



# “Interconnections and volatility transmissions between green equities and green bonds: A dynamic modeling approach”

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## ARTICLE INFO

Hajer Beyrem and Nasreen Khan (2026). Interconnections and volatility transmissions between green equities and green bonds: A dynamic modeling approach. *Investment Management and Financial Innovations*, 23(2), 276-289. doi:[10.21511/imfi.23\(2\).2026.21](https://doi.org/10.21511/imfi.23(2).2026.21)

## DOI

[http://dx.doi.org/10.21511/imfi.23\(2\).2026.21](http://dx.doi.org/10.21511/imfi.23(2).2026.21)

## RELEASED ON

Monday, 25 May 2026

## RECEIVED ON

Tuesday, 09 December 2025

## ACCEPTED ON

Monday, 11 May 2026

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## JOURNAL

"Investment Management and Financial Innovations"

## ISSN PRINT

1810-4967

## ISSN ONLINE

1812-9358

## PUBLISHER

LLC “Consulting Publishing Company “Business Perspectives”

## FOUNDER

LLC “Consulting Publishing Company “Business Perspectives”



NUMBER OF REFERENCES

**36**



NUMBER OF FIGURES

**6**



NUMBER OF TABLES

**5**

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## BUSINESS PERSPECTIVES



LLC "CPC "Business Perspectives"  
Hryhorii Skovoroda lane, 10,  
Sumy, 40022, Ukraine  
[www.businessperspectives.org](http://www.businessperspectives.org)

**Type of the article:** Research Article

**Received on:** 9<sup>th</sup> of December, 2025

**Accepted on:** 11<sup>th</sup> of May, 2026

**Published on:** 25<sup>th</sup> of May, 2026

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# INTERCONNECTIONS AND VOLATILITY TRANSMISSIONS BETWEEN GREEN EQUITIES AND GREEN BONDS: A DYNAMIC MODELING APPROACH

## Abstract

The growing integration of global financial markets has sparked a greater interest in understanding the behavior of green financial assets, particularly in green equities and green bonds. This study aims to investigate the dynamic interconnections and volatility transmission between green equities (Clean Energy Index, Electric Vehicles Index, Global Water Index, and Renewable Clean Technology Index) and green bonds. The analysis covers the period from September 30, 2015, to October 1, 2025, including periods of both turbulence and stability. The study employs the DCC-GARCH model to capture the dynamic correlations, which is further enhanced by the Time-Varying Parameter Vector Autoregressive (TVP-VAR) model to examine time-varying interconnections. The empirical results reveal that the strength and direction of connectedness are highly time-dependent, intensifying during periods of market turbulence and geopolitical uncertainty. The Energy Index acts as a significant net transmitter (+5.69%), indicating its substantial influence on other green asset classes. However, the green bond index appears to be a net receiver (-4.67%), endorsing its position as a safe-haven asset. These findings offer important implications for portfolio diversification and risk management in the green financial market, especially during periods of economic and financial stress. In addition, this study provides policymakers and investors with valuable insights to enhance their understanding of evolving sustainable financial markets.

## Keywords

spillovers, volatility, TVP-VAR, green equities, green bonds

## JEL Classification

G12, G15, C58, Q56

## INTRODUCTION

The rising global importance of sustainable finance has spurred the growth of green financial instruments, particularly green bonds and green equities. These instruments provide a sustainable investment solution for growing environmental challenges, including climate change, resource depletion, and biodiversity loss. As financial markets respond to these associated risks, investors are increasingly directing their capital towards eco-friendly assets (Gargallo et al., 2024; Yousfi & Bouzgarrou, 2025). Emphasizing the importance of green financial instruments, international initiatives, such as the United Nations Sustainable Development Goals, guide the allocation of capital toward projects that promote climate action, clean energy, and resource efficiency. These factors collectively position green finance as a key mechanism for mobilizing capital toward sustainable development.

In 2024, the global clean energy market experienced significant growth, reaching an estimated value of USD 2.1 trillion. This marked a notable increase from previous years, driven by substantial investments in renewable energy technologies, electrified transport, and en-



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### Conflict of interest statement:

Author(s) reported no conflict of interest

ergy storage. However, the issuance of green bonds has increased noticeably, reflecting rapid growth. In 2024, global green bond issuance reached approximately USD 670 billion, marking an 8% increase from the previous year (CBI, 2024).

Green stocks, which represent equity in companies engaged in renewable energy, clean technology, sustainable transportation, or resource management, offer exposure to sectors driving the low-carbon transition and technological innovation. Their inclusion in portfolios provides opportunities for growth and diversification, especially as green industries are supported by policy incentives and rising demand for sustainable solutions. By contrast, green bonds are fixed-income instruments in which the funds raised are earmarked for projects with a positive environmental impact, such as clean energy infrastructure, energy efficiency, or sustainable water management.

Although the literature on green finance is growing, the interconnections and volatility transmission between green equities and green bonds remain underexplored. Prior studies have mainly examined the interconnectedness and spillover effects between traditional stock and commodity markets and a wide range of green financial instruments, overlooking time-varying interactions during periods of global economic and geopolitical events.

