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Sustainability Risk Diffusion Through Clean Energy, Transition Risk, and ESG Market Connectedness in Malaysia

Rinda Siaga Pangestuti[1*], Roszy Non[2], Erwin Susanto Sadirsan[3]
[1]President University, Jababeka Education Park, Cikarang, Bekasi 17550, Indonesia
[2]Selangor University, Zirkon A7/A, Seksyen 7, Shah Alam 40000, Malaysia
[3]Pertamina University, Kebayoran Lama, South Jakarta, DKI Jakarta 12220, Indonesia
*Corresponding Email: rinda.pangestuti@president.ac.id

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ABSTRACT

Climate change and the global low-carbon transition have intensified sustainability-related risks across financial markets, yet evidence on how such risks diffuse into emerging Asian economies remains limited. This study examines the dynamic connectedness and volatility spillovers among the NASDAQ Clean Edge Green Energy Index (CELS), the Transition Risk Index (TRI), and Malaysia's FTSE4Good Bursa Malaysia Index (F4GBM) during 2019-2025. This quantitative econometric study applies a hybrid framework combining the Dynamic Conditional Correlation-Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH) model and the Diebold–Yilmaz connectedness index to daily returns. The results show that CELS is a persistent net transmitter of volatility, TRI is a policy-sensitive net receiver, and F4GBM alternates between absorbing and transmitting shocks. The total connectedness index rises from about 4% in late 2023 to above 8% by mid-2025, signaling deeper integration between climate-related risks and ESG market performance. The study concludes that investors should incorporate transition-risk indicators into diversification and hedging strategies, while policymakers should strengthen ESG disclosure, green taxonomies, and macroprudential climate-finance governance.

Keywords: Clean Energy; Climate Finance; ESG Markets; Transition Risk; Volatility Spillovers

JEL Classification: C58; G11; G15; G32; Q42; Q56

INTRODUCTION

Climate change has emerged as one of the most pervasive threats to global economic and financial stability. The increasing frequency of extreme weather events, the tightening of carbon regulations, and rising geopolitical tensions within the energy sector have collectively heightened uncertainty across global financial markets. Climate-related risks now extend beyond traditional fossil-fuel sectors and have begun to reshape the volatility dynamics of green investments and Environmental, Social, and Governance (ESG)-based financial instruments. The Intergovernmental Panel on Climate Change (Calvin et al., 2023) emphasizes that escalating physical and transition risks can amplify market volatility and induce risk spillovers across economies and asset classes. As the world transitions toward carbon neutrality by 2050, the ability of financial systems to absorb and adapt to climate-induced shocks has become a defining indicator of economic resilience.

Sustainable finance and green investment have become central mechanisms for supporting the transition toward a low-carbon economy. Global investors are increasingly allocating capital to clean energy, green technology, and ESG-based portfolios as part of climate-aligned investment strategies. However, these markets are not isolated from financial instability. Clean energy assets are typically sensitive to technological innovation, policy incentives, energy price fluctuations, and investor sentiment toward decarbonization. ESG markets in emerging economies similarly absorb external shocks from global climate-policy uncertainty and international green investment flows. Recent studies show that green finance markets experience time-varying connectedness and volatility spillovers during periods of global stress, particularly during the COVID-19 pandemic, energy market instability, and transition-policy adjustments (Arif et al., 2021; Lu et al., 2023; Xu et al., 2024).

Several recent studies extend this evidence. Mnif et al. (2025) document quantile-dependent linkages between sustainable investments, Bitcoin, and financial stability indicators, while Armeanu et al. (2025) show asymmetric connectedness between cleantech, clean energy, and climate-policy indicators during recent crises. Yousfi and Bouzgarrou (2024) demonstrate that clean energy and green equity exhibit time-varying spillovers with oil markets that materially affect portfolio implications, and Zeng et al. (2025) report multiscale tail-risk contagion between green finance and large technology stocks. Alessandro et al. (2023) demonstrate that the implementation of sustainable finance affects bank performance indicators in Indonesia, while Sin et al. (2025) document the key success factors of sustainable growth at a major Malaysian bank, highlighting the strategic role of ESG integration in domestic financial institutions. Jian et al. (2024) further show that sustainability perception is a significant driver of consumer behavior in Asian markets, suggesting that ESG signals matter beyond financial markets alone. These contributions collectively suggest that regional ESG integration is still uneven, leaving emerging-market financial systems exposed to externally driven sustainability shocks.

The NASDAQ Clean Edge Green Energy Index (CELS) represents global investor confidence in renewable energy and clean-technology innovation, serving as a benchmark for low-carbon financial performance. The Transition Risk Index (TRI) captures policy-driven uncertainty arising from carbon transition pathways, regulatory changes, and net-zero commitments. Malaysia's FTSE4Good Bursa Malaysia Index (F4GBM) reflects the country's ESG market development through listed firms that meet sustainability-related criteria. Malaysia is an ideal case for examining global-to-domestic diffusion effects because it combines an explicit institutional commitment to sustainable finance with high exposure to external volatility. Its financial system is closely linked to international capital flows and green investment funds, while domestic ESG markets remain in an early stage of development. This structure enables F4GBM to capture both the transmission of global shocks and domestic market adaptation. Despite policy efforts, sustainable finance disclosure across ASEAN remains uneven (Maheresmi et al., 2023), positioning Malaysia as a strategic setting for studying how global sustainability shocks diffuse into emerging domestic financial systems.

