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Research article

Dynamic interconnectedness and portfolio strategies in green finance: Evidence from clean energy, ESG, and smart infrastructure

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Abstract: This paper investigated the dynamic interconnectedness and portfolio implications of five major pillars of green finance: clean energy (CEN), ESG equities (ESG), green bonds (GBD), smart-grid infrastructure (SGI), and ecology-focused equities (ECO). Using daily indices from 2015 to 2025, we applied a TVP-VAR-based extended joint connectedness framework to quantify total, net, and bilateral spillovers. The results indicated a structurally integrated system, led by SGI and ECO as persistent shock transmitters, while GBD consistently operates as a net receiver. CEN and ESG alternate between transmission and absorption depending on market regimes, particularly during COVID-19 and the Inflation Reduction Act period. Portfolio analysis showed that network-aware allocation via the minimum connectedness portfolio (MCoP) outperforms traditional variance- and correlation-based strategies (MVP, MCP) by improving drawdown control and cumulative returns. The study contributes by incorporating infrastructure and ecological assets into green contagion analysis and by translating systemic connectedness into actionable portfolio strategies, offering practical insights for sustainable investment management.

Keywords: time-varying connectedness; green finance; innovation sectors; portfolio optimization; extended joint connectedness; hedging strategies

JEL Codes: G11, Q56, C32, G15, Q43

1. Introduction

In recent years, the global shift toward sustainability and digital transformation has brought green finance and innovation-driven sectors to the forefront of financial research and investment strategies. With the mounting urgency to address climate change, transition to clean energy, and support environmentally conscious infrastructure, capital markets have witnessed the rapid growth of thematic financial instruments, including green bonds, Environmental, Social & Governance (ESG) equity indices, smart grids, and clean technology investments. These developments are supported by growing investor sentiment and intensified policy focus (Wu and Liu, 2023; Pham and Do, 2022). Simultaneously, investors, policymakers, and portfolio managers face increasing challenges in understanding the dynamic behavior and interdependence of these sectors, particularly in the presence of systemic shocks such as the COVID-19 pandemic (Lu et al., 2023; Jiang et al., 2023a) and the Russia–Ukraine war (Wu et al., 2024; Jiang et al., 2023b).

The convergence of green finance and innovation sectors not only reflects global policy goals, such as the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and the Inflation Reduction Act (IRA), but also represents a fertile ground for assessing systemic risk transmission, hedging effectiveness, and sustainable portfolio optimization. A growing body of literature has investigated the interconnectedness of green financial assets and their sensitivity to both market and policy-driven shocks (Zhang and Umair, 2023; Wang et al., 2024; Naifar, 2024). However, the inherent volatility, policy sensitivity, and inter-sectoral feedback mechanisms embedded in these markets require a robust analytical framework to capture their evolving connectedness (Tiwari et al., 2022; Dogan et al., 2022).

Motivated by the need to measure how shocks propagate within green finance and to turn those dynamics into investable choices, this study analyzes time-varying spillovers and portfolio implications across five representative SandP indices: the SandP Global Clean Energy Select Index, the SandP Green Bond Index, the SandP 500 ESG Tilted Index, the SandP Kensho Smart Grids Index, and the SandP Global Eco Index. These benchmarks jointly cover generation, financing, corporate screening, enabling infrastructure, and ecological services, providing a compact representation of the transition value chain. Using daily observations from April 30, 2015, to April 30, 2025, we estimate total, net, and pairwise connectedness with the extended joint connectedness approach embedded in a Time-Varying Parameter Vector Autoregression (TVP-VAR), following Balcilar et al. (2021) and related applications (Lu et al., 2023; Dogan et al., 2022; Naifar, 2025). We then map network information into investable rules by comparing minimum variance, minimum correlation, and minimum connectedness portfolios in the spirit of Tiwari et al. (2022) and Pham et al. (2024), which allows us to assess whether connectedness-aware allocation delivers superior risk mitigation and performance. The main research questions we aim to address are: (i) How do connectedness patterns change across green finance and innovation-driven sectors? (ii) Which sectors act as net transmitters or receivers of shocks under different market regimes? (iii) How can dynamic connectedness measures inform optimal portfolio construction and risk mitigation in sustainability-aligned investments?

These questions are designed to close three documented gaps: first, most studies emphasize green bonds and renewable energy while underrepresenting enabling infrastructure and ecology, so we explicitly track how connectedness changes across these missing pillars (Inglesi-Lotz et al., 2023; Zhang and Umair, 2023; Wang et al., 2024; Naifar, 2024); second, prior evidence often relies on pairwise or rolling-window settings, leaving joint identification of net transmitters and receivers under different regimes less clear, which motivates our use of an extended joint connectedness framework within a TVP-VAR (Balcilar et al., 2021; Lu et al., 2023; Dogan et al., 2022); third, many papers stop at diagnostics without translating spillovers into investable rules, so we test whether connectedness-aware allocation improves risk reduction and performance relative to variance- and correlation-based benchmarks (Tiwari et al., 2022; Pham et al., 2024).

This paper contributes to the literature in several important ways. First, it introduces a novel sectoral triad—clean energy, ESG-oriented equity, and smart infrastructure—to the connectedness literature, offering a more inclusive representation of innovation-driven green finance ecosystems. This addresses a gap in the literature that has so far focused on green bonds and renewable energy in isolation, while largely overlooking infrastructure-led innovation (Inglesi-Lotz et al., 2023). Second, we apply the extended joint connectedness approach within a TVP-VAR framework to jointly model the systemic risk transmission and directional spillovers among these interrelated themes, thereby advancing the methodological scope beyond traditional Diebold–Yilmaz (DY) or Quantile Vector Autoregression (QVAR) models. Third, our study goes beyond diagnostic analysis by implementing connectedness-based portfolio strategies to assess risk-adjusted performance and diversification benefits. This practical angle provides value-added insights for ESG portfolio managers and impact investors (Tiwari et al., 2022; Naeem et al., 2024). Lastly, we contextualize our findings around key geopolitical and policy shocks—COVID-19, Russia–Ukraine war, and the IRA—offering fresh evidence on how green asset linkages respond to both crisis-driven contagion and policy-driven transformation (Pham et al., 2024; Jiang et al., 2023b; Wang et al., 2024).

Key findings of the study indicate that clean energy, smart grids, and ESG equity act as dominant net transmitters of systemic shocks, particularly during crisis periods such as the COVID-19 pandemic and the Russia–Ukraine war, while green bonds (GBD) consistently function as net receivers with limited hedging capacity under stress. The dynamic connectedness index fluctuates markedly in response to policy interventions, including a noticeable shift following the Inflation Reduction Act. Portfolio simulations show that traditional risk-based strategies overweight GBD due to its low volatility, but the asset underperforms in terms of hedging effectiveness. In contrast, portfolios that account for systemic linkages, especially the minimum connectedness portfolio (MCoP), achieve superior cumulative returns and risk-adjusted performance by tilting toward ESG and clean infrastructure assets.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature and theoretical underpinnings. Section 3 describes the data and methodology. Section 4 presents the empirical results. Section 5 provides a focused discussion that interprets mechanisms, portfolio implications, and policy relevance. Section 6 concludes with key takeaways and policy implications.

2. Literature review

To provide a coherent synthesis of prior work, this section is structured into four thematic strands: (i) spillover dynamics in green finance, (ii) macro-financial shocks and uncertainty, (iii) methodological advancements in connectedness analysis, and (iv) gaps concerning infrastructure and ecological integration.

2.1. Spillover dynamics in green financial markets

The empirical literature on green finance has grown rapidly in recent years, indicating the increasing integration and complexity of sustainable investment markets. A central theme emerging from this body of research is the dynamic spillover behavior among green financial assets and its implications for systemic risk, portfolio diversification, and policy effectiveness. Within the broader financial-contagion literature, we interpret contagion as regime-dependent amplification of cross-sector spillovers beyond normal interdependence; operationally, we identify it through spikes in the total connectedness index and sign changes in net and pairwise directional measures estimated with the extended joint connectedness framework in a time-varying VAR. Recent evidence reinforces these features in green markets: Lu et al. (2023) showed clean energy as a persistent transmitter and green bonds as receivers around COVID-19 using an extended joint connectedness specification, while Xu et al. (2024) documented dominance by a European ESG exchange-traded fund in global ESG connectedness, showing that minimum-variance and risk-parity portfolios can reduce volatility during geopolitical stress.

Zhang and Umair (2023) explored the transmission channels among green bonds, renewable energy stocks, and carbon markets using VAR and TVP models, demonstrating that green bonds are closely linked with renewable energy and exhibit a complementary relationship with carbon markets. Similarly, Tiwari et al. (2022) employed a TVP-VAR and LASSO-based framework to assess dynamic return spillovers among green bonds, carbon, and renewable indices. Their findings underscore clean energy as a dominant shock transmitter, with green bonds being a persistent shock receiver, further emphasizing the asymmetric structure of the green financial system. Complementary studies focus on the breadth of sustainability networks and the investability of connectedness results. For instance, Naifar (2025) analyzed China's fintech, robotics, renewable energy, and green bonds, finding sectoral asymmetrical transmission and the feasibility of a minimum connectedness portfolio, which aligns with our emphasis on network-aware allocation. These findings motivate a joint, system-wide lens that explicitly includes enabling infrastructure and ecology. These two pillars remain underrepresented in contagion studies despite their central role in the transition value chain.

