



Connectedness between green bonds and financial instability index: A TVP-VAR-Connectedness Approach

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Abstract

The increasing interconnectedness between conventional financial markets and sustainable financial assets has generated a complex network of uncertainty and systemic risk transmission across global markets. This study utilizes the Time-Varying Parameter Vector Autoregression (TVP-VAR)-Connectedness approach to examine the dynamic spillovers between CIMAX-based financial instability indicators and green bond market risks. The analysis includes major financial market segments, namely equity, energy, commodity, and bond markets, together with three green bond-related indices: the S&P U.S. Municipal Green Bond Index, the S&P Green Bond Index, and the S&P Global Clean Energy Select Index. By integrating the TVP-VAR-Connectedness framework with CIMAX-based risk measures, this research captures the time-varying nature and interconnected structure of systemic risk transmission. The main findings reveal significant and highly dynamic spillover effects, particularly during major global crises such as the COV ID-19 pandemic and the Russia-Ukraine conflict. The results further indicate that equity, energy, and commodity markets dominate the transmission of systemic risk, whereas green bond markets mainly act as net receivers of shocks. Nevertheless, green financial assets occasionally contribute to risk propagation, reflecting their growing integration within the global financial system.

Keywords

financial instability, green bond markets, systemic risk, CIMAX methodology, connectedness spillovers, TVP-VAR-Connectedness model, sustainable finance

1. Introduction

Over the past few years, the global economy has experienced one of the most turbulent periods of the twenty-first century, characterized by successive health, geopolitical, and financial crises that have profoundly disrupted international financial systems. The outbreak of the COV ID-19 pandemic in early 2020 triggered unprecedented uncertainty and generated the deepest global recession since the Second World War. This instability was further intensified by the Russia-Ukraine conflict that erupted in February 2022, causing severe disruptions in energy, commodity, and financial markets worldwide. More recently, escalating geopolitical tensions in the Middle East have increased concerns regarding global economic stability and financial market resilience. Several researchers, including (Gyamerah, 2024), (Yarovaya et al., 2022), (Liu and Zhang, 2024), and (Sharma et al., 2024), characterize these crises as Black Swan events because they were difficult to predict, generated substantial economic consequences, and significantly altered global market dynamics.

In this context, financial instability has become a central concern for policymakers, investors, and researchers due to its adverse effects on economic growth, financial intermediation, and market confidence. Financial stability generally refers to the capacity of the financial system to efficiently allocate resources, absorb shocks, and maintain smooth market functioning without major disruptions to economic activity. However, instability emerges when uncertainty, volatility, and contagion effects intensify across interconnected markets. According to Frederic Mishkin (1991), adverse selection and moral hazard problems in financial markets may be exacerbated by five major factors: interest rate hikes, stock market declines, increases in uncertainty, bank runs, and unexpected declines in the general price level. Consequently,

any of these factors may trigger a financial crisis and shift the economy from a high-output equilibrium to a low-output equilibrium, as financial resources can no longer be efficiently directed toward productive investment opportunities.

The growing integration of global financial markets has further amplified the transmission of systemic risk across asset classes, particularly during periods of economic turmoil. Financial shocks originating in one market segment can rapidly propagate toward other markets through contagion effects, portfolio reallocations, and investor sentiment channels. Recent crises have demonstrated that equity, energy, commodity, and bond markets are increasingly interconnected, thereby strengthening spillover effects and systemic vulnerabilities. In particular, energy and commodity markets have become important channels of financial instability due to fluctuations in oil and gas prices, geopolitical tensions, and disruptions in global supply chains. As a result, understanding the dynamic interactions between financial instability and other market segments has become increasingly important for effective risk management and financial stability policies.

At the same time, sustainable finance has attracted substantial attention from governments, institutional investors, and international organizations seeking to promote environmentally responsible investment practices. Among sustainable financial instruments, green bonds have emerged as one of the fastest-growing segments of global capital markets. Green bonds are debt securities specifically designed to finance environmentally sustainable projects, including renewable energy, energy efficiency, climate adaptation, and clean transportation initiatives. The rapid expansion of green bond markets reflects the increasing importance of climate-related investment strategies and the transition toward low-carbon economies. Nevertheless, despite their environmental orientation, green bond markets remain integrated with traditional financial systems and may therefore be affected by financial instability and systemic risk transmission.

A growing body of literature has examined the relationship between green bond markets and conventional financial markets. For instance, Nguyen et al. (2020) analyze the dynamic interactions between green bonds, equity markets, commodities, clean energy, and conventional bond markets, documenting significant time-varying comovements across assets. Similarly, Hung (2021a) investigates the dependence structure between green bonds and traditional financial assets using dynamic copula techniques and concludes that these relationships vary substantially over time, particularly during periods of market stress. Reboredo et al. (2019) further demonstrate that renewable energy and low-carbon financial assets become increasingly interconnected during extreme market conditions, reducing diversification opportunities for investors.

Other studies also highlight the important role of energy and commodity markets in shaping green financial market dynamics. Naeem et al. (2021) report significant spillover effects between green bonds, energy markets, and conventional financial assets, especially during crisis periods characterized by heightened uncertainty. Likewise, Bouri et al. (2021) show that green financial instruments are increasingly influenced by fluctuations in energy prices and global economic conditions. These findings suggest that green bond markets are not isolated from conventional financial instability and may both receive and transmit shocks within the broader financial network. However, despite the growing literature on green finance connectedness, most previous studies focus mainly on return and volatility spillovers, while limited attention has been devoted to downside risk transmission and crisis-related financial instability.