Despite the rapid expansion of research on green finance and climate-related financial risk, several gaps remain. First, the existing literature concentrates on developed markets, global green-bond portfolios, or aggregated clean-energy indices, while evidence on emerging ESG markets such as Malaysia is scarce. Second, prior studies often examine clean energy, transition risk, or ESG markets in isolation rather than integrating them into a single framework of connectedness. Third, many studies rely on static correlation or conventional volatility models, which cannot fully capture the dynamic and directional character of sustainability risk transmission. This omission is consequential because the role of each market may shift over time, with a single index serving as a transmitter in one period and a receiver in another. A dynamic econometric approach is therefore needed to identify whether clean energy, transition risk, and Malaysia's ESG market function as sources or recipients of sustainability-related shocks.

To address these gaps, this study examines the dynamic connectedness and volatility spillovers among CELS, TRI, and F4GBM during the 2019-2025 period. The objective is to analyze how sustainability-related risks diffuse from global clean energy and transition-risk indicators into Malaysia's ESG market. The novelty of the study lies in integrating global clean-energy performance, climate-transition risk, and a country-level ESG market within a single dynamic connectedness framework. Methodologically, the study contributes by combining the Dynamic Conditional Correlation-Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH) model with the Diebold–Yilmaz connectedness index to capture both time-varying co-movement and directional volatility spillovers. The findings are significant for investors, regulators, and policymakers because they provide empirical evidence on whether Malaysia's ESG market acts mainly as a receiver, transmitter, or adaptive channel of sustainability-related financial shocks. The study contributes to the literature on green financial stability, climate-finance governance, ESG disclosure, and transition-risk monitoring in emerging markets and offers practical implications for portfolio diversification, hedging strategies, and macroprudential climate-finance policy in Malaysia.

LITERATURE REVIEW

Climate Risk and Sustainable Finance

Climate risk has become a defining issue in modern finance because it affects asset valuation, investor behavior, and the stability of the overall financial system. The literature distinguishes between physical risk arising from extreme weather and ecosystem disruption, and transition risk arising from policy shifts, carbon regulation, technological change, and investor reallocation toward low-carbon assets (Calvin et al., 2023; Reboredo & Ugolini, 2022). Both categories affect financial markets through changes in expected cash flows, risk premiums, asset allocation, and volatility. In response, sustainable finance has expanded rapidly, with green bonds, clean-energy equities, climate funds, and ESG-based indices becoming key channels for financing the low-carbon transition (Alessandro et al., 2023; Gaies, 2025). Hambel and Ploeg (2025) show that policy transition risk is increasingly priced in equity markets, generating carbon premiums and affecting valuation across sectors. This evolution indicates that sustainability-related instruments now exhibit financial behavior intrinsically tied to climate policy dynamics.

Clean Energy and ESG Market Connectedness

A growing body of work documents that clean-energy and ESG markets are dynamically interconnected with traditional financial and energy markets. Xu et al. (2024) show that green bonds exhibit varying connectedness with traditional and emerging investments during global crises, while Arif et al. (2021) reveal time-frequency connectedness between green and conventional markets during the COVID-19 pandemic. Lu et al. (2023) confirm that connectedness between returns and volatility among green finance markets intensified during the pandemic, and Ullah et al. (2024) document heightened risk dynamics for sustainable climate exchange-traded funds (ETFs) under stress conditions. Zhang et al. (2022) further establish that DCC-GARCH-based dynamic connectedness and copula models capture asymmetric spillovers among sustainability-related indices. Cocca et al. (2024) and Sen & Chakrabarti (2024) demonstrate that clean-energy stocks display time-varying beta and connectedness profiles that change with macro-financial conditions. While these studies advance understanding of clean-energy and ESG market interconnectedness at the global or developed-market level, the extent to which these dynamics apply to individual emerging ASEAN markets such as Malaysia remains insufficiently examined.

Transition Risk and Financial Spillovers

Transition risk has emerged as a central channel through which climate policy affects financial markets. Reboredo and Ugolini (2022) show that climate-transition risk significantly affects profitability and stock prices, while Hambel and Ploeg (2025) link policy-transition risk to asset-pricing dynamics. Dogan (2025) demonstrates that geopolitical shocks transmit asymmetrically to clean-energy markets through wavelet-quantile channels, and Rao et al. (2023) show that conventional energy shocks spill over into green energy markets, especially during crisis periods. Mnif et al. (2025) document that sustainable investments, Bitcoin, and financial stability indicators are jointly connected across quantile regimes, while Armeanu et al. (2025) report asymmetric connectedness among cleantech, clean energy, and climate policy indicators during contemporary crises. Yousfi & Bouzgarrou (2024) and Zeng (2024) confirm that quantile-based and tail-risk connectedness approaches reveal spillover patterns that linear models miss. Collectively, these studies emphasize that transition risk is not a passive policy variable but an active source of volatility transmission across global green finance.

