ISSN: 1648-715X / eISSN: 1648-9179

VILNIUS TECH
Vilnius Gediminas Technical University

INTERNATIONAL JOURNAL OF STRATEGIC PROPERTY MANAGEMENT

2026
Volume 30
Issue 4
Pages 339–356
https://doi.org/10.3846/ijspm.2026.28591

SHOCK TRANSMISSION AND RISK DIVERSIFICATION BETWEEN REGIONAL REITs AND CLEAN ENERGY MARKETS

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Article History:
- received 27 August 2025
- accepted 16 July 2026

Abstract. This study examines risk transmission among regional real estate markets and evaluates the diversification potential of clean energy stocks within regional REIT portfolios. A quantile time-frequency vector autoregressive model is used to analyse interconnectedness between regional REITs and clean energy markets over the period from November 2008 to March 2025. The results reveal significant risk spillovers between regional housing stock markets under bullish and bearish conditions. Most interconnectedness occurs over short-term horizons and gradually weakens over time, indicating that contagion effects are largely temporary. Clean energy markets act as a shock absorber and provide hedging benefits for REIT portfolios. Under low-risk, shocks from Asian, European, and UK REITs affect the US and South African markets, while the green bond index serves as a diversifier. In normal markets, European, UK, and US real estate shocks transmit to Asia and South Africa, with renewable energy acting as a buffer against risk. During periods of high uncertainty, other regional markets transmit shocks to the US listed real estate market, yet renewable energy continues to offer diversification benefits. Therefore, clean energy stocks consistently mitigate risk in regional REIT portfolios across market conditions and investment horizons.

Keywords: clean energy, regional REITs, risk diversification, shock transmissions, time-frequency QVAR.

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1. Introduction

In an increasingly interconnected global economy, the traditional emphasis on national or international market interactions may overlook the growing importance of regional asset markets. Regional markets embody a distinctive combination of political, economic, and geographic features, influencing asset behaviour not captured by merely national or global analyses (Gyourko & Keim, 1992; Bouri et al., 2020). As economies shift toward regionalisation through policy coordination, trade blocs (i.e., European Union, EU), and cross-border infrastructure development, regional asset classes such as regional real estate investment trusts (REITs) have developed as important instruments for investors seeking for diversification and localised exposure (Bekaert & Harvey, 1995; Flammer, 2021; Reboredo, 2018).

At the same time, the transition toward a low-carbon economy has heightened the prominence of clean energy markets, including renewable energy stocks and green bonds. These assets have gained traction in response to global sustainability goals (SDGs) and region-specific policy incentives. Clean energy markets offer strong growth potential but are often characterised by volatility. In contrast, real estate investments typically provide relatively stable income streams, albeit with exposure to interest rate risk and macroeconomic conditions. Both markets are central to achieving climate targets and advancing sustainable finance, particularly given that the built environment accounts for nearly 40% of global energy consumption and carbon emissions. Consequently, integrating clean energy and real estate assets within investment portfolios has become a vital strategy for decarbonisation and ESG alignment.

Despite their growing importance, the financial interactions between clean energy markets and regional REIT markets remain insufficiently explored, especially in terms of shock transmission, diversification, and hedging dynamics. These markets are influenced by common factors such as inflation expectations, transition risks, capital allocation shifts, interest rate movements, and broader global financial conditions. Developments in clean energy markets reflect expectations about future energy costs and climate policies, which directly affect property cash flows and valuations, particularly given the energy-intensive nature of real estate assets and heterogeneous regional regulatory frameworks. Moreover, both asset classes attract sustainability-oriented investors, increasing the potential for cross-market spillovers through portfolio rebalancing.

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As a result, shocks originating in clean energy markets may asymmetrically transmit to regional REIT markets, generating time-varying spillover effects. Under certain market conditions, clean energy assets may also serve as shock absorbers, mitigating cross-regional contagion and enhancing diversification.

Several theoretical perspectives help explain these interconnections. Safe haven and hedging theory, modern portfolio theory, risk spillover theory, and the energy–real estate nexus theory all provide relevant insights. A weak or low correlation between clean energy and real estate assets may reduce portfolio volatility. Furthermore, housing investments often stimulate demand for renewable energy technologies such as solar panels, as developers increasingly prioritise green and energy-efficient buildings. REITs play a pivotal role in channeling capital into such projects, fostering renewable adoption and market expansion while reducing long-term energy costs (Chegut et al., 2019; United Nations Environment Programme, 2021; Pivo, 2008). Likewise, green bonds, frequently issued by real estate firms to finance sustainable developments, enable access to ESG-oriented capital at lower financing costs (Michetti et al., 2023; Flammer, 2021). Buildings incorporating renewable energy systems and green certifications tend to attract environmentally conscious tenants and investors, potentially enhancing property values and long-term returns (Li et al., 2021). These interdependencies suggest that disturbances in one market may propagate to the other, reinforcing bidirectional spillover effects. A substantial body of literature has examined the linkages between real estate and stock markets (e.g., Chan et al., 2011; Wang et al., 2017; Lou, 2017; Gokmenoglu & Hesami, 2019; Gounopoulos et al., 2019; Yousaf & Ali, 2020; Lin & Stankov, 2026), while another stream focuses on the nexus between clean energy and financial markets (e.g., Ahmad et al., 2018; Bondia et al., 2016; Ferrer et al., 2018; Kocaarslan & Soytas, 2019; Maghyereh et al., 2019; Naeem et al., 2020; Rahman et al., 2021; Cevik et al., 2024; Ziadat et al., 2024). More recently, emerging research has begun exploring the interplay between sustainable assets, technology, and real estate markets (Dell'Anna et al., 2022; Ji et al., 2024; Shah et al., 2025). These studies highlight that clean energy and real estate markets increasingly attract similar ESG-driven investors and may offer diversification and hedging benefits.

However, existing research largely focuses on national or global markets, often neglecting regional interdependencies and economic linkages. With intensifying regional financial integration, the risk of contagion increases, as shocks may transmit across markets through direct and indirect channels (Forbes & Rigobon, 2002; Diebold & Yılmaz, 2014). Regional markets, characterised by shared institutional, economic, and financial structures, may be particularly susceptible to such spillovers. Moreover, traditional portfolio models often fail to capture nonlinear, asymmetric, and time-varying dynamics, especially during periods of extreme uncertainty (Attarzadeh et al., 2024).

Against this backdrop, understanding the dynamic spillover transmissions between clean energy and regional REIT markets within a portfolio framework becomes essential. Identifying periods of risk transmission, amplification, and absorption enables investors to make more informed diversification and hedging decisions while enhancing risk management strategies. Unlike prior studies linking heterogeneous national or global markets, this paper investigates the nexus between regional REIT markets and clean energy markets (renewables and green bonds) within a quantile time-frequency framework. To capture dependence structures across varying market states and investment horizons, the study employs the Time-Frequency Quantile Vector Autoregressive (TF-QVAR) model developed by Ando et al. (2022). By incorporating a regional perspective, the analysis provides both theoretical and practical insights for policymakers and portfolio investors seeking to strengthen resilience and sustainability amid deepening regional integration. In essence, the paper offers a comprehensive regional assessment of shock transmission dynamics, contributing to more informed risk evaluation and diversification strategies.

The remainder of the study is organised as follows: Section 2 reviews the theories and empirical literature on the interplay between energy and stock markets. Section 3 sets out the method for estimating the market interconnectedness and portfolio building. Section 4 presents and interprets empirical estimations, whereas Section 5 concludes the investigations and provides the policy implications, setting the ground for future study.

2. Literature review

The importance of real estate stock and clean energy stock markets in shaping the global economy underscores the need for portfolio investors and policymakers to comprehend their multifaceted interconnections. Several theoretical perspectives explain the potential linkages between these markets, including the safe haven and hedging theory, Modern Portfolio Theory (MPT), the Risk Spillover Theory (RST), the financial market integration theory, and the Energy-Real Estate nexus Theory (ERET). According to the risk spillover theory, the housing and clean energy markets respond to common factors like interest rates, inflation, and economic growth. Thus, volatility originating in one market may transmit to another due to structural interconnections (Zhang et al., 2022; Pham et al., 2025). Financial market integration theory further posits that in an era of regionalisation and deepening economic integration, shocks in one market (e.g., real estate) are likely to spill over to another (e.g., renewable energy).

