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Dynamic spillovers between climate risk, energy transition, and sustainable finance: implications for financial markets

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Abstract

Purpose – The purpose of this paper is to analyze the dynamic interconnections and spillover effects among climate risk, carbon emissions, renewable and nonrenewable energy markets and sustainable finance instruments over time and across different market conditions. By using a time-varying parameter vector autoregression (TVP-VAR) framework, the study aims to capture the temporal evolution and direction of risk transmission across these sectors, particularly during periods of heightened uncertainty such as the COVID-19 pandemic and the Russia–Ukraine conflict.

Design/methodology/approach – To examine the evolving interconnections between climate risk, energy markets and sustainable finance, this study uses the TVP-VAR model. This advanced econometric framework allows for the measurement of dynamic spillovers and risk transmission across multiple markets while accounting for time-varying relationships and structural changes driven by global crises such as the COVID-19 pandemic and the Russia–Ukraine conflict.

Findings – The empirical analysis shows that interconnectedness among climate risk, energy markets and sustainable finance is highly dynamic, intensifying during crises such as COVID-19 and the Russia–Ukraine conflict. Short-term connectedness (1–5 days) dominates, revealing rapid shock propagation and amplified systemic risk, while long-term linkages (>5 days) remain stable, reflecting slower structural effects. Renewable energy markets, though central to the transition, can increase short-term volatility. The consistency of directional spillovers across frequencies validates the robustness of the methodology. Overall, results underscore the need for time- and frequency-sensitive risk management, informing portfolio strategies and regulatory frameworks in a low-carbon, circular economy.

Originality/value – Understanding the dynamic interconnectedness between climate risk, energy markets and sustainable finance is increasingly critical for investors, policymakers and researchers. While previous studies have examined spillovers among commodities and financial assets, there is limited evidence on the time-varying role of renewable and nonrenewable energy markets, carbon emissions and green financial instruments as risk transmitters or absorbers during unprecedented shocks such as COVID-19 and the Russia–Ukraine conflict. This study addresses this gap by using a TVP-VAR and quantile connectedness framework, capturing both short- and long-term spillovers. The findings provide novel insights for portfolio diversification, risk management and policy design in the transition toward a low-carbon, circular economy.

Keywords Carbon emissions, Renewable energy, Sustainable finance, Circular economy, Dynamic spillover effects

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1. Introduction

The accelerating threat of climate change and environmental degradation has heightened global efforts to transition toward a low-carbon and circular economy (IPCC, 2023; Kirchherr *et al.*, 2017; Cao *et al.*, 2025). The circular economy paradigm, emphasizing resource efficiency, waste reduction and sustainable production, has become a cornerstone of contemporary environmental and economic policy (Geissdoerfer *et al.*, 2017). Within this evolving landscape, financial markets play an instrumental role in steering the energy transition by mobilizing capital toward green technologies, renewable energy projects and climate-resilient investments (Fatica and Panzica, 2021; Broadstock *et al.*, 2021). Through mechanisms such as sustainable finance, green bonds and ESG-based investment strategies, capital markets can foster technological innovation and reduce exposure to climate-related risks, thereby aligning financial performance with environmental objectives.

Sustainable finance has consequently emerged as a strategic enabler of decarbonization and green transformation. Instruments such as carbon markets, renewable energy indices and green bonds not only facilitate the pricing of environmental risks but also promote long-term value creation through responsible investment (Reboredo, 2018; Ji *et al.*, 2020). However, the increasing integration of financial, energy and environmental systems has also amplified interdependencies and contagion risks. Shocks in one segment such as abrupt fluctuations in carbon prices or energy supply disruptions can propagate rapidly across sectors, creating systemic vulnerabilities (Antonakakis *et al.*, 2020). These interconnected dynamics are particularly pronounced during periods of geopolitical instability or economic uncertainty, such as the COVID-19 pandemic or the Russia–Ukraine conflict, which have profoundly altered the behavior of global financial and energy markets (Baker *et al.*, 2020; Fang *et al.*, 2023).

In this context, understanding the spillover mechanisms between carbon emissions, renewable and nonrenewable energy markets and sustainable finance assets is essential for both policymakers and investors. Examining these multidimensional linkages enables the identification of channels through which climate-related and geopolitical shocks affect market stability, portfolio diversification and risk transmission. Moreover, capturing these interdependencies can provide valuable insights into how financial markets can accelerate the global energy transition while safeguarding against systemic risks.

Despite growing academic interest in climate-related finance, most existing studies have focused on static correlations or linear dependencies between energy and financial markets. Few have examined the dynamic and frequency-dependent nature of these interactions, particularly across varying investment horizons and crisis periods. Addressing this gap, the present study uses a time-varying parameter vector autoregression (TVP-VAR) model combined with a frequency decomposition framework to disentangle short- and long-term spillovers among carbon emissions, renewable and nonrenewable energy indices and sustainable financial instruments. This methodological approach enables the identification of both transient and persistent transmission mechanisms, offering a more comprehensive understanding of how market interconnectedness evolves over time and under stress conditions (Koop and Korobilis, 2014; Baruník and Křehlík, 2018).

This study makes several important contributions to the literature on carbon, energy and sustainable finance markets. First, it investigates the complex and evolving interconnections among these markets, focusing on their dynamic and asymmetric behavior, particularly during periods of heightened global uncertainty. By using a time-varying framework, the analysis captures changes in interdependence over time and distinguishes between short-term shocks and long-term structural linkages.

The study advances the literature in multiple ways. First, in contrast to previous research that often relies on average-based connectedness measures, we implement a quantile-based

TVP-VAR approach to examine extreme risk spillovers under both bearish and bullish conditions, which are especially relevant during market stress and largely underexplored in existing studies. Second, by incorporating a frequency-domain perspective, we provide insights into how contagion operates differently over short and long horizons, offering a more nuanced understanding of systemic risk transmission. Third, the study identifies key markets that act as primary transmitters and receivers within the green–brown financial ecosystem, delivering practical implications for policymakers, investors and regulators aiming to strengthen financial stability and accelerate the energy transition.

Overall, analyzing the dynamic relationships among carbon, energy and sustainable finance markets under extreme conditions can inform risk management practices, investment decisions and policy strategies. Moreover, these findings help stakeholders anticipate potential market disruptions, enhance resilience and support sustainable development objectives.

Finally, beyond its empirical contributions, the study provides a conceptual innovation by showing how the transmission mechanisms vary across both quantile and frequency dimensions, thus deepening the understanding of market behavior during systemic shocks.

Based on these gaps and motivations, the study is guided by the following research questions:

RQ1. How do dynamic spillovers evolve between carbon emissions, renewable energy, fossil energy markets and sustainable finance assets over time and across crisis periods?

RQ2. Do these spillovers differ across quantile regimes (extreme bearish, median and extreme bullish conditions)?

RQ3. How do short-term and long-term transmission mechanisms differ across the carbon–energy–sustainable finance nexus?

RQ4. Which markets act as net transmitters and net receivers of shocks under different market conditions and geopolitical phases?