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## 1. LITERATURE REVIEW AND HYPOTHESES

Over the past decades, the growing integration of global financial markets has sparked greater interest in understanding the interconnections among asset classes. Fluctuations in one market can quickly spread to others, amplifying systemic risk and affecting diversification strategies (Mensi et al., 2022; Arif et al., 2021). The increased focus on green assets has led to rapid growth and intricate interconnections with other asset classes. In line with this, green stocks and green bonds have emerged as the key components of green financial assets. They are now recognized as attractive investment options because they enable investors to seek financial returns while supporting environmental sustainability goals (Dutta et al., 2020; Hoque & Batabyal, 2022; Arif et al., 2022; Ferreira et al., 2018; Mensi et al., 2022; Li et al., 2024; Umar et al., 2024).

Recent studies have increasingly emphasized that green bonds are valuable tools for managing risk and diversifying portfolios. Reboredo (2018) shows that green bond prices respond strongly to disturbances coming from both corporate and Treasury fixed-income markets; however, even pronounced volatility in stock and energy markets seems to exert negligible influence on green bond prices. Pham and Nguyen (2021) underscore the role of green bond markets as effective diver-

sification tools and safe-haven assets. Naeem et al. (2022) find a highly negative tail dependency between green bonds and specific energy resources, while also observing a marked positive tail dependency with natural gas. According to Arif et al. (2021), the relationship between green and conventional investments is not particularly strong, and these links are more noticeable in the short term. In addition, the study also found that during the COVID-19 subsample, connectedness increased, suggesting that crisis periods reduce the decoupling between green and conventional markets. Alongside the growing literature on green bonds, increasing attention has been given to green equities, which are highlighted as another key component of sustainable financial markets. Green stocks, which represent equity in companies engaged in renewable energy, clean technology, sustainable transportation, or resource management, offer exposure to sectors driving the low-carbon transition and technological innovation. Their inclusion in portfolios provides opportunities for growth and diversification, especially as green industries are supported by policy incentives and rising demand for sustainable solutions. For instance, Dawar et al. (2021) assess the linkage between the prices of crude oil and renewable energy stock under normal market conditions and provide strong evidence that clean energy stock returns are becoming less dependent on crude oil returns. Hoque and Batabyal (2022) reveal the role of carbon futures as a safe-haven

instrument in extreme market conditions, whereas clean energy stocks possess a limited hedging capability. Khalfaoui et al. (2022) highlight that the global clean energy markets emerge as the dominant transmitters of information spillovers in depressed market environments. Ziadat et al. (2024) examined how the frequency of investments in clean energy and global stock markets is interrelated and found that under normal and bullish market states, spillovers are predominantly short-run, whereas during market downturns, they persist into the medium and long term. Mensi et al. (2024) demonstrate that overall connectedness between green bonds and renewable energy increases substantially under extreme market regimes.

A substantial body of literature has also explored how shocks are transmitted across markets through connectedness and volatility spillovers. For example, Pham (2016) finds that shocks in the conventional bond market often spill over into the green bond market, with the spillover varying over time. As noted by Ferrer et al. (2021), green bonds have strong connectedness with treasury bonds and investment-grade corporate bonds, reflecting many shared characteristics (fixed-income nature, issuer quality, regulatory features). Jovović and Popović (2025) highlight the role of green bond markets as effective diversification instruments and potential safe-haven assets.

While earlier research mainly examined the interconnectedness and spillovers between stock, commodity markets, and various categories of green financial assets, our study provides a fresh perspective. The purpose of this study is to examine the time-varying interconnectedness and spillover dynamics between green bonds and sectoral green stock markets, encompassing renewable energy, green transportation, resource management, and green technology over a 10-year period. This gives insight into their dynamic interconnectedness during periods of both turbulence and stability. Sectoral green equities are effectively proxied through thematic indices, such as the S&P Global Clean Energy Transition Index (renewable energy), the S&P Electric Vehicles Index (green transportation), the S&P Global Water Index (resource management), and the S&P/TSX Renewable Clean Technology Index (green technology).

These indices enable a sectoral decomposition of green equity markets, thereby capturing the distinct roles of the energy, transportation, technology, and utilities sectors in driving the dynamics of the green transition. To investigate connectedness and spillover effects, the study employs the DCC-GARCH model, which is further enhanced by the TVP-VAR model. The key advantage of the TVP-VAR approach is its ability to adapt to evolving dynamics, structural changes, and time-varying volatility, making it more reliable than fixed-parameter models for analyzing economies and financial markets. Unlike traditional static VAR models, which assume constant relationships among variables over the entire sample period, the Time-Varying Parameter VAR framework allows model coefficients and shock variances to evolve gradually over time. This flexibility is particularly valuable in financial markets, where structural changes, policy interventions, and crises often alter the interdependence between variables (Primiceri, 2005; Cogley & Sargent, 2005). By capturing such temporal dynamics, the TVP-VAR model provides a more realistic representation of volatility transmission and spillover effects. It enables the estimation of time-varying connectedness measures and impulse-response functions that reflect how market linkages intensify during turbulent periods and weaken during calm phases (Antonakakis & Gabauer, 2017; Diebold & Yilmaz, 2014). Consequently, the TVP-VAR framework offers richer insights into the evolution of systemic risk and market interdependence than its static counterpart, improving both interpretability and forecasting accuracy in environments characterized by structural instability.