Against this background, the present study contributes to the literature by introducing a novel risk-based framework based on the CIMAX methodology to measure financial instability and green bond market risks. Unlike traditional return-based approaches, the CIMAX methodology captures extreme downside movements and crisis conditions, thereby providing a more accurate representation of systemic financial stress. More specifically, the study constructs risk variables derived from the difference between the CIMAX indicator and its associated threshold level for each market index. The analysis includes major financial market segments represented by the S&P GSCI Natural Gas Index, MSCI World Index, S&P 500 Index, Dow Jones Commodity Index, S&P 500 Bond Index, and S&P 500 Energy Index, together with three green bond-related indices: the S&P U.S. Municipal Green Bond Index, the S&P Green Bond Index, and the S&P Global Clean Energy Select Index.

To investigate the dynamic transmission of systemic risk and connectedness across markets, this study employs the Time-Varying Parameter Vector Autoregression (TVP-VAR)-Connectedness framework developed by Antonakakis et al. (2020). The TVP-VAR approach offers several advantages over traditional rolling-window VAR methodologies, as it captures both parameter instability and time-varying spillover dynamics without requiring arbitrary window selection. Furthermore, the methodology effectively identifies directional connectedness, total spillovers, net spillovers, and pairwise shock transmission mechanisms across markets. This dynamic framework is particularly suitable for analyzing financial instability because interconnectedness among markets tends to evolve rapidly during crisis periods and structural economic changes.

Therefore, the main objective of this study is to examine the dynamic connectedness between financial market instability and green bond market risks under major global crisis episodes. More specifically, the study seeks to answer the following research questions: (1) How does financial instability propagate between conventional financial markets and green bond markets? (2) Which markets act as dominant transmitters and receivers of systemic risk? and (3) How do major crises such as the COVID-19 pandemic and the Russia-Ukraine conflict affects the evolution of spillovers and market interconnectedness? By addressing these questions, this study provides important implications for policymakers, regulators, and investors regarding systemic risk management, sustainable finance development, portfolio diversification, and financial stability in increasingly interconnected global markets.

2. Data and Methodology

2.1 Data

This study investigates the dynamic connectedness between financial market instability and green bond market risks using daily data collected from the [S&P Global official website](#). The sample includes major conventional financial market indices together with green finance-related indices in order to capture the interactions between traditional and sustainable financial markets. More specifically, the analysis considers the S&P GSCI Natural Gas Index (R.N.G), MSCI World Index (R.MSCI.W), S&P 500 Index (R.S.P500), Dow Jones Commodity Index (R.DJ.Commodity), S&P 500 Bond Index (R.S.P500.Bond), and S&P 500 Energy Index (R.S.P500.Energy) as proxies for financial market instability across equity, commodity, energy, and bond markets. In addition, three green finance indices are incorporated into the analysis, namely the S&P U.S. Municipal Green Bond Index (R.S.P.Municipal.GB), the S&P Green Bond Index (R.S.P.GB), and the S&P Global Clean Energy Select Index (R.S.P.Global.CE).

The study period extends from March 2017 to June 2025 and covers several major global crisis episodes, including the COV ID-19 pandemic and the Russia–Ukraine conflict. Daily returns are computed as logarithmic differences of consecutive prices according to the following expression:

$$R_t = \ln(P_t) - \ln(P_{t-1})$$

where R_t denotes the return series at time t , while P_t and P_{t-1} represent the closing prices at periods t and $t-1$, respectively. The use of daily frequency data allows the study to accurately capture short-term fluctuations, crisis-related shocks, and dynamic spillover transmission mechanisms across markets.

To measure financial instability and downside risk, this study constructs a novel risk variable based on the CIMAX methodology originally proposed by Patel and Sarkar (1998) and further developed by Vila (2000). The CIMAX indicator is calculated as the ratio between the current market price and the maximum price observed over a fixed rolling window of 40 trading days, corresponding approximately to two months of trading activity. The CIMAX measure is expressed as follows:

$$CIMAX_t = \frac{P_t}{\max(P_{t-40}, \dots, P_t)}$$

Following Patel and Sarkar (1998), a threshold value is then computed as the average value of the CIMAX series minus two standard deviations:

$$Threshold = \bar{CIMAX} - 2\sigma(CIMAX)$$

Finally, the financial instability risk variable is constructed as the difference between the threshold level and the CIMAX value whenever the latter falls below the threshold. This approach enables the identification of periods characterized by severe market stress and downside instability. Compared with traditional return-based indicators, the CIMAX methodology provides a more sensitive and interpretable measure of financial crises and extreme market conditions.

2.2 Methodology

To examine the dynamic connectedness and systemic risk transmission between financial instability indicators and green bond markets, this study employs the Time-Varying Parameter Vector Autoregression (TVP-VAR)-Connectedness framework developed by Antonakakis et al. (2020). The TVP-VAR methodology extends the traditional VAR connectedness approach proposed by Diebold and Yilmaz (2014) by allowing parameters and variance-covariance matrices to evolve over time. Consequently, the model captures structural changes, crisis-related dynamics, and time-varying spillovers more effectively than conventional rolling-window VAR models.

Following Antonakakis et al. (2020), the TVP-VAR model with lag length p , selected according to the Bayesian Information Criterion (BIC), is specified as follows:

$$\begin{aligned} y_t &= A_t z_{t-1} + \varepsilon_t \\ \varepsilon_t | \Omega_{t-1} &\sim N(0, \Sigma_t) \\ \text{vec}(A_t) &= \text{vec}(A_{t-1}) + \xi_t \\ \xi_t | \Omega_{t-1} &\sim N(0, \Xi_t) \end{aligned}$$

where y_t denotes the vector of endogenous variables, A_t represents the matrix of time-varying coefficients, and ε_t is the error term with time-varying variance-covariance matrix Σ_t . The TVP-VAR model is subsequently transformed into its moving average representation in order to compute generalized impulse response functions (GIRFs) and generalized forecast error variance decompositions (GFEVDs).