From a portfolio perspective, Modern Portfolio Theory emphasises diversification benefits across imperfectly correlated assets. A portfolio combining real estate, renewable energy, and green bonds may reduce overall risk due to relatively low correlations between renewable energy and green bond indices (Naqvi et al., 2022; Kuang, 2021). Safe

haven and hedging theories further suggest that certain assets may protect portfolios during periods of market distress. Collectively, these theories provide a framework for understanding why fluctuations in clean energy markets may influence housing investments, particularly during the global transition toward sustainability. Although clean energy and regional REIT markets exhibit distinct pricing dynamics which respond differently to energy costs, climate reforms, and operating expenses, they share exposure to global growth conditions. Such common exposure may align returns during stress periods, potentially reducing diversification benefits and constraining the hedging effectiveness of clean energy within REIT portfolios. This highlights the importance of examining state-dependent and asymmetric spillovers, particularly regarding the potential shock-absorber role of clean energy assets.

A substantial strand of literature examines the relationship between REITs and broader financial markets. Chan et al. (2011), using a Markov Switching model over the period January 1987 to December 2008, identify contagion effects among U.S. stocks, bonds, commodities, and real estate stocks, particularly during crisis regimes. Lou (2017) finds unidirectional causality from stock markets to real estate stocks in Portugal and bidirectional causality in Greece, Italy, and Spain.

In contrast, Wang et al. (2017) report no causal relationship between stock and real estate markets in Taiwan, suggesting diversification potential. Gokmenoglu and Hesami (2019) document cointegration between housing and stock indices in Germany, with real estate markets Granger-causing stock markets. Similarly, Yousaf and Ali (2020) find cointegration between Pakistan's housing and stock markets, indicating substitution effects in portfolio allocation. Lin and Stankov (2026), using data across nine countries, identify lead–lag relationships from stock markets to housing stocks.

While these studies provide valuable insights, they face structural limitations. Listed real estate markets are typically illiquid and locally driven, whereas stock markets are highly liquid and news-sensitive. Differences in investor composition, long-term owner-occupiers versus short-term institutional investors, further complicate causal interpretations. Moreover, endogeneity concerns arise due to shared macroeconomic determinants such as credit conditions and interest rates. These structural differences limit the generalisability of findings across periods and regions.

Another strand of research focuses on clean energy and financial stock markets. Studies employ diverse methodologies, including GARCH models (Ahmad et al., 2018; Kocaarslan & Soytas, 2019), VAR models (Kyritsis & Serletis, 2019; Rahman et al., 2021), wavelets (Ferrer et al., 2018; Maghyereh et al., 2019), and cointegration approaches (Bondia et al., 2016). Empirical evidence remains mixed. Naeem et al. (2020) report weak associations between oil prices and clean energy stock returns. Naeem et al. (2021) find extreme tail dependencies between green bonds and energy commodities. Ziadat et al. (2024), using a quantile frequency connectedness approach, show that renewable energy and clean technology indices act as net shock transmitters, while the global clean energy index serves as a net receiver. From a portfolio perspective, they recommend higher allocations to clean energy assets and green bonds.

Despite these contributions, limitations persist. ESG-driven investor preferences may distort fundamental linkages between clean energy and financial markets (Friede et al., 2015). Additionally, greenwashing practices may obscure the true degree of interconnectedness (Amel-Zadeh & Serafeim, 2018). Importantly, most studies examine markets with fundamentally different structural characteristics, limiting insights into sustainable asset integration.

More recently, a new research stream integrates renewable energy within real estate markets. Dell'Anna et al. (2022) analyse Energy-Efficient Mortgages (EEMs) and find that young homebuyers value energy-efficient properties, suggesting policy-driven sustainability incentives can stimulate real estate investment. Ji et al. (2024), applying DCC-GARCH copula and TV-VAR models, document volatility spillovers from energy ETFs to U.S. real estate ETFs. Similarly, Shah et al. (2025), using a TVP-VAR approach, show that renewable energy and European real estate markets experience significant shock transmissions during major crises such as COVID-19 and the Russia-Ukraine war. These findings highlight increasing interdependence between renewable energy and real estate assets, particularly during global crises. Notably, clean energy markets demonstrated greater resilience than fossil fuel markets following COVID-19, suggesting potential economic benefits of integrating clean energy into real estate portfolios. However, methodological constraints remain. GARCH models assume stationarity, copula approaches may suffer from independence violations, and traditional VAR models often assume linear and symmetric relationships. Such limitations hinder the ability to capture nonlinear, regime-dependent, and tail-risk dynamics features that are crucial during periods of extreme uncertainty.

In general, existing studies largely examine sectoral or national-level markets and frequently link assets with differing structural characteristics. The growing regionalisation of financial markets and heightened environmental challenges suggest that clean energy and regional REIT markets, both attracting sustainability-oriented investors, may exhibit unique interconnectedness patterns that remain underexplored. Given these gaps, the present study investigates the interconnectedness between clean energy indices (renewables and green bonds) and regional REIT markets. Unlike prior research, this study employs a Quantile Time-Frequency Vector Autoregressive (QTF-VAR) model, which captures asymmetric, nonlinear, and time-varying spillovers across market conditions and investment horizons. The QTF-VAR framework extends traditional portfolio theories by allowing regime-specific and horizon-dependent analysis, thereby offering a more

nuanced understanding of diversification and hedging potential. Building on the theoretical and empirical literature, the study proposes the following hypotheses:

H1: *Shocks in clean energy markets affect spillovers across regional REIT markets*.

H2: *Clean energy assets provide diversification and hedging potential within a regional REIT portfolio framework*.

H3: *The hedging and diversification benefits of clean energy assets differ across market conditions*.

To test these hypotheses, this study advances the literature by examining the regional and state-dependent linkages between clean energy markets (renewables and green bonds) and regional REITs. Although both asset classes increasingly attract sustainability-oriented investors, their interconnectedness has rarely been analysed within a single, unified framework. By employing a Quantile Time-Frequency Vector Autoregressive (QTF-VAR) approach, the analysis captures nonlinear, asymmetric, and horizon-specific spillovers that traditional linear models may overlook. This framework enables a deeper assessment of shock transmission, risk amplification and absorption, and the evolving diversification and hedging roles of clean energy assets within regional REIT portfolios across different market conditions. The findings therefore offer important implications for portfolio allocation, regional risk management, and sustainable investment strategies. The following section describes the data and outlines the methodological framework used to empirically examine these dynamic interdependencies.

3. Data and methodology

3.1. Data

The objective of the current study is twofold. The study's first aim is to investigate the dynamic interlinkages between regional housing stock markets and clean energy markets, emphasising the risk spillovers transmissions. Secondly, to the examine possible safe-haven and risk diversification characteristics of clean energy assets, particularly renewable energy stocks and green bonds index, within a regional REIT portfolio framework. To this end, a time-frequency QVAR technique is applied to daily time-series data covering the period from November 28, 2008 to March 18, 2025. The sample includes most recent world events that impacted the global economy, including the global financial crisis of 2008-9, COVID-19 (2019–2021), the Paris Agreement (the climate change summit), the ongoing Russia-Ukraine war, and the trade war. The variables utilised in the empirical assessment include publicly listed real estate investment trusts (Zeng, 2026; Hau et al., 2025; Akinsomi, 2021) proxy for regional housing stock markets and clean energy proxied by renewable energy equity and green bond indices (Ziadat et al., 2024; Chatziantoniou et al., 2022a; Le et al., 2021; Pham, 2021; Tiwari et al., 2022).

The regions of interest include the United States (US), the United Kingdom (UK), Asia, South Africa, and Europe (excluding the UK). Given the size of the US, which serves as the global benchmark, it is included to represent the American REIT market. While a centralised supranational government governs the regional financial markets in Europe, the UK REIT market, following Brexit, operates under differing regulatory and financial frameworks; this may be important for spillover dynamics across regions. The Asian REIT market reflects a heterogeneous yet highly integrated REIT structure, whereas the South African REIT market is the most liquid African market with continuous data availability. Regions lacking data REIT market development or consistent data are excluded to maintain consistency within the connectedness framework. In short, the REIT indices reflect the performance of assets traded in a regional financial market, thereby capturing the behaviour of the region's listed real estate stocks. These regions encompass developed and developing REIT markets, which favour an investigation of heterogeneous financial spillover dynamics across differing market development and climate exposure.