The study aims to investigate the interconnectedness and spillover dynamics among green financial assets; accordingly, the following hypotheses are proposed:

- H1: *The conditional correlations are extremely responsive to financial and pandemic times.*
- H2: *The green bond market acts as a net receiver of shocks.*
- H3: *The net transmitter-receiver roles of markets vary over time and intensify during periods of heightened uncertainty.*

## 2. DATA AND METHODOLOGY

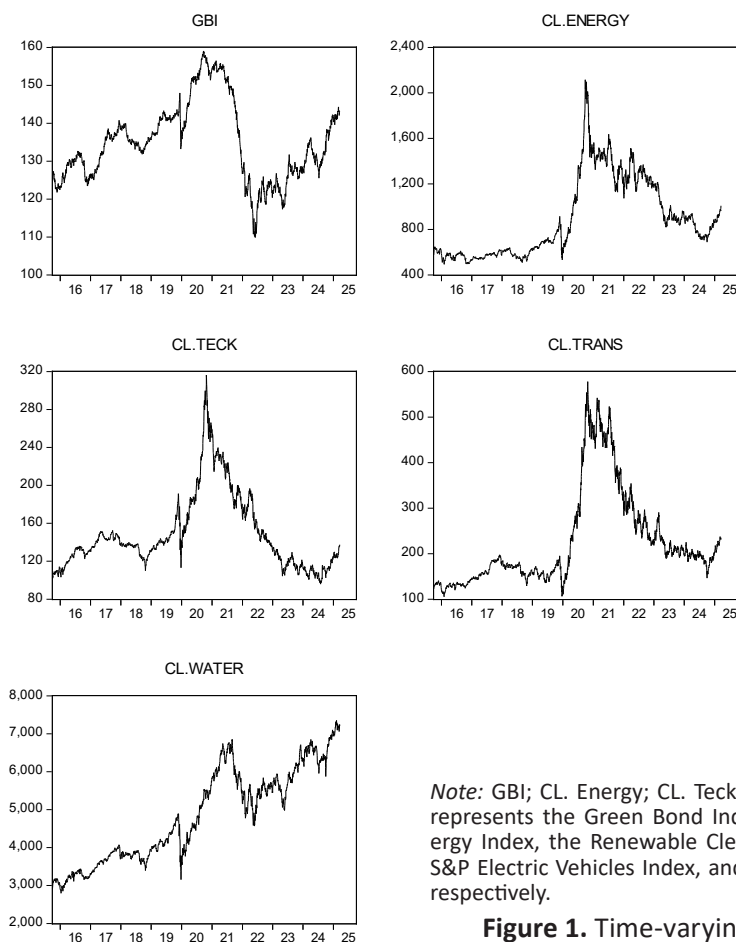
### 2.1. Data and preliminary analysis

The study employs ten years of daily data, covering the period from September 30, 2015, to October 1, 2025, obtained from the S&P Global website, to examine the dynamic interconnections and volatility transmission between green equities and green bonds. This allows us to capture a range of significant events, including the Chinese economic downfall, the COVID-19 pandemic, and the Russia–Ukraine war.

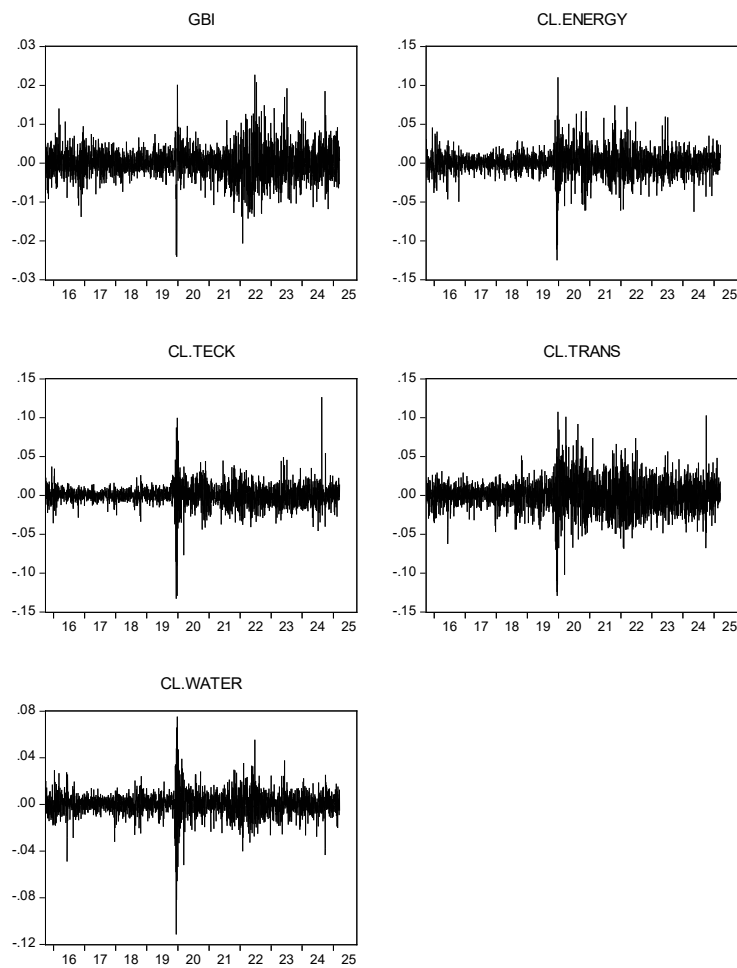
Our dataset comprises daily closing prices for the S&P Green Bond Index, tracking the global green bond market. In addition, four green equities markets are proxied by thematic indices, namely the S&P Global Clean Energy Transition Index (renewable energy), the S&P Electric Vehicles Index (green transport), the S&P Global Water Index (resource manage-

ment), and the S&P/TSX Renewable Clean Technology Index (green technology). These indices enable a sectoral decomposition of green equity markets, thereby capturing the distinct roles of the energy, transportation, technology, and utilities sectors in driving the dynamics of the green transition.