Based on the generalized variance decomposition framework of Diebold and Yilmaz (2014), the study calculates several connectedness measures, including the Total Connectedness Index (TCI), directional spillovers TO and FROM the system, net directional connectedness (NET), and pairwise directional connectedness (PAIR). The TCI measures the overall degree of interconnectedness within the system and is defined as the proportion of forecast error variance explained by cross-market spillovers relative to total variance. The directional connectedness measures identify the magnitude of shocks transmitted and received by each market, while the NET connectedness indicator distinguishes between net transmitters and net receivers of systemic risk. Finally, pairwise connectedness captures bilateral spillover relationships between individual markets.

The TVP-VAR connectedness framework offers several important advantages for the present study. First, unlike rolling-window approaches, it avoids arbitrary window-size selection and information loss. Second, it effectively captures abrupt structural changes and evolving spillover dynamics during crisis periods. Third, the methodology provides a flexible and robust framework for analyzing systemic risk transmission in highly interconnected financial systems. Therefore, the TVP-VAR approach is particularly suitable for investigating the dynamic relationships between financial instability and green bond market risks during periods characterized by elevated uncertainty and global financial turbulence.

3. Empirical results and interpretations

3.1 Descriptive statistics

Descriptive statistics are presented in Table 1. Among financial market risk indicators, the S&P GSCI Natural Gas Index exhibits the highest volatility, while the S&P 500 Bond Index exhibits the lowest variance. Risk measures for green bonds show relatively lower volatility than risks associated with energy and equity markets, indicating partial risk diversification. All series are positively skewed and exhibit significant excess kurtosis, revealing asymmetric, fat-tailed risk distributions. Jarque-Bera statistics strongly reject the null hypothesis of normality for all variables, confirming non-Gaussian behavior. Furthermore, significant ERS statistics indicate strong persistence in risk dynamics. Finally, the highly significant Q(20) and Q²(20) statistics provide evidence of serial correlation and volatility clustering, justifying the application of the TVP-VAR connectivity framework.

Table1 Descriptive statistics

Variables	Mean	Variance	Skewness	Excess Kurtosis	Jarque-Bera	ERS	Q (20)	Q ² (20)
R.N. G	0.095***	0.010	0.879***	0.650***	287.764***	-4.695***	10215.504***	9864.117***
R. MSCI.W	0.029***	0.001	1.931***	5.622***	3809.478***	-6.507***	11366.027***	12467.821***
R.S. P500	0.029***	0.001	1.746***	4.941***	2997.291***	-6.622***	10597.684***	11647.710***
R.DJ. Commodity	0.030***	0.001	1.524***	3.683***	1871.818***	-5.662***	11746.534***	12853.781***
R.S. P500.Bond	0.012***	0.000	2.355***	7.134***	5983.343***	-5.454***	12412.892***	12840.242***
R.S. P500.Energy	0.054***	0.005	1.851***	4.709***	2937.765***	-5.338***	11659.859***	12698.889***
R.S.P. Municipal.GB	0.010***	0.000	2.119***	5.950***	4368.830***	-4.556***	12618.482***	12799.687***
R.S.P.GB	0.014***	0.000	2.309***	7.749***	6661.527***	-5.959***	12454.370***	12645.590***
R.S.P. Global.CE	0.050***	0.003	1.283***	2.447***	1029.890***	-6.173**	11161.960***	10483.024***

Source: Prepared by the authors

3.2 Volatility Analysis

Figure 1 illustrates the dynamics of risk measures for green bond indices over the sample period, highlighting notable heterogeneity in volatility behavior across market segments. The S&P U.S. Municipal Green Bond Index exhibits relatively moderate and stable risk fluctuations, with occasional spikes during periods of heightened financial stress. In contrast, the S&P Green Bond Index shows more pronounced increases in risk, particularly during episodes of major global uncertainty, reflecting its greater exposure to international market conditions. The S&P Global Clean Energy Select Index exhibits the highest level of risk variability, characterized by frequent and sharp spikes, particularly during the COVID-19 pandemic and the energy market turbulence following 2021.

