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The Brown Shadow: How Oil and Gas Shocks Dominate Green Bond Pricing Dynamics in Europe

Abstract. *This paper examines whether European green bonds display distinct pricing dynamics and risk characteristics relative to conventional corporate bonds, with emphasis on sensitivity to transition-related shocks. Using daily data from August 2023 to March 2026, we apply factor regressions, VAR models, time-varying spillover indices, and event study techniques to analyze transmission channels between bond markets, clean energy equities, and oil and gas sectors. Three findings emerge. First, green bonds underperform conventional bonds (-2.7% vs. +1.9% annualized returns) and exhibit higher volatility (3.95% vs. 2.76%), contradicting the expected "greenium." Second, although green bonds show stronger sensitivity to clean energy and oil & gas equities, both bond segments remain highly correlated (0.908), limiting diversification benefits. Third, variance decomposition indicates that about 88% of return variation in both bond types is driven by oil and gas shocks, while clean energy contributes only 10–11%. Granger causality confirms that brown sector dynamics predict bond returns.*

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Overall, results indicate that European green bonds remain strongly linked to carbon-intensive financial channels, with implications for portfolio design and transition risk assessment.

Keywords: *green bonds, transition risk, spillover analysis, vector autoregression, oil and gas sector, clean energy finance.*

JEL Classification: G12, G15, Q54, C32, G11.

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1. Introduction

The European Union has placed the green transition at the core of its economic and regulatory agenda, setting a strategic objective of achieving climate neutrality by 2050 and committing to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, as outlined in the European Green Deal. In conjunction with the Paris Agreement adopted in 2015, this initiative aims to mitigate the progression of climate change (Pörtner et al., 2022, Peiró-Palomino et al., 2025). Central to this transition strategy is the redirection of capital flows away from carbon-intensive activities and toward low-carbon investments (Zambujal-Oliveira & Duque, 2026). Green bonds have emerged as a primary financial instrument designed to channel private capital toward environmentally beneficial projects, with the European green bond market experiencing rapid growth and accounting for a substantial share of global issuance (Flammer, 2021, Wang et al., 2020, Pietrzyk et al., 2025). While the above-mentioned studies predominantly support the benefits of green bonds, the empirical evidence remains mixed, as highlighted by several contributions in the literature (Lebelle et al., 2020, Larcker & Watts, 2020, Pástor et al., 2022). Furthermore, prior research has largely concentrated on China, the United States, or broad international datasets, thereby neglecting the European setting, which is distinguished by more developed regulatory frameworks and a leading role in sustainable finance (Pietrzyk et al., 2025).

Despite this growth, as stated above, fundamental questions remain about whether green bonds function as advertised. The theoretical rationale rests on two assumptions: first, that environmental certification reduces information asymmetries and attracts dedicated demand, thereby lowering the cost of capital - the "greenium" (Zerbib, 2019, Fatica et al., 2021, Baker et al., 2022, Caramichael & Rapp, 2024, Mercuri et al., 2026); - and second, that green bonds offer diversification benefits and improved risk-adjusted returns by providing exposure to transition-aligned assets while insulating portfolios from carbon-intensive risks (Kanamura, 2020, MacAskill et al., 2021, Zhou et al., 2024).

However, empirical evidence remains mixed. Some studies document a negative green bond premium in secondary markets (Hachenberg & Schiereck, 2018, Huynh et al., 2022), while others find no significant pricing differences once liquidity and issuer characteristics are controlled for (Partridge & Medda, 2020, Flammer, 2021, Hacıömeroğlu et al., 2022). Moreover, nearly all existing studies focus on yield spreads or primary market pricing, leaving open the question of whether green bonds exhibit systematically different return dynamics, volatility patterns, and cross-market spillover mechanisms relative to conventional corporate bonds.

If green bonds do not deliver superior risk-adjusted performance and remain structurally exposed to the same financial shocks as conventional bonds, their role as effective transition finance instruments requires reconsideration. Investors relying on environmental labeling may be mispricing downside exposures. Policymakers promoting green bond frameworks may be overestimating their capacity to decouple financial markets from carbon-intensive structures (Krueger et al., 2020, Bolton & Kacperczyk, 2021).

The existing literature on green bond pricing has made important progress in identifying whether a greenium exists in primary markets and documenting determinants of yield spreads (Flammer, 2021, Şahin et al., 2025). However, three critical gaps remain. First, most studies examine yield differences at issuance but do not analyze time-series dynamics of returns, volatility, and drawdowns in secondary markets (Fatica et al., 2021). We know little about whether green bonds exhibit different risk profiles over time or whether their volatility responds differently to market stress.

Second, the literature has largely overlooked how green bonds interact with transition-related financial factors, particularly the relative performance of green versus brown equity sectors. While recent research explores co-movement between green bonds and broader equity markets or commodities (Nguyen et al., 2020, Ur Rehman et al., 2024, Aleknevičienė et al., 2025) no study has explicitly modeled and compared the sensitivities of green and conventional bonds to clean energy versus oil & gas equity performance. Given that transition risk manifests through reallocation between low-carbon and carbon-intensive sectors, understanding whether green bonds are more connected to green-versus-brown sectoral dynamics is essential.

Third, existing studies have not investigated the directionality and temporal evolution of spillovers using dynamic multivariate methods. Correlation analysis and single-equation regressions cannot distinguish whether green bonds are driven by clean energy performance or whether both respond to common shocks. Moreover, static estimates may obscure time variation in transmission mechanisms during energy price volatility or policy uncertainty (Baruník & Ellington, 2024). No prior study has employed VAR modeling, Granger causality, variance decomposition, and rolling-window spillover indices to examine the dynamic interaction between green bonds, conventional bonds, clean energy equities, and oil & gas equities in Europe.

This paper addresses these gaps by investigating three interrelated questions. First, do green bonds exhibit systematically different return, volatility, and downside risk characteristics compared to conventional corporate bonds in European secondary markets? Second, are green bonds more sensitive than conventional bonds to transition-related financial factors - specifically, to clean energy versus oil & gas equity performance - and does this differential sensitivity translate into improved risk-adjusted performance? Third, what are the direction, magnitude, and temporal evolution of cross-market spillovers, and which shocks - green or brown - dominate the variance decomposition of bond returns?

This paper contributes to the growing literature on green finance, transition risk pricing, and cross-market spillovers in several ways. First, we provide novel empirical evidence on the comparative pricing dynamics and risk profiles of green versus conventional corporate bonds in the European market over a recent and policy-relevant sample period (2023-2026). While existing studies have documented the existence of a green bond premium in primary markets or examined the determinants of green bond yields, the question of whether green bonds exhibit systematically different return-volatility characteristics and downside risk exposures relative to conventional bonds remains underexplored in the empirical literature. Our descriptive analysis reveals that, contrary to the theoretical greenium hypothesis, green bonds underperformed conventional bonds and exhibited substantially higher volatility and deeper drawdowns over the sample period, challenging the assumption that environmental credentials automatically translate into superior risk-adjusted performance. Second, we advance the literature on transition risk transmission mechanisms by directly comparing the sensitivity of green and conventional bonds to both green (clean energy equities) and brown (oil and gas equities) financial factors. Using regression analysis with robust inference and bootstrap validation, we demonstrate that green bonds display significantly stronger positive sensitivity to clean energy performance and significantly stronger negative sensitivity to oil and gas performance than conventional bonds. This differential exposure pattern confirms that green bonds are more tightly connected to the green-versus-brown transition dimension, even though both bond segments remain highly integrated within the broader corporate bond market. To our knowledge, this is the first study to explicitly quantify and compare these dual sensitivities using daily return data in a European setting.