2.2. Macro-financial shocks and policy-driven spillovers

A second strand of literature examines how macroeconomic uncertainty and policy shocks influence interconnectedness among green financial assets. Several studies have investigated the sensitivity of green assets to external macro-financial shocks and policy uncertainty. Wang et al. (2024) applied a quantile spillover approach to highlight the disproportionate impact of economic and monetary policy uncertainty on green finance indices relative to climate policy uncertainty. Pham and Do (2022) further explored the hedging role of green bonds against implied volatility, advocating for active portfolio rebalancing to enhance risk-adjusted performance. The use of TVP-VAR models to assess dynamic interdependencies has gained traction across green finance literature. Wu and Liu (2023) found that ESG, clean energy, and water markets serve as central information transmitters, while green bonds and transportation serve as receivers. Their GARCH-MIDAS model also reveals that investor sentiment drives spillovers across green resource markets. Similarly, Lu et al. (2023) employed the extended joint connectedness (EJC) approach to demonstrate that clean energy consistently transmits spillovers, particularly during the COVID-19 pandemic, whereas green bonds remain net recipients. Related evidence links green finance to infrastructure and digital technology channels that transmit policy and macro shocks into valuations (Mahmood et al., 2024; Taghizadeh-Hesary and Rasoulinezhad, 2025), which supports our inclusion of smart-grid and ecology indices as potential transmission hubs.

2.3. Methodological advances in connectedness estimation

A third line of research focuses on methodological innovations designed to capture nonlinear and regime-dependent spillovers. Other contributions have highlighted the role of climate-related events in amplifying connectedness. Pham et al. (2024) and Duan et al. (2023) observed sharp increases in spillover during the COVID-19 pandemic and attributed them to shifts in investor sentiment and market rebalancing. Lin and Zhang (2025) extended this analysis to the clean energy and energy metals nexus, noting that extreme market conditions drastically increase spillover intensity and change risk propagation structures. From a methodological perspective, the adoption of advanced models such as quantile VAR (QVAR), asymmetric dynamic connectedness (Wu and Qin, 2024), and quantile-on-quantile frameworks (Naifar, 2024) has allowed scholars to capture tail risk dynamics and nonlinear dependencies in green asset markets. These approaches indicate that clean energy and ESG stocks frequently serve as net transmitters under normal and extreme conditions. The application of connectedness-based strategies in portfolio management is limited but growing. Tiwari et al. (2022) and Dogan et al. (2022) introduced minimum connectedness portfolios as alternatives to traditional variance or correlation-based methods. Their results highlight superior risk-adjusted returns and hedging efficiency, particularly during crises.

2.4. Gaps in infrastructure and ecological integration

Despite these advancements, existing studies largely overlook the interaction between clean energy, ESG equity, and smart infrastructure, a key omission considering the increasing role of digital and intelligent systems in the energy transition. While Inglesi-Lotz et al. (2023) started to explore smart grids and transportation networks, they did not examine integrated portfolio implications or joint contagion pathways. The literature indicates the importance of modeling dynamic and heterogeneous spillovers in green finance. However, there remains a clear need to extend these analyses to include infrastructure-led innovation sectors, adopt comprehensive joint connectedness measures, and explore how these dynamics inform real-world portfolio construction. Our study seeks to address these gaps by examining the interconnectedness of clean energy, ESG, and smart infrastructure through the lens of the extended joint connectedness framework and linking these findings to actionable portfolio strategies.

This study advances the green-asset contagion literature in an integrated way. First, it enables smart-grid infrastructure and ecosystem services to be integrated into the same system as clean energy, ESG equity, and green bonds, mirroring the transition value chain and allowing for an explicit upstream-to-downstream propagation test that prior work leaves implicit. Second, it applies a joint connectedness estimator embedded in a time-varying VAR, which avoids the arbitrariness of fixed rolling windows and yields internally consistent total, net, and pairwise measures suited to regime analysis of contagion. Third, it translates network diagnostics into implementable portfolio design by constructing a minimum-connectedness allocation and benchmarking it against variance- and correlation-based rules, thereby linking contagion to investable weights and hedging performance. Using a long daily sample spanning COVID-19, the Russia–Ukraine war, and the Inflation Reduction Act, we show that smart-infrastructure and ecology indices act as primary transmission hubs, while green bonds are state-dependent shock absorbers; this mechanism explains the persistently elevated systemwide connectedness after 2020 and the performance edge of network-aware portfolios. What differentiates this manuscript is the joint treatment of enabling infrastructure and ecology with traditional green pillars, the use of a joint (rather than pairwise-only) connectedness framework for contagion detection, and the explicit mapping from contagion metrics to portfolio choices.

3. Data description and methodology

3.1. Data description

This study investigates the dynamic connectedness and portfolio implications across five key indices representing distinct but interrelated segments of green finance and innovation-driven sectors. The dataset comprises daily closing prices from April 30, 2015, to April 30, 2025, obtained from SandP Global. The five indices included in the analysis are as follows: (i) SandP Global Clean Energy Select Index (CEN), which captures the performance of the most liquid and tradable clean energy companies worldwide, making it a benchmark for renewable energy investment. This index is widely used in the literature to represent renewable energy markets and has consistently been found to act as a net transmitter of shocks across green assets (e.g., Tiwari et al., 2022; Lu et al., 2023). (ii) SandP Green Bond Index (GBD) represents the universe of fixed income securities that finance environmentally friendly projects, serving as a direct proxy for climate-aligned debt instruments. (iii) SandP 500 ESG Tilted Index (ESG) provides broad U.S. equity exposure while integrating environmental, social, and governance screening, reflecting investor preferences for sustainable corporate practices. (iv) SandP Kensho Smart Grids Index (SGI), which tracks companies innovating in intelligent energy infrastructure, including smart grids and energy storage, represents the energy sector’s digital transformation. (v) SandP Global Eco Index (ECO) offers exposure to companies involved in environmental services and ecological solutions, adding a broader sustainability perspective beyond energy and finance.

These indices were chosen for their representativeness of core green and innovation-linked financial themes. They span clean energy generation, sustainable finance, ESG-aligned equity, smart infrastructure, and ecological innovation, providing a complete view of the green finance ecosystem. This allows us to capture not only sector-specific dynamics but also cross-sectoral spillovers. The data covers a full decade, encompassing key structural shocks such as the COVID-19 pandemic, the Russia–Ukraine war, and significant policy shifts like the Inflation Reduction Act (IRA).

To make the sampling rule explicit, we select these five SandP benchmarks because they cover the core transition stack of green finance, capturing clean energy generation (CEN), climate-aligned debt financing (GBD), ESG-screened corporate equity (ESG), enabling smart-grid infrastructure (SGI), and ecology-oriented activities (ECO), while providing a single, long, and uninterrupted daily history from 2015-04-30 to 2025-04-30 that is required for reliable TVP-VAR-based extended joint connectedness estimation. Indices are broad, rules-based, investable, and anchored in liquid constituents that make the portfolio exercises implementable; also, keeping a single provider ensures methodological coherence across eligibility screens, rebalancing calendars, bond inclusion rules, and corporate-action treatments, which avoids confounding connectedness estimates with construction differences. Prominent alternatives such as MSCI ESG equity families and the Bloomberg MSCI Green Bond universe, and specialized segments such as carbon credits, green loans, or biodiversity indices, are acknowledged; however, many of these either lack continuous daily coverage over our window, exhibit distinct market microstructure or disclosure constraints that limit comparability with cash equity and broad bond indices, or introduce cross-provider heterogeneity that would blur attribution of changes in connectedness to economic forces rather than index design. To conduct the analysis, all price series are converted into logarithmic returns. Table 1 presents the descriptive statistics for the daily log returns of the five indices spanning clean energy (CEN), green bonds (GBD), ESG equities (ESG), smart grids (SGI), and ecology-related assets (ECO).

Table 1. Descriptive statistics.

	SGI	**CEN**	**GBD**	**ESG**	**ECO**
Mean	0.018	−0.007	0.003	0.040*	0.020
Std. dev.	2.667	2.688	0.151	1.403	1.244
Skewness	−0.448***	−0.245***	−0.064	−0.644***	−0.566***
Kurtosis	7.243***	6.235***	3.938***	15.734***	10.381***
JB	5581.331***	4098.612***	1627.044***	26,115.174***	11,426.591***
ERS	−16.997	−21.831	−16.858	−9.386	−17.214
Q(20)	88.478***	79.798***	50.382***	198.637***	113.979***
$\boldsymbol{Q^2(20)}$	2197.495***	1121.563***	523.598***	2329.603***	2671.892***

Note: This table reports the descriptive statistics of the daily log returns for the five indices: SandP Kensho Smart Grids Index (SGI), SandP Global Clean Energy Select Index (CEN), SandP Green Bond Index (GBD), SandP 500 ESG Tilted Index (ESG), and SandP Global Eco Index (ECO) over the period from April 30, 2015, to April 30, 2025. Reported metrics include the mean, standard deviation (Std. dev.), skewness, kurtosis, Jarque–Bera (JB) test for normality, Elliott–Rothenberg–Stock (ERS) unit root test, and the Ljung–Box Q and Q^2 statistics at lag 20. *** indicates statistical significance at the 1% level.

The average returns are generally low, with ESG (0.040%) showing the highest mean return, followed by ECO (0.020%) and SGI (0.018%). GBD and CEN exhibit the lowest mean returns, with CEN showing a slightly negative average. Regarding volatility, CEN and SGI display the highest standard deviations (2.688% and 2.667%, respectively), suggesting greater risk exposure compared to the relatively stable GBD (0.151%). ESG and ECO show moderate levels of risk, consistent with their diversified and broader thematic exposures. All series, except GBD, exhibit significant negative skewness and high kurtosis, indicating asymmetric return distributions with fat tails, a common feature in financial data. The Jarque–Bera (JB) test confirms non-normality at the 1% significance level across all indices. The Elliott–Rothenberg–Stock (ERS) test results confirm the stationarity of the return series, while the Q(20) and Q^2(20) portmanteau statistics suggest significant autocorrelation and conditional heteroskedasticity, validating the need for time-varying and dynamic modeling approaches such as TVP-VAR.

