonstrate a notable spillover effect across these assets, with a total spillover index of 46.77%. This value reflects a considerable level of interconnectedness, highlighting the significant interplay among these markets.

Table 1: Descriptive statistics

Statistics	Green bond	Sustainability world	Renewable energy	WTI crude oil	Brent crude	Natural gas
Mean	0.003	0.006	0.012	0.020	0.017	0.025
Variance	0.003	0.007	0.014	0.025	0.018	0.023
Skewness	2.460***	4.321***	3.150***	8.131***	3.921***	2.046***
Ex. Kurtosis	10.173***	37.771***	19.218***	126.104***	31.963***	6.646***
JB	12109.094***	142376.894***	38789.505***	1533144.754***	102717.478***	5776.425***
ERS	−12.082***	−8.881***	−11.229***	−10.498***	−12.726***	−9.174***
Q (10)	521.321***	1131.007***	541.454***	1052.364***	436.756***	516.806***
Q^2 (10)	442.991***	1048.249***	356.154***	408.551***	176.600***	308.195***

JB is the Jarque-Bera Test, while ERS (Elliott-Rothenberg-Stock unit root test). *** Indicate significance at the 1% level. Source: Authors estimation

Table 2: Correlation matrix

Variables	Green bond	Sustainability	Renewable energy	WTI crude oil	Brent crude	Natural gas
Green bond	1.000					
Sustainability	0.121	1.000				
Renewable energy	0.125	0.367	1.000			
WTI crude oil	−0.001	0.022	0.005	1.000		
Brent crude	0.011	0.044	0.009	0.853	1.000	
Natural gas	0.150	0.042	0.099	0.103	0.098	1.000

This table presents the correlation matrices between the volatility of green bonds, global sustainability, renewable energy and fossil fuels. The sample period is September 01, 2014 to May 31, 2023. Source: Authors estimation

Table 3: Connectedness table

Variables	Green bond	Sustainability world index	Renewable energy	Crude oil	Brent crude	Natural gas	FROM
Green bond	70.88	5.05	5.98	5.34	5.03	7.72	29.12
Sustainability	10.01	53.05	12.19	9.17	8.77	6.81	46.95
Renewable energy	8.31	14.36	52.95	6.90	6.79	10.70	47.05
Crude oil	6.22	5.88	5.87	38.47	33.88	9.68	61.53
Brent crude	5.80	5.81	5.65	34.65	38.11	9.99	61.89
Natural gas	6.04	6.26	7.91	6.72	7.15	65.93	34.07
TO	36.37	37.36	37.61	62.77	61.61	44.90	280.62
Inc.Own	107.25	90.41	90.56	101.24	99.72	110.82	TCI
NET	7.25	−9.59	−9.44	1.24	−0.28	10.82	46.77%
NPT	4.00	1.00	0.00	3.00	2.00	5.00	

The above table below provides the variance decomposition for the estimated (TVP-VAR) model involving green bonds, Sustainability World Index, renewable energy, and S&P GSCI Fossil Fuels during the period span from September 1, 2014, to May 31, 2023. Using a 1-lag order, which is established by the Bayesian Information Criterion (BIC) for lag length selection all coefficient is given from a 10-step-ahead forecast. Source: Authors estimation

An in-depth examination of the "To" and "From" spillover estimates discloses WTI crude oil as a key player in the dynamics of shock transmission and absorption. WTI crude oil transmits an impressive 62.77% of shocks to other markets while absorbing 61.53% of shocks from them. Similarly, Brent Crude demonstrates substantial spillover activity, transmitting 61.61% and absorbing 61.89% of shocks. Notably, Brent Crude emerges as the largest recipient of shocks, while WTI crude oil emerges as the most prominent source of shocks across markets.

In contrast, green bonds exhibit relatively limited involvement in spillover dynamics, transmitting only 36.37% of shocks and receiving 29.12% from other markets. This indicates that green bonds are less susceptible to external shocks and exert minimal influence on other assets. The results underscore the dominant roles of crude oil and Brent Crude in the propagation of volatility, while green bonds appear to have a more isolated position in these networks.