Third, we contribute methodologically by employing a multivariate VAR framework with forecast error variance decomposition and Granger causality testing to identify the direction and magnitude of cross-market spillovers between bond markets and sectoral equity factors. Most existing green bond studies rely on correlation analysis or single-equation regressions, which cannot disentangle predictive relationships or quantify the relative importance of different shock sources in a system-wide context. Our VAR-based spillover analysis produces a counterintuitive and empirically robust finding: oil and gas equity shocks explain approximately 88% of the variance in both green and conventional bond returns, whereas clean energy shocks account for only 10-11%. This result suggests that, despite their environmental label, green bonds remain predominantly exposed to brown sector financial dynamics rather than being driven by green equity performance. Moreover, Granger causality tests reveal that brown equity returns predict bond market movements, while green equity returns do not, indicating that the transmission channel runs primarily from carbon-intensive sectors to bond markets.

Fourth, we extend the static spillover framework by constructing a time-varying spillover index based on rolling-window VAR estimation. This dynamic approach allows us to track how cross-market interconnectedness evolves over time and to identify periods of intensified or reduced transmission intensity. Our analysis reveals that the degree of connectedness fluctuates substantially (ranging from 16.7% to 45.8%, with an average of 31.7%), with notable increases during late 2023 and spring 2025, coinciding with energy market turbulence and policy uncertainty. This time-varying evidence underscores that transition-related spillovers are episodic rather than constant, and that static correlation or regression coefficients may mask important temporal variation in cross-market linkages. To our knowledge, this is the first application of a rolling spillover index to the comparative analysis of green and conventional bond markets in Europe.

Fifth, we provide event-based evidence on how green and conventional bonds respond to key climate policy and macrofinancial events (e.g., COP28, the first ECB rate cut, and the EU Clean Industrial Deal). Although exploratory due to limited events and a short sample, results show that responses vary and green bonds do not consistently outperform, indicating that the green label does not ensure preferential treatment during policy-driven episodes.

Together, these contributions deepen understanding of green bond pricing, transition sensitivity, and their interaction with conventional bonds and sectoral equities. The dominance of brown sector shocks has implications for diversification, policy design, and the debate on decoupling from carbon-intensive structures. Combining descriptive, regression, VAR, and event-based approaches, the study offers a comprehensive assessment of green bond dynamics during a period of policy transition and energy market volatility.

Section 2 outlines the data and methodology. Section 3 reports the empirical results: descriptive analysis, regressions, VAR-based spillovers, time-varying connectedness, and robustness checks (including event studies). Section 4 concludes with implications, limitations, and future research directions.

2. Data and Methodology

2.1 Data

This study employs a daily dataset spanning the period from August 1, 2023 to March 20, 2026. The starting date (1 August 2023) corresponds to the earliest point at which all selected indices and transition-related variables were simultaneously available in a consistent daily frequency. The end date (20 March 2026) reflects the most recent observation available at the time of data collection. Consequently, the selected period provides the longest common sample that allows a joint analysis of green bonds, conventional bonds, energy markets, and transition-related financial factors. The dataset comprises eight price series: the iBoxx EUR Green Bonds Gross

Price Index, the iBoxx Euro Corporates Gross Price Index, the S&P Global Clean Energy Index, the STOXX Europe 600 Oil & Gas Index, the STOXX Europe 600 Index, the Brent crude oil spot price, the ICE EUA Yearly Energy Future, and the EURO STOXX Low Carbon Index.

The first two indices constitute the primary variables of interest, representing the euro-denominated green bond market and the euro-denominated conventional corporate bond market, respectively. The clean energy index serves as a proxy for green equity market dynamics, while the STOXX Europe 600 Oil & Gas Index captures the performance of carbon-intensive sectors. The STOXX Europe 600 Index is included as a broad market benchmark. Brent crude oil prices are incorporated to reflect energy market shocks, whereas EUA futures are used to proxy carbon pricing and climate policy conditions. The EURO STOXX Low Carbon Index is employed as an alternative green proxy in robustness analyses.

Before estimation, data are standardized: dates were aligned across series, observations were synchronized by trading day, and missing values were either forward-filled or removed where appropriate. The analysis is conducted using daily log returns to capture market dynamics and transmission mechanisms.

2.2 Methodology

The empirical strategy is organized into five main components: descriptive analysis, regression analysis, multivariate spillover analysis, time-varying spillover analysis, and robustness checks.

2.2.1 Descriptive Analysis and Stylized Facts

The first stage provides a descriptive overview of the return series. For each variable, the analysis computes the mean, standard deviation, minimum, maximum, skewness, kurtosis, and annualized volatility. Annualized volatility is calculated as:

$$\sigma_i^{ann} = \sigma_i^{daily}\sqrt{252} \cdot 100$$

where σ_i^{daily} is the standard deviation of daily returns and 252 is the conventional number of trading days in a year. Contemporaneous interdependence across markets is examined through the correlation matrix:

$$\rho_{ij} = \frac{Cov\left(r_{t,t}, r_{j,t}\right)}{\sigma_i \sigma_j}$$

To assess the evolution of risk over time, the analysis computes 30-day rolling volatilities for green and conventional bond returns:

$$\sigma_{i,t}^{(30)} = \sqrt{252} \cdot sd\left(r_{i,t-29}, \dots, r_{i,t}\right)$$

This allows a comparison of whether volatility in green bonds differs persistently from that of conventional bonds, or whether such differences emerge only during periods of market stress. To capture downside risk, cumulative returns are constructed as:

$$CR_{i,t} = \prod_{s=1}^{t} \left(1 + r_{i,s}\right)$$

and drawdowns are measured relative to the running maximum:

$$DD_{i,t} = \frac{CR_{i,t} - max_{s \le t} CR_{i,s}}{max_{s \le t} CR_{i,s}} \cdot 100$$

This procedure makes it possible to compare the magnitude and persistence of losses across green and conventional bond markets over the sample period.

2.2.2 Regression Analysis

The second stage examines the determinants of green and conventional bond returns using ordinary least squares regressions with heteroskedasticity-robust HC3 standard errors. The use of robust standard errors follows the recommendations of White (1980) and MacKinnon and White (1985) for addressing potential heteroskedasticity in financial return series. Two separate equations are estimated, one for green bond returns and one for conventional bond returns:

$$r_t^{GB} = \alpha_G + \beta_{1G} r_t^{CE} + \beta_{2G} r_t^{OG} + \beta_{3G} r_t^{Brent} + \beta_{4G} r_t^{EU\,A} + \beta_{5G} r_t^{MKT} + \varepsilon_{G,t}$$

$$r_t^{CB} = \alpha_C + \beta_{1C} r_t^{CE} + \beta_{2C} r_t^{OG} + \beta_{3C} r_t^{Brent} + \beta_{4C} r_t^{EU\,A} + \beta_{5C} r_t^{MKT} + \varepsilon_{C,t}$$

where:

- r_t^{GB} denotes green bond returns,
- r_t^{CB} denotes conventional bond returns,
- r_t^{CE} denotes clean energy equity returns,
- r_t^{OG} denotes oil and gas equity returns,
- r_t^{Brent} denotes Brent oil returns,
- r_t^{EUA} denotes carbon futures returns,
- r_t^{MKT} denotes returns on the STOXX Europe 600.

These regressions are intended to assess whether green and conventional bond markets display different sensitivities to transition-related factors, carbon-intensive sector dynamics, energy shocks, and climate-policy variables. In particular, the comparison between the coefficients on clean energy and oil and gas returns provides direct evidence on whether green bonds are more closely linked to green financial dynamics than conventional bonds.