The remainder of this paper is organized as follows. Section 2 presents a comprehensive review of the literature on the interlinkages between carbon emissions, energy markets and sustainable finance. Section 3 details the data and methodological framework, emphasizing the TVP-VAR model and frequency decomposition. Section 4 discusses the empirical results, while Section 5 concludes with final remarks and directions for future research.

2. Literature review

The existing literature on carbon emissions, energy markets and sustainable finance provides a solid foundation for understanding the complex interactions among these domains. While numerous studies have examined individual markets or bilateral relationships, there remains a lack of integrative analyses that consider dynamic, asymmetric and frequency-dependent spillovers across carbon, fossil and renewable energy and sustainable finance markets simultaneously. Moreover, although prior studies summarize empirical behaviors across markets, they rarely compare findings systematically, leading to fragmented conclusions regarding the strength, direction and persistence of interconnectedness. This lack of synthesis results in unclear theoretical and practical implications. To overcome these shortcomings, this study not only reviews prior evidence but also critically identifies where the literature diverges, which mechanisms remain unexplained and why integrated frameworks are necessary. Addressing these limitations, the current study adopts a comprehensive approach that integrates time-varying, quantile-based and frequency-domain methodologies to provide a more nuanced understanding of market interconnectedness and its implications for risk management, investment strategies and policy development.

2.1 Carbon emissions, energy markets and climate transition

The urgent need to mitigate climate change has placed carbon emissions at the forefront of economic and financial research. While global climate policies such as the Paris Agreement have promoted a transition toward renewable energy, fossil fuel markets particularly crude oil and natural gas remain central to economic growth and energy security (Ha *et al.*, 2024). Previous studies highlight the growing interconnectedness between carbon emissions and energy markets, but their findings are mixed: some report strong dynamic links, while others observe periods of weak or asymmetric relationships depending on market conditions (Ji *et al.*, 2021; Sun *et al.*, 2024). However, the literature does not clearly explain why these inconsistencies occur, nor does it systematically evaluate how crises reshape these relationships.

Moreover, the role of renewable energy adoption as a hedge against fossil fuel volatility has been emphasized (Cao *et al.*, 2025; Sharif *et al.*, 2023), but few studies systematically explore how these dynamics evolve under global crises or extreme events, such as the COVID-19 pandemic or the Russia–Ukraine conflict (Bouri *et al.*, 2023). This gap highlights the need for models capable of capturing nonlinearity and behavior under extremes rather than average conditions:

H1. Carbon emission markets exhibit significant spillover effects with both renewable and nonrenewable energy markets, with intensity varying under extreme market conditions.

2.2 Sustainable finance and green investment instruments

Sustainable finance, through instruments such as green bonds, ESG indices and sustainability-linked loans, has become a key driver of capital flows toward low-carbon projects (Fatica and Panzica, 2021; Reboredo, 2018). While prior studies demonstrate that ESG investments exhibit resilience during economic downturns (Broadstock *et al.*, 2021), their comparative behavior relative to fossil and renewable energy markets remains insufficiently analyzed. Some studies argue that ESG assets reduce carbon exposure, whereas others highlight contagion amplification yet few attempt to reconcile these contradictions. Furthermore, despite the increasing prominence of green bonds in climate finance (Taghizadeh-Hesary, 2023), their position within the broader energy–carbon spillover structure is still unclear, especially in dynamic or crisis periods:

H2. Sustainable finance assets, including green bonds and ESG indices, act as net receivers of shocks during extreme market conditions but can also transmit risks depending on the crisis context.

2.3 Spillover dynamics in energy-finance interactions

Research on spillovers between energy markets, emissions and finance indicates that volatility transmission is complex and context-dependent (Antonakakis *et al.*, 2020; Ji *et al.*, 2020). Evidence suggests asymmetries in spillover patterns: renewable energy indices can act as transmitters of shocks during innovation-driven growth, whereas fossil fuels dominate during geopolitical or macroeconomic disruptions (Bouri *et al.*, 2023). Meanwhile, sustainability-linked assets increasingly function as shock receivers, reflecting regulatory pressures and investor sentiment (Cao *et al.*, 2025).

However, these findings are mostly derived from static or short-sample models, preventing a thorough understanding of how spillovers evolve structurally. In addition, prior literature rarely considers frequency-specific channels, leaving short-term speculative dynamics and long-term transition trends undistinguished:

H3. Renewable energy indices act as net transmitters under normal market growth, whereas fossil energy markets dominate as transmitters during crises, reflecting asymmetric spillover behavior.

2.4 *Time-varying parameter vector autoregression in sustainability and finance research*

The TVP-VAR model has emerged as a robust tool for capturing evolving market linkages, accommodating structural breaks and nonlinear interactions (Koop and Korobilis, 2014; Antonakakis *et al.*, 2019). Recent applications to climate-finance interactions highlight significant time-varying spillovers between carbon markets, renewable energy and ESG investments, particularly during crises (Alrweili and Ben-Salha, 2024; Cao *et al.*, 2025). However, most studies focus on single markets or limited time frames, leaving a gap in understanding how interconnectedness evolves across carbon, fossil and renewable energy and sustainable finance markets simultaneously:

H4. Spillovers among carbon, energy and sustainable finance markets are time-varying and asymmetric, and they differ across short-term versus long-term horizons.

2.5 *Research gap and contribution*

Overall, prior literature demonstrates substantial progress in understanding market interconnectedness, yet several gaps remain. Few studies integrate carbon, energy and sustainable finance markets within a dynamic, frequency-sensitive framework. More importantly, existing work does not explicitly compare results across crises, quantify nonlinear tail dependencies or clarify the structural role of green finance within energy–carbon spillovers.

This study addresses these gaps by applying a quantile-based TVP-VAR model with a frequency-domain perspective, capturing dynamic and asymmetric spillovers among carbon, fossil and renewable energy and sustainable finance markets. By bridging these methodological and conceptual gaps, the study provides a more coherent and integrated understanding of the transition toward sustainable energy systems. The approach provides actionable insights for risk management, investment strategy and policymaking in the context of energy transition and climate finance.

3. Methodology and data source

3.1 *Methodology*

To examine spillover effects across the returns of carbon emissions indices (CO_2), renewable and fossil energy benchmarks and sustainability-linked financial products such as green bonds and ESG indices, we adopt the quantile-based connectedness approach proposed by Bouri *et al.* (2021a, 2021b) and Chatziantoniou (2021). This approach captures the dependence structure across different parts of the conditional distribution, providing insights into extreme market events (e.g. stress or boom periods) that are not observable using traditional mean-based models. To assess overall connectedness among the variables, we implement a quantile vector autoregression (QVAR(p)) model, which forms the basis of the quantile connectedness framework. This model allows the parameters to vary across quantiles, capturing tail-dependent interactions among variables. The model is defined as follows:

$$\boldsymbol{x}_t = \boldsymbol{\mu}_{\mathrm{t}}(\tau) + \Phi_1(\tau)\boldsymbol{x}_{t-1} + \Phi_2(\tau)\boldsymbol{x}_{t-2} + \ldots + \Phi_{\mathrm{p}}(\tau)\boldsymbol{x}_{t-\mathrm{p}}\boldsymbol{\mu}_t(\tau) \tag{1}$$

Let x_t et x_{t-i} (where i = 1,….p) vectors representing internal variables of size N × 1. The parameter τ confined to the interval [0,1], represents the quantile level of the return volume of the pair. The value p indicates the lag length of the QVAR model.