3.2. Methodology

To examine the dynamic spillovers across clean energy, ESG, green bonds, smart infrastructure, and ecological industries, this study adopts the extended joint connectedness approach proposed by Balcilar et al. (2021). This approach builds upon the foundational connectedness framework developed by Diebold and Yilmaz (2012) by addressing its main limitation, the dependence on fixed-size rolling windows. The extended method flexibly captures interactions across assets by embedding the model into a TVP-VAR framework. It is particularly effective under shifting market regimes such as those induced by climate policy, global shocks, or geopolitical risks. The joint total directional connectedness from others to asset i is computed as:

$$S_{i\leftarrow\bullet,t}^{jnt,from} = \frac{E\left(\vartheta_{i,t}^{2}(H)\right) - E[\vartheta_{i,t}(H) - E\vartheta_{i,t}(H))| \in \forall \neq i,t+1,\ldots,\in \forall \neq i,t+H]^2}{E\left(\vartheta_{i,t}^{2}(H)\right)} \tag{1}$$

$$= \frac{\sum_{h=o}^{H-1} e_i' \mathrm{A}_{ht} \sum_t M_i (M_t' \Sigma_t M_t')^{-1} M_t' \sum_t \mathrm{A}_{ht}' e_i}{\sum_{h=0}^{H-1} e_i' \mathrm{A}_{ht} \sum_t \mathrm{A}_{ht}' e_i} \tag{2}$$

This formulation measures the fraction of the H-step forecast error variance of a variable i, which is attributable to joint future shocks from all other variables. In this structure, M_i is a rectangular matrix of dimension $K \times (K-1)$, excluding variable i from the joint shock conditioning. The Joint Total Connectedness Index is then expressed as:

$$jSOI_t = \frac{1}{K} \sum_{i=1}^{K} S_{i\leftarrow\bullet,t}^{jnt,from} \tag{3}$$

Moreover, the joint directional spillovers satisfy the following internal consistency properties:

$$S_{i\bullet\rightarrow,t}^{jnt,to} = \sum_{j=1,i\neq j}^{K} jSOT_{ji,t} \tag{4}$$

$$S_{j,t}^{jnt,net} = S_{i\rightarrow\bullet,t}^{jnt,to} - S_{i\leftarrow\bullet,t}^{jnt,from} \tag{5}$$

$$S_{ij,t}^{jnt,net} = jSOT_{ji,t}^{jnt,to} - jSOT_{ij,t}^{jnt,from} \tag{6}$$

These equations enable us to trace directional, net, and pairwise connectedness dynamically across the five sectors represented by the indices in this study. The robustness and relevance of this framework have been demonstrated in various applications. For instance, Polat et al. (2024) used it to study spillovers between Fintech and renewable energy; Dogan et al. (2022) applied it to green finance and renewable energy; and Xie and Cao (2024) employed it for cryptocurrency and carbon market interlinkages. In addition to spillover analysis, we assess portfolio management implications by computing optimal bilateral portfolio weights following Kroner and Ng (1998):

$$\omega_{ij,t} = \frac{\Sigma_{ii,t} - \Sigma_{ij,t}}{\Sigma_{ii,t} - 2\Sigma_{ij,t} + \Sigma_{jj,t}} \tag{7}$$

where $\Sigma_{ij,t}$ denotes the conditional covariance between assets i and j at time t. Portfolio allocation strategies used in this study include:

Minimum variance portfolio (MVP) weights:

$$\omega_{\Sigma_t} = \frac{\Sigma_t^{-1} I}{I \Sigma_t^{-1} I} \tag{8}$$

Minimum correlation portfolio (MCP) weights:

$$\omega_{R_t} = \frac{R_t^{-1} I}{I R_t^{-1} I} \tag{9}$$

Minimum connectedness portfolio (MCoP) weights:

$$\omega_{C_t} = \frac{PCI_t^{-1} I}{I PCI_t^{-1} I} \tag{10}$$

where R_t is the conditional correlation matrix, and PCI_t is the pairwise connectedness matrix obtained from the extended joint connectedness framework. To evaluate hedging performance, we adopt the hedging effectiveness (HE) measure proposed by Antonakakis et al. (2020):

$$HE_i = 1 - \frac{var(r_p)}{var(r_i)} \tag{11}$$

where $var(r_p)$ denotes the variance of the portfolio, and $var(r_i)$ denotes the variance of the individual asset. These portfolio strategies have been widely validated for their effectiveness in risk management under uncertainty.

4. Empirical results

4.1. Static joint connectedness results

To establish a baseline understanding of the systemic interdependencies across the selected green finance and innovation-driven sectors, we begin by examining the average joint connectedness estimates. Table 2 reports the time-averaged spillover measures computed using the extended joint connectedness approach. The table displays the own-variance shares on the main diagonal, the directional spillovers between sectors in the off-diagonal elements, and aggregate metrics such as total spillovers transmitted (TO), received (FROM), net spillovers (NET), and normalized pairwise directional connectedness (NPDC).

Table 2. Averaged joint connectedness.

	SGI	CEN	GBD	ESG	ECO	FROM
SGI	26.59	20.06	2.12	28.31	22.92	73.41
CEN	21.20	27.77	4.46	15.26	31.32	72.23
GBD	3.51	6.15	79.63	3.82	6.89	20.37
ESG	30.34	15.45	1.99	28.53	23.70	71.47
ECO	22.82	29.59	4.27	21.93	21.39	78.61
TO	77.86	71.25	12.83	69.32	84.83	316.10
NET	4.44	−0.98	−7.54	−2.15	6.23	TCI
NPDC	3.00	2.00	0.00	1.00	4.00	63.22

Note: This table presents the average joint connectedness matrix computed using the extended joint connectedness approach over the period from April 30, 2015, to April 30, 2025. NPDC reports a dominance score for each index equal to the count of counterparts (out of four) to which it is a net transmitter on average; values therefore range from 0 (net receiver to all) to 4 (net transmitter to all).

The results indicate a dense and asymmetric network of interactions, with significant heterogeneity in the transmission and absorption of shocks across sectors. The SandP Kensho Smart Grids Index (SGI) and the SandP Global Eco Index (ECO) emerge as key net transmitters of spillovers. SGI, for instance, transmits substantial shocks to ESG (28.31), ECO (22.92), and CEN (20.06), contributing to a high total spillover transmission (TO = 77.86) and a positive net connectedness value of 4.44. ECO, similarly, exhibits the highest total spillovers sent to the system (TO = 84.83), with strong contributions to CEN (29.59) and ESG (21.93), resulting in the highest positive net spillover (NET = 6.23). These findings highlight the dominant role of infrastructure and ecological innovation sectors in disseminating systemic shocks throughout the green investment landscape. A plausible mechanism for the prominence of SGI and ECO as net transmitters is their position at the upstream and enabling layers of the transition value chain. SGI aggregates firms in grid digitalization, storage, power electronics, and related equipment—sectors whose cash flows are highly sensitive to policy sequencing, capital expenditure cycles, advanced components supply chains, and rate case expectations. News about investment tax credits, interconnection rules, or transmission build-outs reaches these enablers first. Then, it propagates to downstream clean energy producers and broad ESG screens through valuation channels and expectations about deployment speed. ECO spans environmental services, water technologies, waste management, and pollution control across industries, materials, and utilities. These businesses are exposed to input costs and regulation intensity, as well as concession contracts, which provide ECO a conduit to transmit shocks from the commodity and regulatory spheres into equity benchmarks. High operating leverage, narrative-driven exchange-traded fund flows, and overlapping investor bases further amplify the pass-through from SGI and ECO to CEN and ESG, which is consistent with the off-diagonal spillovers reported in Table 2.

In contrast, the SandP Green Bond Index (GBD) remains the most insulated among the five indices, with the highest own-variance share (79.63) and the lowest total spillovers transmitted (TO = 12.83). Its negative net connectedness score of −7.54 indicates its role as a net shock absorber, consistent with its lower volatility and fixed-income nature. The net shock-absorbing role of GBD is consistent with two state-dependent bond channels. In high-uncertainty episodes, flight-to-quality reallocations and duration effects mitigate green bond returns relative to equity-like exposures, which increases the share of shocks received and decreases those transmitted. In calmer regimes, carry and primary-market issuance may modestly raise co-movement through credit spread dynamics while still leaving GBD a net receiver, as the index is diversified across high-grade sovereign, supranational, agency, and corporate issuers.

Clean energy (CEN) and ESG indices occupy more intermediate positions. While CEN interacts actively with other indices, especially ECO (31.32) and SGI (21.20), it absorbs slightly more shocks than it transmits, as evidenced by its marginally negative net spillover of -0.98. Similarly, ESG demonstrates a nearly balanced spillover profile (TO = 69.32, FROM = 71.47), suggesting a dual role as both transmitter and receiver in the system.

The Total Connectedness Index (TCI) across all sectors is 63.22, indicating a moderate-to-high level of overall interconnectedness in the green financial ecosystem. This systemic tightness points to strong co-movements and risk propagation pathways, particularly under joint market conditions. Additionally, the normalized pairwise directional connectedness (NPDC) indicates that ECO (NPDC = 4.00) and SGI (NPDC = 3.00) dominate the bilateral information flows, further reinforcing their systemic importance as innovation-aligned transmitters of volatility. These static results emphasize the differentiated roles the various green and innovation sectors play in the volatility transmission network. While innovation-centric indices such as SGI and ECO are primary shock originators, green bonds maintain their identity as defensive assets. Such heterogeneity presents valuable implications for portfolio construction and systemic risk monitoring within sustainability-driven investment frameworks. These findings align with previous evidence by Lu et al. (2023) and Dogan et al. (2022), who similarly found clean energy and ESG-related innovation indices to be dominant net transmitters, whereas green bonds consistently acted as shock absorbers, reinforcing their defensive characteristics within diversified sustainable portfolios.