As an additional robustness exercise, the clean energy index is replaced by the EURO STOXX Low Carbon index, yielding an alternative specification:

$$r_t^{GB} = \alpha'_G + \gamma_{1G} r_t^{LC} + \gamma_{2G} r_t^{OG} + \gamma_{3G} r_t^{Brent} + \gamma_{4G} r_t^{EU\,A} + \gamma_{5G} r_t^{MKT} + u_{G,t}$$

$$r_t^{CB} = \alpha'_C + \gamma_{1C} r_t^{LC} + \gamma_{2C} r_t^{OG} + \gamma_{3C} r_t^{Brent} + \gamma_{4C} r_t^{EU\,A} + \gamma_{5C} r_t^{MKT} + u_{C,t}$$

where r_t^{LC} denotes returns on the low-carbon equity index. This alternative proxy is used to verify whether the main conclusions depend on the specific definition of green equity exposure.

2.2.3 Spillover Analysis Based on VAR

To investigate dynamic interactions across markets, the study estimates a vector autoregressive model using four core variables: green bond returns, conventional bond returns, clean energy equity returns, and oil and gas equity returns. The VAR framework follows the seminal contribution of Sims (1980) and the comprehensive treatment provided by Lütkepohl (2005). Let

$$y_t = \begin{bmatrix} r_t^{GB} \\ r_t^{GB} \\ r_t^{CE} \\ r_t^{OG} \end{bmatrix}$$

The VAR(p) system is written as:

$$y_t = c + A_1 y_{t-1} + A_2 y_{t-2} + \cdots + A_p y_{t-p} + u_t$$

where c is a vector of intercepts, $A_1, \dots, A_p$ are coefficient matrices, and u_t is a vector of innovations.

Prior to estimation, stationarity is assessed using the Augmented Dickey-Fuller test. The lag length p is selected according to the Akaike Information Criterion. Based on the estimated VAR, the analysis then conducts Granger causality tests, impulse response analysis, and forecast error variance decomposition.

Granger causality tests are used to determine whether lagged values of one variable contain predictive information for another. This is particularly relevant in assessing whether green or brown equity dynamics precede movements in bond returns, or whether green and conventional bond markets transmit shocks to one another.

Impulse response functions are computed over a 10-period horizon in order to trace the dynamic effect of shocks across the system. In moving-average form, the VAR can be represented as:

$$y_t = \mu + \sum_{h=0}^{\infty} \psi_h u_{t-h}$$

where the matrices Ψ_h describe the propagation of shocks through time. This allows a comparison of how green and conventional bond returns react to shocks originating in clean energy and oil and gas equity markets.

Forecast error variance decomposition is used to quantify the contribution of each shock to the forecast error variance of each variable. For variable i, the contribution of shocks in variable j at forecast horizon h is denoted by $\theta_{ij}(h)$. This decomposition provides a direct measure of cross-market spillovers and the relative importance of own versus external shocks. Variance decomposition techniques are commonly used to evaluate the relative importance of shocks within multivariate financial systems (Lütkepohl, 2005).

2.2.4 Time-Varying Spillover Index

A key extension of the baseline VAR analysis is the construction of a time-varying spillover index. The construction of the spillover index is conceptually related to the connectedness framework proposed by Diebold and Yilmaz (2012, 2014), which has become a standard approach for measuring dynamic shock transmission across financial markets.

While the full-sample VAR provides an average measure of connectedness over the entire period, it does not capture whether transmission mechanisms strengthen or weaken over time. To address this issue, the study estimates the VAR recursively over rolling windows of 126 trading days, which correspond approximately to six months of observations.

For each rolling window, forecast error variance decomposition is computed over a 10-period horizon, and a total spillover index is constructed from the off-diagonal elements of the FEVD matrix. The time-varying spillover index is defined as:

$$S_t = \frac{\sum_{i \neq j} \theta_{ij,t}(h)}{N^2}$$

where $\theta_{ij,t}(h)$ denotes the contribution of shocks in variable j to the h-step-ahead forecast error variance of variable i in the rolling window ending at time t, and N is the number of variables in the VAR system.

This measure captures the degree of cross-market shock transmission at each point in time. Higher values of S_t indicate stronger interconnectedness and greater spillover intensity among green bonds, conventional bonds, clean energy equities, and oil and gas equities. This approach is particularly useful in the context of transition risk, since it allows the empirical analysis to identify whether connectedness increases during periods of energy market turbulence, policy uncertainty, or climate-related events.

2.2.5 Robustness Checks

The final stage of the empirical strategy consists of a set of robustness checks designed to verify the stability of the main results.

First, the study uses bootstrap resampling to assess the robustness of the regression coefficients. The sample is resampled with replacement 1,000 times, and the baseline regressions are re-estimated for each bootstrap draw. This produces an empirical distribution for each coefficient:

$$\{\hat{\beta}^{(1)}, \hat{\beta}^{(2)}, \ldots, \hat{\beta}^{(1000)},\}$$

From this distribution, median estimates and 90% percentile confidence intervals are obtained. This procedure reduces reliance on asymptotic normality and provides an additional check on statistical significance.

Second, the robustness analysis includes the alternative low-carbon proxy discussed above, replacing the clean energy index with the EURO STOXX Low Carbon index. This verifies whether the conclusions regarding green versus conventional bond sensitivities are robust to alternative measures of green equity performance.

Third, the study implements an event study[1] to compare the responses of green and conventional bond markets around major climate-related and macro-financial events. A symmetric event window of ± 5 trading days is used around each event date. Abnormal returns are computed relative to the STOXX Europe 600 benchmark according to:

$$AR_{i,t} = r_{i,t} - \hat{\beta}_i r_t^{MKT}$$

where $\hat{\beta}_i$ is estimated over a pre-event window. Cumulative abnormal returns are then calculated as:

$$CAR_i(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} AR_{i,t}$$

The event study focuses on three dates included in the empirical design: December 13, 2023 (COP28 UAE Consensus), June 6, 2024 (first ECB rate cut), and February 26, 2025 (EU Clean Industrial Deal). These events were selected because they are directly relevant either to climate transition policy or to euro-area financial conditions, both of which may influence the relative behavior of green and conventional bond markets.

The methodology combines descriptive analysis, factor regressions, multivariate time-series models, and dynamic spillover measures to examine interactions between green and conventional bonds, energy sectors, prices, and policy variables. The mix of static and time-varying approaches captures both average relationships and their evolution under transition-related uncertainty.

3. Results and discussion

3.1 Descriptive Statistics and Market Characteristics

Table 1 presents the summary statistics for the daily return series included in the analysis and provides an initial comparison between green bonds, conventional corporate bonds, and the financial, energy, and climate-related factors considered in the empirical framework. Three main results emerge.

First, green bonds appear to have underperformed conventional bonds over the sample period. Conventional bonds exhibit a positive annualized mean return of 1.9%, whereas green bonds record a negative annualized mean return of -2.7%. At the same time, green bonds are more volatile, with an annualized volatility of 3.95%, compared with 2.76% for conventional bonds. This suggests that, over the period considered, green bonds did not provide either higher returns or lower risk relative to conventional corporate bonds.

Second, the non-bond variables display substantially higher volatility than both bond indices. Brent and EUA futures are the most volatile series, with annualized volatilities of 28.5% and 31.6%, respectively, while clean energy and oil and gas

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[1] For detailed methodological discussions on the implementation of event study approaches, see, for example, Albu et al. (2014a), Albu et al. (2014b), or Călin (2015).

equities also show markedly higher volatility than the bond markets. This pattern is consistent with the role of these series as external financial and transition-related factors that may transmit shocks to bond returns rather than being driven by them.

Table 1. Summary Statistics

	mean	**std**	**volatility**	**min**	**max**	**skewness**	**kurtosis**
conv_bonds	1.897	0.174	2.761	-0.01	0.007	-0.169	2.222
green_bonds	-2.699	0.249	3.947	-0.014	0.009	-0.294	2.51
oil_gas	18.031	1.147	18.205	-0.084	0.038	-0.974	5.272
stoxx600	7.498	0.759	12.045	-0.051	0.036	-1.071	6.933
brent	10.537	1.794	28.481	-0.122	0.178	1.904	31.174
eua	-8.4	1.991	31.613	-0.078	0.082	0.201	1.209
low_carbon	7.517	0.864	13.72	-0.048	0.038	-0.581	3.47
clean_energy	-1.494	1.253	19.893	-0.048	0.046	-0.029	1.086

Source: Authors' processing.