Malaysia's ESG Market Integration

Malaysia provides a distinctive case for studying ESG market integration in an emerging-market context. The FTSE4Good Bursa Malaysia Index (F4GBM) was introduced to capture listed firms that meet ESG criteria, and Bursa Malaysia has progressively embedded sustainability disclosure into its listing requirements (Ezuma & Matthew, 2022). Maheresmi et al. (2023) show that sustainable finance disclosure among ASEAN-listed banks, including those in Malaysia, is shaped by firm ownership and tax-avoidance behavior, suggesting that institutional commitment to ESG remains uneven. Alessandro et al. (2023) find that the implementation of sustainable finance influences bank performance indicators in a regional context, while Sin et al. (2025) examine the key success factors driving sustainable growth at Hong Leong Bank, one of the largest Malaysian banks, highlighting how institutional-level ESG integration shapes domestic financial dynamics. Jian et al. (2024) further document that sustainability perception is a meaningful driver of consumer behavior in Asian markets, suggesting that ESG signals affect both real-economy and financial decisions. AlGhazali et al. (2024) and Oliveira et al. (2024) show that sustainability indices in emerging markets are sensitive to oil-price

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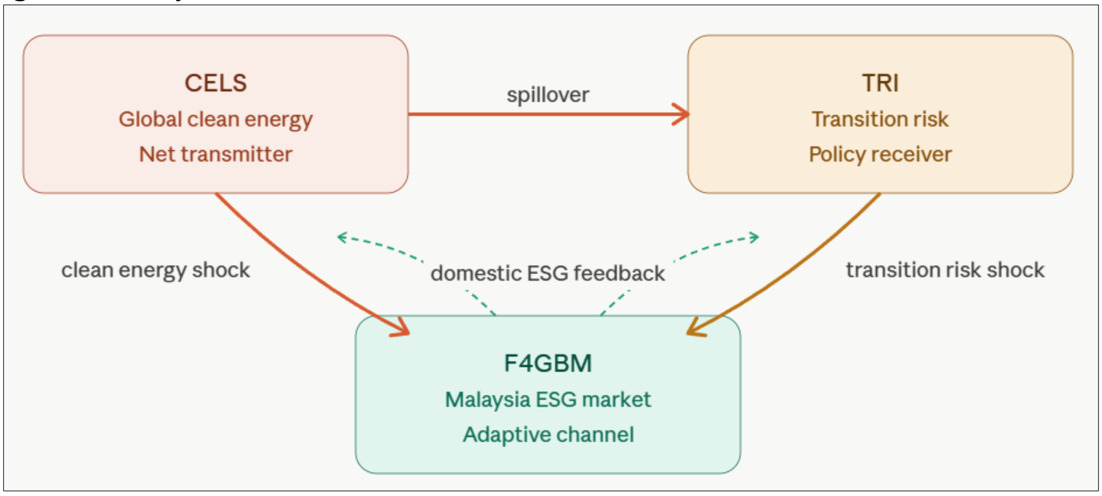
and extreme-event shocks, reinforcing the view that emerging ESG markets are exposed to global spillovers. However, no prior study integrates Malaysia's ESG market with global clean energy and transition-risk indicators within a single time-varying connectedness framework. This study addresses that gap by examining how sustainability shocks propagate from CELS and TRI into F4GBM under different market regimes.

Analytical Framework

The analytical framework for sustainability risk diffusion among CELS, TRI, and F4GBM is shown in Figure 1.

Figure 1. Analytical Framework



Based on Figure 1, CELS represents the global clean-energy market and is expected to act primarily as a transmitter, given that innovation cycles, renewable investment flows, and technology shocks originate primarily in advanced markets. TRI captures global transition-policy uncertainty and is expected to serve as a policy-sensitive receiver, absorbing spillovers from clean-energy markets while occasionally transmitting policy shocks. F4GBM represents Malaysia's ESG market and is expected to serve as an adaptive channel that absorbs external shocks from CELS and TRI while also transmitting domestic ESG signals as the market matures. The relationships are expected to be time-varying, with stronger spillovers during global crises (COVID-19, post-2022 energy disruption, post-2023 decarbonization policy intensification). The empirical direction and magnitude of these spillovers are examined in the Results section.

RESEARCH METHOD

Research Design

This study employs a quantitative econometric research design based on time-series modeling of daily index returns. The design integrates two complementary modeling approaches: the DCC-GARCH model of Engle (2002) and the Diebold–Yilmaz generalized connectedness index (Diebold & Yilmaz, 2012, 2014). The DCC-GARCH component estimates time-varying conditional correlations among the indices, while the Diebold–Yilmaz component decomposes the variance of forecast errors to quantify the direction and intensity of volatility spillovers. A rolling-window estimation is applied to capture the evolution of connectedness over time. This design follows the framework adopted by Cocca et al. (2024), Mensi et al. (2018), and Zhang et al. (2022) for analyzing sustainability-related financial markets.

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Data Sources and Variables

Three daily indices form the empirical sample for the period 2019-2025. The CELS and F4GBM series are obtained from Capital IQ, while the TRI series is obtained from www.policyuncertainty.com. CELS represents the global clean-energy innovation market and includes companies operating in solar, wind, smart-grid, and related technologies (Dogan, 2025). TRI reflects global climate-transition policy risks, including the impact of carbon policies, environmental regulation, and investor expectations regarding the low-carbon transition (Hambel & Ploeg, 2025; Reboredo & Ugolini, 2022). F4GBM represents Malaysia's country-level ESG market and includes Bursa Malaysia-listed firms that satisfy ESG criteria (Ezuma & Matthew, 2022). The CELS and F4GBM series are converted into daily log returns, while TRI series enters the analysis in its native units as a daily text-based transition-risk index rather than as returns, prior to estimation. Table 1 summarizes the data sources and the role of each index in the analytical framework.