4.2. Dynamic total connectedness

To deepen the understanding of systemic linkages among green finance and innovation-driven sectors, we examine the temporal evolution of the Total Connectedness Index (TCI) using the extended joint connectedness framework. Figure 1 presents the TCI over the period from April 2015 to April 2025. The index reflects the share of forecast error variance attributed to cross-sector spillovers, thereby capturing the degree of systemic integration in the network.

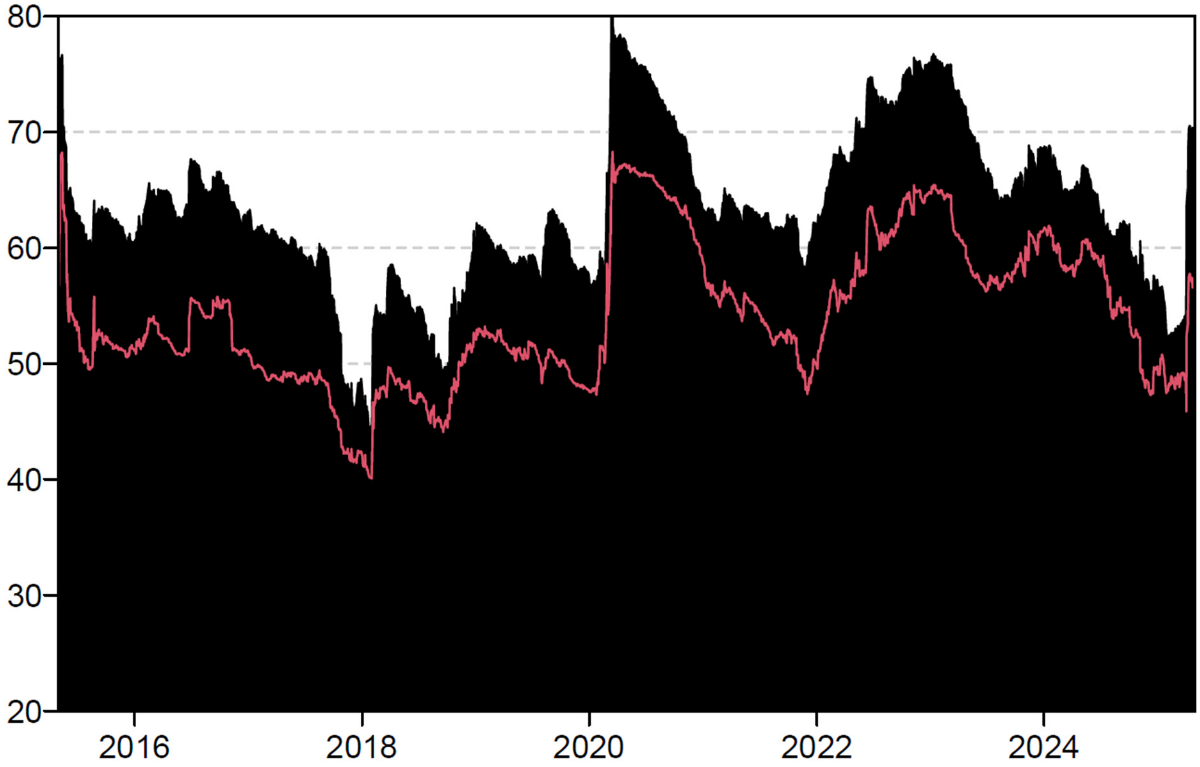

Figure 1. Time-varying total connectedness index.

Note: This figure illustrates the temporal evolution of the Total Connectedness Index (TCI) for five key green finance and innovation indices. The black-shaded region represents the joint connectedness estimated using the extended joint connectedness approach of Balcilar et al. (2021), while the red line corresponds to the standard connectedness measure proposed by Diebold and Yilmaz (2012). The results are obtained from a time-varying parameter vector autoregression (TVP-VAR) model, with the lag length selected by the Bayesian Information Criterion (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

Figure 1 indicates several prominent surges in connectedness, notably around early 2020, mid-2022, and again in early 2025. The sharp spike in 2020 aligns with the onset of the COVID-19 pandemic, which triggered widespread uncertainty across financial and commodity markets. This period is marked by elevated correlation and joint volatility transmission among clean energy, ESG equity, green bonds, and smart infrastructure, reflecting systemic risk amplification across sustainable assets. A second, more moderate peak occurs around early 2022, consistent with geopolitical tensions from the Russia–Ukraine war, which disrupted energy markets and intensified risk transmission in both traditional and green assets, as highlighted by Wu et al. (2024) and Jiang et al. (2023b). For clarity, we use COVID-19 in early 2020 and the IRA enactment in August 2022 as temporal anchors to contextualize the dynamics in Figure 1. Our discussion is descriptive rather than causal, and the timing cues are employed solely to interpret the observed spikes. The temporal profile of the spikes is also consistent with sector-specific transmission channels. During early 2020, policy uncertainty and supply chain disruptions initially repriced SGI and ECO, as project timing, component availability, and regulatory approvals are embedded in their cash flows. The ensuing co-movement then propagated to CEN and ESG, as deployment and profitability expectations were revised. In early 2022, energy price shocks and geopolitical risk again repriced, enabling infrastructure and ecological services first, with spillovers cascading to clean energy producers and broad ESG screens. This sequencing supports the view that SGI and ECO act as upstream transmitters rather than merely high-beta followers.

Furthermore, we observe another upswing in the TCI beginning around mid-to-late 2022, which persists through 2023. This period coincides with the implementation and market digestion of the U.S. Inflation Reduction Act (IRA) in August 2022. While the IRA was designed to stimulate clean energy investment and promote sustainable infrastructure, its enactment also led to significant repricing and structural shifts within green asset classes. The increased connectedness during this phase likely reflects the market's synchronized response to policy-driven investment flows and forward-looking expectations around green capital allocation. Rather than acting as a shock absorber, policy-induced optimism appears to have temporarily elevated co-movement across clean energy, ESG, and smart infrastructure indices, reducing diversification benefits and reinforcing systemic coupling. In contrast to the sharp, front-loaded COVID-19 spike, the IRA phase is characterized by a slower-building and more persistent elevation in connectedness, led by equity segments, most notably smart infrastructure, clean energy, and ESG, consistent with policy-driven synchronization rather than a pure risk-off episode. Green bonds exhibit a state-contingent absorption pattern over these windows. When uncertainty rises and policy rates fall or stabilize, duration effects and high credit quality strengthen the shock-absorption capacity of GBD, thereby dampening its outward spillovers. When policy optimism lifts all green equities simultaneously, as around the initial digestion of the Inflation Reduction Act, issuance pipelines, spread sensitivity, and benchmark inclusion effects can raise short-horizon co-movement with equities and temporarily reduce hedging gains without overturning the net-receiver status observed in the static matrix. This helps explain why the systemwide connectedness increases while GBD continues to absorb more shocks than it transmits.

Interestingly, the TCI does not return to pre-COVID lows even after temporary declines, suggesting a structural increase in integration among green finance components over the last decade. This persistent elevation points to the growing maturity and interdependence of sustainable financial markets, where innovations in one segment (e.g., smart infrastructure) are increasingly transmitted to others (e.g., ESG or clean energy) through investor sentiment, shared policy exposure, or technological convergence. These dynamic connectedness patterns corroborate earlier findings by Lu et al. (2023) and Pham et al. (2024), who documented persistent and elevated volatility and return spillovers among green assets in the aftermath of COVID-19 and climate policy interventions. Similarly, Trancoso and Gomes (2024) emphasized the increasing synchronization of green equity indices during global transitions, reinforcing the argument that systemic integration across sustainable markets is structurally rising. The fact that the TCI remains elevated relative to pre-2020 levels indicates a structural rise in integration that interacts with these mechanisms. As grid modernization, storage deployment, and environmental services expand, SGI and ECO serve as transmission hubs that convert policy and technology news into valuation shocks across the broader complex. At the same time, GBD's absorption varies with the balance between duration movements and credit spread dynamics.

4.3. Time-varying net total directional connectedness

Figure 2 illustrates the time-varying net total directional connectedness of five green finance indices.