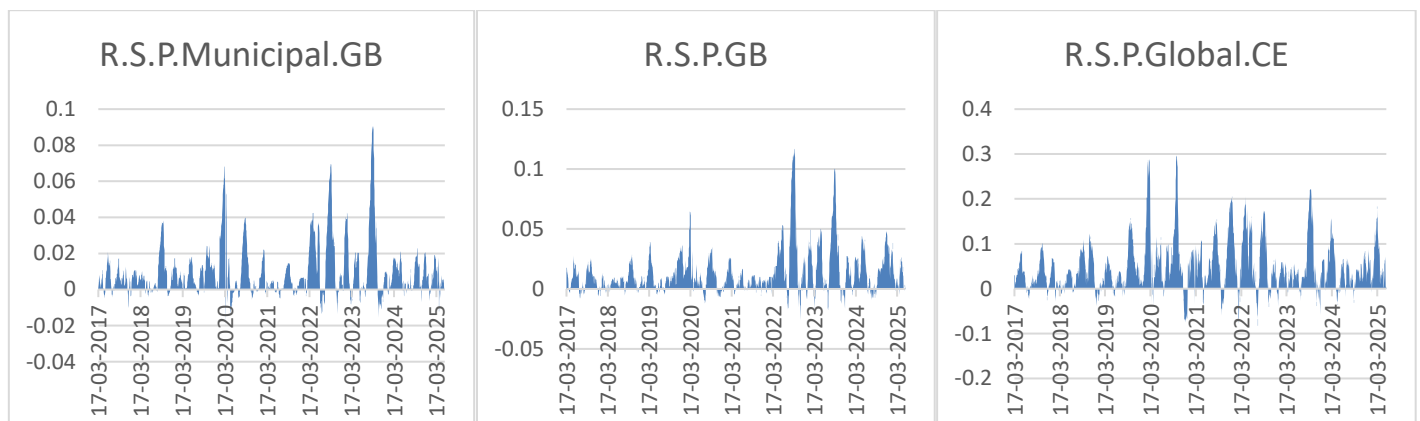


Fig. 1 Volatility analysis of green bond indices

Source: Prepared by the authors

Figure 2 illustrates the evolution of risk measures for the major financial market indices over the study period, revealing pronounced risk dynamics that vary over time and common reactions to episodes of major global shocks. The S&P GSCI Natural Gas Index and the S&P 500 Energy sector exhibit the highest risk volatility, with frequent and sharp spikes, particularly during the COVID-19 pandemic and post-2021 energy and geopolitical tensions, reflecting their high sensitivity to supply-demand imbalances and disruptions in the energy market. Equity-based indicators, represented by

the MSCI World and S&P 500 indices, exhibit relatively moderate but persistent fluctuations in risk, with notable increases during periods of heightened global uncertainty. The Dow Jones Commodity Index exhibits sporadic risk spikes linked to commodity price cycles, while the S&P 500 Bond Index remains relatively more stable, despite temporary spikes in risk during periods of systemic stress.

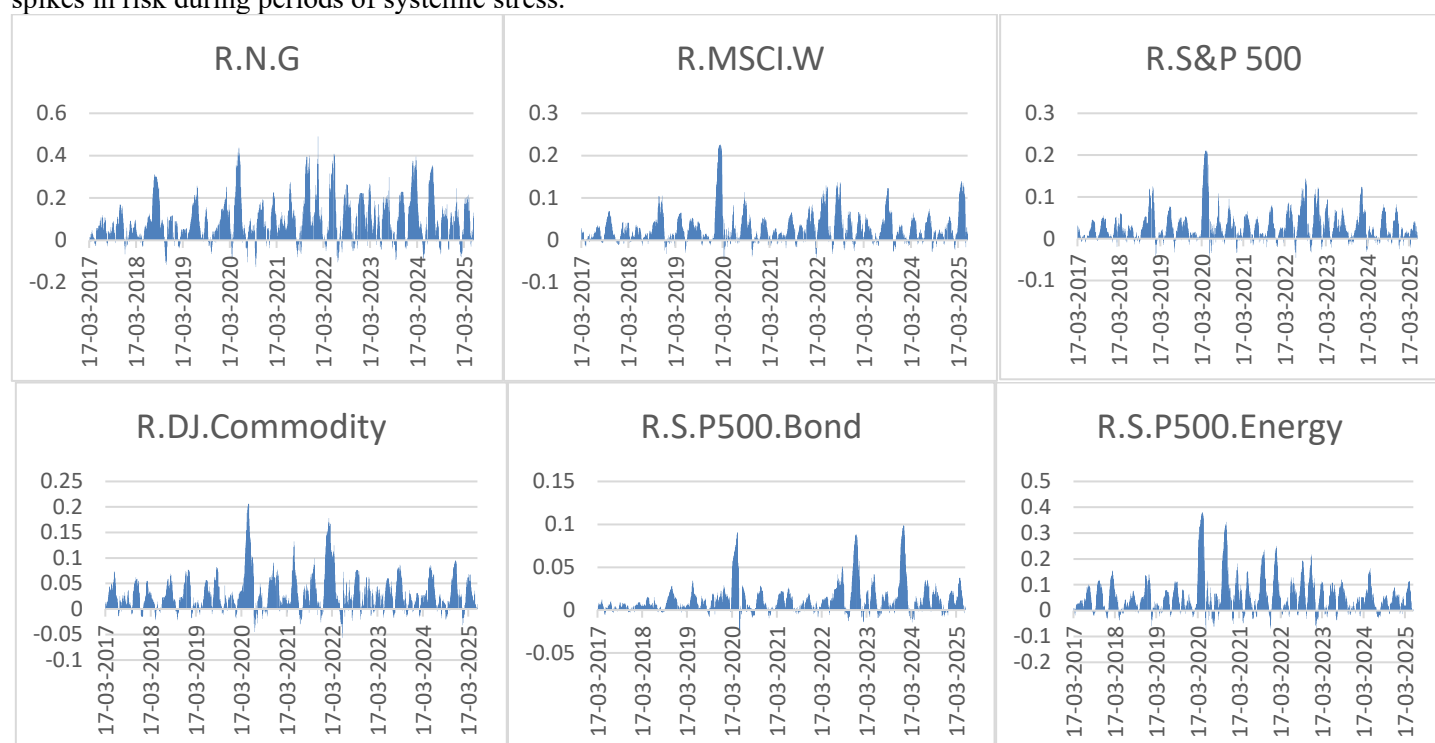


Fig. 2 Volatility analysis of financial instability indicators

Source: Prepared by the authors

3.3 Connectivity Analysis

Table 2 presents the time-invariant structure of contagion risks and the links between financial market instability indicators and risks associated with the green bond market, estimated within the TVP-VAR connectivity framework using risk measures based on the CMAX model. The results reveal a moderate but economically significant level of systemic interconnectedness, as reflected by the total connectivity index (TCI) of 37.82%, indicating that more than one-third of the variance in forecast errors in the system is attributable to risk transmission across markets rather than market-specific innovations. When market-specific effects are taken into account, the corrected total connectivity index (cTCI) rises to 42.55%, highlighting the existence of significant systemic risk links between markets. The diagonal elements of the connectivity matrix reflect the impact of market-specific risks, which remain relatively high for all indices, underscoring the importance of market-specific risk dynamics. In contrast, the off-diagonal elements represent bilateral directional spillovers, revealing significant interdependencies between risks in traditional financial markets, commodity-related volatility indicators, and green bond market risks.