To better visualize data dynamics, Figure 1 depicts the time-varying behavior of green prices. We calculate logarithmic returns of the data series, as displayed in Figure 2. These patterns suggest a range of significant events, including the Russia–Ukraine war, and particularly the COVID-19 pandemic waves in 2020 and 2021, making them appropriate for GARCH family models. These uncertain periods would undoubtedly impact financial assets, changing the degree of spillover between them, which would redefine the function of each asset. Thus, all the green markets have been profoundly affected by global economic and geopolitical events.



**Figure 1.** Time-varying price dynamics



**Figure 2.** Logarithmic returns series

Table 1 shows the summary statistics of the return series and the augmented Dickey–Fuller (ADF) test. The mean values of all the variables are positive. The Clean Energy Index and Clean Transport Index are the most volatile markets. Conversely, the Green Bond Index is the least volatile market. According to the skewness statistic, the negative values indicate that almost all the variables are left skewed, reflecting higher downside risk and

a greater likelihood of extreme losses. The kurtosis value is greater than 3 for all variables. The presence of heavier tails signals implies that outlier events occur more frequently. The Jarque-Bera (JB) statistics are significant, reasserting the rejection of the normality hypothesis. Finally, the ADF test indicates that the data series has a unit root. The LM-ARCH test (Table 2) indicates the presence of significant autoregressive conditional het-

**Table 1.** Summary statistics of return series

Variables Statistics	GBI	CL.ENERGY	CL.TECK	CL.TRANS	CL.WATER
Mean (%)	0.0056	0.0226	0.0119	0.0259	0.0365
Std. Dev.	0.0038	0.0154	0.0134	0.0201	0.0102
Skewness	-0.0327	-0.3287	-0.4178	-0.1614	-0.7171
kurtosis	6.9783	10.407	19.173	6.6875	16.166
JB	1627***	5687***	26971***	1409***	18038***
ADF	-43.82***	-17.24***	-50.53***	-32.76***	-15.22***

Note: \*\*\* indicates significance at the 1% level.

**Table 2.** ARCH LM test statistics

Time-series	GBI	CL.ENERGY	CL.TECK	CL.TRANS	CL.WATER
ARCH-LM Test statistic	201.115***	129.529***	130.247***	123.441***	151.765***

Note: \*\*\* indicates significance at the 1% level.

**Table 3.** Linear correlation matrix: Pearson correlation

Variables	GBI	CL.ENERGY	CL.TECK	CL.TRANS	CL.WATER
GBI	1.000				
CL.ENERGY	0.3206	1.000			
CL.TECK	0.1844	0.6972	1.0000		
CL.TRANS	0.1511	0.6831	0.6590	1.0000	
CL.WATER	0.3932	0.6569	0.6093	0.6334	1.0000

eroskedasticity in the analyzed series. This constitutes a fundamental prerequisite for deploying GARCH models in volatility analysis.

Preliminary analysis of the correlation matrix (Table 3) reveals a high degree of association between the green equities (Clean Energy Index, Electric Vehicles Index, Global Water Index, and Renewable Clean Technology Index), indicating a strong positive correlation. However, the linear correlation analysis reveals that green equities maintain only modest correlations with green bonds.

## METHODOLOGY

For this study, we employ a multivariate time-series approach to assess the interconnections and volatility spillovers between green bonds and green equities. To capture this effect, we adopt the DCC-GARCH model, initially developed by Engle (2002). The Time-Varying Parameter Vector Autoregression further enhances the DCC-GARCH model to examine volatility spillovers and connectedness.

### 2.1.1. DCC-GARCH

The DCC-GARCH model traces a time-varying correlation matrix. The variance-covariance matrix,  $H_t$ , is described as

$$H_t = D_t \cdot R_t \cdot D_t, \quad (1)$$

where  $D_t$  represents the square roots of the estimated conditional variances generated by the univariate GARCH model, this implies that  $D_t$  is

a diagonal matrix that contains the conditional standard deviations, and  $R_t$  is the conditional correlation matrix.

The exponential smoothing approach discussed by Engle (2002) followed the specification of the model as

$$Q_t = S \circ (u_t' - A - B) + A \circ u_{t-1} \cdot u_{t-1}' + B \circ Q_{t-1}, \quad (2)$$

where  $Q_t$  is an  $N \times N$  symmetric positive definite variance-covariance matrix using recent shocks ( $u_{t-1} u_{t-1}'$ ); past correlation ( $Q_{t-1}$ ); and  $S$  as reverting long-run covariance.  $A$  and  $B$  are scalars following the same process for all the conditional correlations. Element-by-element matrix or Hadamard multiplication procedure is denoted by  $\circ$ , while ( $u_t = D_t^{-1} \varepsilon_t$ ) is a standardized residual and is a vector of ones.

Engle (2002) formulated a dynamic modelling  $Q_t$  with the conditional correlation matrix,  $R_t$  can be described as

$$R_t = \text{diag}(Q_t^*)^{-1} \cdot Q_t \cdot \text{diag}(Q_t^*)^{-1}. \quad (3)$$

The estimation step involves maximizing the conditional likelihood to obtain the unknown parameters associated with the dynamic correlation matrix.

The log-likelihood function is specified as follows:

$$\ell(\theta_2 | \theta_1) = \sum_{t=1}^T (\log R_t + u_t' R_t^{-1} u_t), \quad (4)$$

where  $\theta_1$  denotes all the unknown parameters that were estimated in the first stage, and  $\theta_2$  denotes all those to be estimated in the second stage. Estimation using this two-step procedure will be consistent but inefficient as a result of any parameter uncertainty from the first stage being carried through to the second (Anderson et al., 2021).