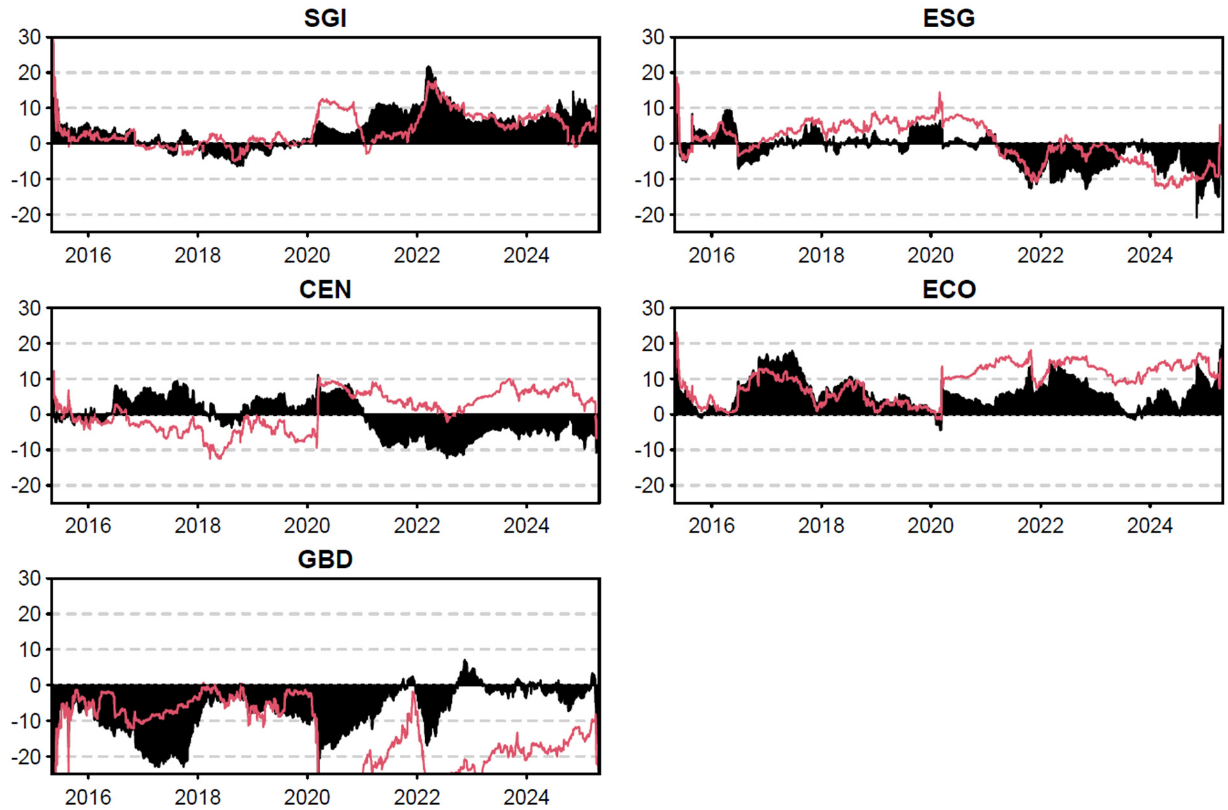

Figure 2. Time-varying net total directional connectedness of green finance driven assets.

Note: This figure displays the net total directional connectedness for each of the five indices: SGI, CEN, GBD, ESG, and ECO. The black-shaded region represents the net total directional connectedness estimated using the extended joint connectedness approach of Balcilar et al. (2021), while the red line corresponds to the standard connectedness measure proposed by Diebold and Yilmaz (2012). Values above zero indicate a net transmitter of shocks, and values below zero indicate a net receiver.

Figure 2 indicates that a positive value (above the zero line) implies that the index is contributing shocks to the broader system, whereas a negative value indicates the index is absorbing shocks from other sectors. Throughout the sample period, SGI demonstrates a shifting behavior. Prior to 2020, the smart grids sector was relatively neutral in its influence, oscillating mildly between receiving and transmitting shocks. However, after the onset of the COVID-19 pandemic, SGI transitions into a prominent net transmitter, particularly during 2021 and beyond. This shift coincides with increased global investment in digital infrastructure, the acceleration of electrification trends, and government-backed stimulus packages aimed at modernizing energy systems (Wu and Liu, 2023; Inglesi-Lotz et al., 2023). CEN, representing clean energy, reveals a more bifurcated pattern. In the earlier part of the sample, it acts as a net transmitter, reflecting its central role in driving the green finance narrative. However, from late 2021 onward, it increasingly behaves as a net receiver of shocks. This reversal may be attributed to tightening financial conditions, the delayed impact of climate legislation, and volatility in energy prices, which reduced investor confidence in the sector's short-term returns (Lin and Zhang, 2025; Duan et al., 2023).

GBD consistently emerges as a net receiver of shocks, indicating its function as a financial stabilizer. This persistent absorptive role aligns with the relatively low-risk profile of green bonds and their appeal during periods of heightened uncertainty. Notably, GBD continues to attract capital inflows during crises such as the COVID-19 shock and the Russia–Ukraine conflict, reinforcing its role as a hedging instrument in ESG portfolios (Pham and Do, 2022; Lu et al., 2023; Duan et al., 2023). The ESG index shows a moderately active transmitter role prior to 2021, benefiting from growing investor interest in ESG integration. However, it shifts into a net receiver position during and after the geopolitical tensions in 2022, suggesting intensified sensitivity of ESG-tilted equities to global risk-off episodes. This behavior implies that while ESG indices are important transmitters during stable conditions, they become more vulnerable during turbulent periods. ECO, which represents ecology-related industries, follows a declining trend in its systemic influence. Initially a mild transmitter, it gradually shifts into a consistent net receiver, particularly from 2021 onward. This pattern may reflect growing investor scrutiny regarding the commercial scalability and policy support for ecologically focused innovations, especially in the face of macroeconomic headwinds.

The findings from Figure 2 demonstrate the heterogeneous and time-varying nature of interdependence across green finance–driven sectors. Smart infrastructure and clean energy emerge as early influencers, while green bonds play a stabilizing role, and ESG and ecology indices reflect more cyclical and sentiment-driven patterns. This heterogeneity of systemic positioning provides valuable insights for risk management and strategic asset allocation in sustainable investment portfolios.

4.4. Time-varying net pairwise directional connectedness

Figure 3 presents the pairwise net connectedness dynamics among all combinations of the five green finance–aligned indices. The black-shaded areas denote the net directional spillovers between each pair, where positive values indicate net transmission of shocks from the first to the second asset in the pair (e.g., SGI → CEN), and negative values represent net reception of shocks.

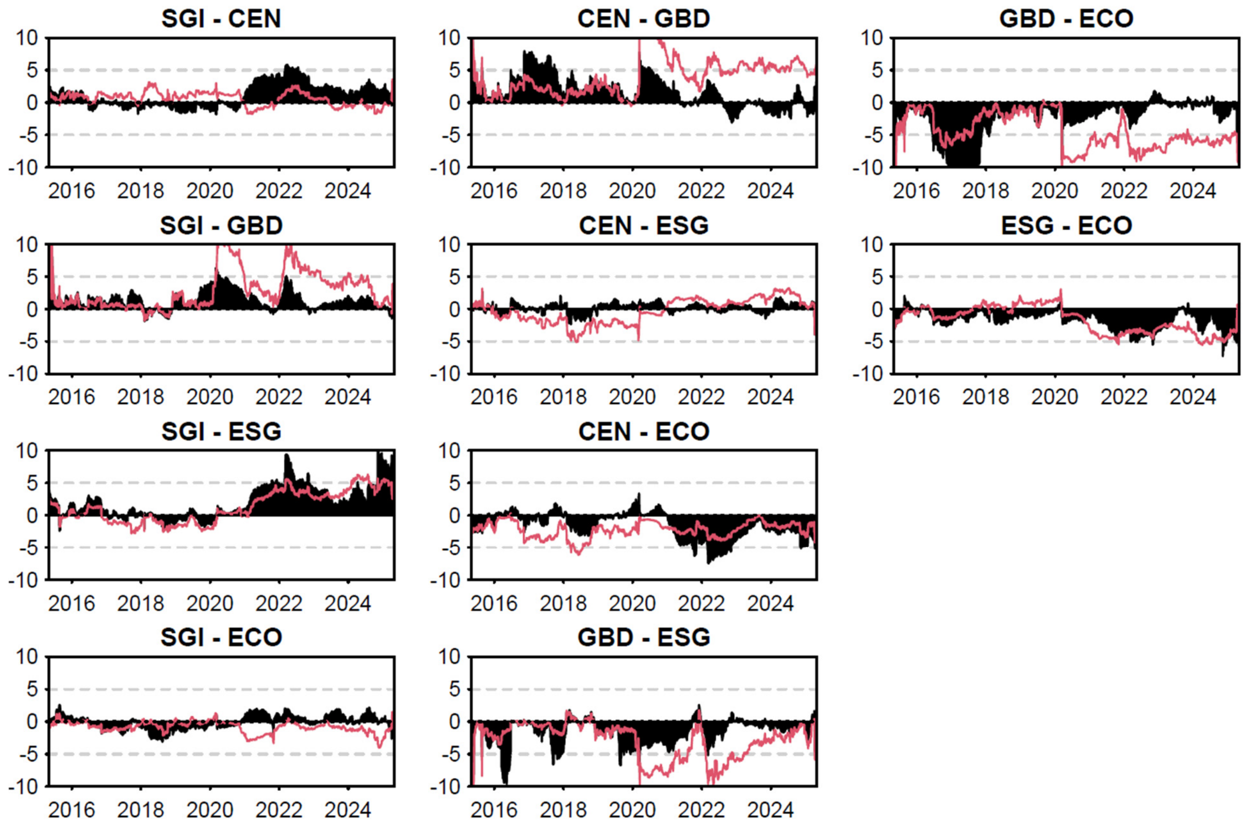

Figure 3. Time-varying net pairwise directional connectedness among green finance-driven assets.

Note: This figure presents the net pairwise directional connectedness between all combinations of the five indices: SGI, CEN, GBD, ESG, and ECO. The black-shaded region represents the net pairwise directional connectedness estimated using the extended joint connectedness approach of Balcilar et al. (2021), while the red line corresponds to the standard connectedness measure proposed by Diebold and Yilmaz (2012). In each panel, positive values indicate that the row index is a net transmitter to the column index, and negative values indicate that it is a net receiver.

The results from Figure 3 indicate that the pairwise relationships are highly time-varying and sensitive to external market conditions. For instance, SGI appears to be a consistent net transmitter to GBD, especially after 2020, coinciding with the surge in infrastructure modernization following the pandemic and policy responses such as green recovery packages. Similarly, SGI also exerts increasing influence over ESG post-2021, suggesting a growing systemic role for smart grid innovations within sustainable equity investment frameworks. CEN's pairwise dynamics indicate significant interdependence with both GBD and ECO. Between 2021 and 2023, CEN transmits strong shocks to ECO, likely reflecting the tight integration between clean energy transitions and ecological outcomes. However, its relationship with GBD remains more variable, with alternating roles, possibly reflecting capital reallocation across sectors in response to climate policy uncertainty and macro-financial volatility.