In consequence, the spillover assessment as objected to by the current study would reflect financial return transmissions across regional real estate asset markets, not across physical housing markets. REIT indices are inherently location-based. They are therefore constructed at the regional or country level, as seen in empirical REIT spillover research across the U.S., U.K., Asian, and European REIT markets (AlGhazali et al., 2026; Wang et al., 2022).

As far as clean energy assets are concerned, the choice of global clean energy lies in its ability to capture global changes in clean energy markets, reduce regional energy shocks, and provide a direct link to sustainable and climate finance potential. On the other hand, global green bond indices provide market-based instruments to finance environmental-based projects, thereby promoting portfolio resilience. In fact, clean energy markets are increasingly integrated globally because firms operate in various regions worldwide, with international investors driving common exposure. Therefore, considering these global indices helps capture systemic energy and climate-related risks that regional indices might miss. Additionally, clean energy markets are constructed using international indices that capture cross-border technological, policy, and supply-chain shocks (Yousfi & Bouzgarrou, 2025; Rehman et al., 2023). Moreover, Karim et al. (2022) analyse clean energy market indices alongside regional and national markets, confirming that global clean-energy shocks interact with financial systems at the regional and national levels. As such, the study can capture realistic interactions between regional real estate markets and global clean-energy shocks.

Thus, the current study considers regional REITs and global clean energy indices to reflect the economic structures of both assets. This structure allows to capture realistic interactions between regional real estate markets

and global clean-energy shocks. Daily returns for all series are calculated as $R_t = \left(\frac{P_t - P_{t-1}}{P_{t-1}}\right) * 100$. Data on all relevant stock indices of interest are collected from Thomson Reuters DataStream. However, the mixed representation of country- and regional-level REIT markets may constitute a limitation, introducing heterogeneity in market coverage and possibly influencing dynamic spillovers.

3.2. Methodology

To assess the interconnectedness between regional real estate markets and clean energy, the study follows a time-frequency quantile vector autoregressive (QVAR) with connectedness approach introduced by Ando et al. (2022). QVAR is an econometric approach primarily used to assess the spillover and connectedness of risk in financial systems at different risk profiles (quantiles) in a multivariate framework. The model extends the Standard Vector Autoregressive (VAR) models, capturing conditional quantile relationships between economic and financial variables. Put differently, the QVAR model combines the quantile regression and the VAR model (Cunado et al., 2023). Quantile regression allows the estimation of quantile relationships by providing more insights into the interactions between variables at different quantiles. In addition, quantile regression helps to capture tail dependencies, which is crucial in understanding risks and extreme events (White et al., 2015). VAR models are used to investigate dynamic interactions between multiple time series variables. Thus, VAR models help to model the effects of changes in one variable on other(s) in a system over time. Combining the two statistical approaches into QVAR is essential in understanding how risk factors are connected at different quantiles and how shocks at specific quantiles spill over to other variables in a multivariate framework. The QVAR connectedness approach provides insights into conditional interactions between financial variables during extreme conditions. In other words, QVAR is a straightforward model that helps to assess tail risks and understand the behaviour of financial variables under stressed financial conditions. Low, normal, and high-risk profiles correspond to low, median, and high quantiles. The computation of the connectedness measures is expressed as follows (Ando et al., 2022):

$$Y_t = \mu(\tau) + \sum_{j=1}^{p} \varnothing_j(\tau) Y_{t-j} + u_t(\tau), \quad (1)$$

with Y_t and Y_{t-j} are $k*1$ dimensional dependent variable vectors, τ stands for the quantile level, p represents the lag length of the QVAR approach. $\mu(\tau)$ is a $k*1$ dimensional conditional mean vector, $\varnothing_j(\tau)$ denotes a $k*k$ dimensional QVAR coefficient matrix, and $u_t(\tau)$ illustrates the $k*1$ dimensional error vector that has a $k*k$ dimensional variance-covariance matrix, $\Sigma(\tau)$. The Wold's theorem is used to transform the QVAR(p) to its quantile vector moving average (QVMA (∞)) representation and can be expressed as follows:

$$Y_t = \mu(\tau) + \sum_{j=1}^{p} \varnothing_j(\tau) Y_{t-j} + u_t(\tau) = \mu(\tau) + \sum_{i=0}^{\infty} \varphi_i(\tau) u_{t-i}. \quad (2)$$

The next step concerns the H-step ahead Generalised Forecast Error Variance Decomposition (GFEVD) proposed by Koop et al. (1996), which indicates that the effects of shocks in a variable (j) on another variable (i) and is calculated as follows:

$$\varphi_{ij}^{g}(H) = \frac{\Sigma(\tau)_{ii}^{-1} \sum_{h=0}^{H-1} \left(e_i' \varphi_h(\tau) \Sigma(\tau) e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i' \varphi_h(\tau) \Sigma(\tau) \varphi_h(\tau)' e_i\right)}; \quad (3)$$

$$\overline{\varphi}_{ij}(H) = \frac{\varphi_{ij}^{g}(H)}{\sum_{j=1}^{k} \varnothing_{ij}^{g}(H)};$$

where e_i denotes a zero vector with unity on the i-th position. This normalisation will lead to the following two equalities:

$$\sum_{j=1}^{k} \overline{\varphi}_{ij}(H) = 1 \text{ and } \sum_{i,\, j=1}^{k} \overline{\varphi}_{ij}(H) = k$$

The information on the overall shock of a variable (i) on other variables (j) is given by the total directional connectedness TO others and calculated as follows:

$$C_{i \to j}^{g}(H) = \sum_{j=1, i \neq j}^{k} \overline{\varphi}_{ij}(H). \quad (4)$$

Shocks in all other variables (j) and on variable (i) is provided by the total directional connectedness FROM others and calculated as follows:

$$C_{i \leftarrow j}^{g}(H) = \sum_{j=1, i \neq j}^{k} \overline{\varphi}_{ij}(H). \quad (5)$$

The differences between the total directional connectedness TO and FROM yields the NET total directional connectedness, which can be seen as the NET impact that a particular variable (i) might have on the network system being analysed. The NET total directional connectedness can be expressed as follows:

$$C_i^{g}(H) = C_{i \to j}^{g}(H) - C_{i \leftarrow j}^{g}(H). \quad (6)$$

Lastly, the connectedness measure can be adjusted into the total connected index (TCI) as introduced by Chatziantoniou et al. (2022b), ranging between zero and one. The TCI can be mathematically expressed as follows:

$$TCI(H) = \frac{\sum_{i,\, j=1; i \neq j}^{k} \overline{\varphi}_{ij}(H)}{k-1}. \quad (7)$$

Net and total directional connectedness measures the characteristics of the transmission dynamics across markets but does not capture risk-return trade-offs. Lower connectedness values suggest lower systemic interdependence, which can be a prerequisite for diversification or hedging properties. As such, the portfolio implications discussed in this study are interpreted in terms of shock

absorption and contagion attenuation rather than mean–variance optimality.

Eq. (7) can be readjusted and break down into TCI from (to) others (Cunado et al., 2023).

$$TCI(H) = \frac{1}{k}\sum_{i=1}^{k} \overline{\varphi}_{i\leftarrow *}^{from}(H), \tag{8}$$

$$TCI(H) = \frac{1}{k}\sum_{i=1}^{k} \overline{\varphi}_{i\rightarrow *}^{to}(H). \tag{9}$$

The study explores three time-frequency domains: short term (1–5 days), medium term (5–20 days), and long term (20-infinity) frequencies.

This approach is consistent with recent studies (Yousfi & Bouzgarrou, 2025; Liu et al., 2024) analysing financial systems and clean energy markets using a quantile-based connectedness approach. More importantly, the connectedness approach in the Diebold–Yilmaz literature allows heterogeneous nodes to be included within a unified spillover framework when they reflect distinct economic structures (Diebold & Yilmaz, 2015). The time-frequency quantile vector autoregressive methodology, therefore, allows for accurate modelling of the interaction between regional REIT markets, which transmit localised real estate information, and global clean-energy indices, which capture worldwide sectoral shocks.