$\mu(\tau)$ denotes an N × 1vector representing the conditional mean, while $\Phi j(\tau)$ represents an N × N matrix of QVAR coefficients. ut(τ) corresponds to an N × 1 error vector, accompanied by an N × N error variance-covariance matrix denoted by $\Sigma(\tau)$.

By applying Wold’s Theorem, the QVAR(p) model can be transformed into its Quantile Vector Moving Average representation, referred to as QVMA(∞). This transformation is made possible through the application of Wold’s decomposition:

$$\boldsymbol{x}_t = (\tau) + \sum_{j=1}^{p} \Phi j(\tau)\boldsymbol{x}_{t-j} + \boldsymbol{u}_t(\tau) = \boldsymbol{\mu}(\tau) + \sum_{i=0}^{\infty} \psi\mathrm{i}(\tau)\boldsymbol{u}_{t-\mathrm{I}} \tag{2}$$

Next, we proceed to the calculation of the generalized forecast error variance decomposition (GFEVD), a pivotal element of the interconnectedness methodology (Koop *et al.*, 1996; Pesaran and Shin, 1998). The GFEVD evaluates the impact of a shock in series *j* on series *i*, by quantifying its contribution to the forecast error variance of *i*. This can be represented as follows:

$$\theta_{ij}(\mathrm{H}) = \frac{(\Sigma(\tau))_{jj}^{-1} \sum_{\mathrm{h}=0}^{\mathrm{H}-1} \left(\left(\Psi_h(\tau)\Sigma(\tau)\right)_{ij}\right)^2}{\sum_{\mathrm{h}=0}^{\mathrm{H}} \left(\Psi_h(\tau)\Sigma(\tau)\Psi_h^{'}(\tau)\right)_{ii}} \tag{3}$$

$$\tilde{\tilde{\theta}}_{ij}(H) = \frac{\theta_{ij}(H)}{\sum_{k=1}^{N} \theta_{ij}(H)} \tag{4}$$

Since, the row sums of $\tilde{\theta}_{\mathrm{ij}}$ (H) are not equal to one, it becomes essential to normalize the matrix. This procedure involves dividing each element in a row by the sum of that particular row, resulting in $\tilde{\theta}_{\mathrm{ij}}$. This normalization process establishes the following relationships:

$$\sum_{\mathrm{i}=1}^{\mathrm{N}} \tilde{\theta}_{\mathrm{ij}}\ (\mathrm{H}) = 1 \text{ and } \sum_{j=1}^{N} \sum_{i=1}^{N} \tilde{\tilde{\theta}}_{ij}(H) = N$$

As a result, the sum of each row of $\tilde{\theta}_{\mathrm{ij}}$ totals one, indicating how a shock in series i has influenced both that specific series and all other series j.

Subsequently, the next step involves calculating all the interconnectedness measures. The total directional connectedness to others, To, measures the extent to which a shock in series i influences all other series j:

$$TO_i(H) = \sum_{i=1, i\neq j}^{N} \tilde{\tilde{\theta}}_{ji}(\mathrm{H}) \tag{5}$$

The general cumulative directional impact from other series, FROM, quantifies the extent to which series i is influenced by shocks from all other series j:

$$FROM_i(\mathrm{H}) = \sum_{\mathrm{i}=1,\mathrm{i}\neq \mathrm{j}}^{\mathrm{N}} \widetilde{\theta}_{\mathrm{ij}}(\mathrm{H}) \tag{6}$$

The total net directional connectivity NET represents the difference between the total directional connectivity to other series and the total directional connectivity from other series. This distinction can be understood as the net impact of series i on the established network.

$$\mathrm{NET}(H) = TO(H) - FROM_i(H) \tag{7}$$

When NETi> 0 (NETi< 0), series i exerts a greater (lesser) influence on all other series j compared to the influence it receives from them. Consequently, this categorizes it as a net transmitter (receiver) of shocks.

The level of network interconnectedness is assessed through the total connectedness index (TCI), which can be computed using the following formula:

$$TCI(d) = N^{-1}\sum_{i=1}^{N} TO_i(d) = N^{-1}\sum_{i=1}^{N} FROM_i(d) \tag{8}$$

3.2 Data source

We adopted the quantile connectedness framework introduced by Bouri *et al.* (2021a, 2021b) and further refined by Chatziantoniou *et al.* (2021, 2022) to examine the dynamic spillover effects between carbon emissions, renewable energy indices, nonrenewable energy indices and sustainable finance instruments. This approach allows for the analysis of asymmetric and extreme market behaviors, offering deeper insights into the transmission of shocks under varying market conditions. For this study, we collected adjusted closing prices for four main asset classes: global CO_2, the WilderHill Clean Energy Index ECO representing renewable energy, crude oil and natural gas as proxies for nonrenewable energy and sustainable finance instruments including the Global X Global Sustainability Leaders Index ETF and the Green Bond Index. The data set spans the period from November 7, 2018 to December 31, 2024, capturing the impact of major global events such as the COVID-19 pandemic and the Russia–Ukraine conflict, both of which have had profound effects on energy and financial markets. All price data were obtained from Datastream, and daily returns were calculated as the logarithmic differences of consecutive daily prices. Based on this data, we construct and analyze spillover indices to quantify both the magnitude and direction of shock transmission across these markets, identifying the main transmitters and receivers of risk in normal as well as extreme market conditions.

Figure 1 illustrates the return series of CO_2, renewable energy assets (represented by the WilderHill Clean Energy Index – ECO), nonrenewable energy commodities (crude oil and natural gas) and sustainable finance instruments (Global X Global Sustainability Leaders Index ETF and the Green Bond Index). The series display broadly similar patterns, particularly during periods of heightened market volatility, underscoring the interdependence among these asset classes. Global events such as the COVID-19 pandemic and the Russia–Ukraine war, have further amplified these fluctuations, emphasizing the sensitivity of these markets to external shocks. Interestingly, crude oil and natural gas exhibit distinct return dynamics in response to these disruptions, suggesting that nonrenewable energy markets play a unique and influential role in the transmission of economic and financial shocks at the global level.