The GBD-ECO and GBD-ESG pairs stand out for their consistently negative net connectedness, indicating that green bonds largely absorb shocks from these sectors. This pattern aligns with GBD's characterization as a defensive asset in ESG portfolios, especially during turbulent periods such as the COVID-19 pandemic and energy market disruptions linked to the Russia-Ukraine war. Interestingly, the ESG–ECO relationship displays increasing negative connectedness from 2021 onward, suggesting that as ESG equities grow in systemic importance, ecology-related industries become more reactive to their fluctuations. This may point to asymmetric risk propagation within the broader green finance complex.

4.5. Bilateral portfolio allocation and hedging performance

Table 3 presents bilateral optimal portfolio weights, standard deviations, confidence intervals, and hedging effectiveness (HE) between each pair of green and innovation-linked indices.

Table 3. Bilateral optimal portfolio weights.

	Mean	***σ***	**5%**	**95%**	**HE**	**p-value**
SGI/CEN	0.50	0.22	0.14	0.92	0.19	0.00
SGI/GBD	0.04	0.05	0.00	0.14	0.95	0.00
SGI/ESG	0.03	0.10	0.00	0.26	0.48	0.00
SGI/ECO	0.02	0.05	0.00	0.14	0.54	0.00
CEN/SGI	0.50	0.22	0.08	0.86	0.19	0.00
CEN/GBD	0.02	0.03	0.00	0.09	0.94	0.00
CEN/ESG	0.19	0.21	0.00	0.67	0.53	0.00
CEN/ECO	0.02	0.05	0.00	0.14	0.54	0.00
GBD/SGI	0.96	0.05	0.86	1.00	0.04	0.28
GBD/CEN	0.98	0.03	0.91	1.00	0.02	0.68
GBD/ESG	0.90	0.08	0.73	1.00	0.10	0.01
GBD/ECO	0.95	0.06	0.84	1.00	0.03	0.45
ESG/SGI	0.97	0.10	0.74	1.00	0.01	0.89
ESG/CEN	0.81	0.21	0.33	1.00	0.11	0.00
ESG/GBD	0.10	0.08	0.00	0.27	0.90	0.00
ESG/ECO	0.42	0.26	0.00	0.79	0.26	0.00
ECO/SGI	0.98	0.05	0.86	1.00	0.01	0.87
ECO/CEN	0.98	0.05	0.86	1.00	0.00	0.97
ECO/GBD	0.05	0.06	0.00	0.16	0.88	0.00
ECO/ECO	0.58	0.26	0.21	1.00	0.16	0.00

Note: This table presents the bilateral optimal portfolio weights, standard deviations (σ), 5th and 95th percentiles of the weight distributions, hedging effectiveness (HE), and p-values for each pair of indices. Portfolio weights are computed using the Kroner and Ng (1998) methodology based on conditional variance-covariance matrices derived from the TVP-VAR framework. HE reflects the percentage reduction in portfolio risk due to diversification, where higher values imply stronger hedging performance.

Table 3 indicates several key insights into optimal asset allocation strategies and the role of individual assets in risk mitigation. First, smart grids (SGI) and clean energy (CEN) exhibit a perfectly balanced allocation in both directions (SGI/CEN and CEN/SGI at 0.50), suggesting a symmetrical risk-reward relationship and strong diversification synergy. This balanced allocation is accompanied by moderate hedging effectiveness (HE = 0.19), implying that these assets, while highly correlated, still offer portfolio smoothing benefits when combined. This aligns with the findings of Tiwari et al. (2022), who documented strong co-movement and diversification benefits among renewable energy segments. Green bonds (GBD), although generally assigned small portfolio weights in most pairings, typically ranging from 0.02 to 0.10, consistently demonstrate high hedging effectiveness. For example, SGI/GBD and CEN/GBD show HE values of 0.95 and 0.94, respectively. This demonstrates the defensive nature of GBDs, which provide substantial risk reduction benefits due to their relatively stable return profiles, especially when paired with more volatile equity-based indices. Despite their low weight, GBDs play a critical hedging role within sustainability-themed portfolios. This defensive property of green bonds is consistent with evidence reported by Pham and Do (2022) and Lu et al. (2023), who show that GBDs absorb volatility from equity markets and act as safe havens in turbulent times.

ESG equities show a wide spectrum of behaviors. They receive low portfolio weights when paired with SGI (0.03) and GBD (0.10) but higher allocations with ECO (0.42) and CEN (0.81), indicating complementary dynamics and moderate risk-sharing. Notably, ESG/ECO demonstrates the highest HE in this group (0.26), reflecting shared exposure to broad sustainability themes and the capacity for mutual volatility dampening. The ESG/CEN pair also performs well from a diversification standpoint, combining two growth-oriented themes with relatively strong HE (0.11). These results are broadly in line with Wu et al. (2024), who emphasized the importance of pairing ESG with innovation-linked assets to enhance portfolio resilience. ECO, representing a broader ecological index, tends to dominate portfolio allocations, especially in ECO/CEN (0.98) and ECO/SGI (0.98), consistent with its diversified sector exposure. These pairs also show acceptable hedging effectiveness (0.02 and 0.01, respectively), suggesting that ECO performs as a volatility buffer when paired with narrower innovation-focused indices. This is supported by Jiang et al. (2023a), who found that ecological investments often act as passive recipients of market-wide volatility, making them suitable as complements to riskier green assets.

From a practical perspective, these findings have key implications for sustainable and innovation-driven portfolio design. Investors seeking diversification should consider pairing volatile growth assets like SGI and CEN with defensive instruments such as GBD. Meanwhile, ESG and ECO indices provide a middle ground, offering thematic exposure with a moderate risk-reducing capacity. Importantly, the very low p-values (mostly 0.00) across pairs indicate statistical significance and robustness of the estimated weights. The results support hybrid portfolio strategies combining innovation (SGI, CEN), broad ESG coverage (ESG, ECO), and fixed-income stability (GBD). While GBD consistently receives a lower portfolio weight, its strong hedging effectiveness confirms its role as an essential tool in reducing downside risk. These insights extend previous work by Pham et al. (2024), who advocate for adaptive ESG portfolios that integrate both growth and defensive components.

4.6. Optimal hedge ratios and hedging effectiveness

Table 4 presents the optimal hedge ratios for various pairs of ESG-driven and innovation-linked assets, along with their standard deviations, confidence intervals, and hedging effectiveness (HE). A higher hedge ratio suggests stronger co-movement and risk transfer potential, whereas a lower value indicates weaker hedging utility. Additionally, hedging effectiveness quantifies the extent to which variance in a position can be reduced by adding the hedge asset.

Table 4. Optimal hedge ratio.

	Mean	σ	5%	95%	HE	p-value
SGI/CEN	0.68	0.14	0.46	0.90	0.54	0.00
SGI/GBD	0.54	0.80	−0.67	1.81	0.07	0.00
SGI/ESG	1.13	0.12	0.88	1.30	0.67	0.00
SGI/ECO	1.07	0.14	0.85	1.28	0.60	0.00
CEN/SGI	0.67	0.18	0.40	0.93	0.54	0.00
CEN/GBD	1.10	0.82	−0.29	2.34	0.13	0.00
CEN/ESG	0.80	0.19	0.42	1.04	0.36	0.00
CEN/ECO	1.22	0.20	0.86	1.52	0.74	0.00
GBD/SGI	0.03	0.05	−0.04	0.11	0.08	0.00
GBD/CEN	0.06	0.05	−0.02	0.15	0.15	0.00
GBD/ESG	0.02	0.07	−0.08	0.16	0.07	0.00
GBD/ECO	0.10	0.07	−0.01	0.22	0.15	0.00
ESG/SGI	0.57	0.13	0.35	0.79	0.71	0.00
ESG/CEN	0.42	0.17	0.19	0.73	0.41	0.00
ESG/GBD	0.23	0.58	−0.70	1.23	0.06	0.00
ESG/ECO	0.75	0.20	0.47	1.11	0.58	0.00
ECO/SGI	0.49	0.09	0.35	0.65	0.61	0.00
ECO/CEN	0.56	0.08	0.45	0.69	0.74	0.00
ECO/GBD	0.77	0.51	−0.07	1.67	0.13	0.00
ECO/ECO	0.68	0.12	0.48	0.87	0.56	0.00

Note: This table presents the estimated optimal hedge ratios (mean), their standard deviations (σ), confidence intervals (5% and 95%), hedging effectiveness (HE), and p-values for statistical significance. A higher HE value indicates stronger hedging benefits, based on time-varying covariance dynamics derived from a TVP-VAR model.

Table 4 indicates several noteworthy findings. A key finding is the strong hedging alignment among innovation-related indices. Notably, SGI/ESG (1.13), SGI/ECO (1.07), and CEN/ECO (1.22) exhibit the highest hedge ratios, along with strong hedging effectiveness values of 0.67, 0.60, and 0.74, respectively. These combinations suggest that infrastructure-oriented and clean energy indices (SGI, CEN) effectively mitigate risk when paired with ESG and ecological indices. This indicates the systemic integration of sustainability themes and supports the construction of diversified green portfolios across these pillars. This is in line with Lu et al. (2023), who showed that ESG and clean energy exhibit strong hedging relationships with broader sustainability indices, especially during periods of systemic volatility. Similarly, Wu and Liu (2023) identified ESG and water markets as important information transmitters in green finance networks, contributing to their utility as hedging instruments.