An analysis of directional connectivity measures provides a better understanding of markets' heterogeneous exposure to systemic risk. The "FROM" column summarizes the extent to which each market absorbs the spillover effects of risk from the rest of the system. The results indicate that risk associated with the Dow Jones Commodity Index (45.47%), the S&P Global Clean Energy Select Index (43.84%), the S&P Green Bond Index (42.03%), and the S&P 500 Index (42.97%) are among the most exposed to external shocks, reflecting their heightened sensitivity to instability in the network as a whole. It should be noted that green bond indices exhibit significant exposure to the spillover effects of risks in financial markets, suggesting that sustainable financial markets are closely integrated into the broader network of financial risks. However, the S&P U.S. Municipal Green Bond Index exhibits relatively low exposure to shocks (41.20%), indicating a relatively higher degree of insulation and diversification benefits.

In addition, the "TO" line reflects the extent of risk contagion transmitted by each market to the rest of the system and identifies the main sources of systemic risk propagation. The S&P 500 Energy Sector Risk (54.92%) and the MSCI World Risk Indicator (51.02%) emerge as the most influential shock vectors, highlighting their central role in the spread of financial instability across markets. Green bond markets also play an active role in risk transmission, with the S&P U.S. Municipal Green Bond Index (36.84%), the S&P Green Bond Index (33.32%), and the S&P Global Clean Energy Select Index (30.52%) contributing significantly to system-wide repercussions. NET connectivity measures further clarify this dynamic: positive values identify net risk transmitters, such as the MSCI World Index, the S&P 500 Energy sector, and the S&P 500, while negative values indicate net receivers, including commodity-related risk indicators and green bond indices.

Table 2 Mean connectivity results

Variables	R.N. G	R. MSCI. W	R.S. P500	R.DJ. Commodity	R.S. P500.Bond	R.S. P500.Energy	R.S.P. Municipal.G B	R.S.P.G B	R.S.P. Global.C E	From
R.N. G	71.49	4.47	3.72	4.40	3.49	3.10	2.61	2.84	3.88	28.51
R. MSCI.W	4.88	67.96	3.89	3.02	2.95	3.56	5.23	4.68	3.84	32.04
R.S. P500	4.04	6.34	57.03	3.90	6.52	15.33	2.15	2.24	2.45	42.97
R.DJ. Commodity	3.81	3.20	9.79	54.53	2.35	17.33	2.71	3.09	3.17	45.47
R.S. P500.Bond	3.08	2.98	3.72	4.02	73.11	3.55	3.13	3.69	2.71	26.89
R.S. P500.Energy	3.28	4.41	13.90	5.00	3.86	62.53	2.75	2.36	1.91	37.47
R.S.P. Municipal.GB	3.79	8.32	2.96	3.07	3.73	4.21	58.80	7.87	7.24	41.20
R.S.P.GB	2.59	6.80	4.03	2.96	3.57	4.25	12.53	57.97	5.30	42.03
R.S.P. Global.CE	2.90	14.50	4.45	3.60	2.52	3.59	5.72	6.55	56.16	43.84
TO	28.37	51.02	46.47	29.98	28.99	54.92	36.84	33.32	30.52	340.41
Inc.Own	99.86	118.98	103.5 1	84.50	102.11	117.45	95.64	91.29	86.67	cTCI / TCI
NET	-0.14	18.98	3.51	-15.50	2.11	17.45	-4.36	-8.71	-13.33	42.55/37. 82
NPT	4.00	7.00	4.00	4.00	4.00	5.00	1.00	4.00	3.00	

Source: Prepared by the authors

Bloomberg Barclays Euro Aggregate Treasury Total Return Index Value Unhedged EU (Treasury-EU), l'indice Bloomberg Barclays Euro Aggregate Corporate Total Return Index Value Unhedged EU (Corporate-EU), l'indice Bloomberg Barclays Pan-European High Yield Total Return Index Value EUR (High Yield-EU)

3.4 Total Connectivity Index (TCI)

The Total Connectivity Index (TCI) shown in Figure 3 reflects the extent and dynamic evolution of shock transmission within the financial market instability and green bond risk system, as estimated using the TVP-VAR connectivity framework. The black-shaded area indicates the overall level of connectivity, which reflects positive and negative spillovers between markets. A key feature of the figure is the pronounced behavior of the TCI, which varies over time, confirming that the interconnection between financial instability indicators and green bond risks is inherently dynamic rather than static. Over the entire sample period, from March 2017 to June 2025, the TCI remains at relatively high levels and fluctuates within a wide range, indicating a significant degree of systemic integration. This suggests that shocks originating from financial market risk factors are rapidly transmitted to green bond markets and vice versa, underscoring the importance of adopting a dynamic connectivity framework rather than measures that remain constant over time.