Table 1. Data Sources and Variables

Index	Description	Data Source	Frequency / Period	Role in the Analysis
CELS	NASDAQ Clean Edge Green Energy Index (renewable energy and clean-technology stocks)	Capital IQ	Daily, 2019-2025	Proxy for global clean-energy / green-innovation market
TRI	Transition Risk Index capturing climate-policy uncertainty and low-carbon transition risks	Economic Policy Uncertainty (Climate Risk Indexes)	Daily, 2019-2025	Proxy for global climate-transition policy risk
F4GBM	FTSE4Good Bursa Malaysia Index of ESG-compliant listed firms	Capital IQ	Daily, 2019-2025	Proxy for Malaysia's country-level ESG / sustainable-finance market

DCC–GARCH Estimation

To examine time-varying co-movements among the three indices, this study applies the DCC-GARCH model proposed by Engle (2002). DCC-GARCH is well-suited to financial return data because it allows both conditional variances and conditional correlations to evolve over time, capturing volatility clustering and time-varying interdependence. In the first stage, univariate GARCH(1,1) processes are fitted to the residuals of each return series:

$$r_{i,t} = \mu_i + \varepsilon_{i,t}$$
$$\varepsilon_{i,t} = h_{i,t}^{1/2} z_{i,t} \quad , \quad z_{i,t} \sim N(0,1)$$
$$h_{i,t} = \omega_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i h_{i,t-1}$$

where $h_{i,t}$ denotes the conditional variance, ω_i is a constant, and α_i ~~i~~and β_i capture the effects of past shocks and volatility persistence, respectively. In the second stage, the conditional correlations are modeled as time–varying through the DCC specification:

$$Q_t = (1 - a - b)\bar{Q} + a\,(z_{t-1} z_{t-1}) + bQ_{t-1}$$
$$R_t = diag(Q_t)^{-1/2} Q_t \, diag(Q_t)^{-1/2}$$

where Q_t is the conditional covariance matrix of standardized residuals z_t, and $\bar{Q}$ is its unconditional expectation. The parameters a and b govern the persistence and adjustment speed of conditional correlations. The resulting correlation matrix R_t captures the dynamic interdependence between markets.

Diebold–Yilmaz Connectedness Index

To measure the magnitude and direction of risk transmission across markets, this study employs the Diebold–Yilmaz connectedness index (Diebold & Yilmaz, 2012, 2014), based on the Generalized Forecast Error Variance Decomposition (GFEVD) from a vector autoregressive (VAR) model. The baseline VAR(*p*) model is given as:

$$x_t = \sum_{i=1}^{p} A_i x_{t-i} + \varepsilon_t \quad , \quad \varepsilon_t \sim (0, \Sigma)$$

where x_t is a *k*×1 vector of returns, A_i are coefficient matrices, and Σ is the variance–covariance matrix of innovations, from the moving average representation:

$$x_t = \sum_{i=0}^{\infty} \phi_i \varepsilon_{t-i}$$

the *H*–step–ahead GFEVD of variable *i* to shocks in variable *j* is computed as:

$$\theta_{ij}^{(H)} = \frac{\sigma_{jj}^{-1} \Sigma_{h=0}^{H-1} \left(e_i' \Phi_h \Sigma_{ej}\right)^2}{\sum_{h=0}^{H-1} \left(e_i' \Phi_h \Sigma \Phi_h' e_i\right)}$$

where e_i is a selection vector with 1 in the *i-th* position and zeros elsewhere. Each element $\theta_{ij}^{(H)}$ captures the proportion of forecast error variance in variable *i* explained by innovations in variable *j*. The Generalized Total Connectedness Index (TCI) is defined as:

$$TCI = \frac{1}{k} \sum_{i,j=1, i \neq j}^{k} \tilde{\theta}_{ij}^{(H)} \times 100$$

where $\tilde{\theta}_{ij}^{(H)}$ are normalized contributions ensuring that each row sums to 1.

The directional spillovers are expressed as:

$$TO_j = \sum_{i=1, i \neq j}^{k} \tilde{\theta}_{ij}^{(H)} \quad , \quad FROM_j = \sum_{i=1, i \neq j}^{k} \theta_{ji}^{(H)}$$

and the net spillover for market *j* is:

$$NET_j = TO_j - FROM_j$$

Rolling–Window Connectedness

Following Diebold & Yilmaz (2012) and Mensi et al. (2018), the rolling-window connectedness was computed using a fixed window of 132 daily observations with a 10-day forecast horizon. This window length balances estimation stability with responsiveness to regime shifts, allowing the model to capture medium-term spillover dynamics while mitigating short-term noise. For each subsample, a VAR(1) model and the corresponding GFEVD were re-estimated, producing a time-varying series of three connectedness measures: the Total Connectedness Index (TCI), which captures overall market interdependence; the directional spillovers (TO and FROM), which identify the sources and recipients of shocks; and the net spillover, which determines whether each market acts as a net transmitter or net receiver of risk.