Conversely, hedge pairs involving GBD consistently display low hedge ratios and poor hedging effectiveness. For example, GBD/SGI (0.03, HE = 0.08), GBD/ESG (0.02, HE = 0.07), and GBD/ECO (0.10, HE = 0.15) offer minimal protection. These findings demonstrate the limited ability of fixed-income green instruments to serve as effective hedges against equity- and infrastructure-based volatility due to their distinct market sensitivities and lower beta exposure. This aligns with findings by Pham and Do (2022), who emphasized that while green bonds offer stability, their hedging capacity is limited under high-volatility scenarios. Additionally, Tiwari et al. (2022)

highlighted the relatively weak diversification power of green bonds in multi-asset portfolios during market stress.

ESG itself serves as a robust hedge when paired with smart grid investments (ESG/SGI, OHR = 0.57, HE = 0.71) and ecological sectors (ESG/ECO, OHR = 0.75, HE = 0.58). The reciprocal pair ECO/ESG also performs well (OHR = 0.68, HE = 0.56), suggesting meaningful bidirectional hedging potential between ESG and nature-focused investments. These findings are valuable for investors aiming to balance environmental performance with volatility control. This is consistent with Jiang et al. (2023a), who observed that ESG and eco-focused indices exhibit bidirectional volatility dynamics and hedging complementarities.

Financially, the implications are twofold. First, portfolios integrating clean infrastructure (SGI, CEN) with ESG and ECO indices offer not only diversification but also efficient risk mitigation. Second, while green bonds provide stability and sustainable certification, they are less suitable as hedge instruments for dynamic, equity-based assets. As such, asset allocators may prefer using ESG or clean energy equities over green bonds for active risk hedging in green innovation portfolios. These results extend the observations of Pham et al. (2024), who advocated for diversified and adaptive ESG portfolios with selective inclusion of growth-oriented assets to enhance hedging effectiveness.

4.7. Multivariate portfolio optimization

Table 5 illustrates the multivariate optimal portfolio weights of five indices across three distinct allocation strategies: minimum variance portfolio (MVP), minimum correlation portfolio (MCP), and minimum connectedness portfolio (MCoP). These strategies reflect different dimensions of risk control, with MVP focusing on volatility minimization, MCP on minimizing inter-asset correlations, and MCoP targeting systemic spillover risk reduction. Each panel of the table presents the average portfolio weights, standard deviations, confidence intervals, hedging effectiveness (HE), and p-values for significance testing.

Under the MVP framework, GBD dominates the portfolio with an average weight of 0.81, signaling its traditionally low volatility and appeal as a conservative asset. However, its hedging effectiveness is slightly negative (–0.03), suggesting that during periods of systemic stress, green bonds may not offer sufficient protection. In contrast, SGI and CEN receive zero average weights but exhibit very high HE scores (0.94), indicating that even small allocations to these clean energy-linked indices can effectively hedge portfolio risk. ESG and ECO earn modest weights (0.14 and 0.04, respectively) while delivering strong risk-reduction benefits. This observation is consistent with Tiwari et al. (2022), who highlight the limited hedging performance of green bonds in multivariate portfolios and underscore the value of clean energy as a volatility diversifier.

In the MCP strategy, which minimizes return correlations, GBD remains heavily weighted (0.38) but again registers a significantly negative HE (–3.61), reinforcing concerns about its failure to decouple from systemic fluctuations. Instead, CEN (0.21) and ESG (0.30) contribute to portfolio diversification with solid HE values (0.74 and 0.50). SGI’s role increases to 0.10, also providing meaningful hedging capability (HE = 0.74). ECO, while lightly weighted (0.01), remains a low-risk contributor with positive effectiveness. These findings align with Wu and Liu (2023) and Lu et al.

(2023), who documented that ESG and infrastructure-based indices (such as smart grids) tend to offer robust diversification properties when systemic risks intensify.

Table 5. Multivariate portfolio weights.

Minimum variance portfolio (MVP)						
	Mean	σ	5%	95%	HE	p-value
SGI	0.00	0.01	0.00	0.04	0.94	0.00
CEN	0.00	0.01	0.00	0.01	0.94	0.00
GBD	0.81	0.10	0.65	0.94	−0.03	0.53
ESG	0.14	0.09	0.03	0.35	0.89	0.00
ECO	0.04	0.06	0.00	0.17	0.88	0.00
Minimum correlation portfolio (MCP)						
	Mean	σ	5%	95%	HE	p-value
SGI	0.10	0.08	0.00	0.23	0.74	0.00
CEN	0.21	0.09	0.08	0.40	0.74	0.00
GBD	0.38	0.05	0.27	0.45	−3.61	0.00
ESG	0.30	0.06	0.18	0.39	0.50	0.00
ECO	0.01	0.03	0.00	0.08	0.44	0.00
Minimum connectedness portfolio (MCoP)						
	Mean	σ	5%	95%	HE	p-value
SGI	0.12	0.08	0.00	0.23	0.72	0.00
CEN	0.25	0.09	0.12	0.44	0.73	0.00
GBD	0.36	0.07	0.19	0.45	−3.89	0.00
ESG	0.23	0.12	0.03	0.38	0.47	0.00
ECO	0.04	0.06	0.00	0.14	0.41	0.00

Note: This table presents the optimal asset weights and hedging effectiveness (HE) of three multivariate portfolio strategies: minimum variance portfolio (MVP), minimum correlation portfolio (MCP), and minimum connectedness portfolio (MCoP). The results are based on time-varying estimates using the conditional variance-covariance, correlation, and connectedness matrices, respectively.

The MCoP strategy, which explicitly accounts for connectedness among assets, results in more diversified allocations. CEN (0.25), ESG (0.23), and SGI (0.12) maintain meaningful presence, offering strong hedging outcomes (HEs above 0.70). GBD again holds the largest weight (0.36), but its negative HE (–3.89) suggests that its influence may stem more from statistical optimization than from actual protective utility. ECO, though marginally included (0.04), consistently shows positive and stable effectiveness (HE = 0.44). This supports recent empirical results from Pham et al. (2024) and Naeem et al. (2024), who found that systemic-aware allocation strategies outperform traditional ones under volatility clustering and during extreme events.

Table 5 demonstrates the critical trade-offs in sustainable portfolio construction. While GBD offers volatility and correlation benefits in traditional frameworks, it underperforms when systemic risk is considered. Clean energy and ESG assets, despite their relatively higher volatility, emerge as reliable hedging instruments under interconnected market conditions. These findings suggest that asset managers focused on sustainability should diversify across clean energy infrastructure and ESG indices rather than relying exclusively on green bonds, particularly in times of elevated financial contagion. This echoes the portfolio-level recommendations made by Trancoso and Gomes (2024) and Dogan et al. (2022), advocating for the inclusion of innovation-driven assets to balance systemic exposure.

Extending this analysis, Figure 4 visually compares the cumulative portfolio returns associated with the three strategies, MVP, MCP, and MCoP, over the full sample period.

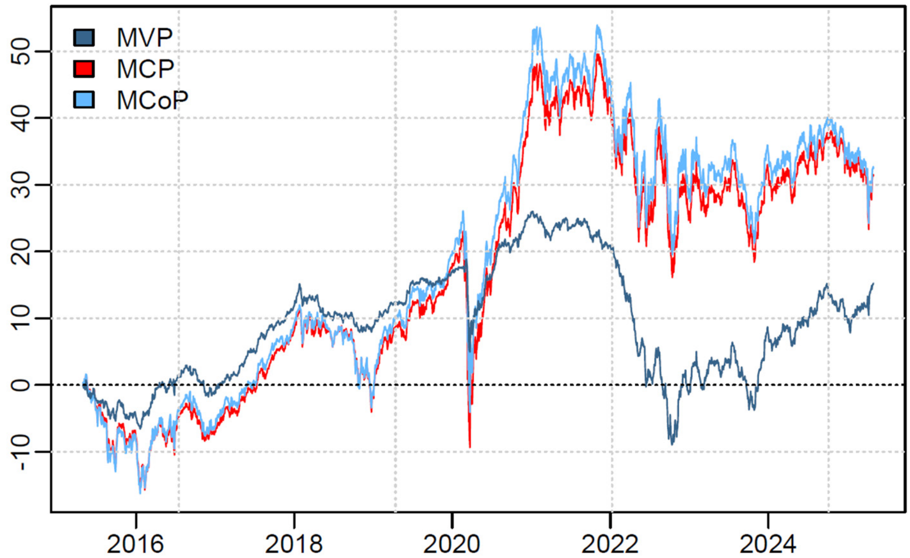

Figure 4. Cumulative portfolio returns: MVP, MCP, and MCoP strategies.

Note: Cumulative portfolio returns: MVP, MCP, and MCoP strategies. This figure compares the cumulative performance of the minimum variance portfolio (MVP), minimum correlation portfolio (MCP), and minimum connectedness portfolio (MCoP) from 2015 to 2025. The MCoP strategy consistently outperforms MCP and MVP, especially during periods of market stress such as COVID-19 (2020) and the Russia–Ukraine conflict (2022), demonstrating superior resilience and faster recovery. In contrast, MVP remains the most defensive but captures limited upside during post-crisis expansions.

Figure 4 highlights the superior performance of the MCoP strategy, which consistently outpaces both the MVP and MCP strategies across most time horizons. This reinforces the notion that accounting for spillover and systemic linkages among assets yields better long-term performance. The MCoP portfolio not only achieved higher cumulative returns but also demonstrated a quicker recovery following major downturns, such as during the COVID-19 shock in early 2020 and the heightened market turbulence around the Russia–Ukraine conflict in 2022. These dynamics are supported by findings in Jiang et al. (2023b) and Wu et al. (2024), who observed stronger recovery in green assets with higher systemic integration following global shocks.

In contrast, the MVP portfolio, while less volatile, lags substantially in performance, especially during post-2020 market expansions. This indicates its defensive character, valuable in times of severe downturns but less capable of capturing upside momentum when markets stabilize or grow. The MCP strategy falls somewhere in between, performing moderately well but still trailing the MCoP in most periods. These results validate the advantage of minimizing connectedness instead of merely targeting variance or correlation, especially in environments where financial and geopolitical uncertainties amplify systemic risk.