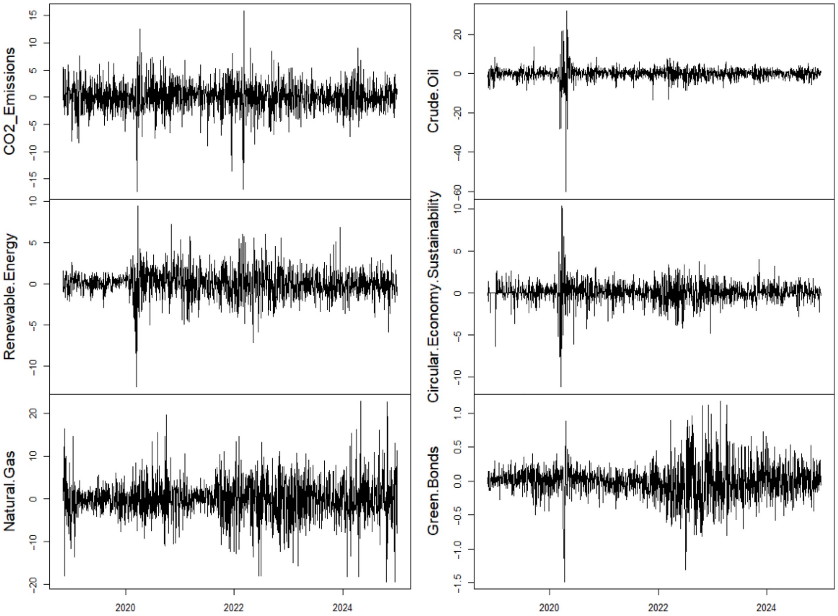

Figure 1. Time series plot of carbon emissions, renewable energy nonrenewable energy and sustainable finance

Source: Author

Table 1 provides a comprehensive overview of the return characteristics of carbon emissions, renewable energy, nonrenewable energy and sustainable finance indices. The mean returns indicate that most assets generate positive average returns, with CO_2 emissions (0.083%) and circular economy sustainability (0.047%) achieving the highest averages, whereas green bonds exhibit slightly negative mean returns (−0.003%). The standard deviations (reported in parentheses) highlight substantial volatility, particularly in nonrenewable energy markets, with natural gas and crude oil showing elevated risk exposure.

Variance estimates confirm that nonrenewable energy assets are significantly more volatile than sustainable finance instruments, such as green bonds and circular economy sustainability, which display comparatively lower risk. Skewness and excess kurtosis statistics reveal that most return distributions deviate from normality. Specifically, CO_2 emissions, renewable energy and crude oil demonstrate negative skewness, indicating a greater likelihood of extreme downside movements. Crude oil, in particular, exhibits exceptionally high excess kurtosis (71.137), emphasizing the frequency of extreme price jumps and underscoring the importance of robust risk management strategies.

The Jarque–Bera test strongly rejects the null hypothesis of normality for all series, while the Elliott–Rothenberg–Stock test confirms stationarity at the 1% significance level. In addition, the Ljung–Box Q(20) and $Q^2(20)$ tests detect significant autocorrelation and volatility clustering across all series, suggesting that advanced econometric approaches such as ARCH/GARCH-family or TVP-VAR models are well-suited to capture volatility spillovers and dynamic linkages.

Table 1. Descriptive statistics and correlations of return series

Variables	CO_2	Renewable.Energy	Natural.Gas	Crude.Oil	Circular.Economy. Sustainability	Green.Bonds
Mean	0.083 (0.216)	0.004 (0.929)	0.001 (0.990)	0.009 (0.917)	0.047 (0.141)	−0.003 (0.596)
Variance	7.238***	2.821***	20.225***	12.203***	1.610***	0.063***
Skewness	−0.311*** (0.000)	−0.289*** (0.000)	0.055 (0.369)	−3.151*** (0.000)	−0.471*** (0.000)	0.020 (0.743)
Ex.Kurtosis	4.007*** (0.000)	4.632*** (0.000)	2.813*** (0.000)	71.137*** (0.000)	13.048*** (0.000)	3.242*** (0.000)
JB	1088.045*** (0.000)	1441.479*** (0.000)	524.494*** (0.000)	337461.934*** (0.000)	11323.291*** (0.000)	695.521*** (0.000)
ERS	−3.688*** (0.000)	−8.257*** (0.000)	−18.610*** (0.000)	−14.048*** (0.000)	−17.900*** (0.000)	−14.048*** (0.000)
Q(20)	32.682*** (0.000)	74.519*** (0.000)	24.845*** (0.002)	66.397*** (0.000)	72.532*** (0.000)	59.276*** (0.000)
Q2(20)	167.921*** (0.000)	456.414*** (0.000)	111.137*** (0.000)	293.373*** (0.000)	1643.613*** (0.000)	639.442*** (0.000)
Kendall	CO_2	Renewable.Energy	Natural.Gas	Crude.Oil	Circular.Economy. Sustainability	Green.Bonds

Note(s): *** represent significance at 1%. Values in parentheses indicate the probability of significance
Source(s): Author

4. Empirical results

Before presenting the detailed empirical outcomes, this section is organized to offer a clear and coherent understanding of our results. First, we examine the dynamic and asymmetric connectedness among carbon emissions, fossil energy, renewable energy and sustainable finance markets across different market conditions, allowing us to capture spillover behavior during normal, bearish and bullish regimes. Second, we extend the analysis to the frequency domain to distinguish short-term contagion effects from long-term structural interdependencies. This combined framework provides deeper insights into systemic risk propagation and enhances the interpretability and robustness of the empirical findings.

4.1 Dynamic spillover effects between carbon emissions and energy markets

The Total Dynamic Connectedness Index (TCI), illustrated in Figure 2, provides a comprehensive measure of systemic interdependence among carbon emissions, renewable and nonrenewable energy markets and sustainable finance instruments over time. The heatmap visualization highlights how the strength of market interconnectedness fluctuates, with warmer colors indicating periods of heightened cross-market spillover effects. Empirical evidence demonstrates that connectedness substantially intensifies during extreme market events, corresponding to the tails of the conditional distribution (below the 25th percentile and above the 75th percentile). This reveals that market linkages become especially pronounced during periods of significant downturns or rapid upswings, implying that financial and energy markets are highly vulnerable to systemic risk transmission in times of stress. This supports *H1*: that extreme market conditions amplify spillovers among carbon, energy and sustainable finance markets. The observed symmetric pattern of the TCI at both distribution tails suggests a balanced propagation mechanism where negative and positive shocks exert similar systemic influence, corroborating findings from recent literature (Umar and Bossman, 2023; Mensi *et al.*, 2023). At median market conditions (50th percentile), the connectedness remains dynamic with noticeable fluctuations aligning with major geopolitical and health crises, notably the COVID-19 pandemic onset and the escalation of the Russia–Ukraine conflict. These exogenous shocks amplify the systemic risk and contribute to cascading effects across the interconnected markets. These observations are consistent with *H2*: that geopolitical and health crises significantly alter the interdependence among the studied markets. The cyclical pattern of TCI underscores that periods of relative tranquility are intermittently punctuated by spikes in market interdependencies, highlighting their sensitivity to macroeconomic and geopolitical developments. This emphasizes the importance for portfolio managers and policymakers to incorporate tail-dependent connectedness into their risk assessment and diversification strategies, as traditional risk mitigation approaches may be insufficient during market extremities. In conclusion, the quantile-based TCI approach advances our understanding of market interconnectedness by capturing its asymmetric and time-varying nature. Its ability to pinpoint when and how financial and energy markets co-move under different market conditions is critical for anticipating systemic risk and guiding resilient investment and regulatory frameworks.