4. Empirical analysis

4.1. Preliminary analysis

Table 1 provides the summary statistics of the markets of interest in this paper, with all regional house markets and clean energy found to be stationary at first difference. The table indicates that region REITs in the US and South Africa appear more volatile (riskier) since they record the highest standard deviation values. In contrast, the green bond index is the least risky index. In addition, the regional house market indices in the US and South Africa record the highest mean values, while the REITs index in Asia has the lowest mean value. Table 1 further suggests that the variables are not normally distributed since they are all skewed to the left except the European stock market and renewable energy, which are skewed to the right, with heavy and low tail distributions. This suggests a platykurtic distribution (negative excess kurtosis) for most indices except that of renewable energy, which has a positive excess kurtosis (leptokurtic distribution).

Table 2 summarises the correlation matrix results for the regional REITs and clean energy and suggests relatively high interactions in general between the regional real estate markets and the clean energy sector. The renewable energy index interacts positively with the Asian, the UK and the US regional house markets, while it correlates negatively with the European and South African house markets. The results concerning the green bond index contrast with those of renewable energy, being a mirror image of the relationships between renewable energy and the regional house markets. The table also highlights the existence of positive and negative relationships among the regional real markets.

Table 3 summarises the quantile unit roots test and the null hypothesis of non-stationarity at a specific quantile. Additionally, a positive value of the test statistic indicates that the series/process is explosive, not mean-reverting

Table 1. Descriptive statistics

	Asia	Europe	UK	US	SA	RENIXX	GBI
Mean	63.908	183.053	682.252	1985.782	1463.946	735.960	103.565
StandD	12.904	58.375	311.886	645.154	519.541	478.726	10.681
Kurtosis	–0.581	–1.325	–1.170	–0.419	–1.331	0.138	–0.456
Skewness	–0.053	0.040	–0.312	–0.112	–0.202	1.090	–0.590
Count	4276	4276	4276	4276	4276	4276	4276

Note: UK, US, and SA stand for the United Kingdom, the United States, and South Africa. RENIXX and GBI represent the renewable energy and green bond index. Lastly, StandD denotes standard deviation.

Table 2. Correlation matrix

	Asia	Europe	UK	US	SA	RENIXX	GBI
Asia	1						
Europe	–0.333	1					
UK	0.772	–0.753	1				
US	0.710	–0.705	0.922	1			
SA	0.066	0.700	–0.369	–0.412	1		
RENIXX	0.249	–0.676	0.583	0.605	–0.808	1	
GBI	–0.054	0.790	–0.576	–0.524	0.482	–0.502	1

Note: UK, US, and SA stand for the United Kingdom, the United States, and South Africa. RENIXX and GBI represent the renewable energy and green bond index. Lastly, StandD denotes standard deviation.

Table 3. Unit root test

Markets	Level			First difference		
	τ = 0.05	τ = 0.5	τ = 0.95	τ = 0.05	τ = 0.5	τ = 0.5
Asia	0.009***	–0.001	–0.014***	–0.931***	–1.000***	–1.001***
Europe	0.001	–0.000	–0.001	–0.875***	–0.973***	–1.028***
UK	0.014***	0.000	–0.021***	–0.864***	–0.989***	–0.981***
US	0.019***	–0.000	–0.021***	–1.093***	–1.075***	–1.274***
SA	0.008***	0.000	–0.010***	–0.914***	–1.000***	–0.971***
RENIXX	–0.005***	0.000	0.006***	–0.961***	–0.977***	–1.019***
Green Bonds	0.000	0.000	–0.004*	–0.959***	–0.982***	–1.018***

Note: ***, * indicate significance level at 1% and 10%. RENIXX denotes renewable energy index. UK, US, and SA stand for the United Kingdom, the United States, and South Africa.

(non-stationary). A positive and significant value suggests a strong instability, explained by policy response or that market participants are less responsive to bad news. On the other hand, negative values and significant values indicate a mean-reverting, thus stationary. The strength and speed of mean-reversion depend on the magnitude of the test statistics. For instance, a small value would mean weak stationarity.

At the level, the table shows that strong instability in all regional housing stocks (REITs), except the European ones, where it is insignificant at the lower quantile. The renewable energy index (RENIXX) appears to have a weak mean-reverting process. However, at a higher quantile, all variables of interest show significant and weak mean-reversion characteristics. At first difference, all housing stocks and clean energy index (RENIXX and green bonds) appear to be significantly and strongly mean-reverting across quantiles.

4.2. Empirical results and interpretations

The results of the static connectedness index are displayed in Table 4 and indicate strong connectedness between housing stocks (REITs) and clean energy indices (RENIXX and green bond) under extreme market conditions, judging by the relatively high values of the total connectedness index (TCI) of 78.05% and 77.31% under low and high quantiles, respectively. Under normal market conditions, the estimation results indicate low connectedness among the indices (TCI = 28.11%). These results suggest that spillover effects are subject to market regimes. In other words, shock transmissions among housing stock markets are stronger during bullish and bearish market conditions compared to normal conditions. This finding is consistent with the study by Shah et al. (2025), which finds strong shock transmissions and interconnectedness among markets of interest.

The negative NET values indicate that the related index absorbs shocks, thus can act as a safe haven or a risk diversifier in the portfolio. On the other hand, positive NET values suggest that the related index is a shock transmitter. Panel A, Panel B, and Panel C record the connectedness index related to the lower (5th) quantile, normal conditions (50th quantile), and higher (95th) quantile, respectively, in Table 4. The table reports that the Asian and the South African house stocks receive shocks from the regional housing stocks from Europe, the US, the UK, and the renewable energy index can serve as a risk diversifier across all quantiles.

Tables 5–7 exhibit each quantile's time-frequency connectedness results, categorising the connectedness per frequency domain. Panels A, B, and C, in these tables, gather the results related to the short (1–5 days), medium (5–22 days), and long-term (>22 days) time horizons, respectively. The Tables 5–7 report a strong interconnection between regional house stocks and clean energy indices, particularly in the short run, recording the highest total connectedness index across market conditions. More precisely, the TCI index negatively correlates with the time frequency domain since the connectedness decreases from the short-term horizon to the longer ones. This suggests that most interconnectedness among the market indices occurs in the short run.

As far as the lower quantile is concerned, Table 5 suggests that the Asian, European, and UK house stocks transmit shocks to the US and the South African house stocks, along which the green bond index could be used to hedge risks within the system in the short run. In addition, the Asian REITs and the UK REITs absorb shocks originating from the European, the US, and the South African REITs, and renewable energy helps mitigate risks in the portfolio in the medium term. Lastly, in the long run, the European and the US house stocks spill shocks onto the Asian, the UK, and the South African house stocks, along with which the renewable energy index appears as a risk diversifier within the system.

Table 6 reports that information stemming from the European, the US, and the UK regional house stocks is transmitted to the Asian and the South African house stocks, while the renewable energy index plays the safe haven role across time horizons in the medium quantile. It is also important to emphasise that the Asian house stocks serve as the principal receivers across periods, whereas the European REITs act as the principal transmitters of shocks within the system in the shorter period, and the US ones appear to be the main transmitters in other periods.