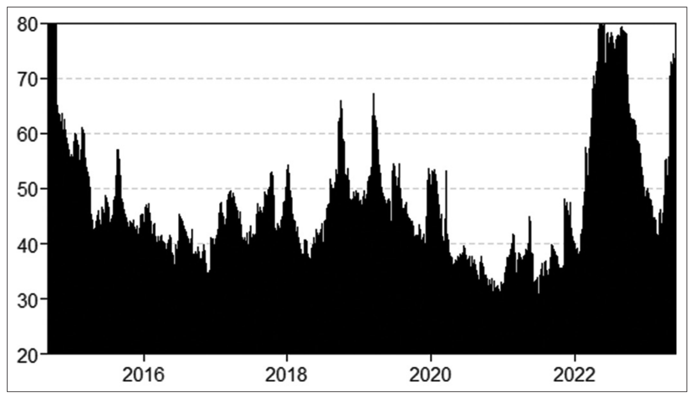
The net spillover values provide additional clarity on the direction of volatility transmissions. Green bonds, crude oil, and natural gas are identified as net shock transmitters, indicating their tendency to spread volatility across markets. Conversely, sustainability, renewable energy, and Brent Crude are net receivers, absorbing more volatility than they transmit. Among the assets, the biggest net source of volatility transmission is natural gas, whereas sustainability emerges as the most significant net receiver, highlighting its sensitivity to external shocks.

5.2. Dynamic Total Connectedness

Figure 1 illustrates a visual depiction of the overall connectedness among green bonds, the DJ Sustainability World Index, renewable energy, and the S&P GSCI Fossil Fuels over the period from September 01, 2014, to May 31, 2023. This figure reveals a series of distinct cycles, characterized by fluctuations in connectedness both above and below the average value for the observed period.

The total connectedness index demonstrates notable variability, indicating a dynamic and unstable relationship among these financial markets. The index values shift considerably over time, reflecting changes in the level of interconnectedness. Notably, the total volatility connectedness oscillates within a range of approximately 35-85%, underscoring the evolving nature of interrelations among the studied markets.

Figure 1: Total Connectedness Index using a 1-step-order lag and a 10-step-ahead forecast. This graph displays the dynamic total connectedness from September 01, 2014 to May 31, 2023 between green bonds, Sustainability World Index, renewable energy, and Fossil Fuels



Source: Authors estimation

Upon closer analysis, these fluctuations can be categorized into distinct cycles, each exhibiting unique characteristics. This variability highlights the influence of external factors and market-specific events that periodically alter the degree of interconnectedness amongst green bonds, sustainability indices, renewable energy, and fossil fuel.

The first cycle, covering the period from September 2014 to December 2015, shows a gradual rise in total connectedness, peaking at 70% in November 2015. This trend likely reflects growing interest in renewable energy and sustainability, driven by heightened awareness of climate change issues. The peak connectedness value of 85% underscores a substantial level of interconnection among the markets, indicating active investor engagement with green bonds and renewable energy. During this time, a strong positive correlation between green bonds and the DJ Sustainability World Index suggests an increasing influence of sustainability-related factors on market volatility. The second cycle, spanning January 2016 to June 2017, is marked by a decline in total connectedness, reaching its lowest point of 55%

in February 2017. This decrease may be attributed to uncertainties surrounding the Paris Accord and the election for U.S. president, which created hesitation in the renewable energy sector. The reduced connectedness highlights a period of investor caution, with limited interest in green bonds and renewable energy during this time. The third cycle, from July 2017 to December 2019, experienced a steady rise in total connectedness, culminating at 68% in November 2019. This upward trend was likely fueled by growing momentum in the renewable energy industry and the increasing adoption of sustainable investing practices. The heightened connectedness during this period suggests that investors actively sought opportunities in green bonds and renewable energy, reflecting optimism in the sector's growth prospects. The beginning of the COVID-19 pandemic in March 2020 resulted in a notable rise in the total connectedness index, which then gradually decreased to approximately 55% by the end of 2021.

During this period, there was a notable positive correlation between renewable energy and the S&P GSCI Fossil Fuels, illustrating the significant impact of energy-related factors on market volatility. Both Corona virus and Russia Ukraine conflict had profound effects on spillovers between green bonds, the DJ Sustainability World Index, renewable energy, and fossil fuels, amplifying their interconnectedness. The ongoing Russia-Ukraine conflict has further influenced global agricultural and energy markets, intensifying volatility and interdependence. This has accelerated the shift towards renewable energy and heightened investor interest in sustainable finance. The peak connectedness value of 80% during this period indicates an exceptionally high level of interconnection, with investors aggressively pursuing opportunities in green bonds and renewable energy. A strong positive correlation between green bonds and the DJ Sustainability World Index during this time highlights the increasing role of sustainability factors in shaping market volatility.