The net total directional connectedness analysis reveals the time-varying roles of each market as either a net transmitter or receiver of shocks, as visualized in the color-coded spectrum of Figure 3. Red indicates periods where an asset predominantly acts as a risk transmitter, while blue reflects periods where it mainly absorbs shocks. At the 0.5 quantile (median), renewable energy and circular economy sustainability emerge as consistent shock transmitters, actively propagating market risk to other asset classes which aligns with recent studies highlighting the leadership role of sustainable assets in risk transmission during transition periods (Bouri *et al.*, 2021a, 2021b; Mensi *et al.*, 2023). In contrast, green bonds and natural gas mostly function as

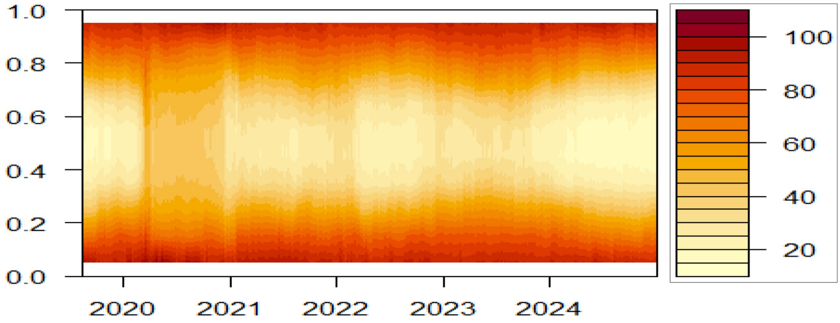

Figure 2. Dynamic total connectedness for all market
Source: Author

shock receivers, absorbing volatility from the system consistent with recent research on their diversification and safe-haven properties (Broadstock *et al.*, 2021; Chatziantoniou *et al.*, 2022). Crude oil and CO_2 emissions display more balanced behavior, oscillating between transmitting and receiving shocks, in line with earlier findings on the bidirectional risk dynamics in energy and emission markets (Diebold and Yilmaz, 2012; Antonakakis *et al.*, 2020). This observation supports *H3*: that renewable energy and circular economy assets primarily act as net transmitters of shocks, whereas green bonds and natural gas act as net receivers. Moreover, the magnitude and direction of connectedness are highly dynamic, with pronounced shifts during crisis periods or policy changes (e.g. COVID-19 or the Russia–Ukraine conflict), confirming the sensitivity of connectedness to macroeconomic and geopolitical events (Umar and Bossman, 2023; Chatziantoniou *et al.*, 2022). Therefore, understanding these evolving patterns of net connectedness is critical for effective risk management and strategic asset allocation in financial and energy markets, as supported by recent empirical literature (Diebold and Yilmaz, 2012; Mensi *et al.*, 2023; Bouri *et al.*, 2021a, 2021b).

To reinforce the robustness of our empirical findings, we use a quantile connectedness framework that computes the total connectedness index (TCI) and net spillover measures at three distributional levels $\tau = 0.05$, $\tau = 0.5$ and $\tau = 0.95$ across three major phases: the pre-COVID-19 period, the COVID-19 crisis and the Russia–Ukraine conflict. This methodological design allows us to distinguish how interconnectedness evolves under normal market conditions compared to periods of extreme downside or upside pressure.

As shown in Table 2, the median quantile ($\tau = 0.5$) reveals a TCI of 17.12% in the pre-COVID period, increasing to 23.82% during COVID-19 and then declining to 18.03% during the Russia–Ukraine war. These fluctuations indicate stronger systemic linkages during the global health crisis, while geopolitical tensions generated more heterogeneous and asset-specific spillovers.

At the lower tail ($\tau = 0.05$), TCIs are substantially higher 75.19% (pre-COVID), 75.56% (COVID) and 73.55% (war) indicating that severe negative shocks considerably amplify return spillovers among carbon emission indices, the renewable energy index (ECO), crude oil and natural gas and sustainable finance instruments such as the Global X Global Sustainability Leaders Index ETF and the Green Bond Index. A similar pattern is observed at the upper tail ($\tau = 0.95$), where TCIs remain consistently elevated, showing that strong positive market movements also increase cross-market connectedness.

The large gap between the median and tail quantiles clearly reflects nonlinear and regime-dependent transmission mechanisms. This is consistent with recent evidence suggesting that interconnectedness becomes more pronounced under market stress and extreme events. In

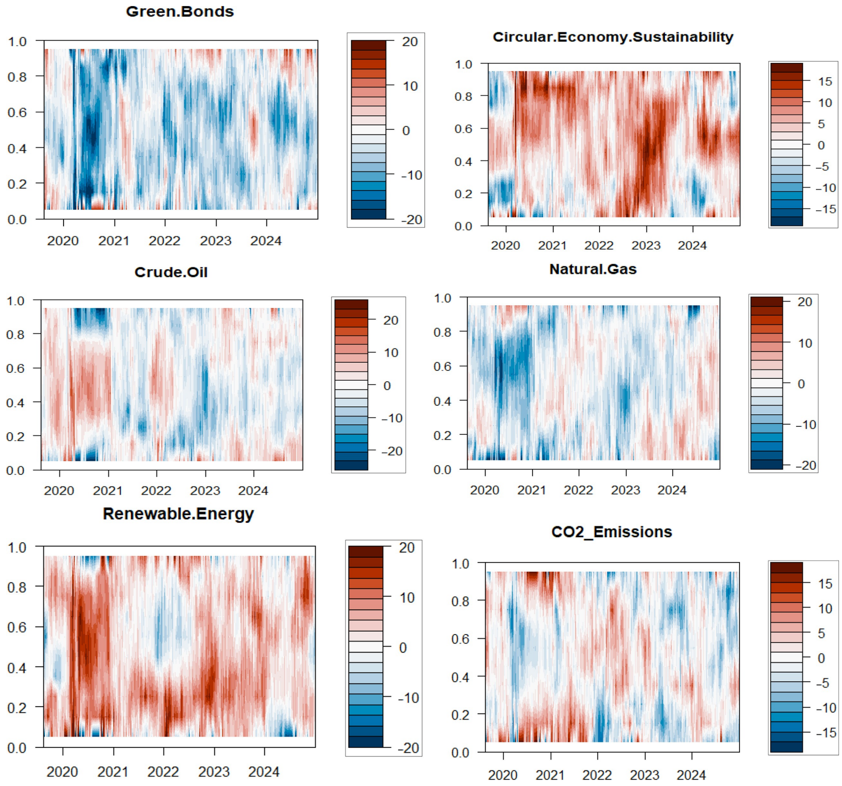

Figure 3. Net total directional connectedness for all assets
Source: Author

terms of directional spillovers, renewable energy (ECO) and green crypto or circular-economy–oriented assets tend to act as net transmitters of shocks, whereas natural gas, carbon emission indices and green bonds frequently emerge as net receivers. Fossil energy markets particularly crude oil and natural gas alternate between transmitting and absorbing shocks depending on the phase and the level of market pressure.

Overall, these findings reveal the asymmetric and time-varying nature of risk transmission within the carbon energy sustainable finance nexus. They also highlight the value of quantile-based connectedness approaches for capturing tail-risk dependencies, improving hedging effectiveness and guiding policy frameworks aimed at accelerating the low-carbon transition.