Third, the distributional moments point to non-normality in several explanatory variables. Most series exhibit negative skewness, including both bond indices, which suggests a greater tendency toward downside risk. In contrast, Brent and EUA show positive skewness, indicating occasional large positive movements. Kurtosis is especially high for Brent, STOXX 600, and oil and gas equities, revealing fat-tailed distributions and the presence of extreme market episodes. By comparison, the two bond indices display lower kurtosis, indicating more stable return distributions.

Table 2. Correlation Matrix

	conv_bonds	**green_bonds**	**oil_gas**	**stoxx600**	**brent**	**eua**	**low_carbon**	**clean_energy**
conv_bonds	1	0.908	0.029	0.264	-0.024	-0.052	0.187	0.288
green_bonds	0.908	1	-0.021	0.192	-0.021	-0.047	0.131	0.247
oil_gas	0.029	-0.021	1	0.547	-0.046	0.135	0.496	0.328
stoxx600	0.264	0.192	0.547	1	-0.097	0.147	0.959	0.402
brent	-0.024	-0.021	-0.046	-0.097	1	0.009	-0.116	-0.071
eua	-0.052	-0.047	0.135	0.147	0.009	1	0.142	0.102
low_carbon	0.187	0.131	0.496	0.959	-0.116	0.142	1	0.379
clean_energy	0.288	0.247	0.328	0.402	-0.071	0.102	0.379	1

Source: Authors' processing.

Table 2 reports the contemporaneous correlations between bond returns and the financial, energy, and climate-related variables included in the analysis. The most striking result is the very high correlation between green bonds and conventional bonds (0.908), indicating that the two bond markets move closely together over the sample period. This suggests that, despite their different labels, both segments remain strongly integrated within the broader corporate bond market environment.

At the same time, both bond indices display only moderate correlations with the explanatory variables. Green bonds are positively correlated with clean energy (0.247), STOXX 600 (0.192), and low carbon (0.131), while their correlation with oil and gas is slightly negative (-0.021). Conventional bonds show a similar pattern, with somewhat stronger correlations with clean energy (0.288) and STOXX 600 (0.264), but again very weak associations with oil and gas, Brent, and EUA. These results suggest that broad market and green-related equity dynamics are more closely linked to bond returns than direct energy price shocks.

Another notable result is the extremely high correlation between STOXX 600 and low carbon (0.959), which indicates that the low-carbon index largely tracks broad market conditions. This is important for the robustness analysis, as it suggests that the alternative green proxy may capture not only transition-related effects but also general equity market movements.

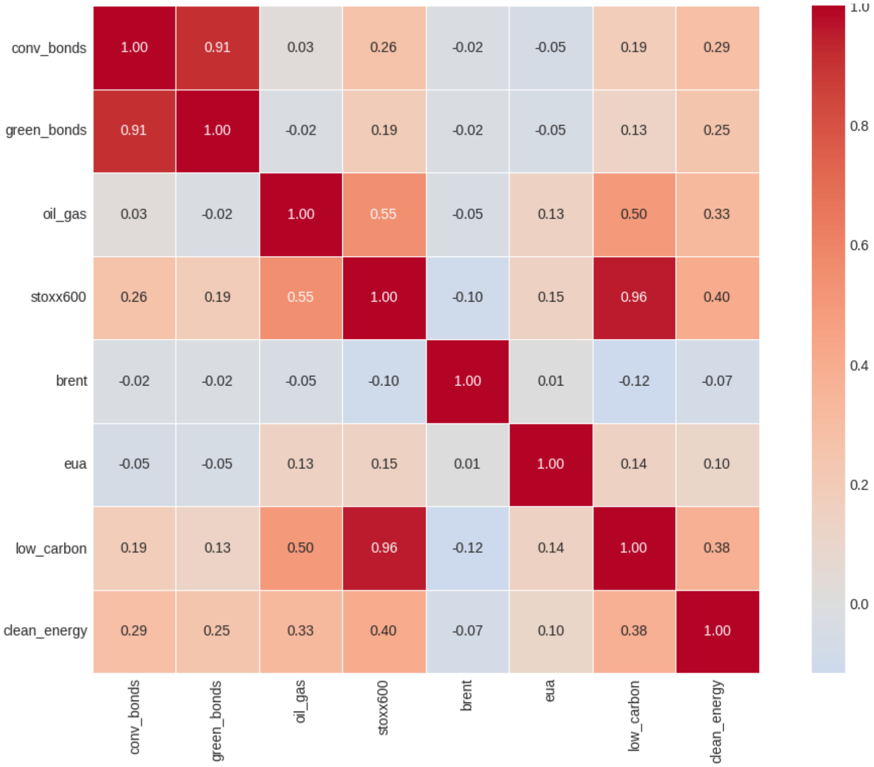

Figure 1. Correlation Heatmap

Source: Authors' own creation.

Figure 1 confirms the patterns in Table 2, showing strong comovement between green and conventional bonds and a high correlation between STOXX 600 and low carbon. Correlations with Brent and EUA are weak, indicating bonds are more linked to equity and green factors than to direct energy or carbon price shocks.

Figure 2 shows the evolution of 30-day rolling annualized volatility for green bonds and conventional bonds over the sample period. Two main patterns stand out. First, green bonds are consistently more volatile than conventional bonds throughout most of the sample. The green bond series remains above the conventional bond series almost continuously, which is fully consistent with the summary statistics reported earlier. This suggests that the green bond market was exposed to stronger short-term fluctuations and a less stable risk profile than the conventional corporate bond market.

Second, volatility is clearly time-varying for both markets, rather than constant over time. Both series experience periods of elevated volatility, most notably in late 2023, again around early to mid-2025, and toward the end of the sample. However, these spikes are systematically larger for green bonds. In particular, the surge observed around early 2025 indicates that green bond returns were more sensitive to episodes of market stress or changing financial conditions.

Figure 2. 30 day Rolling Volatility

Source: Authors' own creation.

Figure 2 reinforces the view that green bonds were not only riskier on average than conventional bonds, but also more exposed to time-varying volatility during the period under analysis. This is an important result, as it suggests that any comparison between the two bond segments should account not only for average returns, but also for differences in the dynamics of market risk over time.

Figure 3 compares the drawdown dynamics of green bonds and conventional bonds over the sample period and provides additional evidence on downside risk. The figure shows that green bonds experience consistently deeper and more persistent drawdowns than conventional bonds. While the conventional bond index generally remains within a relatively narrow negative range, the green bond index undergoes substantially larger cumulative losses, especially in the second half of the sample.

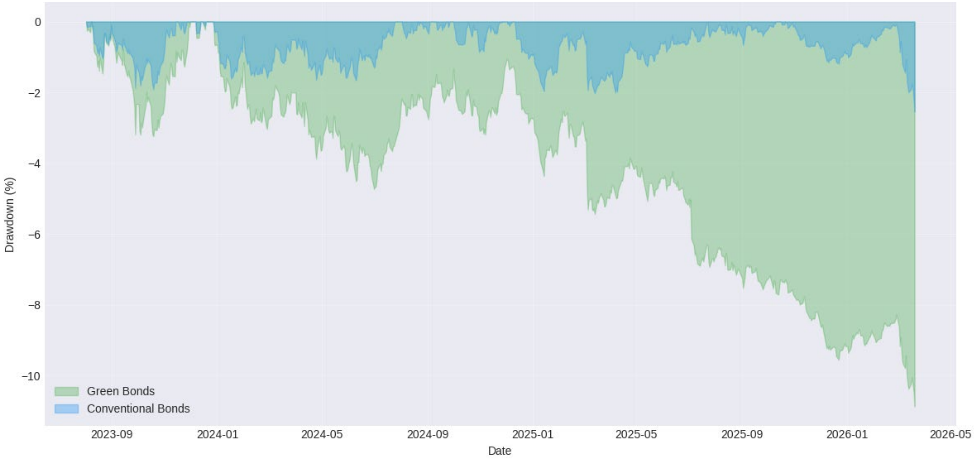

Figure 3. Drawdown Comparison
Source: Authors' own creation.