The return dynamics in Figure 4 complement the allocation insights from Table 5, emphasizing that portfolio strategies rooted in network-based risk measures (like connectedness) are better suited to managing ESG-driven portfolios in an increasingly complex and interdependent financial landscape. For sustainable investors, this finding suggests that systemic-aware allocation frameworks such as MCoP enhance hedging efficiency and support superior return generation over time. This conclusion is broadly consistent with evidence from Pham and Do (2022) and Lu et al. (2023), advocating for adaptive portfolio frameworks grounded in dynamic spillover diagnostics.

5. Discussion

This study demonstrates that upstream enablers in the transition value chain exert a disproportionate systemic influence. Smart infrastructure (SGI) and ecology-related activities (ECO) act as information leaders because their cash flows depend on project pipelines, component supply, regulation intensity, and rate cases. News about grid build-out, interconnection rules, or environmental compliance first reprices these enablers, then propagates to downstream clean energy producers and broad ESG screens through valuation and deployment expectations. This mechanism explains the significant off-diagonal spillovers from SGI and ECO reported in Table 2, as well as the persistent transmitter roles observed in Figures 2 and 3. These findings highlight a structural shift in green finance, where capital markets increasingly price long-horizon technological commitments and infrastructure policy signals rather than short-term earning cycles.

The behavior of GBDs is state-dependent. During uncertainty spikes, duration and flight-to-quality channels increase the share of shocks that GBD absorbs, which matches its net-receiver status in the static matrix and the negative pairwise net measures with ESG and ECO. When policy optimism synchronizes equity segments, as was the case around the Inflation Reduction Act, short-horizon co-movement with equities can increase through issuance and spread channels. This temporarily reduces hedging gains without overturning the net-receiver role. The contrast between the sharp, front-loaded surge in early 2020, and the slower, equity-led rise from mid-2022 supports this interpretation, indicating that connectedness is regime-sensitive rather than constant. This asymmetry further suggests that GBD serves less as a continuous hedge and more as a conditional stabilizer, whose utility depends on macro-liquidity cycles and monetary policy expectations.

Portfolio results link these network features with investable choices. In bilateral settings, adding a small GBD sleeve to volatile exposures carries sizable variance reductions, consistent with its defensive profile. In multivariate settings, minimum variance portfolios overweight GBD due to its low own volatility; however, hedging effectiveness can be negative when benchmarked against the variance of a pure GBD position. Minimum connectedness portfolios perform best because they use the spillover network to down-weight central transmitters and diversify across assets that are less tightly coupled. In practice, when the Total Connectedness Index rises, tilting away from the most central transmitters (often SGI and ECO) toward lower-centrality assets while maintaining only a modest allocation to GBD, drawdown control and cumulative returns are improved. These insights are particularly relevant to institutional investors, pension funds, and climate-aligned sovereign wealth portfolios transitioning from simple ESG screening to multi-asset allocation guided by systemic risk diagnostics.

Beyond portfolio construction, the results carry implications for financial supervision and sustainable finance policy. If SGI and ECO function as transmission hubs, they warrant closer inclusion in stress-testing frameworks and macroprudential surveillance. Traditional indicators such as Value-at-Risk or volatility may underestimate systemic exposure when network centrality is elevated. Regulators could integrate connectedness metrics into green financial stability dashboards to identify contagion channels triggered by infrastructure bottlenecks, supply-chain shocks, or climate policy redesign. For asset owners, network-aware allocation offers a disciplined alternative to variance-only or correlation-only strategies in periods of elevated systemic coupling.

Two boundaries of interpretation are important. First, the timing references to COVID-19, the Russia–Ukraine war, and the Inflation Reduction Act are used to organize the discussion and are not presented as causal identification. Second, the results pertain to representative indices with a daily frequency and therefore speak to liquid, broad exposures, rather than to private green loans, specific technologies, or permit markets. Within these bounds, the evidence that upstream enablers transmit and that network-aware allocation improves portfolio resilience is robust across the descriptive exercises reported in Section 4. Nevertheless, future research could extend this framework to private climate debt, biodiversity-linked instruments, carbon markets, and transition finance vehicles, where contagion channels may be more opaque but potentially more destabilizing. Incorporating nonlinear models, regime switching, or market microstructure data could further capture tail-risk dynamics under climate transition shocks.

This study positions connectedness-based analysis not merely as an econometric tool but as a forward-looking risk lens for the net-zero transition. As sustainable markets mature, understanding how financial infrastructure responds to climate legislation, technological scaling, and geopolitical disruption will be crucial for building portfolios that are both environmentally aligned and systemically resilient.

6. Conclusions

This study focuses on the dynamic interconnectedness and portfolio implications of five key ESG-driven asset classes: clean energy (CEN), green bonds (GBD), ESG equity (ESG), smart infrastructure (SGI), and eco-efficient equity (ECO). Using the extended joint connectedness measures and optimal portfolio strategies, we provide novel insights into how these sustainable investment instruments interact over time and respond to systemic shocks. The connectedness analysis indicates several important findings. First, static joint connectedness estimates suggest that the system is highly integrated, with SGI and ECO acting as dominant shock transmitters, while GBD consistently appears as a net receiver. Second, the dynamic analysis shows that total connectedness is not constant but fluctuates significantly in response to major global events, such as the COVID-19 pandemic and geopolitical disruptions. Third, net directional connectedness and pairwise dynamics confirm the emerging leadership of clean energy and ESG assets in transmitting volatility, particularly after 2020 and during the IRA implementation period, which coincides with a sharp increase in systemic integration. During turbulent episodes, system-wide connectedness rises sharply; smart infrastructure (SGI) is the most persistent transmitter, while ecology (ECO) leads early but increasingly shifts to a receiver role after 2021. Clean energy (CEN) and ESG equities toggle between transmitting and absorbing, depending on the regime. Green bonds (GBD) remain a net receiver throughout, consistent with their defensive profile.

From a portfolio management perspective, our results underscore the limitations of conventional diversification strategies. In bilateral mean-variance settings, pairing volatile growth exposures with GBD delivers significant variance reductions even when the green-bond weight is small. In contrast, when hedging is evaluated directionally via optimal hedge ratios, GBD is a weak standalone hedge against equity- and infrastructure-based risks. In contrast, ESG-with-SGI/ECO pairs exhibit stronger hedging effectiveness. Under the MVP framework, green bonds receive the largest allocation but often fail to deliver effective hedging, particularly in the face of systemic risk. The MCP marginally improves diversification by incorporating ESG and clean energy assets, but the most compelling performance arises from the MCoP, which integrates spillover effects. MCoP outperforms MVP and MCP by tilting toward ESG, CEN, and SGI while keeping a limited allocation to GBD, thereby improving cumulative returns and drawdown control when connectedness is elevated.

Policy implications arising from these findings are multifaceted. For institutional investors and asset managers, the evidence supports moving beyond variance-based models and adopting network-based risk management frameworks, especially when managing sustainable portfolios exposed to systemic uncertainty. Concretely, implications are as follows: (i) monitor the TCI and net connectedness as regime signals and shift from MVP or MCP toward MCoP when the TCI enters the top quintile of its in-sample distribution; (ii) set exposure caps on the most central transmitters, typically SGI and ECO, during high-connectedness regimes and tilt toward lower-centrality assets; (iii) use GBD primarily as a volatility dampener and pair it with equity hedges, such as index options or rate futures, rather than relying on GBD as a standalone hedge for equity-type risk; and (iv) disclose connectedness diagnostics alongside VaR and tracking error to improve risk transparency. For regulators and central banks, the findings suggest that green financial instruments, particularly clean energy and ESG equities, play an increasingly systemic role. This indicates the need for stronger macroprudential oversight and stress-testing frameworks that incorporate green financial networks. In practice, supervisors can integrate connectedness metrics into monitoring dashboards for green-tilted funds, require scenario stress tests that shock policy and energy variables while preserving the observed spillover structure, and activate liquidity tools such as swing pricing or anti-dilution levies when the TCI breaches predefined thresholds. For governments and climate policymakers, the results reinforce the critical role of public policy in shaping financial interlinkages. The observable jump in connectedness post-IRA reflects how legislative instruments can rapidly alter capital flows and risk transmission patterns in ESG markets. This supports the case for targeted policies that not only mobilize capital toward sustainability goals but also enhance the stability of the financial ecosystem. Policy design should phase incentives across subsectors to avoid synchronized repricing, prioritize interconnection and permitting reforms that reduce bottlenecks in grid and ecology projects, strengthen green bond taxonomies and use-of-proceeds verification, and support market liquidity through measures such as repo eligibility or market-making facilities for high-quality green bonds. Finally, index providers and data vendors can publish concentration and connectedness statistics for green benchmarks and consider capping theme or constituent concentration to mitigate systemic clustering.

Despite its contributions, this study is subject to certain limitations. First, the analysis is based solely on five representative indices, which, while broad-based, may not capture the full heterogeneity of the green finance universe. Second, our framework does not explore nonlinear or regime-switching dynamics, which may offer additional insights under structurally changing market conditions. Upcoming studies could extend the connectedness framework to include additional sustainable asset classes, such as biodiversity-linked instruments, carbon credits, or tokenized ESG assets. Furthermore, integrating copula-based models or quantile regression approaches would allow researchers to explore tail-risk spillovers and asymmetric dynamics in greater depth.

Author contributions

The author is solely responsible for the conception, design, analysis, and writing of this manuscript, and has approved the final version.

Use of AI tools declaration

The author used AI-assisted tools (ChatGPT by OpenAI) only to support language editing and formatting. All ideas, analyses, and conclusions are the author's own.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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