To further validate our results, Figure 4 presents the bilateral net pairwise connectedness network among CO_2, the WilderHill Clean Energy Index (ECO), crude oil, natural gas, circular economy assets and green bonds under different quantile conditions, providing a visual depiction of directional spillovers. In this network, blue nodes denote net transmitters, representing assets that channel risk to others during turbulent periods, while yellow nodes indicate net receivers, which absorb shocks and can act as safe havens or portfolio diversifiers. The arrows show the asymmetric and bilateral relationships among assets, reflecting the nonlinear and time-varying nature of market linkages.

Table 2. Spillovers measures based on the quantile VAR (mean quantile $\tau = 0.5$)

Variables	CO_2	Renewable. Energy	Natural.Gas	Crude.Oil	Circular. Economy	Green. Bonds	FROM
Lower quantile τ=0.05							
Pre-COVID-19 pandemic period							
CO_2	86.72	3.22	1.89	3.73	2.32	2.12	13.28
Renewable.Energy	2.92	75.83	2.11	6.67	10.29	2.19	24.17
Natural.Gas	2.26	2.05	86.33	3.15	2.87	3.35	13.67
Crude.Oil	3.33	7.66	3.06	81.67	1.41	2.88	18.33
Circular.Economy	2.14	11.99	1.15	1.01	81.71	1.99	18.29
Green.Bonds	2.42	2.35	4.16	3.45	2.60	85.02	14.98
TO	13.07	27.26	12.36	18.00	19.48	12.53	102.71
Inc.Own	99.79	103.10	98.70	99.67	101.19	97.56	cTCI/TCI
NET	−0.21	3.10	−1.30	−0.33	1.19	−2.44	20.54/17.12
NPT	2.00	4.00	2.00	3.00	4.00	0.00	
COVID-19 pandemic period							
CO_2	77.54	5.59	3.86	5.96	5.33	1.72	22.46
Renewable.Energy	4.58	64.02	2.26	4.81	21.50	2.83	35.98
Natural.Gas	4.82	1.67	85.45	2.12	2.83	3.11	14.55
Crude.Oil	5.77	5.33	1.68	77.71	7.62	1.88	22.29
Circular.Economy	4.38	20.49	1.03	7.19	65.35	1.56	34.65
Green.Bonds	1.83	2.15	2.95	4.05	2.01	87.01	12.99
TO	21.37	35.24	11.78	24.14	39.28	11.10	142.91
Inc.Own	98.92	99.26	97.23	101.85	104.63	98.12	cTCI/TCI
NET	−1.08	−0.74	−2.77	1.85	4.63	−1.88	28.58/23.82
NPT	2.00	2.00	1.00	3.00	5.00	2.00	
Russia–Ukraine war							
CO_2	88.48	2.05	2.37	2.16	3.17	1.76	11.52
Renewable.Energy	1.50	70.13	3.00	3.63	20.05	1.68	29.87
Natural.Gas	1.45	3.67	87.40	1.80	3.43	2.25	12.60
Crude.Oil	2.84	4.80	2.42	84.13	4.23	1.58	15.87
Circular.Economy	1.65	20.05	1.42	2.45	73.02	1.41	26.98
Green.Bonds	1.90	2.32	2.23	1.61	3.29	88.65	11.35
TO	9.34	32.90	11.44	11.66	34.16	8.69	108.19
Inc.Own	97.82	103.03	98.84	95.79	107.18	97.34	cTCI/TCI
NET	−2.18	3.03	−1.16	−4.21	7.18	−2.66	21.64/18.03
NPT	2.00	5.00	2.00	1.00	4.00	1.00	
Median quantile τ=0.5							
Pre-COVID-19 pandemic period							
CO_2	25.84	16.43	14.55	13.98	13.58	15.63	74.16
Renewable.Energy	14.50	24.44	14.79	14.71	16.14	15.42	75.56
Natural.Gas	14.87	15.91	24.94	14.86	12.74	16.68	75.06
Crude.Oil	16.10	17.07	15.91	23.42	12.46	15.04	76.58
Circular.Economy	14.27	18.20	13.62	14.01	24.78	15.11	75.22
Green.Bonds	13.90	15.97	15.41	14.89	14.36	25.47	74.53
TO	73.65	83.58	74.27	72.45	69.27	77.89	451.11
Inc.Own	99.49	108.02	99.21	95.88	94.06	103.36	cTCI/TCI
NET	−0.51	8.02	−0.79	−4.12	−5.94	3.36	90.22/75.19
NPT	3.00	5.00	2.00	1.00	0.00		

(*continued*)

Table 2. Continued

Variables	CO_2	Renewable. Energy	Natural.Gas	Crude.Oil	Circular. Economy	Green. Bonds	FROM
COVID-19 pandemic period							
CO_2	24.47	15.45	14.35	14.79	16.65	14.30	75.53
Renewable.Energy	14.89	23.42	13.85	13.99	18.87	14.99	76.58
Natural.Gas	14.94	14.93	24.42	14.16	15.54	16.01	75.58
Crude.Oil	15.11	15.01	13.58	24.26	17.37	14.67	75.74
Circular.Economy	15.01	17.04	13.78	14.87	24.54	14.76	75.46
Green.Bonds	14.39	14.71	15.02	14.06	16.30	25.52	74.48
TO	74.33	77.14	70.57	71.88	84.72	74.73	453.37
Inc.Own	98.80	100.55	94.99	96.14	109.26	100.25	cTCI/TCI
NET	−1.20	0.55	−5.01	−3.86	9.26	0.25	90.67/75.56
NPT	3.00	3.00	0.00	1.00	5.00	3.00	
Russia–Ukraine war							
CO_2	26.95	14.88	14.17	15.61	14.70	13.68	73.05
Renewable.Energy	13.74	24.74	14.77	15.49	18.59	12.67	75.26
Natural.Gas	13.58	15.66	27.67	14.73	14.35	14.01	72.33
Crude.Oil	14.37	15.57	14.44	26.00	15.35	14.28	74.00
Circular.Economy	13.76	18.58	14.09	15.28	24.59	13.69	75.41
Green.Bonds	13.62	14.13	14.11	14.77	14.65	28.72	71.28
TO	69.07	78.82	71.60	75.88	77.63	68.33	441.33
Inc.Own	96.01	103.57	99.27	101.88	102.23	97.05	cTCI/TCI
NET	−3.99	3.57	−0.73	1.88	2.23	−2.95	88.27/73.55
NPT	0.00	4.00	2.00	3.00	5.00	1.00	
Upper quantile $\tau=0.95$							
Pre-COVID-19 pandemic period							
CO_2	25.59	14.47	16.06	14.60	15.30	13.97	74.41
Renewable.Energy	14.30	26.52	13.49	14.68	16.74	14.27	73.48
Natural.Gas	15.10	13.74	27.53	14.77	12.92	15.94	72.47
Crude.Oil	15.29	15.09	15.70	25.92	12.92	15.07	74.08
Circular.Economy	14.69	17.52	13.62	14.23	25.23	14.70	74.77
Green.Bonds	14.05	14.59	16.39	15.15	15.14	24.67	75.33
TO	73.43	75.42	75.26	73.45	73.02	73.96	444.54
Inc.Own	99.03	101.93	102.80	99.37	98.25	98.63	cTCI/TCI
NET	−0.97	1.93	2.80	−0.63	−1.75	−1.37	88.91/74.09
NPT	26.31	13.97	16.53	13.35	14.89	14.96	73.69
COVID-19 pandemic period							
CO_2	26.47	15.54	14.28	15.17	15.32	13.21	73.53
Renewable.Energy	15.19	24.20	13.50	15.01	18.03	14.07	75.80
Natural.Gas	15.62	15.40	25.97	13.74	14.76	14.52	74.03
Crude.Oil	15.47	15.17	13.50	26.76	15.86	13.25	73.24
Circular.Economy	14.54	18.77	12.95	15.35	24.94	13.45	75.06
Green.Bonds	14.71	14.63	15.01	13.94	14.05	27.67	72.33
TO	75.52	79.50	69.24	73.21	78.01	68.50	443.99
Inc.Own	101.98	103.71	95.21	99.97	102.95	96.17	cTCI/TCI
NET	1.98	3.71	−4.79	−0.03	2.95	−3.83	88.80/74.00
NPT	3.00	5.00	1.00	2.00	4.00	0.00	