This divergence becomes particularly pronounced from mid-2025 onward, when green bonds enter a sustained drawdown phase and reach losses of around 10%, whereas conventional bonds remain much closer to zero and recover more quickly after periods of weakness. The figure therefore suggests that green bonds were not only more volatile in short-term rolling terms, but also more exposed to prolonged downside episodes.

3.2 Baseline Regression Results

Table 3 reports the baseline regression results obtained using ordinary least squares regressions with HC3 heteroskedasticity-robust standard errors. Overall, the results indicate that both bond markets are significantly influenced by broad equity market conditions and by the relative performance of green versus brown equity sectors, although the magnitude of these sensitivities differs across the two bond segments. The coefficient on clean energy is positive and highly significant in both regressions, suggesting that stronger performance in green-related equity markets is associated with higher returns for both green and conventional bonds. However, the effect is somewhat stronger for green bonds (0.0464) than for conventional bonds (0.0344), which is consistent with the expectation that green bond markets should be more closely linked to green financial dynamics.

Table 3. Baseline Regression Results

Variable	Green Bonds	Conventional Bonds
Constant	-0.0001 (0.0001)	0.0001 (0.0001)
Clean Energy	0.0464*** (0.0087)	0.0344*** (0.0067)
Oil & Gas	-0.0457*** (0.0105)	-0.0296*** (0.0075)
Brent	0.0012 (0.0046)	0.0013 (0.0037)
EUA	-0.0095* (0.0050)	-0.0082** (0.0034)
STOXX Europe 600	*0.0739*** (0.0151)*	*0.0657*** (0.0110)*

Notes: Heteroskedasticity-robust (HC3) standard errors are reported in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' processing.

By contrast, the coefficient on oil and gas is negative and strongly significant in both models. This implies that stronger brown-sector equity performance is associated with lower bond returns, with the negative effect again being more pronounced for green bonds (-0.0457) than for conventional bonds (-0.0296). Taken together, the clean energy and oil and gas coefficients suggest that green bonds exhibit greater sensitivity to the green-versus-brown transition dimension than conventional bonds.

Regarding the other controls, Brent oil does not appear to have a statistically significant effect in either regression, indicating that direct oil price movements do not have an independent contemporaneous impact once the other market variables are taken into account. EUA carbon futures have a negative coefficient in both models, but the effect is only marginally significant for green bonds and statistically significant for conventional bonds. Finally, the coefficient on STOXX 600 is positive and highly significant in both regressions, confirming that broad market conditions remain an important common driver of bond returns.

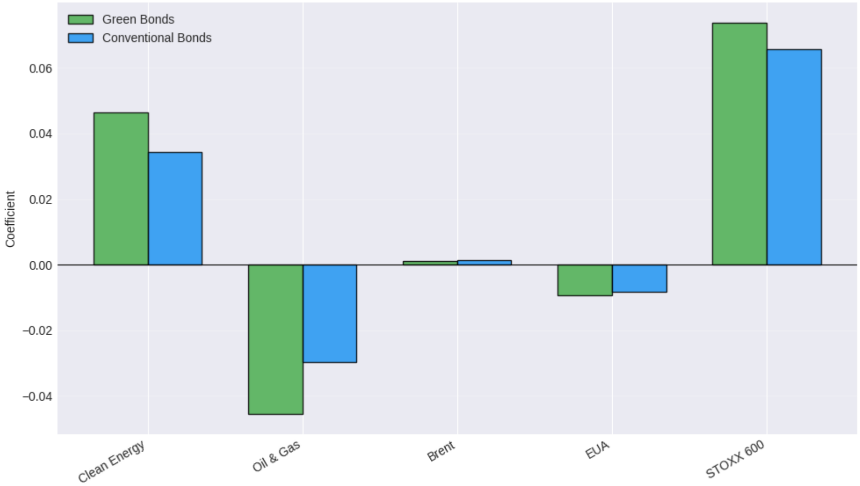

Figure 4. Coefficients Comparison

Source: Authors' own creation.

Figure 4 visually confirms the regression results reported in Table 3. In particular, green bonds exhibit stronger positive sensitivity to clean energy and stronger negative sensitivity to oil and gas than conventional bonds. At the same time, both bond segments respond positively to the broad market index, while the coefficients on Brent and EUA remain comparatively small.

3.3 Dynamic Spillovers and VAR Evidence

Before estimating the VAR model, the stationarity of the return series was assessed using the Augmented Dickey-Fuller (ADF) test. Detailed ADF statistics are reported in Appendix A1. The results strongly reject the null hypothesis of a unit root for all return series at conventional significance levels, indicating that the variables are stationary and can therefore be included directly in the VAR specification without additional differencing.

Table 4. Granger Causality

	X	Y	F_stat	p_value
0	clean_energy	green_bonds	0.001	0.9744
1	oil_gas	green_bonds	4.0095	0.0456
2	clean_energy	conv_bonds	0.8288	0.363
3	oil_gas	conv_bonds	5.5518	0.0187
4	green_bonds	conv_bonds	0.101	0.7507
5	conv_bonds	green_bonds	1.5354	0.2157

Source: Authors' processing.

Table 4 reports the Granger causality test results and provides evidence on the predictive direction of spillovers across bond and equity markets. The main finding is that oil and gas equity returns Granger-cause both green bond returns and conventional bond returns, with statistically significant effects at conventional levels. By contrast, clean energy returns do not Granger-cause either bond market, as the corresponding p-values are not statistically significant.

The results also show no evidence of Granger causality between green bonds and conventional bonds in either direction. This suggests that, although the two bond markets are highly correlated contemporaneously, they do not appear to exert strong predictive influence on one another once lagged dynamics are taken into account.

Table 5. Forecast Error Variance Decomposition (FEVD): Contributions to Green and Conventional Bond Return Variance

	Green_Bonds	Conv_Bonds
green_bonds	0.0004	0.0006
conv_bonds	0.012	0.012
clean_energy	0.105	0.1103
oil_gas	0.8825	0.8771

Source: Authors' processing.

Table 5 reports the forecast error variance decomposition for green bond and conventional bond returns. The results show that, in both cases, the largest share of forecast error variance is explained by shocks originating in the oil and gas equity market, which account for approximately 88% of the variance in both bond series. By contrast, the contribution of clean energy shocks is much smaller, at around 10–11%, while the contribution of shocks coming directly from the other bond market is negligible.

These results suggest that, within the VAR system, bond return dynamics are driven predominantly by shocks related to the brown sector rather than by clean energy shocks or direct cross-bond spillovers. At the same time, the decomposition is very similar for green and conventional bonds, indicating that both markets are exposed to a broadly comparable spillover structure in variance terms.

From a theoretical perspective, these findings suggest that European green bonds remain closely connected to broader corporate financing conditions rather than being exclusively linked to environmentally oriented investment channels. Although green bonds are specifically designed to finance sustainable projects, the underlying issuers continue to operate within economic sectors exposed to energy prices, financing conditions, and macroeconomic uncertainty. Consequently, shocks originating from carbon-intensive sectors may continue to influence green bond pricing even in the presence of dedicated green finance frameworks. This result is consistent with the view that transition finance remains embedded within the broader economic structure and has not yet fully decoupled from traditional brown-sector dynamics.