Table 4. Quantile total connectedness

Panel A: Lower quantile (τ = 0.05)								
	ASIA	EUR	UK	US	SA	REN	GBI	FROM
ASIA	22.15	13.08	12.79	13.55	12.56	11.47	14.40	77.85
EUR	12.32	21.26	14.35	13.66	12.34	11.62	14.46	78.74
UK	12.19	14.14	21.32	14.12	12.58	12.55	13.08	78.68
US	12.11	13.21	13.98	21.95	12.58	12.55	13.61	78.05
SA	12.42	13.21	13.38	13.58	22.28	12.19	12.94	77.72
REN	11.62	12.52	13.62	14.01	12.24	23.49	12.51	76.51
GBI	13.56	14.49	13.07	13.87	12.32	11.50	21.18	78.82
TO	74.23	80.65	81.19	82.78	74.62	71.88	81.00	**TCI**
NET	**–3.62**	**1.91**	**2.51**	**4.74**	**–3.10**	**–4.63**	**2.18**	**78.05**
Panel A: Medium quantile (τ = 0.5)								
	ASIA	EUR	UK	US	SA	REI	GBI	FROM
ASIA	77.52	4.09	2.95	3.51	1.60	2.47	7.86	22.48
EUR	2.42	62.85	11.42	5.16	3.14	2.86	12.15	37.15
UK	1.48	12.80	66.87	6.23	3.51	4.89	4.21	33.13
US	1.23	5.62	6.22	75.01	2.43	4.60	4.90	24.99
SA	1.05	4.43	4.24	3.09	80.61	3.55	3.03	19.39
REI	1.33	3.92	5.49	5.41	3.01	75.87	4.98	24.13
GBI	6.02	12.84	4.67	4.78	2.75	4.43	64.51	35.49
TO	13.52	43.70	35.00	28.18	16.44	22.80	37.13	**TCI**
NET	**–8.95**	**6.55**	**1.87**	**3.19**	**–2.95**	**–1.33**	**1.63**	**28.11**
Panel A: Upper quantile (τ = 0.95)								
	ASIA	EUR	UK	US	SA	REI	GBI	FROM
ASIA	22.41	13.04	13.09	12.87	12.74	11.19	14.66	77.59
EUR	12.13	21.89	14.38	13.06	12.54	11.22	14.78	78.11
UK	12.03	14.27	22.12	13.65	12.91	12.18	12.83	77.88
US	12.06	13.10	14.04	22.65	12.58	12.24	13.33	77.35
SA	12.46	12.95	13.58	13.08	22.74	11.92	13.28	77.26
REI	11.38	12.25	13.46	13.17	12.61	25.13	12.00	74.87
GBI	13.77	14.57	12.90	13.29	12.62	10.93	21.92	78.08
TO	73.83	80.16	81.45	79.14	76.01	69.68	80.87	**TCI**
NET	**–3.77**	**2.05**	**3.58**	**1.79**	**–1.26**	**–5.18**	**2.79**	**77.31**

Note: The frequency QVAR model is estimated by a 200 rolling window with lag length order of 1 and a 20-step-ahead forecast. EUR, UK, US, and SA stand for Europe, the United Kingdom, the United States, and South Africa. REN and GBI denote RENIXX, a proxy for the renewable energy index and green bond index.

Table 5. Quantile time-frequency connectedness (τ = 0.05)

	ASIA	EUR	UK	US	SA	REI	GBI
Panel A: 1–5 days							
TO	58.34	62.95	64.04	63.65	58.39	56.52	63.02
FROM	58.18	62.74	60.05	63.75	61.41	56.26	64.52
NET	**0.16**	**0.20**	**3.99**	**–0.09**	**–3.03**	**0.27**	**–1.50**
TCI	**60.99**						
Panel A: 5–20 days							
TO	9.93	11.04	10.74	11.95	10.22	9.57	11.28
FROM	12.28	10.16	11.76	8.93	10.14	12.58	8.88
NET	**–2.35**	**0.87**	**–1.02**	**3.02**	**0.08**	**–3.01**	**2.40**
TCI	**10.67**						

End of Table 5

Panel A: 20– inf days							
TO	5.96	6.67	6.41	7.18	6.01	5.79	6.70
FROM	7.38	5.83	6.87	5.37	6.17	7.67	5.42
NET	**–1.42**	**0.83**	**–0.46**	**1.81**	**–0.16**	**–1.88**	**1.28**
TCI	**6.39**						

Note: EUR, UK, US, and SA stand for Europe, the United Kingdom, the United States, and South Africa. REI and GBI denote RENIXX, a proxy for the renewable energy index and green bond index.

Table 6. Quantile time-frequency connectedness (τ = 0.5)

	ASIA	EUR	UK	US	SA	REI	GBI
Panel A: 1–5 days							
TO	11.33	36.31	29.11	21.85	13.85	19.15	30.58
FROM	17.84	30.93	27.53	21.68	15.33	19.58	29.29
NET	**–6.52**	**5.38**	**1.58**	**0.17**	**–1.48**	**–0.43**	**1.29**
TCI	**23.17**						
Panel A: 5–20 days							
TO	1.46	4.90	3.91	4.19	1.72	2.42	4.35
FROM	3.06	4.14	3.73	2.20	2.69	3.03	4.11
NET	**–1.61**	**0.76**	**0.18**	**1.99**	**–0.97**	**–0.60**	**0.24**
TCI	**3.28**						
Panel A: 20- inf days							
TO	0.74	2.48	1.98	2.13	0.87	1.22	2.20
FROM	1.57	2.08	1.88	1.11	1.36	1.52	2.09
NET	**–0.83**	**0.40**	**0.10**	**1.02**	**–0.50**	**–0.30**	**0.10**
TCI	**1.66**						

Note: EUR, UK, US, and SA stand for Europe, the United Kingdom, the United States, and South Africa. REI and GBI denote RENIXX, a proxy for the renewable energy index and green bond index.

Table 7 shows that the US house market index solely receives shocks from other regional real estate markets, and the renewable energy index acts as a safe haven in the portfolio in shorter investment periods. However, in more extended investment periods, house stock markets from Europe, the US, and the UK appear to transmit shocks to house stock markets from Asia and South Africa, while the clean energy indices of interest. Specifically, shocks within the system mainly originate from the UK REITs and the US REITs in the shorter and longer-term horizons. At the same time, the Asian REITs act as the principal shock absorber, while the green bond index can be used as the main hedging instrument in the portfolio in long-term investment horizons. Moreover, the main transmitter and receiver of shocks are the UK and the US house stocks, while renewable energy is the principal hedging instrument in the short run.

The Tables 5–7 exhibit the results of the static connectedness index across quantiles and time horizons. This may not reflect the dynamic time-frequency connectedness among market indices. Hence, the static connectedness might fail to capture the dynamics of the spillover of the sample period. The figures illustrate the dynamics surrounding the connectedness and contagion results, with Panel A–C corresponding to the 5th, 50th, and 95th quantiles. Figure 1 displays the dynamic total time-frequency connectedness index across market conditions. Judging by the colour and size, one can infer substantial connectedness among the markets of interest, with time-varying perspectives, in the short- and long-term horizons. For instance, the quantile time-frequency TCI increased toward the end of 2015, which can be attributed to the adoption of the Paris Agreement. Another spike can be observed around 2019–2020, coinciding with the COVID-19 pandemic era, while the increase around 2022 may be explained by the Russia-Ukraine war and energy shock, which may have accelerated the transition toward clean energy. This could have enhanced the interconnection between house stocks and clean energy through energy efficiency retrofits. Finally, the increased size and colour around 2025 is attributed to the fact that solar energy has surpassed nuclear for the first time, prompting real estate investors to opt for renewable (solar) technologies in house facilities. These findings are consistent with the study by Khalfaoui et al. (2022), which suggests that spillover connectedness is sensitive to market conditions when it comes to clean energy stock markets.

Table 7. Quantile time-frequency connectedness (τ = 0.95)

	ASIA	EUR	UK	US	SA	REI	GBI
Panel A: 1–5 days							
TO	61.26	66.00	66.67	63.98	62.95	57.36	66.37
FROM	60.63	65.40	65.07	66.34	61.93	62.24	62.98
NET	**0.63**	**0.60**	**1.60**	**–2.37**	**1.03**	**–4.88**	**3.39**
TCI	**63.51**						
Panel A: 5–20 days							
TO	8.07	9.08	9.42	9.74	8.35	7.86	9.24
FROM	10.99	8.26	8.18	6.94	9.78	8.05	9.57
NET	**–2.92**	**0.82**	**1.24**	**2.80**	**–1.43**	**–0.19**	**–0.33**
TCI	**8.82**						
Panel A: 20- inf days							
TO	4.50	5.08	5.36	5.42	4.71	4.46	5.26
FROM	5.98	4.45	4.62	4.07	5.56	4.57	5.53
NET	**–1.47**	**0.63**	**0.74**	**1.35**	**–0.85**	**–0.11**	**–0.27**
TCI	**4.97**						

Note: EUR, UK, US, and SA stand for Europe, the United Kingdom, the United States, and South Africa. REI and GBI denote RENIXX, a proxy for the renewable energy index and the green bond index.