Rolling–Window Connectedness

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RESULTS

Descriptive Statistics and Stationary Tests

Table 2 reports descriptive statistics and Augmented Dickey-Fuller (ADF) stationarity tests for the daily returns of CELS, TRI, and F4GBM over the 2019-2025 period. CELS exhibits the highest unconditional volatility (SD = 3.507) among the equity indices, while TRI shows the largest scale because it is expressed in policy-uncertainty units rather than returns. F4GBM exhibits pronounced positive skewness (3.25) and kurtosis (23.43), reflecting the heavy-tailed behavior typical of emerging-market ESG indices. The ADF test confirms that all three series are stationary at the 1% level, supporting the use of GARCH-based modeling.

Table 2. Summary of Descriptive and Stationarity Statistics

Statistic	NASDAQ Clean Edge Green Energy (CELS)	Transition Risk Index (TRI)	FTSE4Good Bursa Malaysia Index (F4GBM)
Mean	0.0686	3.7964	0.0930
Median	0.1665	9.5233	-0.0117
SD	3.5070	160.2360	1.1517
Min	-13.7680	-463.4000	-4.0007
Max	15.2471	482.2310	7.9568
Skewness	0.3111	-0.0986	3.2536
Kurtosis	6.1436	4.1142	23.4252
ADF Statistic	-5.7273	-6.9130	-4.6856
ADF Critical (1%)	-3.4600	-3.4600	-3.4600
Significance	**	**	**
ADF Result	Stationary	Stationary	Stationary

Note: ** denotes rejection of the unit-root null at the 1% level.

Bollerslev (1986) and Engle (2002) emphasize that volatility clustering motivates the use of conditional heteroskedasticity models, while Diebold and Yilmaz (2012) note that connectedness-based approaches are robust to non-normal innovations because they rely on variance-covariance dynamics rather than distributional assumptions. The data are therefore appropriate for the DCC-GARCH and Diebold–Yilmaz analyses that follow.

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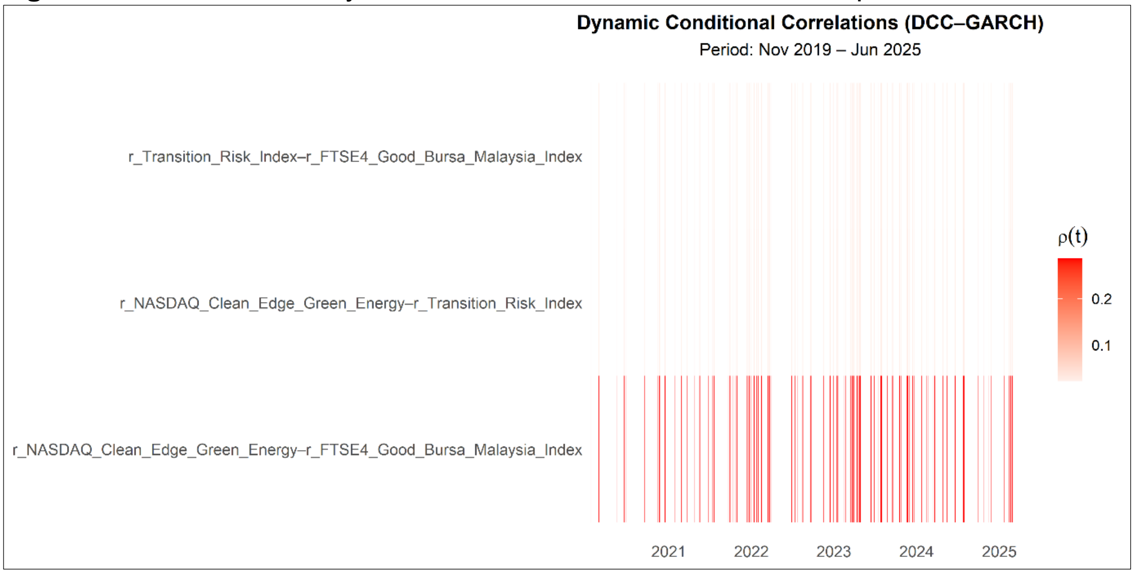
DCC-GARCH Results

Figure 2 presents the DCC-GARCH estimated conditional correlations among CELS, TRI, and F4GBM. The analysis covers November 2019 to June 2025 and encompasses the COVID-19 pandemic, oil market volatility, and post-pandemic green recovery initiatives. The DCC-GARCH heatmap reveals persistent but time-varying positive correlations among the three indices. The intensity of red bands, which correspond to higher dynamic correlations ρ(t), identifies periods of heightened co-movement, particularly during the 2020-2021 transition phase when renewable-energy adoption accelerated. The pattern suggests that investors in both global and domestic green markets reacted synchronously to climate and energy policy developments such as stimulus packages supporting decarbonization and ESG integration.

The CELS-TRI correlation strengthens after 2022, implying that global clean-energy performance increasingly reflected transition-risk pricing as markets internalized policy uncertainty related to carbon regulation and net-zero commitments. The F4GBM-TRI pair displays moderate and lagged correlation shifts, signaling Malaysia's adaptation to global transition-policy pressures with a delay. Overall, the DCC-GARCH results confirm interdependence between transition risk and sustainable-finance indices, suggesting that policy shocks and technological advancements in clean energy propagate across financial markets and necessitate climate-aligned diversification strategies in emerging economies.