Furthermore, Figure3 shows sharp increases in total connectivity during major episodes of global tension. A pronounced increase in the TCI is observed at the beginning of 2020, coinciding with the onset of the COVID-19 pandemic, reflecting heightened uncertainty and intensified spillover effects on financial instability indicators and green bond risks. High levels of connectivity persist during the subsequent recovery phase, indicating that the pandemic generated lasting interdependencies within the system. Further fluctuations and sporadic spikes appear in 2022–2023, corresponding to the intensification of geopolitical tensions following the conflict between Russia and Ukraine and the tightening of global financial conditions. These events are accompanied by a further intensification of contagions, suggesting that financial market instability constitutes a key transmission channel influencing the dynamics of green bond risks during times of crisis.

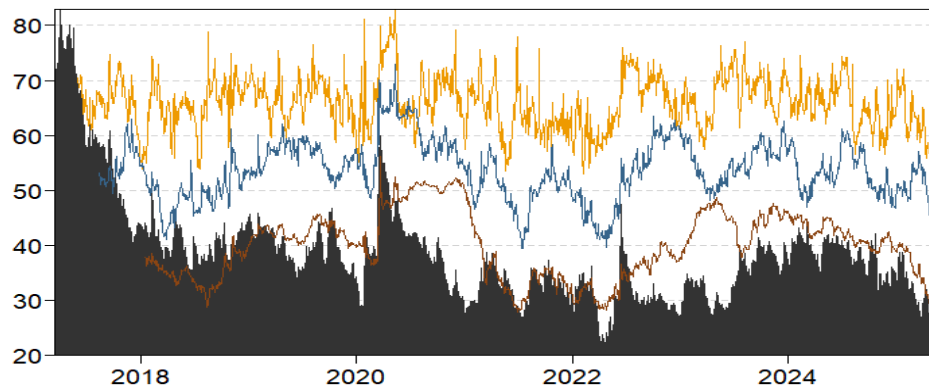


Fig. 3 Total Connectivity Index (TCI)

Source: Prepared by the authors

3.5 Dynamic net directional connectivity (NET effects)

Figure 4 illustrates the dynamic net directional connectivity (NET spillovers) derived from the TVP-VAR connectivity framework, which measures the difference between the shocks transmitted by each market to the system and the shocks received from the system. This figure shows that conventional financial market risk indicators, particularly those related to equity, energy, and commodity markets, such as the S&P 500, the S&P 500 Energy Index, the natural gas market, and the Dow Jones Commodity index, often appear as persistent net transmitters of shocks. Their net contagion measures exhibit pronounced positive peaks during periods of heightened global uncertainty, notably around the COVID-19 pandemic in 2020 and the conflict between Russia and Ukraine beginning in 2022. These findings underscore the central role of financial market instability in the propagation of systemic risk across asset classes. In contrast, financial risk indicators related to bonds tend to show negative net connectivity during relatively calm periods, suggesting a partial shock-absorbing or stabilizing function within the system.

In contrast, risk indices related to green bonds and clean energy exhibit a more moderate, yet economically significant, pattern of net spillover effects. The S&P Green Bond Index sometimes acts as a net transmitter of shocks, particularly during periods marked by heightened volatility and increased focus on sustainable finance, reflecting its growing importance in the global financial system. Furthermore, the S&P U.S. Municipal Green Bond Index and the S&P Global Clean Energy Select Index more often act as net shock receivers, reflecting their sensitivity to financial market instability originating from conventional markets.