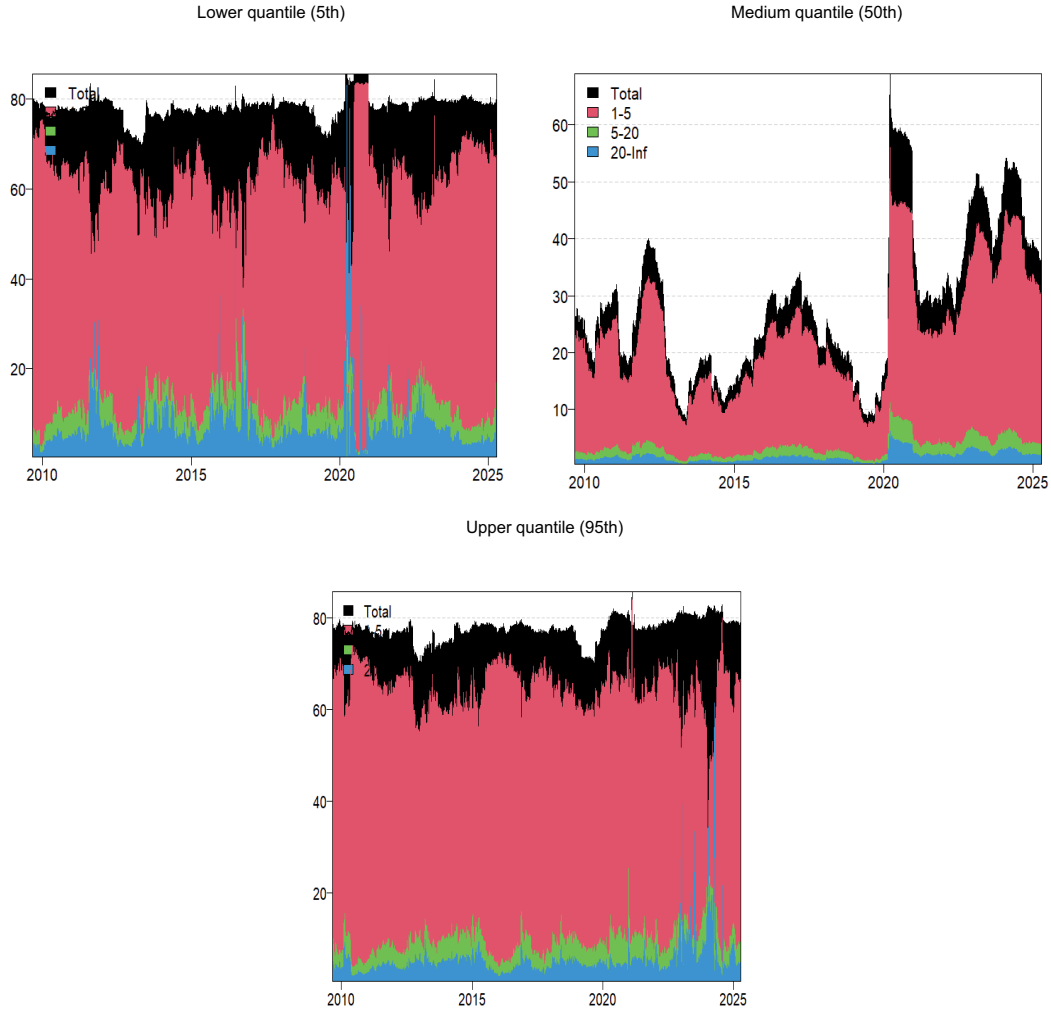


Figure 1. Dynamic total quantile time-frequency connectedness index

Figure 2 portrays the dynamic NET time-frequency connectedness across quantiles and horizons and intense variability in bullish and bearish market conditions compared to normal market conditions. Indeed, housing stock markets and clean energy indices constantly switch roles across time horizons and quantiles. The colours red, green, and blue denote the short, medium-, and long-term horizons, respectively. Under bearish market conditions, the receiving role of the house stock index in Asia (2020), Europe (around 2011, 2020, and early 2025), the US (between 2014 and 2018), and South Africa (around 2020 and early 2025), while the role of transmitter is played by house stocks in the UK (around 2020 and between 2016 and 2018) and the US (around 2020). On the other hand, the renewable energy index (2011 and 2014) and the green bond index (end of 2014 and 2019) absorb risks, implying that clean energy has a safe haven role in the portfolio. The roles played by these stock indices are more pronounced in the shorter time horizon.

As far as the bullish market condition is concerned, renewable energy first absorbs, being a risk diversifier, shocks in the short-term horizon between 2011 and 2015, while the green bond market switches to acts as a hedging instrument in 2015. Analysing the roles played by the regional REITs, the US index alternates between receiver and transmitter over time, while the European index absorbs shocks in the years 2010, 2015, and 2019 before becoming a transmitter in 2020. In addition, the Asian house markets are transmitters around 2015 and switch to a receiver role around 2013. The house stocks in the UK absorb shocks in the short- and long-term in around 2010 before switching to a transmitting role in the shorter period and a receiving role in the long period between 2023 and 2024. Finally, the South African house markets play the receiving role in 2010, switch to the transmitting role up to 2015, and change to the absorber role.

Lastly, under normal conditions, the Asian house stocks serve as a constant receiver of shock absorbers over time, while the European and the UK stocks appear to transmit shock within the system from 2020. Additionally, the US house stock markets tend to significantly transmit shocks between 2019 and 2021 before switching to a receiver