Figure 5 presents the impulse response functions from the VAR model and illustrates how green and conventional bond returns react to shocks originating in clean energy, oil and gas, and the bond markets themselves. The most pronounced responses are observed following a shock to oil and gas equities. Both green and conventional bond returns react positively on impact, but the response of green bonds is visibly stronger than that of conventional bonds. This result is consistent with the Granger causality and FEVD evidence, which also pointed to oil and gas as the most important source of predictive spillovers within the system.

By contrast, the response to a clean energy shock is much smaller and less stable. Green bonds initially react negatively and then briefly reverse, while conventional bonds show only a very modest positive response. This suggests that clean energy shocks do not generate strong or persistent transmission effects in the bond markets over the sample period.

The lower panels show that own-market shocks dominate immediately, but their effects dissipate quickly. In addition, a shock to conventional bonds generates only a limited response in green bonds, which is consistent with the absence of significant bilateral Granger causality between the two bond markets.

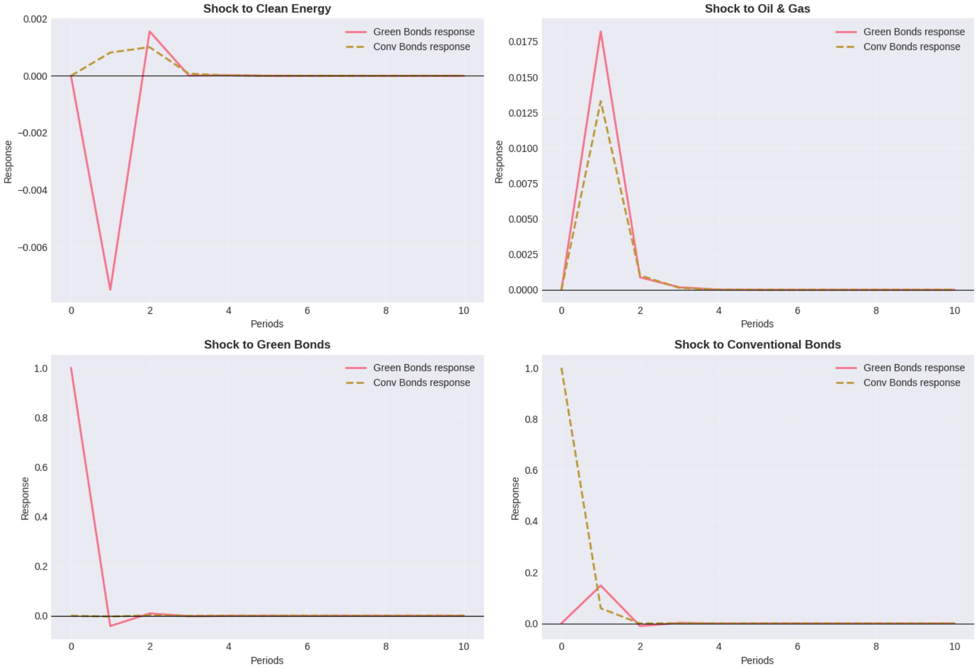

Figure 5. Impulse Response Functions
Source: Authors' own creation.

Figure 6 provides a visual representation of the forecast error variance decomposition for green and conventional bond returns. The figure confirms the pattern reported in Table 5: as the forecast horizon increases, the importance of own shocks declines rapidly, while shocks from the oil and gas equity market become the dominant source of variance for both bond indices. The contribution of clean energy shocks also increases over time, but remains clearly below that of oil and gas, whereas direct spillovers from the other bond market stay very limited.

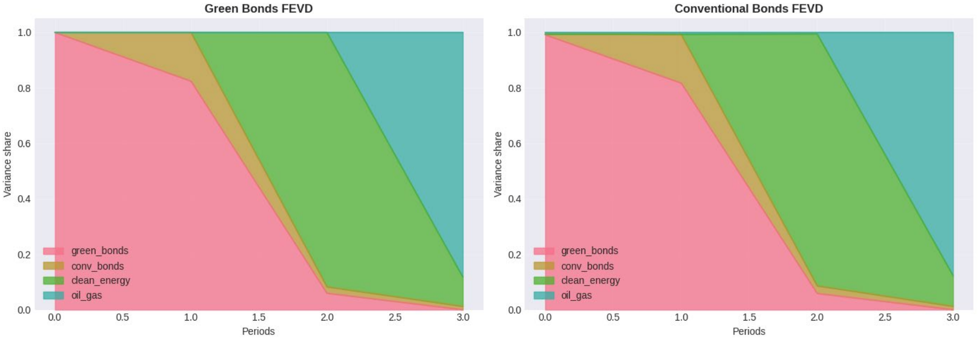

Figure 6. Forecast Error Variance Decomposition
Source: Authors' own creation.

3.4 Robustness Results

Table 6. Bootstrap Regression Results

	Green_Coef	Green_CI_Lower	Green_CI_Upper	Conv_Coef	Conv_CI_Lower	Conv_CI_Upper
const	-0.0001	-0.0002	0	0.0001	0	0.0002
clean_energy	0.0462	0.0331	0.0611	0.0342	0.0238	0.0455
oil_gas	-0.0462	-0.0634	-0.0292	-0.0301	-0.042	-0.0175
brent	0.0013	-0.0055	0.0092	0.0013	-0.0038	0.0076
eua	-0.0097	-0.0167	-0.0012	-0.0082	-0.0134	-0.0027
stoxx600	0.0753	0.0504	0.0979	0.0662	0.048	0.0827

Source: Authors' processing.

Table 6 reports the bootstrap regression results based on 1,000 replications, providing an additional robustness check for the baseline estimates. Overall, the bootstrap evidence confirms the main conclusions of the baseline regressions. For both green and conventional bonds, the coefficients on clean energy remain positive and their confidence intervals exclude zero, while the coefficients on oil and gas remain negative and statistically robust. Similarly, the coefficient on STOXX 600 remains positive and significant in both models.

The results also confirm that the magnitude of the clean energy and oil and gas effects is stronger for green bonds than for conventional bonds, reinforcing the view that green bonds are more sensitive to transition-related financial dynamics. By contrast, the confidence intervals for Brent include zero in both regressions, indicating that the Brent effect is not robust. The coefficient on EUA remains negative in both cases, with confidence intervals excluding zero, suggesting that carbon market dynamics retain explanatory power once bootstrap uncertainty is taken into account.

Figure 7 shows that the degree of cross-market connectedness is clearly time-varying over the sample period. The spillover index fluctuates substantially, ranging from approximately 16.7% to 45.8%, with an average level of about 31.7%. This indicates that the transmission of shocks across green bonds, conventional bonds, clean energy equities, and oil and gas equities was far from constant and changed meaningfully over time.

The figure also reveals periods of intensified interconnectedness, particularly in late 2023, again around spring 2025, and toward the end of the sample. By contrast, a marked decline in the spillover index is observed during the second half of 2025, suggesting a temporary weakening in cross-market shock transmission. This pattern implies that the linkage between bond and equity-related transition factors strengthens during some subperiods and relaxes during others, rather than remaining stable throughout the sample.

Table 7 reports the event study results for three selected climate - and policy-related events, using cumulative abnormal returns over an 11-day event window.

Overall, the results suggest that green and conventional bonds responded differently across events, but the estimated differences are not statistically significant.

Figure 7. Time-Varying Spillover Index

Source: Authors' own creation.