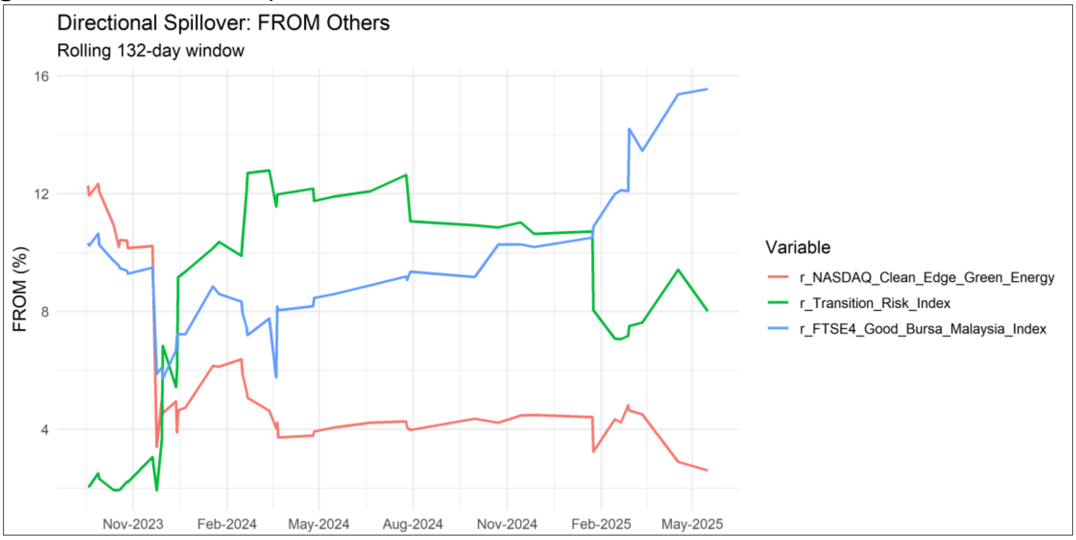
Figure 2. DCC–GARCH Dynamic Conditional Correlation Heatmap



Directional Spillover FROM Other Markets

Figure 3 shows the directional spillovers received from other markets. TRI consistently receives the largest share of shocks from other indices throughout 2024, with spillovers exceeding 12% in several subperiods. This finding indicates that transition risk in the financial system is strongly influenced by external sources, particularly global clean-energy performance and sustainability-oriented market sentiment. F4GBM also shows increasing susceptibility to external volatility after 2023, reflecting Malaysia's growing integration into the global sustainable-finance network. CELS shows relatively lower FROM values, indicating resilience and a more autonomous role in the green-finance ecosystem.

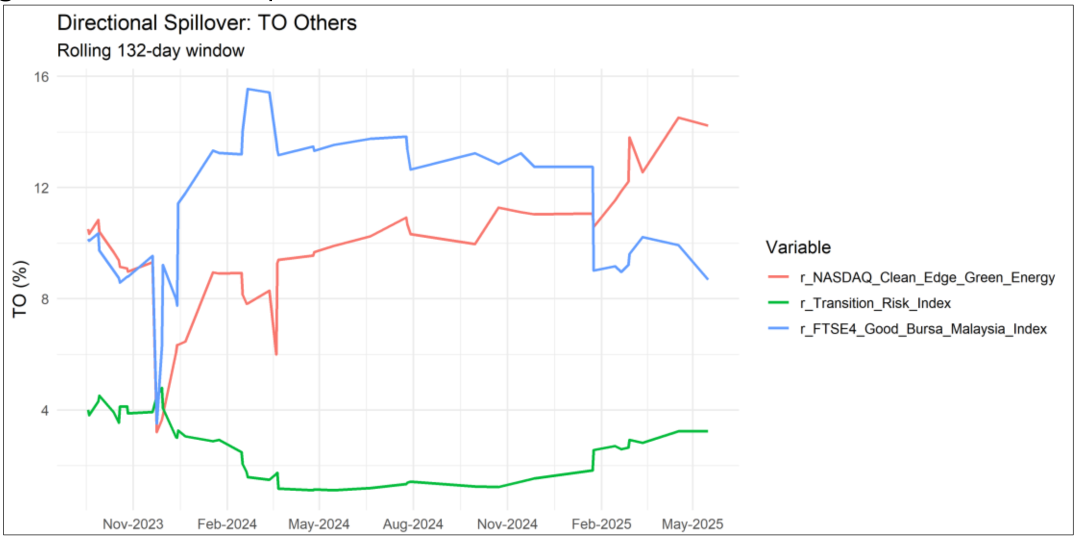
Figure 3. Directional Spillover FROM Other Markets



Directional Spillover TO Other Markets

Figure 4 displays the directional spillover transmitted to other markets. CELS acts as the main transmitter of risk, followed by F4GBM, while TRI remains the primary net receiver. CELS demonstrates consistent transmission exceeding 10%, confirming its central role as a global source of volatility within sustainability-linked markets. F4GBM, although secondary, exhibits notable outward spillovers during mid-2024, highlighting Malaysia's increasing participation in the diffusion of sustainability shocks. By contrast, the persistently low outward spillover of TRI reinforces its function as a receiver of policy-driven and climate-related risks.