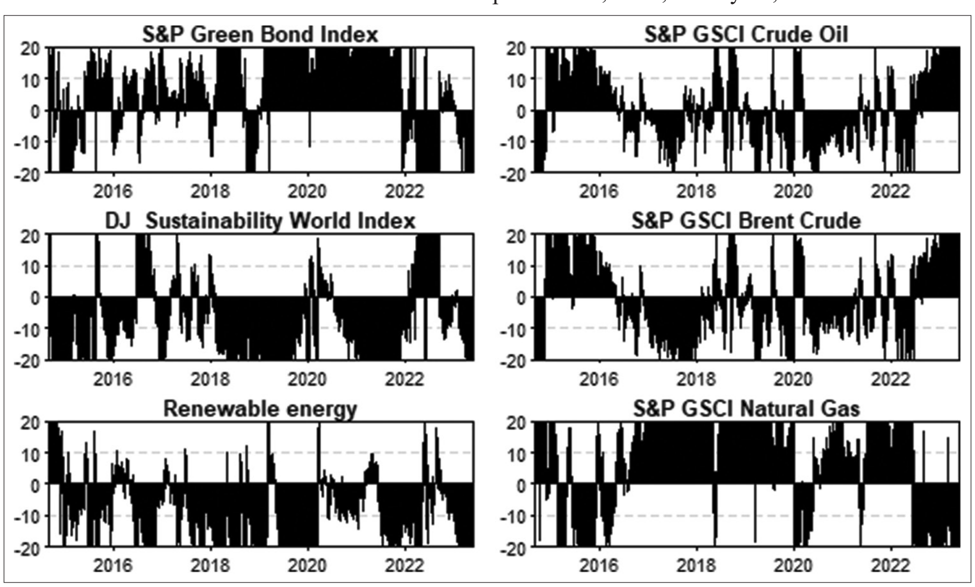
Overall, the analysis confirms that both Russia-Ukraine battle and the COVID-19 epidemic made a substantial contribution to financial contagion across green finance and fossil fuel markets. These crises heightened financial volatility, systemic risk, and market uncertainty, which in turn strengthens the connections between international financial markets. These findings align with studies by Yousfi and Bouzgarrou (2023; 2024), underscoring the critical role of interconnectedness in shaping investment decisions, particularly in the realm of green finance and sustainable investing. The results emphasize the importance of understanding market linkages to navigate the complexities of sustainable investment strategies effectively.

5.3. Net total Directional Connectedness

Figure 2 presents the net total directional volatility connectedness among several indices, namely S&P Green Bond Index, DJ Sustainability World Index, Renewable Energy, S&P GSCI Crude Oil, S&P GSCI Natural Gas, and S&P GSCI Brent Crude, spanning the period from September 01, 2014, to May 31, 2023. The figure captures the distinction between the shocks each index transmits ("emitters") and those it receives ("receivers") within the network. Indices with positive values act as net transmitters, contributing more volatility to the system than they absorb, while negative values indicate net receivers, reflecting a greater absorption of volatility from other indices within the network.

Figure 2 reveals several notable observations regarding the dynamic net directional volatility connectedness between the indices. The relationships among the variables are bi-directional, meaning that each index both transmits and receives volatility over time. A closer look at the figure identifies several distinct periods and peaks, highlighting the evolving patterns of volatility transmission among the indices.

Figure 2: Net total connectedness index is measured using the lag length selection criterion BIC, forecast for 10 steps ahead with a 1 lag order. This figure illustrates the net total directional volatility connectivity between renewable energy, green bonds, the DJ Sustainability World Index, and S&P GSCI Fossil Fuels from September 01, 2014, to May 31, 2023



Source: Authors estimation

From 2014 to 2016, a period marked by the global oil price collapse and increasing focus on sustainability, the DJ Sustainability World Index, Renewable Energy, and S&P GSCI Brent Crude showed negative net connectedness values, indicating that these indices were net receivers of shocks. In contrast, the S&P Green Bond, S&P GSCI Crude Oil, and S&P GSCI Natural Gas displayed positive net connectedness values, positioning them as net transmitters of volatility throughout this period. Between 2016 and 2018, the net connectedness values for Natural Gas and Crude Oil rose significantly, aligning with OPEC's stabilization efforts and the growth of U.S. shale production. This shift suggests that these indices became major sources of volatility in the system during this time. Conversely, the DJ Sustainability World Index and Renewable Energy continued to show negative net connectedness values, remaining net receivers of shocks. COVID-19 crises, which unfolded from 2018 to 2020, caused the net connectedness values for S&P GSCI Natural Gas and S&P GSCI Crude Oil to decline, suggesting a decrease in their influence on volatility. Meanwhile, the S&P Green Bond Index maintained a positive net connectedness, continuing to be a significant transmitter of shocks. During the post-pandemic recovery period from 2020 to 2022, marked by unprecedented market disruptions, the S&P Green Bond Index saw a significant increase in its net connectedness, indicating a heightened ability to transmit shocks. In contrast, the DJ Sustainability World Index and Renewable Energy continued to exhibit negative net connectedness, remaining net receivers of volatility. Finally, between 2022 and 2023, energy price volatility and the S&P Green Bond Index's net connectedness value fell as a result of the Russia-Ukraine military fight. However, S&P GSCI Natural Gas and S&P GSCI Crude Oil maintained positive net connectedness values, suggesting that they continued to play an important function as channels for transmitting shocks.