(*continued*)

Table 2. Continued

Variables	CO_2	Renewable. Energy	Natural.Gas	Crude.Oil	Circular. Economy	Green. Bonds	FROM
Russia–Ukraine war							
CO_2	25.90	14.50	14.18	14.54	16.01	14.86	74.10
Renewable.Energy	14.14	23.72	14.75	14.28	18.85	14.25	76.28
Natural.Gas	14.64	14.98	25.72	14.40	15.41	14.85	74.28
Crude.Oil	14.63	14.35	14.44	26.08	15.93	14.56	73.92
Circular.Economy	14.70	17.37	14.45	14.40	24.50	14.57	75.50
Green.Bonds	15.34	13.67	15.06	13.87	15.87	26.19	73.81
TO	73.45	74.87	72.90	71.50	82.07	73.09	447.87
Inc.Own	99.35	98.59	98.62	97.58	106.57	99.29	cTCI/TCI
NET	−0.65	−1.41	−1.38	−2.42	6.57	−0.71	89.57/74.65
NPT	3.00	3.00	2.00	0.00	5.00	2.00	

Note(s): This table present the directional connectedness indices between the return of global carbon emissions indices, the WilderHill Clean Energy Index (ECO) representing renewable energy, crude oil and natural gas as proxies for nonrenewable energy and sustainable finance instruments including the Global X Global Sustainability Leaders Index ETF and the Green Bond Index using the TVP-VAR method by Antonakakis *et al.* (2020). The rightmost column (FROM) in the table shows the directional spillover received by a specific market from all other markets. The penultimate row (TO) displays the directional spillover transmitted from a specific market to all others. The bottom row (NET) represents the net spillover, calculated as the difference between the TO and FROM spillovers for a given market. The bold number in the bottom right corner is the Total Connectedness Index (TCI) for all the markets
Source(s): Author

4.2 *The dynamic frequency connectedness*

Figures 5 and 6 decompose total connectedness into short-term (1–5 days) and long-term (>5 days) components while presenting the overall interdependence among carbon markets, renewable and fossil energy and sustainable finance instruments. The results clearly show that short-term connectedness dominates, particularly during periods of stress such as the COVID-19 pandemic and the Russia–Ukraine conflict. For example, the total connectedness TCI is 21.90, with 17.38 attributed to the short-term and 4.51 to the long term, confirming *H4* that spillovers are asymmetric, dynamic and dependent on the time horizon.

The surge in the short-term total connectedness index (TCI) during these turbulent episodes reflects the rapid transmission of shocks across markets, heightening systemic risk and posing significant challenges to traditional portfolio diversification and risk management frameworks. In contrast, the long-term connectedness component remains comparatively stable across time, capturing persistent but slower-moving interlinkages that embody structural dependencies and long-term strategic investment horizons. This dichotomy underscores the heterogeneous nature of financial contagion, where short-term linkages amplify crisis-induced volatility while long-term relationships mirror enduring economic and policy-driven ties. Further insights from Figure 6 highlight the net directional connectedness across frequencies. Renewable energy, circular economy sustainability and CO_2 emissions consistently emerge as net transmitters of shocks at both short- and long-term frequencies, underscoring their driving role in systemic risk propagation amid the global energy transition. Conversely, green bonds and natural gas more frequently appear as net receivers of shocks, acting as stabilizing assets and offering effective hedging and diversification opportunities across multiple investment horizons. Importantly, the consistency of these directional dynamics across frequency domains corroborates the aggregate connectedness results, enhancing the robustness and credibility of our empirical

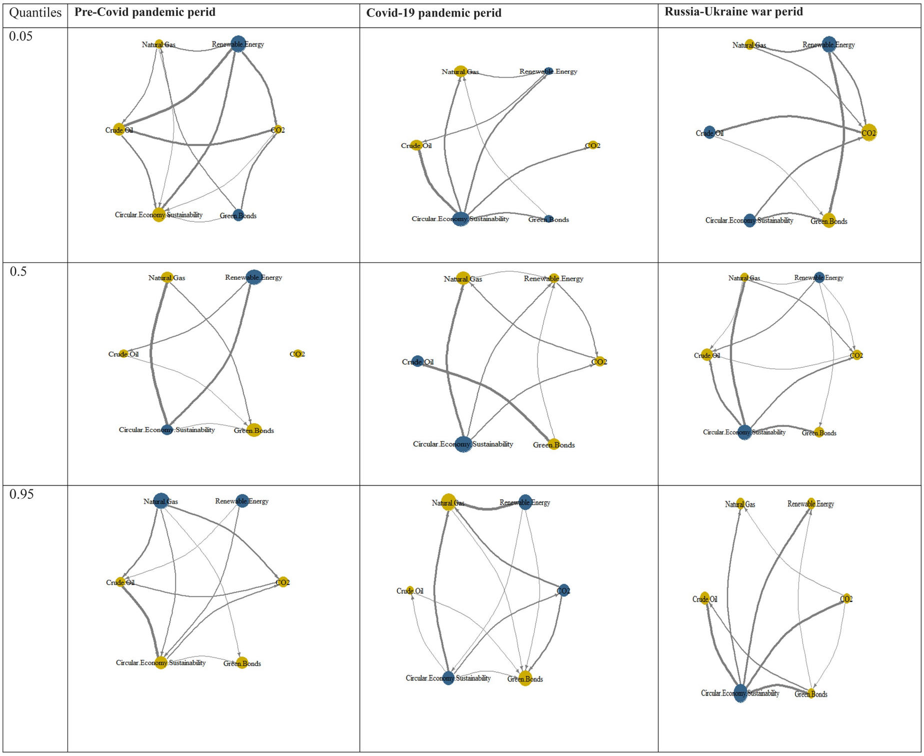

Figure 4. Net pairwise connectedness network between carbon emissions, renewable and nonrenewable energy markets and sustainable finance instruments