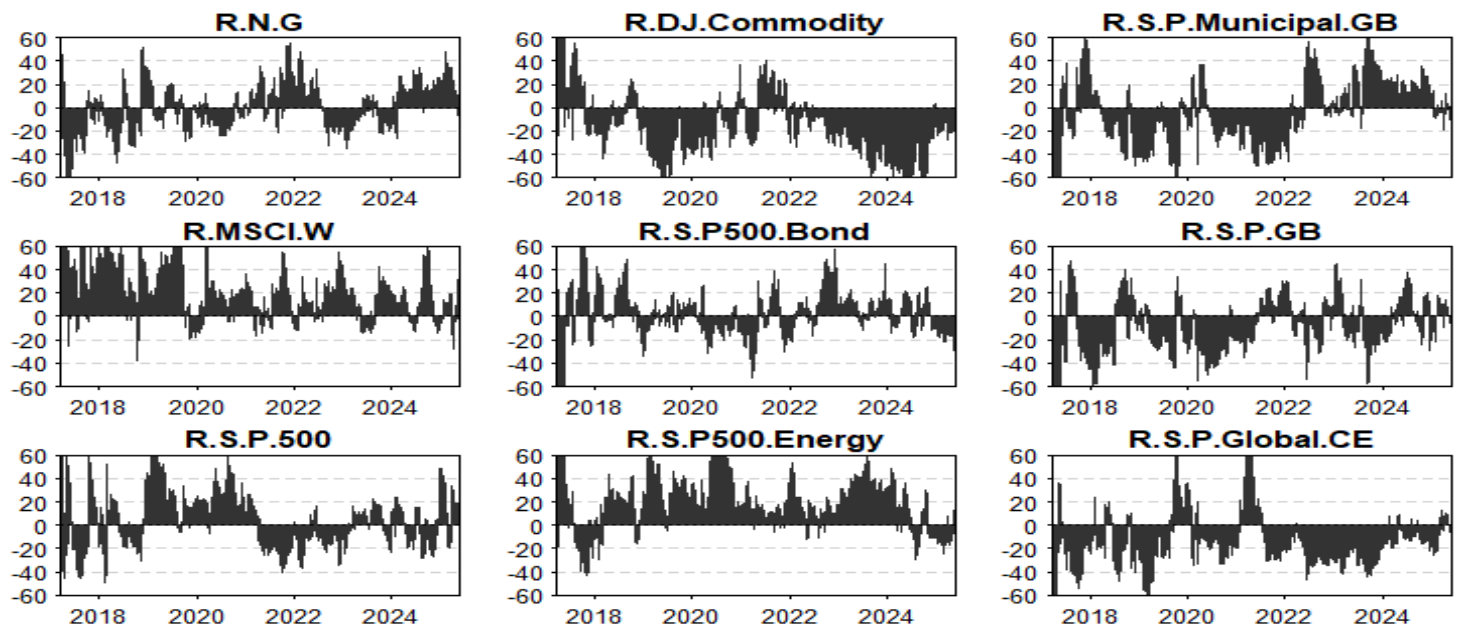


Fig. 4 Dynamic Net Directional Connectivity (NET)

Source: Prepared by the authors

3.6 Net Dynamic Directional Connectivity by Pairs (PAIR)

Figure 5 illustrates the dynamic patterns of net directional connectivity between financial market volatility indicators and green bond indices, where positive (negative) values indicate that the first market in each pair acts as a net transmitter (receiver) of shocks. It is interesting to note that measures of instability related to energy and commodities, particularly natural gas, the S&P 500 energy sector, and the Dow Jones Commodity Index, frequently dominate green bond indices across most sub-periods, particularly during periods of heightened uncertainty such as the COVID-19 pandemic (2020) and the conflict between Russia and Ukraine (beginning in 2022). During these periods, volatility increases significantly, reflecting sudden shifts in the direction and magnitude of impacts as energy price shocks and supply-side disruptions spillover into green bond and clean energy markets. Conversely, green bond indices, notably the S&P U.S. Municipal Green Bond Index, are more often in a net receiving position, suggesting that volatility stemming from financial markets and conventional commodities tends to outweigh the feedback effects of the green finance segment during periods of systemic stress. Nevertheless, this figure also reveals heterogeneous and sometimes symmetrical bilateral relationships between certain pairs, particularly those involving the S&P Green Bond Index and the S&P Global Clean Energy Index. Over several sub-periods, the net trajectories of spillovers fluctuate around zero, indicating a near-equilibrium between transmitted and received shocks and implying mutual interaction rather than clear dominance.

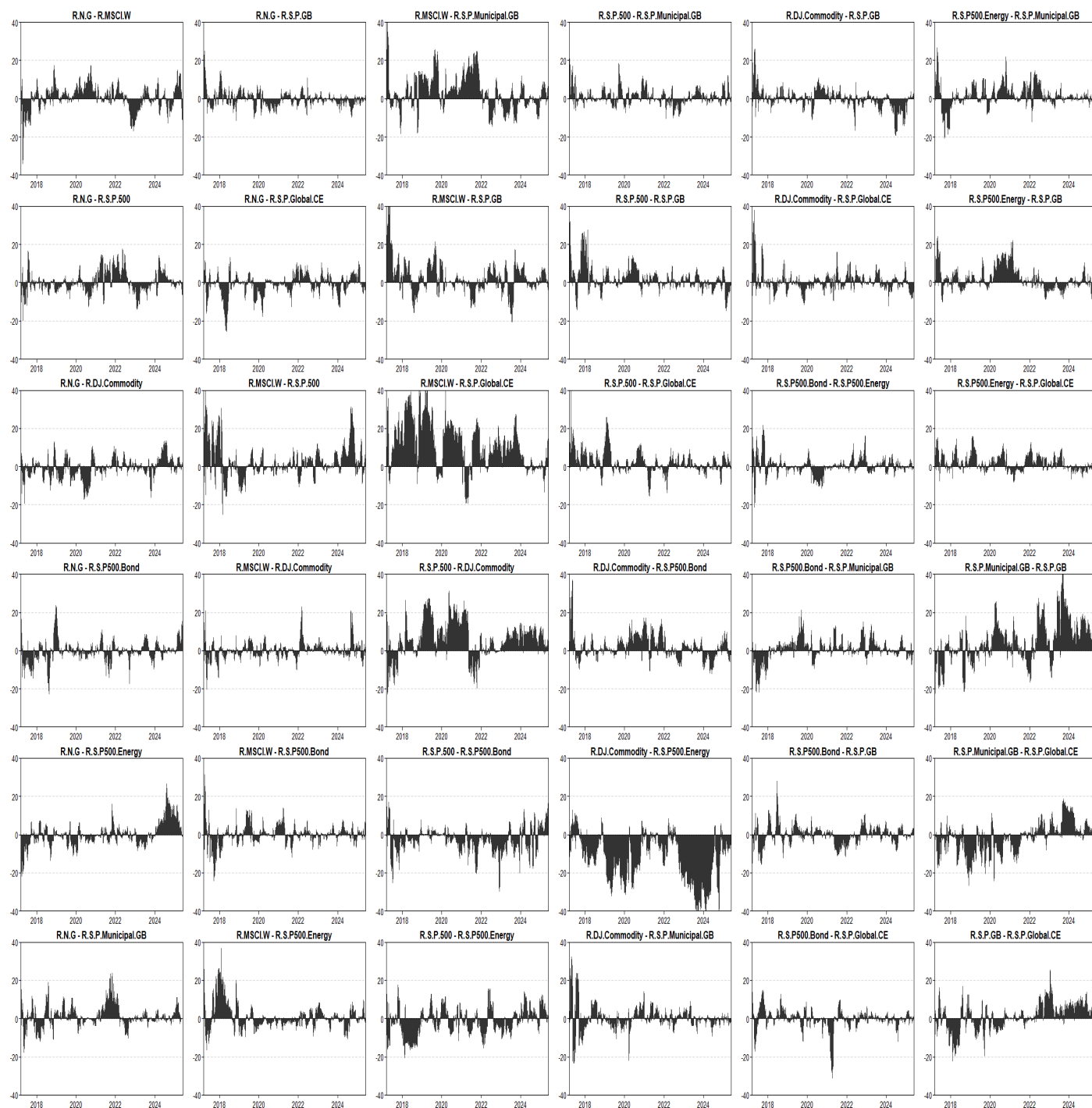


Fig. 5 Net dynamic directional connectivity by pairs (PAIR)