Table 7. Event Study Results for Green and Conventional Bonds around Selected Climate and Policy Events

	Event	Requested_Date	Date_Used	CAR_Green	CAR_Conv	Difference	t_stat	n_days
0	COP28 UAE Consensus	13/12/2023	13/12/2023	1.7733	1.2606	0.5127	1.2276	11
1	ECB First Rate Cut	06/06/2024	06/06/2024	-0.0118	0.4057	-0.4175	-1.0148	11
2	EU Clean Industrial Deal	26/02/2025	26/02/2025	-1.4865	-0.8803	-0.6062	-1.1805	11

Source: Authors' processing.

After the COP28 UAE Consensus, both bond types show positive abnormal returns, with green bonds performing slightly better. In contrast, around the ECB rate cut and the EU Clean Industrial Deal, green bonds underperform, with the largest negative differential during the EU Clean Industrial Deal. However, t-statistics are modest across all events, indicating weak statistical differences between green and conventional bond responses.

Figure 8 visually summarizes the event study results reported in Table 7. Both bond segments reacted positively to the COP28 UAE Consensus, with stronger gains for green bonds. In contrast, green bonds slightly underperformed around the ECB rate cut, and both markets showed negative returns during the EU Clean Industrial Deal, particularly for green bonds.

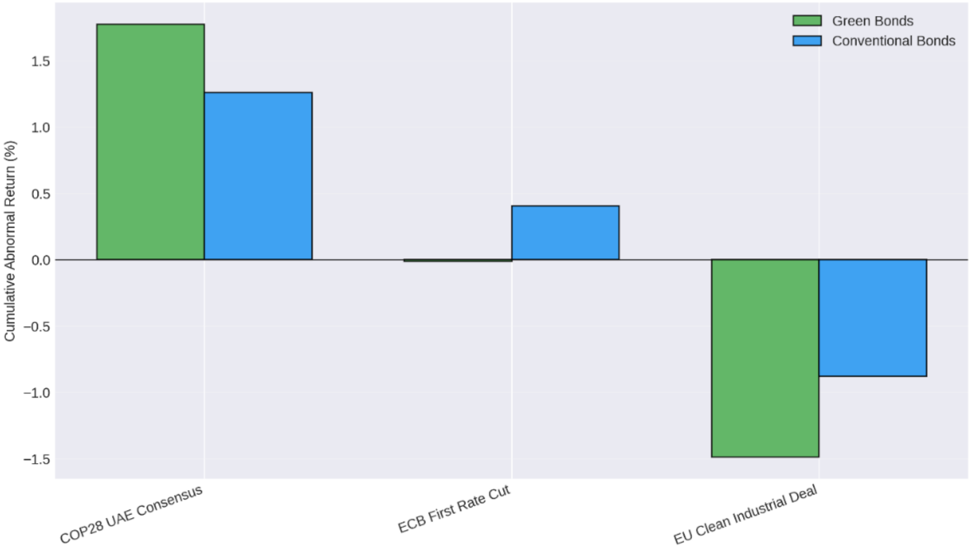

Figure 8. Event Study: Cumulative Abnormal Returns of Green and Conventional Bonds around Climate and Policy Events
Source: Authors' own creation.

4. Conclusions

This study analyzes pricing, volatility, and cross-market spillovers between European green and conventional corporate bonds, focusing on sensitivity to transition factors, energy shocks, and climate policy. Using daily data from August 2023 to March 2026, it applies descriptive statistics, regressions, VAR models, spillover indices, and event studies to assess whether green bonds exhibit distinct market characteristics.

Three main findings emerge. First, green bonds underperformed conventional bonds and exhibited higher volatility. They delivered an annualized return of -2.7% versus 1.9% and volatility of 3.95% versus 2.76%. Rolling volatility and drawdown analysis confirm deeper and more persistent losses, especially from mid-2025 onward. Overall, contrary to the expected "greenium," green bonds showed weaker performance and greater downside risk.

Second, despite differences in return and volatility, green and conventional bonds remain highly integrated, with a correlation of 0.908, indicating common macro-financial drivers. However, regressions show that green bonds are more sensitive to transition-related equity factors, with a stronger positive response to clean energy (0.0464 vs. 0.0344) and a stronger negative response to oil and gas (-0.0457 vs. -0.0296), highlighting their closer link to the green–brown transition.

Third, VAR-based spillover analysis yields a counterintuitive result: oil and gas shocks dominate bond return variance, not clean energy. Forecast error variance decomposition shows about 88% of variance in both bond indices is driven by oil and gas, versus 10–11% by clean energy. Granger causality confirms that oil and gas returns predict bond movements, while clean energy does not, highlighting the dominant role of the brown sector. The time-varying spillover index also shows that interconnectedness fluctuates between 16.7% and 45.8%, with peaks in late 2023 and spring 2025.

The empirical findings carry several important implications for investors, policymakers, and academics working on green finance and transition risk.

From an investment perspective, the results challenge the view that green bonds offer superior returns or lower risk. Over the sample period, they show negative returns, higher volatility, and deeper drawdowns than conventional bonds, indicating that the green label does not ensure better risk-adjusted performance. Their strong integration with conventional bonds also limits diversification benefits. At the same time, their greater sensitivity to clean energy and oil and gas equities suggests that investors should account for sectoral transition exposures in pricing and portfolio construction.

From a policy perspective, the dominance of brown sector shocks in bond return variance questions the effectiveness of current green finance frameworks. Green bonds remain exposed to fossil fuel dynamics, likely reflecting issuer structure, incomplete transition, or broader macrofinancial linkages. Strengthening their role may require stricter eligibility criteria, better disclosure, and targeted support to reduce exposure to brown sector shocks.

From an academic perspective, the results stress the need to distinguish between transition exposure and transition performance. Although green bonds are more sensitive to green and brown equities in regressions, their variance is not primarily driven by green sector performance. This points to a more complex relationship between green finance and real-economy transition factors, suggesting future research should examine nonlinearities, threshold effects, and regime-switching dynamics.

Several limitations apply. First, the sample spans only about 2.5 years, limiting generalizability and long-run inference. Second, the use of aggregate indices prevents analysis of firm-level heterogeneity. Third, the study omits policy factors such as regulatory changes or subsidies that may affect pricing. Finally, the event study covers only three episodes and remains exploratory.

Future research can extend this analysis in several ways. First, with longer time series, it can assess whether brown sector dominance persists or green bonds gradually decouple. Second, firm-level matched samples could offer more granular evidence on transition risk pricing. Third, adding macrofinancial variables (e.g., monetary policy, sovereign risk, credit spreads) may improve understanding of broader influences. Fourth, cross-country comparisons could test whether results are euro-area specific. Finally, nonlinear approaches (e.g., regime-switching or threshold VARs), volatility-based models, and alternative dynamic econometric frameworks could identify conditions under which green and conventional bonds diverge in response to transition shocks and provide additional insights into the transmission of climate-related financial risks.

References

[1] Albu, L.L., Lupu, R., Calin, A.C., Popovici, O.C. (2014a), *Estimating the impact of quantitative easing on credit risk through an ARMA-GARCH model. Romanian Journal of Economic Forecasting*, 17(3), 39-50.

[2] Albu, L.L., Lupu, R., Călin, A.C., Popovici, O.C. (2014b), *The effect of ECB's quantitative easing on credit default swap instruments in Central and Eastern Europe. Procedia Economics and Finance*, 8, 122-128.

[3] Aleknevičienė, V., Staugaitis, A.J., Gudaitienė, R., Bendoraitytė, A. (2025), *How do uncertainties affect the connectedness between the green bond market and conventional financial markets? Evidence from the Russian-Ukrainian war. Green Finance*, 7(4), 634.

[4] Baker, M., Bergstresser, D., Serafeim, G., Wurgler, J. (2022), *The pricing and ownership of US green bonds. Annual Review of Financial Economics*, 14(1), 415-437.