**2.1.2. TVP-VAR**

To examine the dynamic relationships and spill-over effects among green equities and green bonds, the study employs a Time-Varying Parameter Vector Autoregression (TVP-VAR) model. This approach extends the traditional VAR framework by allowing the coefficients and error variances to evolve over time, thereby capturing potential structural changes and time-varying interactions across variables (Diebold & Yilmaz, 2012). The TVP-VAR model of order  $p$  is specified as:

$$Y_t = A_{0,t} + A_{1,t}Y_{t-1} + \dots + A_{p,t}Y_{t-p} + \epsilon_t \quad (5)$$

where  $Y_t$  denotes an  $n \times 1$  vector of endogenous variables at time  $t$ .  $A_{i,t}$  are time-varying coefficient matrices and the error term  $\epsilon_t \sim N(0, \Sigma_t)$  follows a multivariate normal distribution with a time-varying covariance matrix.

To assess the degree of interdependence among variables, the study employs the H-step-ahead forecast error variance decomposition (FEVD) based on the moving average representation of the TVP-VAR model (Koop et al., 1996; Pesaran & Shin, 1998)

$$Y_t = \sum_{h=0}^{\infty} \Phi_{t,ht-h} \epsilon_{t-h} \quad (6)$$

Using the generalized framework, the contribution of shocks in variable  $j$  to the forecast error variance of variable  $i$  at horizon  $H$  is given by:

$$\theta_{ij,t}^{(H)} = \frac{\sum_{h=0}^{H-1} (e_i' \Phi_{t,h} \sum_j e_j)^2}{\sum_{h=0}^{H-1} (e_i' \Phi_{t,h} \sum \Phi_{t,h}' e_i)} \quad (7)$$

The Total Connectedness Index (TCI) is then computed as the average of the off-diagonal elements of the normalized variance decomposition matrix:

$$TCI^{(H)} = \frac{\sum_{i,j=1,i \neq j}^N \Phi_{ij,t}^{(H)}}{N} \cdot 100. \quad (8)$$

**3. RESULTS**

This section presents empirical results from the DCC-GARCH and the Time-Varying Parameter Vector Autoregressive (TVP-VAR) models, which reveal substantial time-varying correlations and connectedness dynamics among the selected green financial assets.

**3.1. DCC-GARCH results**

Using a multivariate Dynamic Conditional Correlation (DCC-GARCH) framework, the study investigates the existence and persistence of volatility spillovers between green bonds and green equity markets over both short- and long-term horizons. The results are presented in Table 4.

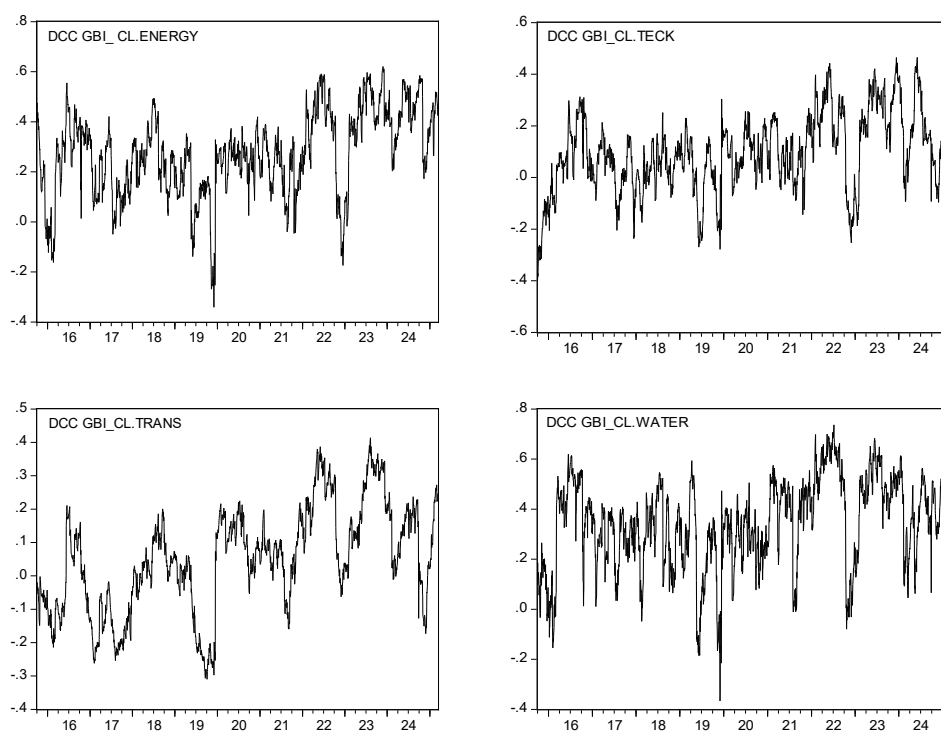
The coefficients for alpha and beta are statistically significant across all series. This indicates that the dynamic conditional correlations between assets are influenced by immediate shocks and persistent past dependence. A larger and significant beta value implies strong persistence, meaning that volatility takes longer to revert to its mean after a shock.