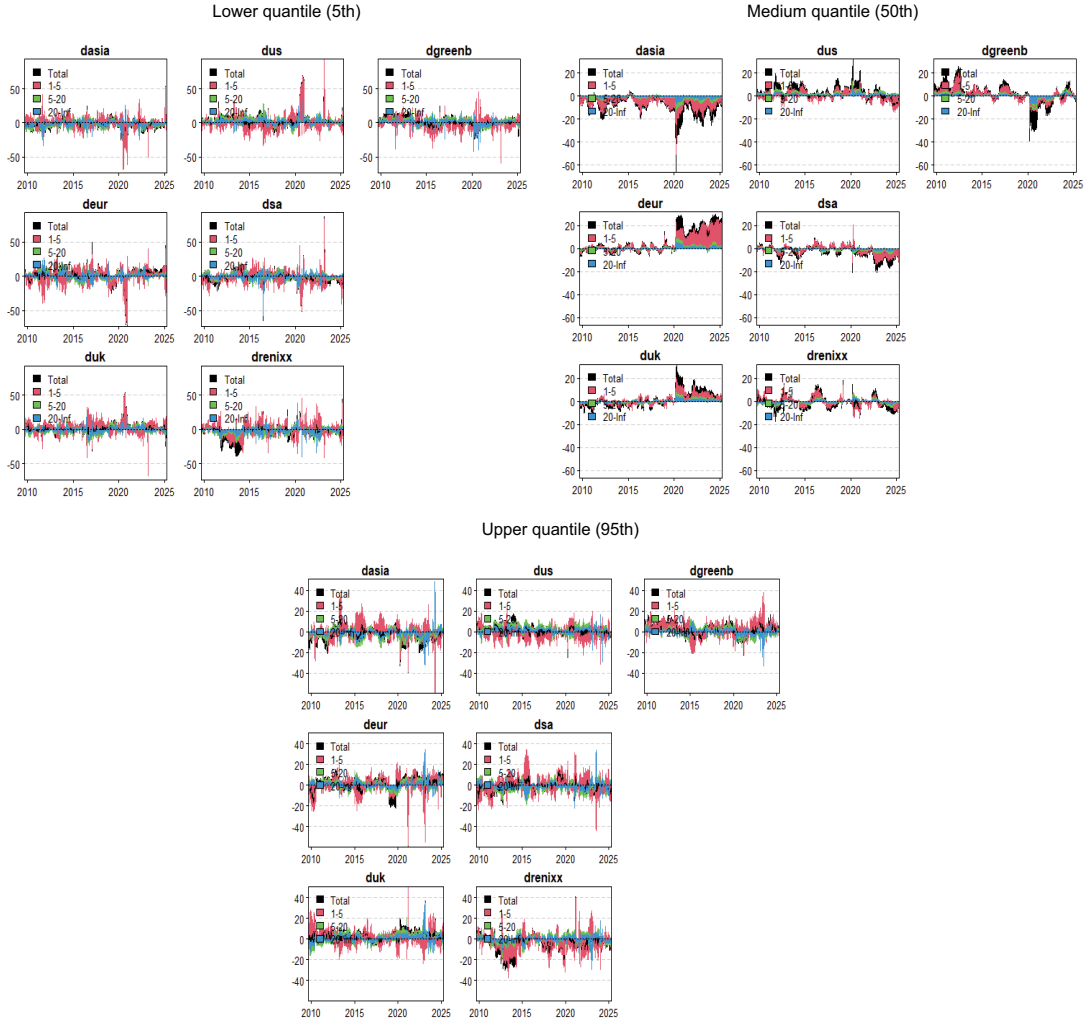


Figure 2. Dynamic NET time-frequency connectedness index

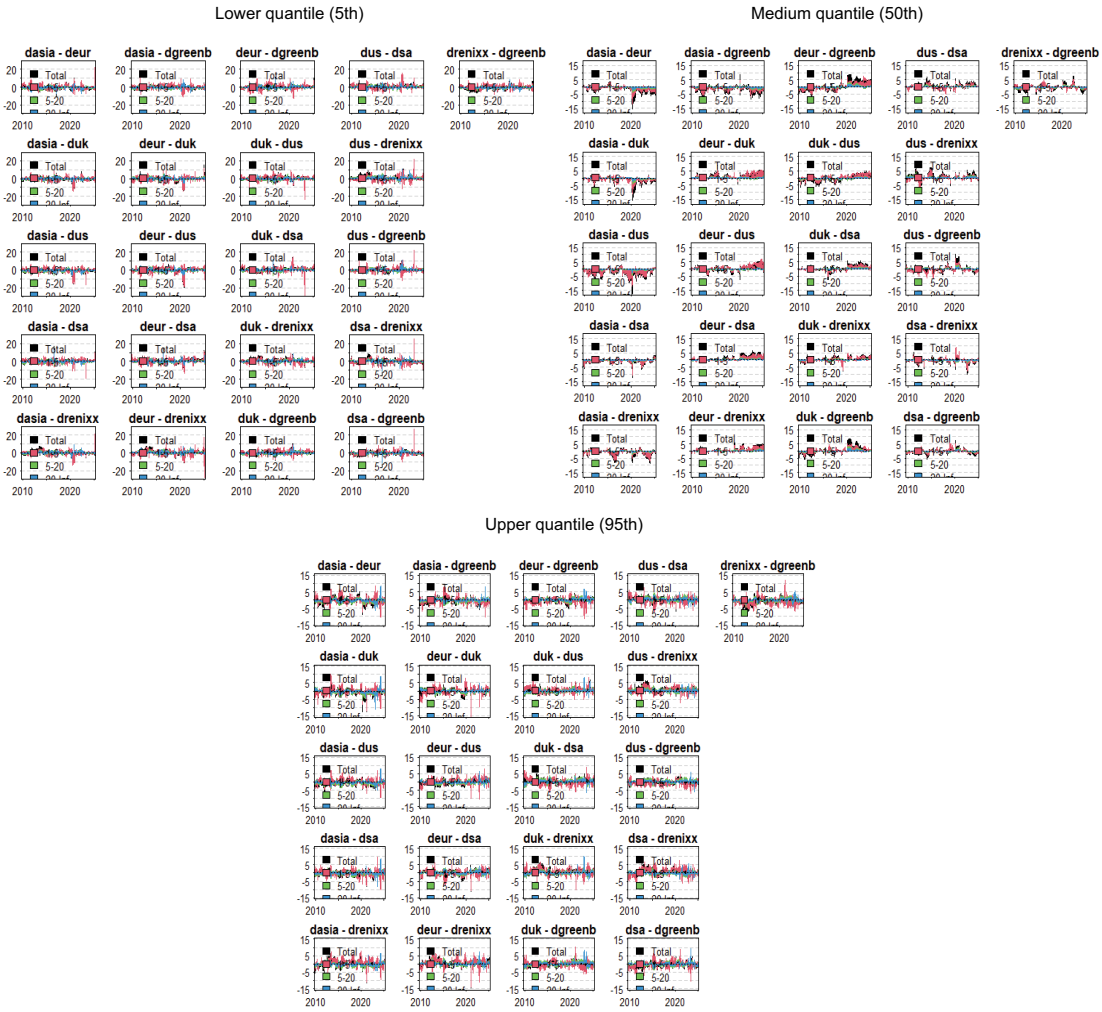


Figure 3. Dynamic NET directional pairwise connectedness

role afterwards. On the other hand, house stock markets in South Africa recorded a structural change around 2020 and play the receiving role up to the end of the sample period. Finally, the clean energy indices, particularly the green bond that serves as a risk stabiliser after 2020. More importantly, the role played by these indices is more pronounced in the short-term horizon.

Figure 3 depicts all quantiles' net directional pairwise connectedness (NDPC). The figure further shows that the NDPC is stronger in the short-frequency domain, and a few markets stand out for different reasons. For instance, the US and South African listed real estate markets would transmit information to other regional REITs around 2023. It is notable to observe the consistent domination of the UK and the European house markets within the system after 2020. Viewing the NDPC under higher quantiles, Asian and European regional real estate markets convey news to other markets, particularly the renewable energy market, playing the role of portfolio stabiliser.

Figure 4 differs from Figure 3 in that it does not differentiate the spillover sent and received, providing insights into the true exchange level between markets at play. The figure shows strong connectedness among the markets under consideration. Indeed, the pairwise connectedness barely drops below 50 under extreme market conditions (bearish and bullish) across frequency domains. However, under neutral market conditions, the connectedness falls beyond 30 at a specific time, which is the case between all regional house stock and clean energy around 2014.

Figures 5–7 show the quantile time-frequency network connectedness for the 5th, 50th, and 95th quantiles. Blue indicates the net transmitter of information, while yellow indicates the net absorber of shocks. Additionally, the size and boldness of the node evaluate the strength of the interconnectedness between markets. The figures show noticeable and significant levels of interplay among the markets of interest. Panels C and D in Figure 5 show that shocks are strongly transmitted from the US housing stocks to the Asian real estate markets while renewable energy stabilises the portfolio. On the other hand, the UK REITs significantly transmit news to the South African REITs, and the green bond index serves as a shock diversifier,



Figure 4. Dynamic pairwise connectedness

as informed by Panel B, depicting the short-run investment period. Panel A, displaying the total interrelationships among the markets, indicates that the US and Asian house stocks are the system's primary transmitters and receivers of information, and renewable energy serves as the main risk stabiliser under low-risk profiles.

Figure 6a–d depicts the network time-frequency connectedness under regular periods and displays similarities across time-frequency domains. More precisely, the South African and the Asian REITs act as net absorbers of news from other regional REITs. Renewable energy (long-term horizon) and green bond (short-term horizon) markets can be used as hedging instruments within the system. Furthermore, the European and US house stock markets mainly convey news to the Asian stock market in the short and long term. On the other hand, the Asian regional estate market serves as the main receiver of shocks within the system and across time frames.

Under high market volatility, Figure 7a–d exposes the network connectedness across time-frequencies. The figure highlights strong interconnectedness among markets of interest in the short term (1–5 days), with the US house market capturing information released by house markets from other regions in the short-term investment horizons, while renewable energy serves as the risk diversifier in the portfolio. Considering long-term investment horizons, the UK, the US, and the European listed real estate markets spill shocks onto the Asian and South African real estate markets. Notably, the UK REITs and the US REITs are the principal shock transmitters in the short- and long-run.

In summary, the dynamic connectedness analysis confirms the evidence of significant risk spillovers among regional housing stock markets. The analysis further highlights the importance of using the green bond index to hedge risk when considering short-term investment horizons and the renewable energy index, otherwise, under low-risk profiles. Moreover, under high uncertainty periods, both clean energy markets can better serve as a risk diversifier, whereas under normal market conditions, the renewable energy market has more hedging power across investment horizons.