[5] Baruník, J., Ellington, M. (2024), *Persistence in financial connectedness and systemic risk. European Journal of Operational Research*, 314(1), 393-407, https://doi.org/10.1016/j.ejor.2023.11.023.

[6] Bolton, P., Kacperczyk, M. (2021), *Do investors care about carbon risk? Journal of Financial Economics*, 142(2), 517-549, https://doi.org/10.1016/j.jfineco.2021.05.008.

[7] Călin, A.C. (2015), *Eloquence is the key–the impact of monetary policy speeches on exchange rate volatility. The Romanian Economic Journal*, 18(56), 3-18.

[8] Caramichael, J., Rapp, A.C. (2024), *The green corporate bond issuance premium. Journal of Banking & Finance*, 162, 107126.

[9] Diebold, F.X., Yilmaz, K. (2012), *Better to give than to receive: Predictive directional measurement of volatility spillovers. International Journal of Forecasting*, 28(1), 57–66, https://doi.org/10.1016/j.ijforecast.2011.02.006.

[10] Diebold, F.X., Yilmaz, K. (2014), *On the network topology of variance decompositions: Measuring the connectedness of financial firms. Journal of Econometrics*, 182(1), 119–134, https://doi.org/10.1016/j.jeconom.2014.04.012.

[11] Fatica, S., Panzica, R., Rancan, M. (2021), *The pricing of green bonds: Are financial institutions special? Journal of Financial Stability*, 54, 100873.

[12] Flammer, C. (2021), *Corporate green bonds. Journal of Financial Economics*, 142(2), 499-516, https://doi.org/10.1016/j.jfineco.2021.01.010.

[13] Hachenberg, B., Schiereck, D. (2018), *Are green bonds priced differently from conventional bonds? Journal of Asset Management*, 19, 371-383, https://doi.org/10.1057/s41260-018-0088-5.

[14] Hacıömeroğlu, H.A., Danışoğlu, S., Güner, Z.N. (2022), *The grass is greener on the other side: Comparison of green versus brown corporate bonds. Borsa Istanbul Review*, 22(6), 1182-1194, https://doi.org/10.1016/j.bir.2022.08.006.

[15] Huynh, T.L.D., Ridder, N., Wang, M. (2022), *Beyond the shades: The impact of credit rating and greenness on the green bond premium (SSRN Scholarly Paper No. 4038882). Social Science Research Network,* https://doi.org/10.2139/ssrn.4038882.

[16] Kanamura, T. (2020), *Are green bonds environmentally friendly and good performing assets? Energy Economics*, 88, 104767.

[17] Krueger, P., Sautner, Z., Starks, L.T. (2020), *The importance of climate risks for institutional investors. The Review of Financial Studies*, 33(3), 1067-1111, https://doi.org/10.1093/rfs/hhz137.

[18] Larcker, D.F., Watts, E.M. (2020), *Where's the greenium? Journal of Accounting and Economics*, 69(2), 101312, https://doi.org/10.1016/j.jacceco.2020.101312.

[19] Lebelle, M., Lajili Jarjir, S., Sassi, S. (2020), *Corporate green bond issuances: An international evidence. Journal of Risk and Financial Management*, 13(2), 25, https://doi.org/10.3390/jrfm13020025.

[20] Lütkepohl, H. (2005), *New Introduction to Multiple Time Series Analysis*. Berlin: Springer, Germany, https://doi.org/10.1007/978-3-540-27752-1.

[21] MacAskill, S., Roca, E., Liu, B., Stewart, R.A., Sahin, O. (2021), *Is there a green premium in the green bond market? Systematic literature review revealing premium determinants. Journal of Cleaner Production*, 280, 124491, https://doi.org/10.1016/j.jclepro.2020.124491.

[22] MacKinnon, J.G., White, H. (1985), *Some heteroskedasticity-consistent covariance matrix estimators with improved finite sample properties. Journal of Econometrics*, 29(3), 305-325, https://doi.org/10.1016/0304-4076(85)90158-7.

[23] Mercuri, L., Rroji, E., Stefani, I. (2026), *Analyzing the greenium term structure of twin government bonds. European Journal of Operational Research.* Advance online publication, https://doi.org/10.1016/j.ejor.2026.03.008.

[24] Nguyen, T.T.H., Naeem, M.A., Balli, F., Balli, H.O., Vo, X.V. (2020), *Time-frequency comovement among green bonds, stocks, commodities, clean energy, and conventional bonds. Finance Research Letters*, 101739, https://doi.org/10.1016/j.frl.2020.101739.

[25] Partridge, C., Medda, F.R. (2020), *The evolution of pricing performance of green municipal bonds. Journal of Sustainable Finance & Investment*, 10(1), 44-64.

[26] Pástor, L., Stambaugh, R.F., Taylor, L.A. (2022), *Dissecting green returns. Journal of Financial Economics*, 146(2), 403-424.

[27] Peiró-Palomino, J., Gianmoena, L., Picazo-Tadeo, A.J., Rios, V. (2025), *Is social capital a driver of the green transition in the European Union? Ecological Economics*, 230, 108500, https://doi.org/10.1016/j.ecolecon.2024.108500.

[28] Pietrzyk, R., Frydrych, S., Węgrzyn, P., Biegun, K. (2025), *The value of being green: Assessing the impact of green bond issuance on stock prices of European listed companies. International Review of Economics & Finance*, 104, 104764, https://doi.org/10.1016/j.iref.2025.104764.

[29] Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., et al. (2022), *Climate change 2022: Impacts, adaptation and vulnerability. Intergovernmental Panel on Climate Change,* https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryVolume.pdf.

[30] Şahin, S., Kaplan, E.A., Yılmaz, Ö. (2025), *Green bonds and sustainable finance: A multidimensional analysis of macroeconomic and environmental determinants across nine countries. Research Square,* https://doi.org/10.21203/rs.3.rs-6065016/v1.

[31] Sims, C.A. (1980), *Macroeconomics and reality. Econometrica*, 48(1), 1-48, https://doi.org/10.2307/1912017.

[32] Ur Rehman, M., Nautiyal, N., Zeitun, R., Vo, X.V., Ghardallou, W. (2024), *Unraveling the multiscale comovement of green bonds and structural shocks: An oil-driven analysis. The North American Journal of Economics and Finance*, 72, 102122, https://doi.org/10.1016/j.najef.2024.102122.

[33] Wang, J., Chen, X., Li, X., Yu, J., Zhong, R. (2020), *The market reaction to green bond issuance: Evidence from China. Pacific-Basin Finance Journal*, 60, 101294, https://doi.org/10.1016/j.pacfin.2020.101294.

[34] White, H. (1980), *A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica*, 48(4), 817-838, https://doi.org/10.2307/1912934.

[35] Zambujal-Oliveira, J., Duque, J. (2026), *Stochastic carbon taxes and capital turnover: A real options model for decarbonization investment. Results in Engineering*, 29, 109902, https://doi.org/10.1016/j.rineng.2026.109902.

[36] Zerbib, O.D. (2019), *The effect of pro-environmental preferences on bond prices: Evidence from green bonds. Journal of Banking & Finance*, 98, 39-60.

[37] Zhou, Y., Lin, L., Huang, Z. (2024), *Diversification value of green bonds: Fresh evidence from China. The North American Journal of Economics and Finance*, 74, 102254, https://doi.org/10.1016/j.najef.2024.102254.

Appendix A1.

Table A1. Augmented Dickey-Fuller (ADF) Unit Root Test Results

Variable	ADF Statistic	p-value
Green Bonds	-25.056	<0.001
Conventional Bonds	-4.909	<0.001
Clean Energy	-24.958	<0.001
Oil & Gas	-25.203	<0.001
STOXX Europe 600	-16.652	<0.001
Brent	-9.349	<0.001
EUA	-26.048	<0.001
Low Carbon	-25.669	<0.001

Source: Authors' processing.