Source: Prepared by the authors

3.7 Network diagram illustrating the effects of price volatility.

Figure 6 presents a network diagram illustrating the static links between financial market instability indicators and green bond indices, based on pairwise directional spillovers. The network structure reveals that financial markets and traditional commodity markets, particularly the energy sector of the S&P 500, the S&P 500, the MSCI World Index, and the Dow Jones Commodity Index, are the primary vectors for the propagation of instability throughout the system. These markets occupy a central position in the network and exert a strong influence on other nodes, highlighting their dominant role in the propagation of shocks. In contrast, green bond indices and clean energy-related assets, notably the S&P Green Bond Index, the S&P U.S. Municipal Green Bond Index, and the S&P Global Clean Energy Index, are primarily positioned as recipients of spillovers, indicating greater sensitivity to shocks originating from financial and energy markets more broadly. It is worth noting that the S&P Green Bond Index has a relatively larger node size than other green assets, suggesting a higher degree of integration and responsiveness within the interconnected system.

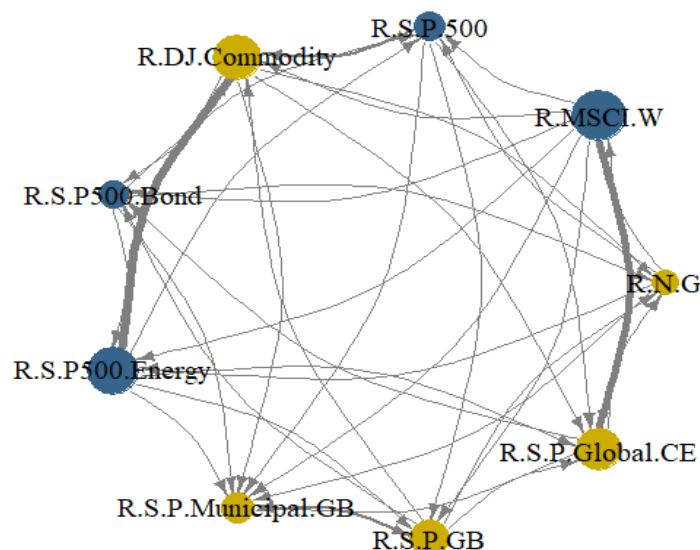


Fig. 6 Network diagram illustrating the effects of price volatility.

Source: Prepared by the authors

4. Conclusion

This study examines the dynamic mechanisms of connectivity and spillover transmission between conventional financial markets and green financial instruments, with a particular focus on green bond markets. Adopting a time-varying analytical framework, the research aims to identify the magnitude, direction, and evolution of return spillovers between markets, particularly during major global crises such as the COVID-19 pandemic and the conflict between Russia and Ukraine. In doing so, the study contributes to a better understanding of how sustainable financial instruments interact with traditional financial markets under varying market conditions and in the event of systemic stress.

Empirical results indicate that the spillover effects in terms of returns across the markets examined are substantial, highly variable over time, and strongly sensitive to periods of heightened uncertainty. The total connectivity index increases significantly during periods of crisis, reflecting greater market integration and amplified shock transmission. Conventional financial markets, particularly equity, energy, and commodity indices, consistently emerge as the primary net transmitters of shocks, while green bonds and clean energy indices act primarily as net receivers. This asymmetry suggests that, despite their distinct objectives and sustainability focus, green financial assets remain closely linked to traditional financial systems and are not immune to external financial disruptions.

These findings have significant implications for both policymakers and investors. From a policy perspective, the high degree of integration of green bond markets into conventional financial systems underscores the need to establish supportive regulatory frameworks that enhance market depth, liquidity, and resilience, particularly during times of market turmoil. For investors, the findings suggest that while green bonds can contribute to portfolio diversification when markets are calm, their hedging potential diminishes during periods of systemic crisis, underscoring the importance of dynamic risk management and adaptive asset allocation strategies.

The contribution of this research lies in enriching the literature on sustainable finance by providing time-varying evidence on the dynamics of spillover effects between green and conventional financial markets. Unlike static approaches, the methodology adopted captures the evolving nature of market interdependence and offers a more realistic view of how shocks propagate through financial systems over time. Furthermore, by jointly examining several crisis episodes, the study extends existing empirical work and improves the understanding of green bond behavior under extreme market conditions. Despite these contributions, certain limitations should be acknowledged. The analysis focuses on a specific set of global indices and primarily examines the impact on returns, excluding other relevant dimensions such as volatility, liquidity, and higher-order risk measures. Future research could address these limitations by incorporating nonlinear and frequency-domain approaches, expanding the sample to include green financial instruments at the regional or firm level, and explicitly examining the role of institutional arrangements, economic policy uncertainty, and climate-related risks in the dynamics of spillovers between sustainable and conventional financial markets.

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