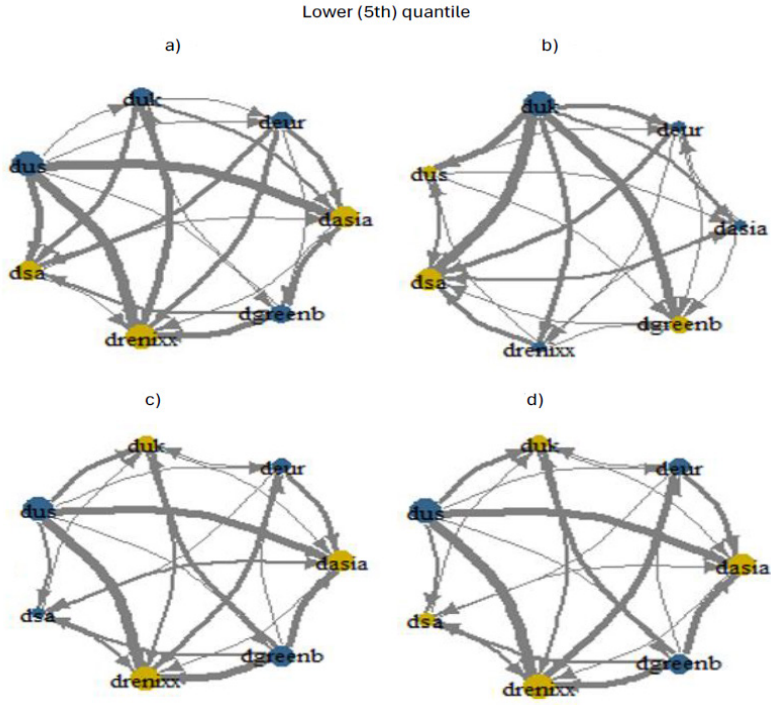


Figure 5. Quantile time-frequency pairwise connectedness network at lower quantile (τ = 0.05): a) Total; b) 1–5 days; c) 5–20 days; d) 20-inf days

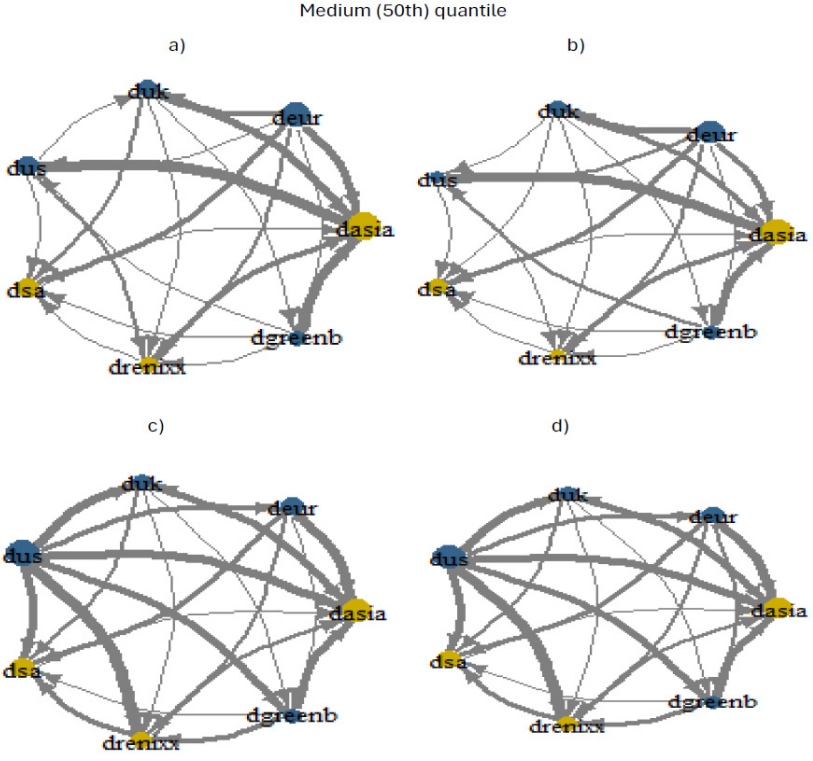


Figure 6. Quantile time-frequency pairwise connectedness network at medium quantile (τ = 0.5): a) Total; b) 1–5 days; c) 5–20 days; d) 20-inf days

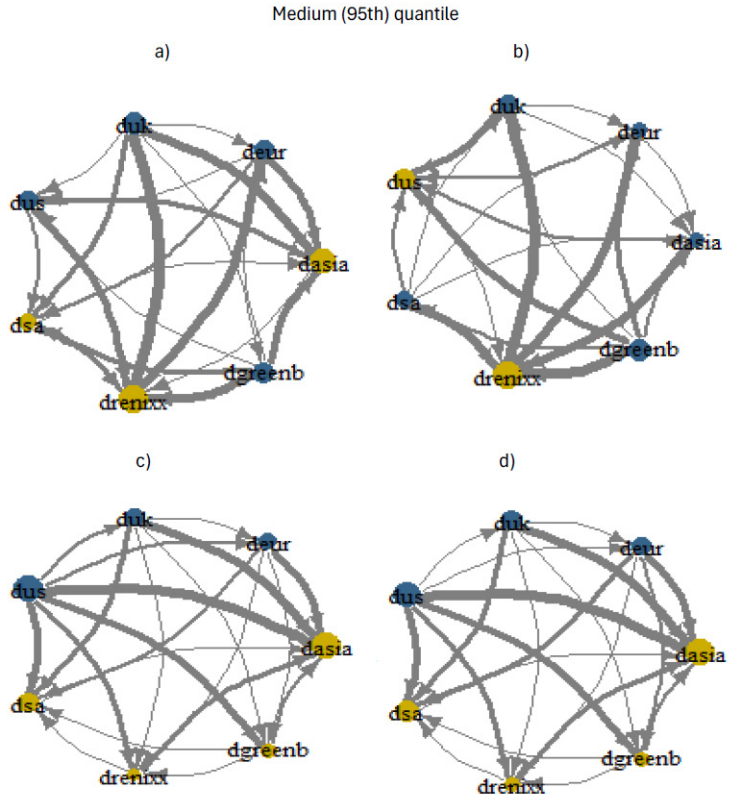


Figure 7. Quantile time-frequency pairwise connectedness network at upper quantile (τ=0.95): a) Total; b) 1–5 days; c) 5–20 days; d) 20-inf days

5. Conclusions

Understanding the dynamics between the real estate and clean energy markets is vital for portfolio diversification, aiding investors and policymakers in making informed decisions. Considering market network connectedness, the current study explores the interconnections between regional real estate investments and the hedging potential of clean energy markets. Empirical findings from a quantile time-frequency vector autoregressive model reveal significant interconnectedness and shock transmission in extreme quantiles, bearish or bullish market conditions. Furthermore, most interconnectedness among the regional REITs is concentrated in short-term across risk profiles and diminishes over time, indicating a short-lived contagion that tends to normalise quickly. On the other hand, clean energy markets act as a shock absorber, indicating some hedging property for regional REIT portfolios.

Under low market volatility, REITs in Asia, Europe, and the UK appear to convey shocks to the US and South African markets, with the UK REITs and the South African REITs being the main transmitters and receivers of news. At the same time, the green bond index helps mitigate risk in the short-term portfolio investments under low uncertainty. Considering long-term investment horizons, the US and Asian real estate markets turn out to be the principal shock transmitter and receiver, while renewable energy is the risk diversifier in the portfolio. Under normal market conditions, volatility spills mainly from the European and the US real estate markets to the Asian one in the portfolio, considering short- and extended time frequencies, respectively. Additionally, renewable energy appears as a safer instrument in containing uncertainty within the portfolio across investment horizons. Lastly, during periods of high market uncertainty, the UK REITs transfer volatility to the US REITs in short time periods, with renewable energy playing the risk diversifier role. On the other hand, the US REITs transfer volatility mainly to the Asian REITs over longer time periods and clean energy markets can be used as a hedging instrument in a portfolio of the regional housing stock markets. These results highlight clean energy's hedging, safe haven, and risk diversification characteristics across market conditions and time horizons.

An adequate portfolio diversification for real estate investment requires a contingency plan that includes regional real estate, stocks, and clean energy assets to build resilience during crises and promote investment stability. Investors are encouraged to adjust their portfolio allocations based on market conditions and time horizons, as different investment periods have unique impacts. Furthermore, the innovation within renewable energy and green bonds sectors as hedging assets or risk diversifiers highlights that policymakers and investors should consider leveraging clean energy investments to manage and reduce risks in regional real estate markets.

Disclosure statement

The authors have no relevant financial or non-financial interests to disclose.

Data availability statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

AI declaration

During the preparation of this work, the author(s) used ChatGPT-5 in order to proofread. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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