The estimated DCC parameters (dcca, dccb) indicate that the conditional correlations between green bond and green equity markets (Energy, Transport, Technology, and Utilities) exhibit weak short-term sensitivity to new information but strong persistence over time. The high sum of the parameters (dcca + dccb  $\approx$  1) suggests a high degree of persistence in the conditional correlations between the green bond and green equity markets. This implies that once a volatility shock occurs, its impact on the correlation structure remains significant over an extended period, indicating slow mean reversion and long-lasting interdependence between the two markets.

Figure 3 illustrates the dynamic conditional correlation between green bonds and green equity markets. As illustrated in the graph, the conditional correlations vary throughout the study period and are extremely responsive to financial and pandemic times. The increase in conditional correlations between green bonds and green equities observed during

**Table 4.** DCC-GARCH results

Variables	Coefficient	St. Error	P-value
[CL. ENERGY]. Omega	1.67 E-06	3.68E-07	0.0000
[CL. ENERGY]. Alpha	0.068240	0.005353	0.0090
[CL. ENERGY]. Beta	0.925543	0.005446	0.0000
[GBI]. Omega	8.52E-08	2.23E-08	0.0001
[GBI]. Alpha	0.047312	0.003433	0.0000
[GBI]. Beta	0.947566	0.003544	0.0000
[Corr]. dcca	0.040010	0.005183	0.0000
[Corr]. dccb	0.946873	0.006745	0.0000
[CL. TECK]. Omega	4.89E-07	1.66E-07	0.0032
[CL. TECK]. Alpha	0.082074	0.006320	0.0000
[CL. TECK]. Beta	0.920690	0.004435	0.0000
[GBI]. Omega	8.54E-08	2.35E-08	0.0003
[GBI]. Alpha	0.048203	0.003660	0.0000
[GBI]. Beta	0.946582	0.004026	0.0000
[Corr]. dcca	0.036380	0.006563	0.0000
[Corr]. dccb	0.943499	0.010901	0.0000
[CL. TRANS]. Omega	1.95E-06	6.24E-07	0.0018
[CL. TRANS]. Alpha	0.067933	0.006808	0.0000
[CL. TRANS]. Beta	0.928928	0.006615	0.0000
[GBI]. Omega	6.80E-08	2.18E-08	0.0018
[GBI]. Alpha	0.046636	0.003646	0.0000
[GBI]. Beta	0.949584	0.003927	0.0000
[Corr]. dcca	0.019473	0.004006	0.0000
[Corr]. dccb	0.972419	0.005932	0.0000
[CL. WATER]. Omega	2.51E-06	3.662E-07	0.0000
[CL. WATER]. Alpha	0.107082	0.008372	0.0000
[CL. WATER]. Beta	0.864517	0.009632	0.0000
[GBI]. Omega	1.10E-07	2.35E-08	0.0000
[GBI]. Alpha	0.046698	0.003459	0.0000
[GBI]. Beta	0.945491	0.003776	0.0000
[Corr]. dcca	0.052656	0.004779	0.0000
[Corr]. dccb	0.926672	0.007093	0.0000



**Figure 3.** Time-varying correlations estimated by the DCC-GARCH model

both the COVID-19 pandemic and especially during the Russo-Ukraine conflict indicates a temporary convergence in their return dynamics. The highest degree of correlation is found between green bonds and the Green Water Index, which shows that the two assets fail to provide mutual hedging capabilities.

During these crisis episodes, systemic risk and investor herding behavior led to a stronger synchronization between the two markets, thereby reducing diversification and hedging opportunities. This suggests that in periods of heightened uncertainty, green financial assets do not remain immune to global shocks, but rather move in tandem with broader risk sentiment.

### 3.2. TVP-VAR results

To provide a deeper understanding of the linkage direction and magnitudes between the analyzed

markets, the TVP-VAR approach was used to analyze the volatility spillover between equity, commodities, and the green bond.

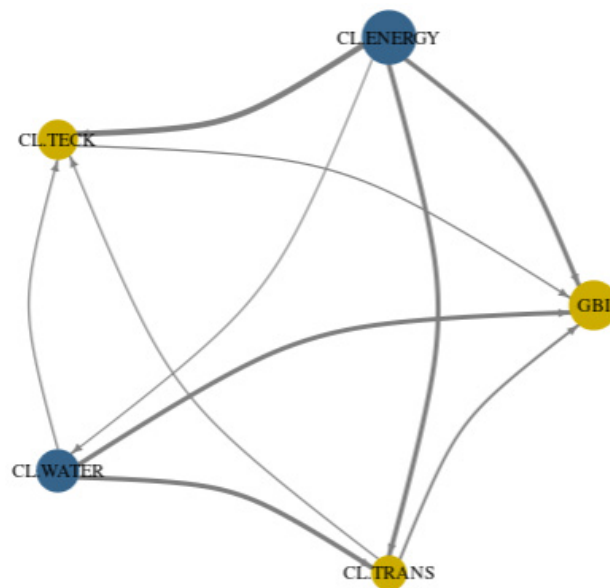
Analysis of Table 5 reveals that the average index reaches 46.27%, highlighting strong intra-green equity spillovers and a relative dependence on the green bonds index.

Strong self-dependency is observed for GBI, with diagonal values of 76.97%. Conversely, the Clean Transport Index is more sensitive to cross-market linkages, with diagonal values of 45.82%. Energy Index is stated as the primary net transmitter (+5.69%), contributing mostly to Clean transport index (18.47%), Green water (17.13%), and clean Technology (16.92%). Additionally, GBI appears to be the crucial net receiver in the system with net spillover values of -4.67%. This indicates that it is more influenced by external shocks than it transmits.