Figure 4. Directional Spillover TO Other Markets



Net Spillover Index

Figure 5 reports the net spillover index for each market. CELS maintains a consistently positive net spillover that strengthens toward mid-2025, indicating that global clean-energy assets function as persistent net transmitters of shocks due to their sensitivity to technological innovation, renewable-investment cycles, and climate-policy adjustments. TRI exhibits strongly negative net spillover values throughout most of 2024, confirming its dependence on external markets and its position as a net receiver of financial and policy spillovers. F4GBM's net spillover fluctuates between positive and negative

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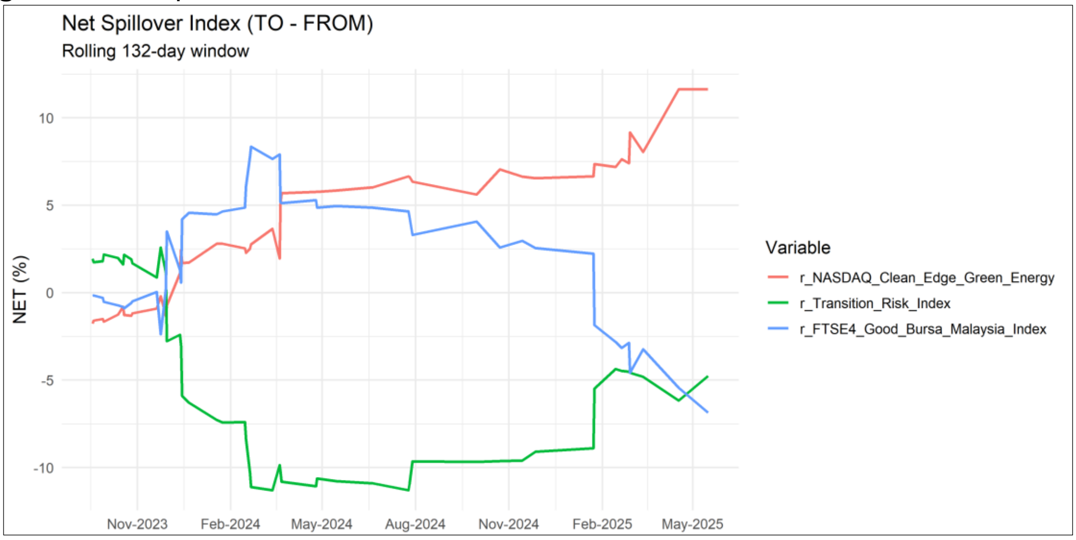
territory, indicating an evolving stage of market maturity in which Malaysia's ESG market alternates between absorbing and transmitting shocks. Collectively, the results identify a hierarchical pattern of sustainability risk transmission in which global green-energy markets function as primary transmitters, transition-risk indicators behave as policy-sensitive receivers, and country-level ESG markets serve as adaptive channels.

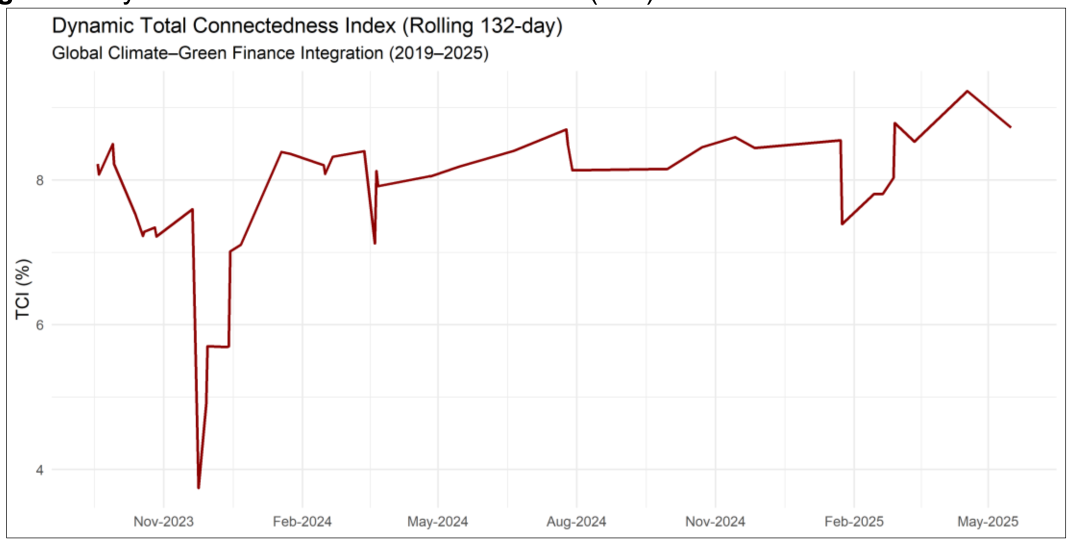
Figure 5. Net Spillover Index for CELS, TRI, and F4GBM



Dynamic Total Connectedness Index (TCI)

Figure 6 presents the evolution of the Total Connectedness Index (TCI) from late 2023 to mid-2025, based on the 132-day rolling-window estimation. The TCI fluctuates within a range of approximately 4-9%. A notable dip occurs in late 2023, when the TCI falls to about 4%, indicating a temporary decoupling among climate-related financial indicators, likely reflecting short-term market stabilization following earlier volatility in global clean-energy and transition-risk markets. From early 2024 onward, the TCI rises steadily, stabilizing above 8% throughout 2024 and 2025. This sustained increase signals stronger integration between climate-oriented investment instruments and country-level sustainability markets, reflecting enhanced co-movement between environmental and financial systems.