Note(s): Figure 4 net pairwise connectedness network between global carbon emissions indices, the WilderHill Clean Energy Index (ECO) representing renewable energy, crude oil and natural gas as proxies for nonrenewable energy and sustainable finance instruments including the Global X Global Sustainability Leaders Index ETF and the Green Bond Index. The blue nodes represent net spillover transmitters, while the yellow nodes indicate net spillover receivers. The size of the node radius reflects the intensity of the spillover effect. The arrows between nodes indicates the intensity of the directional spillover

Source: Author

analysis. This multidimensional perspective highlights the necessity for investors, policymakers and regulators to adopt dynamic, time- and frequency-sensitive approaches when evaluating systemic risk and designing resilient financial and sustainability-oriented strategies. Overall, our findings reinforce the evidence that financial market interdependencies are asymmetric, time-varying and frequency-dependent, particularly under the influence of exogenous shocks such as the COVID-19 pandemic and geopolitical tensions (Mellouli, 2025; Arif *et al.*, 2021; Chatziantoniou *et al.*, 2022; mellouli *et al.*, 2025). The observed predominance of short-term spillovers during crises underscores the importance of incorporating temporal and event-driven dimensions into systemic risk assessments. Furthermore, the persistence of directional roles across frequencies provides a robust empirical foundation for predictive modeling and early-

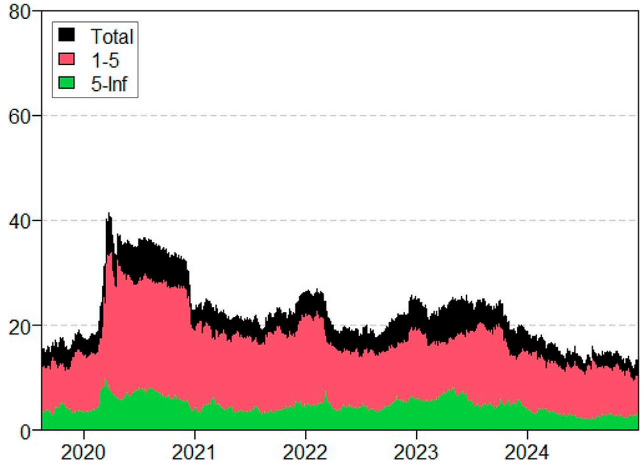

Figure 5. Short-term, long-term and overall dynamic total connectedness
Source: Author

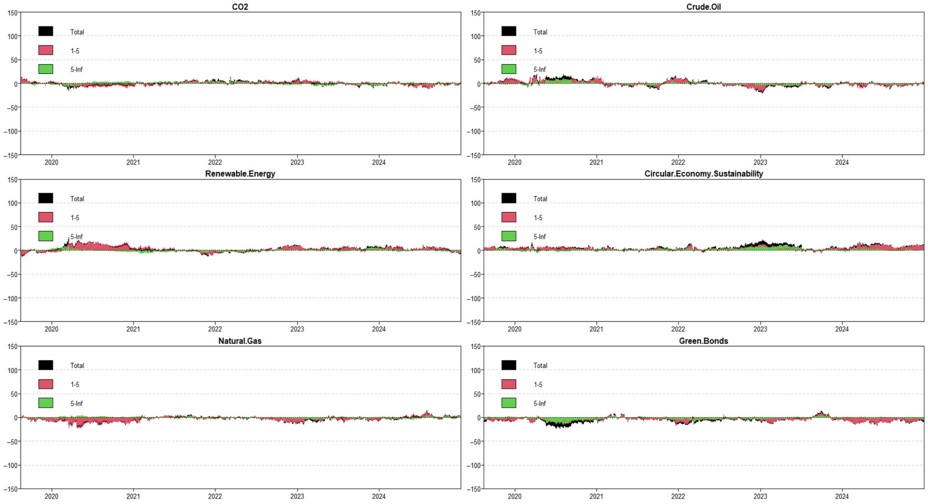

Figure 6. Short-term, long-term and overall net total directional connectedness
Source: Author

warning systems aimed at anticipating risks associated with the energy transition and the evolution of sustainable finance markets.

5. Conclusion

This study investigates the dynamic and frequency-dependent interconnectedness between carbon emissions, renewable and nonrenewable energy markets and sustainable finance instruments using a TVP-VAR combined with a quantile-based connectedness approach. The empirical results reveal that total connectedness intensifies sharply during periods of market stress, notably during the COVID-19 pandemic and the Russia–Ukraine conflict, highlighting the vulnerability of global markets to systemic shocks. Short-term spillovers dominate, reflecting rapid contagion, while long-term linkages remain relatively stable, capturing structural interdependencies associated with the global energy transition. Directional analysis shows that renewable energy, circular economy sustainability and CO_2 emissions act as consistent shock transmitters, whereas green bonds and natural gas absorb shocks and stabilize the system. These findings demonstrate that interconnectedness is asymmetric, time-varying and highly sensitive to extreme events, providing a multidimensional perspective on systemic risk and sustainable finance.

5.1 Implications for research, practice and policy

5.1.1 Research implications. Renewable energy and CO_2 emissions as consistent shock transmitters support the theoretical understanding of leadership effects in clean-energy markets. Future studies could extend the TVP-VAR framework with machine learning or copula-based models to capture higher-order nonlinear dependencies.

The dominance of short-term spillovers during crises highlights the need for high-frequency connectedness measures and mixed-frequency VAR models to better capture rapid market dynamics.

Green bonds stabilizing role suggests further investigation into sustainable asset-pricing frameworks, including green cryptocurrencies, ESG equity indices or biodiversity credits.

5.2 Practical implications (investors and portfolio managers)

Renewable energy and CO_2 emissions, as net shock transmitters, require active monitoring and dynamic hedging strategies, particularly in crisis periods.

Green bonds and natural gas, acting as net receivers, offer diversification and stabilization benefits; portfolio managers can increase allocation to these instruments to reduce risk exposure.

Tail-risk monitoring through quantile-based connectedness enables proactive adjustments in asset allocation, enhancing portfolio resilience under extreme market conditions.

5.3 Policy implications

Policymakers should account for the systemic risk transmitted by renewable energy and CO_2 emissions when designing energy transition strategies and macroprudential frameworks.

The stabilizing properties of green bonds support policies promoting deep, liquid sustainable finance markets, aligned with EU Green Deal, IPCC mitigation pathways and national green taxonomies.

Real-time supervisory tools and stress-testing frameworks incorporating quantile-specific spillovers are critical, especially for emerging economies undergoing structural transitions in energy and carbon dependency.

5.4 Societal implications

Understanding these spillovers informs smoother, socially equitable energy and financial transitions, mitigating abrupt price shocks and protecting vulnerable sectors.

By guiding investment strategies, regulatory policies and risk management, these insights contribute to a stable, low-carbon economy, supporting climate resilience and sustainable development goals.

5.5 *Limitations and future research*

The study focuses on a limited set of assets; including green cryptocurrencies, ESG indices or agricultural commodities could broaden insights.

Incorporating macroeconomic uncertainty, geopolitical risks and investor sentiment would enrich interpretation of transmission channels.

Exploring geographical heterogeneity and adopting multiband frequency decomposition can further illuminate spillover dynamics across regions and time horizons.

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