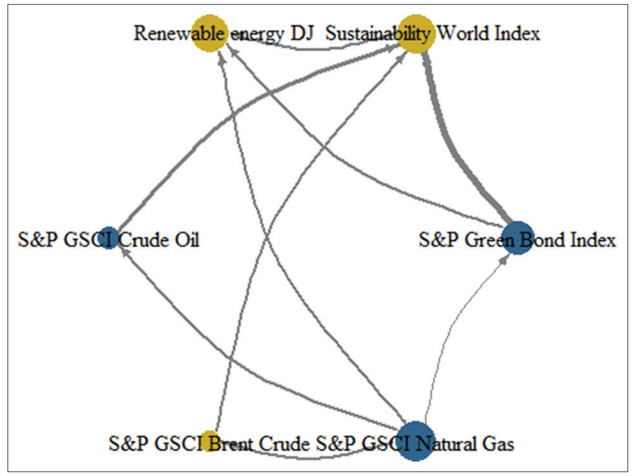
Overall, the figure illustrates that S&P Green Bond, S&P GSCI Crude Oil, as well as S&P GSCI Natural Gas play a central role in driving volatility within the system, while DJ Sustainability World Index, Renewable Energy, and S&P GSCI Brent Crude appear to be more susceptible to external influences. The relationships between these indices are dynamic, with varying levels of influence over time, as indicated by periods of heightened and reduced volatility transmission. Additionally, our analysis highlights that the net pairwise directional volatility spillovers are dynamic and exhibit considerable fluctuations, particularly during periods of market turbulence (Naeem et al., 2020).

5.4. Net pairwise Directional Connectedness

Figure 3 illustrates a network diagram that visualizes the directional volatility connectedness between six key market indices: S&P Green Bond, DJ Sustainability World Index, Renewable Energy, S&P GSCI Crude Oil, S&P GSCI Natural Gas, and S&P GSCI Brent Crude. This diagram offers a clear depiction of the net pairwise directional interconnections across the entire sample period.

In the diagram, each node's size is proportional to the degree of net pairwise connectivity. Larger nodes indicate stronger spillover effects, signifying markets with a higher influence on others. The color of the nodes is used to differentiate the roles of the markets within the network: Blue nodes signify transmitters (markets that propagate shocks to others), while yellow nodes signify receivers (markets that absorb shocks from other markets).

Figure 3: Network diagrams. The network's shock recipients and transmitters are noted by yellow and blue nodes. The average total net spillover is indicated by the size of the nodes. Arrows indicate the inter-asset spillover direction, while the thickness of the arrows indicates the strength of the spillover



Source: Authors estimation

The network diagram supports the conclusions drawn from the static tables, showing that, S&P GSCI Crude Oil, S&P GSCI Natural Gas and S&P Green Bond operate as net sender of volatility shocks to other markets, whilst DJ Sustainability World Index, Renewable Energy and S&P GSCI Brent Crude seem to be net recipients. Notably, S&P GSCI Natural Gas stands out as the greatest net transmitter of volatility shocks, while the DJ Sustainability World Index and Renewable Energy emerge as the most significant net receivers of shocks. The strongest connections are observed between the S&P Green Bond and DJ Sustainability World Index, as well as between S&P GSCI Crude Oil and DJ Sustainability World Index.

5.5. Robustness Tests

To validate our results, we performed a robustness analysis by adjusting the prediction horizon via the TVP-VAR model while maintaining a consistent lag order. Specifically, we set the prediction steps to H = 15 and H = 20, with the findings detailed in Tables A1 and A2. Importantly, results reveal no substantial variations, suggesting that extending the forecast horizon has little to no impact on the estimated outcomes.