**Table 5.** TVP-VAR connectedness

Variables	GBI	CL.ENERGY	CL.TECK	CL.WATER	CL.TRANS	FROM
GBI	76.97	7.27	3.41	9.01	3.34	23.03
CL.ENERGY	5.75	45.90	14.91	16.57	16.88	54.10
CL.TECK	2.76	16.92	51.58	12.09	16.65	48.42
CL.WATER	7.45	17.13	11.42	48.35	15.65	51.65
CL.TRANS	2.41	18.47	16.04	17.26	45.82	54.18
TO	18.36	59.79	45.77	54.93	52.52	231.37
NET	-4.67	5.69	-2.65	3.28	-1.65	46.27

*Note:* The table is constructed using the TVP-VAR-based connectedness framework with one lag selected according to the BIC criterion and a 10-day forecast horizon.



**Figure 4.** Network plot

Figure 4 displays a network visualization depicting the net pairwise directional connectedness among green bonds and green equities. Each market appears as a node in the network, with node size indicating the strength of the connectedness stemming from or directed toward that market.

The graphical representation illustrates a significant level of connectedness between all markets. Clean Energy Index plays a key role as a transmitter, with four outgoing connections to GBI; CL. TRNS; CL. TECK et CL. WATER. While it is not as influential as the Clean Energy Index, the Clean Water Index position highlights its role in contributing to the interconnectedness, with three outgoing to GBI; CL. TRNS and CL. TECK. However, the clean transport index plays a dual role as transmitter and receiver of volatilities, indicating that its influence within the system is not static but varies across time and market conditions. On the other side, GBI and the clean technology index are the most prominent recipients of returns.

The net total directional connectedness (Figure 5) indicates the overall role of each market within the system. For instance, the green bond market exhibits a negative net connectedness, implying that it mainly receives shocks from other assets, whereas the clean energy sector acts as a net transmitter, being more influenced by external shocks. During periods of the COVID-19 crisis, clean water and clean technology indices often emerge as net transmitters of shocks, reflecting their domi-

nant role in propagating return spillovers across markets. However, as market conditions stabilize, these assets tend to revert to net receivers, reflecting a normalization in their interdependence and a reduced capacity to propagate shocks.

However, the Clean Transport Index became the key net receiver during periods of heightened uncertainty. These findings regarding the changing dynamics of overall connectedness in times of heightened uncertainty are consistent with evidence reported in previous studies examining a range of markets, including commodity, currency, and renewable energy (Hanif et al., 2023). These studies have shown that interconnections and interdependence change during turbulent market periods. This finding offers additional support for the view that financial markets become increasingly dynamic and complex during crisis episodes.

Figure 6 displays the Dynamic total connectedness index, which oscillated between roughly 35% and 68% from the outset of the sample period up to February 2020. In March 2020, the connectedness index experienced a pronounced spike, reaching its maximum value, approximately 80%. This occurred simultaneously with the outbreak of the COVID-19 pandemic.

Furthermore, the index showed a consistent upward trend over the period 2022–2024. The surge in levels of interconnectedness in 2022 can be attributed to the Russia–Ukraine war.

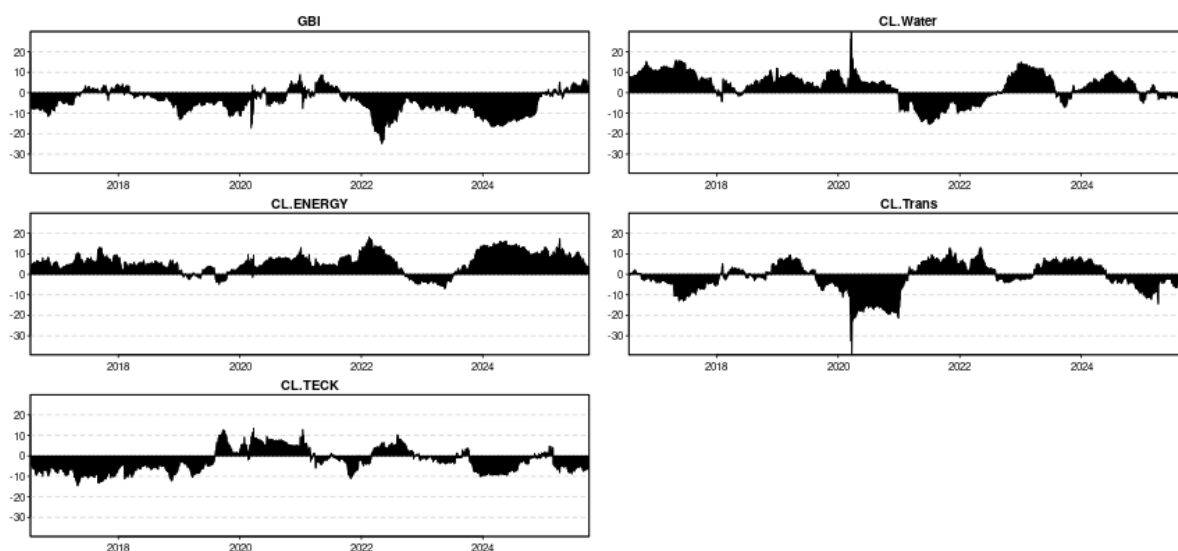


Figure 5. Net total directional connectedness



**Figure 6.** Total connectedness index (TCI) evolution

The geopolitical and economic uncertainty caused by the Russia-Ukraine conflict has important implications for the linkage between green assets. Fluctuations influence spillover behavior in renewable-energy-related equities, driven by a sharp rise in global energy prices and surges in oil and gas markets; green bonds often provide refuge during periods of elevated risk, as investors shift towards safer financial instruments. This shift in investor behavior can either strengthen or weaken the co-movement between the two asset classes. In a nutshell, the Russia-Ukraine conflict intensifies macroeconomic and financial stress, significantly reshaping spillovers and dynamic connectedness between green equities and green bonds.

The findings support H1 and H3, suggesting that the strength and direction of connectedness are highly time-dependent, intensifying during periods of market turbulence and geopolitical uncertainty. The results further confirm H2, indicating a relatively passive role of the green bond market in the connectedness network.

## 4. DISCUSSION

This paper contributes to the existing literature by shedding light on the dynamic connectedness across various green financial asset classes during a significant period of time. This fills the gap on cross-market spillovers and provides insights into potential systemic risk resilience during calm and chaotic periods. For policymakers and investors, the presence of interconnectedness implies that

investors must carefully consider the timing and flow of capital across assets to maximize diversification benefits and mitigate risks.

The results suggest a high degree of persistence in the conditional correlations between green bonds and green equity markets, indicating slow mean reversion and long-lasting interdependence between the two markets. Our results are consistent with Jovović and Popović (2025), Zhang and Umair (2023), and Chatziantoniou et al. (2021). Yadav et al. (2023) argue that the behavior and perceptions of different investor groups in relation to the analyzed markets can be attributed to evidence of long-term spillovers.

The conditional correlations vary throughout the study period and are extremely responsive to financial and pandemic times. The increase in conditional correlations between green bonds and green equities observed during both the COVID-19 pandemic and especially during the Russo-Ukraine conflict indicates a temporary convergence in their return dynamics. Indeed, during these crisis episodes, systemic risk and investor herding behavior led to a stronger synchronization between the two markets, thereby reducing diversification and hedging opportunities. This suggests that in periods of heightened uncertainty, green financial assets do not remain immune to global shocks, but rather move in tandem with broader risk sentiment. Our results are consistent with Yousfi and Bouzgarrou (2025). The authors demonstrate that the connectedness of green finance markets has been significantly impacted by the economic and financial effects of the pandemic.

Energy Index is stated as the primary net transmitter, indicating its substantial influence on other asset classes. Moreover, GBI appears to be the crucial net receiver in the system, endorsing its position as a safe-haven asset. This indicates that it is more influenced by external shocks than it transmits. During periods of the COVID-19 crisis, clean water and clean technology indices often emerge as net transmitters of shocks, reflecting their dominant role in propagating return spillovers across markets. However, as market conditions stabilize, these assets tend to revert to net receivers, reflecting a normalization in their interdependence and a reduced capacity to propagate shocks. These findings regarding the changing dynamics of overall connectedness in times of heightened uncertainty are consistent with evidence reported in previous studies examining a range of markets, including commodity, currency, and renewable energy (Hanif et al., 2023). These studies have shown that interconnections and interdependence change during turbulent market periods. This finding offers additional support for the view that financial markets become

increasingly dynamic and complex during crisis episodes.

Our results are consistent with Billah et al. (2022) and Yousfi and Bouzgarrou (2025), as both studies report pandemic-exacerbated uncertainty, systemic risk, and market volatility, leading to more pronounced correlations across international financial markets. Tiwari et al. (2023) indicate that during bullish market conditions, investors tend to take on more risk, leading to increased market co-movements.

The results provide valuable insights into the dynamics of connectedness among green assets. They help identify the key assets that either propagate or absorb shocks across markets and offer a comprehensive view of the overall interconnectedness within the financial network. Such findings are particularly useful for portfolio managers, risk analysts, and investors, as they enable a better assessment of potential contagion effects and support the design of more effective risk management and diversification strategies (Hanif et al., 2021; Hanif et al., 2023).

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## CONCLUSION

This study offers an analysis of dynamic connectedness and volatility spillover between green bonds and distinct sectors of the green equity markets, enabling investors to devise more elaborate and effective diversification and hedging strategies.

The empirical results reveal that the strength and direction of connectedness are highly time-dependent, intensifying during periods of market turbulence and geopolitical uncertainty. The green bond market exhibits a negative net connectedness, implying that it mainly receives shocks from other assets, whereas the clean energy sector acts as a net transmitter, being more influenced by external shocks. Furthermore, Clean technology indices shift from being a net absorber of spillovers to a net giver of spillovers during the COVID-19 crisis, reflecting its transition from a safe-haven asset to a driver of market uncertainty.

Indeed, our results show that both the pandemic and the geopolitical crisis significantly intensified spillovers between green equities and the green bond, leading to a marked rise in overall connectedness.

Our findings refer to the potential role of policymakers in monitoring the key contributors' assets, including green equities and green bonds, serving as crucial elements in the financial system. Furthermore, the dynamic spillover indices could be exploited to detect systemic risk in order to preserve financial stability and economic activity.

## AUTHOR CONTRIBUTIONS

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 Funding acquisition: Nasreen Khan.  
 Investigation: Hajer Beyrem.  
 Methodology: Nasreen Khan.  
 Project administration: Hajer Beyrem.  
 Resources: Nasreen Khan.  
 Software: Hajer Beyrem.  
 Supervision: Hajer Beyrem.  
 Validation: Nasreen Khan.  
 Visualization: Hajer Beyrem.  
 Writing – original draft: Hajer Beyrem.  
 Writing – review & editing: Nasreen Khan.

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