6. CONCLUSION

This research investigates the dynamic volatility interconnections among green bonds, global sustainability, renewable energy, and fossil fuels by employing the TVP-VAR-based connectedness method. The analysis employs daily closing prices from four key indices: The S&P GSCI Green Bonds, Dow Jones Sustainability World Index, Global Renewables Index (RENIXX), and S&P GSCI Fossil Fuels, which includes crude oil, Brent crude, and natural gas. The study spans a period marked by significant global events, such as the drop in oil prices from 2014 to 2016, commodity price shocks due to China's economic transition in 2015, the US shale energy boom from 2015 to 2016, the Coronavirus pandemic in 2020, and the continuing Russia-Ukraine war between 2022 and 2023. The results indicate that the overall connectedness index for the analyzed variables throughout the sample period is 46.77%, with the volatility spillovers being notably high throughout the period, particularly during times of unexpected events (Khemakhem and Gallas, 2025). Spillover effects peaked between 2015 and 2016, the first quarter of 2020-2022, alongside the surge in US oil supply, the Coronavirus crisis, along with the geopolitical tensions triggered by Russia's invasion of Ukraine.

In periods of financial turmoil, the connections and spillover effects among global financial markets often become more pronounced. This is consistent with previous studies, which suggest that contagion effects emerge from the transmission of market risk and uncertainty (Cheikh and Zaied, 2023; Nguyen et al., 2021). This heightened volatility indicates the presence of contagion among the studied variables. Furthermore, the results identify S&P Green Bond, S&P GSCI Crude Oil, and S&P GSCI Natural Gas as the primary net transmitters of volatility shocks, while the DJ Sustainability World Index, Renewable Energy, and S&P GSCI Brent Crude emerge as the main net receivers of these shocks.

The directional volatility spillovers are bidirectional, showing that these indices both transmit and receive shocks over time. The study shows that the net pairwise directional volatility spillover is time-varying and exhibits considerable variability, particularly in times of heightened market stress (Naeem et al., 2020). These results have significant implications for a range of stakeholders, including speculators, portfolio managers, and decision-makers. The paper underscores the necessity for risk management strategies that take these spillovers and the importance of diversifying portfolios to mitigate risk. Policymakers should be aware of how worldwide occurrences, like economic crises and geopolitical disputes, impact financial markets, highlighting the necessity of policies that strengthen market stability and promote the shift towards to green finance.

For traditional investors and portfolio managers, understanding the interconnectedness between green equity, renewable energy, and fossil fuels is crucial. During periods of heightened spillover, investors need to evaluate risk exposures meticulously also diversify to protect against large shocks. Ultimately, this study offers insights into the dynamic relationships between these markets, enabling investors and policymakers to make better-informed decisions that manage risks while leveraging the opportunities presented by the interconnected nature of these markets.

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APPENDICES

Table A1: Forecast Horizon: 15

Variables	Green Bond	Sustainability World Index	Renewable energy	Crude Oil	Brent Crude	Natural Gas	FROM
Green Bond	70.78	5.08	6.12	5.28	5.02	7.72	29.22
Sustainability	10.02	52.92	12.28	9.13	8.77	6.88	47.08
Renewable energy	8.25	14.40	52.75	6.98	6.81	10.81	47.25
Crude Oil	6.15	5.95	5.82	38.46	33.84	9.77	61.54
Brent Crude	5.79	5.82	5.77	34.60	38.07	9.94	61.93
Natural Gas	6.03	6.34	7.93	6.71	7.16	65.83	34.17
TO	36.26	37.58	37.92	62.69	61.60	45.13	281.18
Inc.Own	107.04	90.50	90.67	101.15	99.68	110.96	TCI
NET	7.04	−9.50	−9.33	1.15	−0.32	10.96	46.86
NPT	4.00	1.00	0.00	3.00	2.00	5.00	

The variance decomposition among commodities and stock markets is analyzed using TVP-VAR with a lag order of 1, providing forecasts for 15 steps ahead

Table A2: Forecast Horizon: 20

Variables	Green Bond	Sustainability World Index	Renewable energy	Crude Oil	Brent Crude	Natural Gas	FROM
Green Bond	70.69	5.14	6.05	5.29	5.02	7.82	29.31
Sustainability	9.97	52.91	12.21	9.17	8.77	6.96	47.09
Renewable energy	8.27	14.37	52.82	6.96	6.82	10.75	47.18
Crude Oil	6.17	5.93	5.94	38.41	33.83	9.71	61.59
Brent Crude	5.78	5.86	5.76	34.55	38.03	10.01	61.97
Natural Gas	5.99	6.38	7.87	6.77	7.19	65.81	34.19
TO	36.18	37.69	37.83	62.74	61.63	45.26	281.33
Inc. Own	106.87	90.60	90.65	101.15	99.66	111.06	TCI
NET	6.87	−9.40	−9.35	1.15	−0.34	11.06	46.89
NPT	4.00	1.00	0.00	3.00	2.00	5.00	

The variance decomposition among commodities and stock markets is analyzed using the TVP-VAR with a lag order of 1, providing forecasts for 20 steps ahead