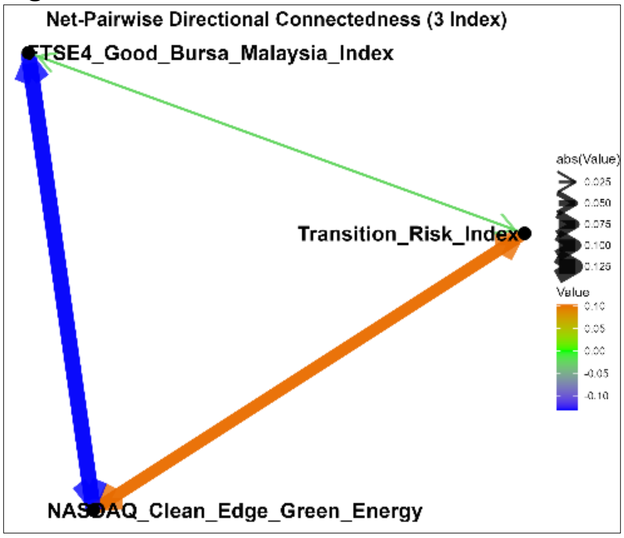
Figure 6. Dynamic Total Connectedness Index (TCI)



Net-Pairwise Directional Connectedness Network

Figure 7 visualizes the net-pairwise directional connectedness network among CELS, TRI, and F4GBM, computed from the average net-pairwise spillover matrix over the sample period. The aggregated network identifies the dominant pairwise direction of volatility flows: from F4GBM to TRI and from TRI to CELS over the full sample. This pairwise visualization complements rather than contradicts the directional results in Figures 3-5. While Figures 3-5 measure the cumulative spillover of each market to or from all other markets, the network in Figure 7 isolates the bilateral net flow between each pair of markets, averaged over the sample. As a result, CELS remains the largest aggregate transmitter (Figure 4) even though, in pairwise terms, its bilateral net position vis-à-vis TRI may be smaller in magnitude. The combined evidence indicates that aggregate sustainability spillovers are dominated by global clean energy, while bilateral interactions reveal that domestic ESG and policy-risk channels also play an active role in shaping the network structure.

Figure 7. Net-Pairwise Directional Connectedness Network



DISCUSSION

Co-movement Dynamics from DCC-GARCH

The DCC-GARCH evidence of persistent yet time-varying co-movement among CELS, TRI, and F4GBM is consistent with prior studies showing that sustainability-related indices are dynamically linked to global financial conditions (Arif et al., 2021; Cocca et al., 2024; Zhang et al., 2022). The intensification of co-movement during 2020-2021 mirrors the global synchronization documented by Lu et al. (2023) during the COVID-19 pandemic, suggesting that crisis episodes generate common climate-finance shocks that simultaneously affect both developed and emerging green markets. The strengthening of the CELS-TRI correlation after 2022 supports the view of Hambel & Ploeg (2025) and Reboredo & Ugolini (2022) that transition risk has become an explicit pricing factor in global clean-energy equities.

The lagged adjustment of F4GBM relative to CELS and TRI suggests information frictions in Malaysia's ESG market, possibly related to the relative novelty of mandatory sustainability disclosure on Bursa Malaysia and the slower diffusion of ESG ratings to domestic institutional investors. From a theoretical perspective, the findings reinforce the climate-finance integration hypothesis: as policy, technology, and investor preferences align with decarbonization, sustainability-related assets exhibit stronger and more persistent co-movement. This pattern also implies that conventional diversification benefits between global clean energy and emerging-market ESG portfolios are gradually eroding, in line with the findings of Yousfi & Bouzgarrou (2024) and Zeng et al. (2025) for other regional contexts.

Directional Spillovers and Transmission Hierarchy
The directional results identify a hierarchical transmission pattern in which CELS is the dominant net transmitter, TRI is a policy-sensitive net receiver, and F4GBM is an adaptive intermediate channel. This pattern is consistent with Dogan (2025), Xu et al. (2024), and Yousfi & Bouzgarrou (2024), who report that global clean-energy and green-equity indices serve as primary sources of spillover within sustainability-linked markets. The receiver role of TRI extends the findings of Reboredo & Ugolini (2022) and Şahinler et al. (2024) by showing that transition-risk indicators are themselves shaped by external financial dynamics rather than acting purely as exogenous policy variables. The intermediate role of F4GBM aligns with Alessandro et al. (2023), Maheresmi et al. (2023), and Sin et al. (2025), who argue that ESG markets and Malaysian financial institutions are increasingly integrated into global capital flows while retaining idiosyncratic domestic features. For Malaysia, this suggests that international sustainability shocks reach the F4GBM through both clean-energy market channels and transition-risk pricing, with domestic ESG signals only partially mitigating their effect.

Two further inferences follow from the transmission hierarchy. First, the consistent net-transmitter status of CELS implies that global clean-energy investors set the marginal price of sustainability risk that other markets, including TRI and F4GBM, must absorb. This is consistent with the view in Rao et al. (2023) and Sen & Chakrabarti (2024) that clean-energy equities have evolved from a niche segment into a systemic source of green-finance volatility. Second, the alternating net position of F4GBM, switching between net receiver and net transmitter at different points in 2024-2025, indicates that Malaysia's ESG market is in a transitional phase: it imports volatility from global green markets during stress episodes but transmits domestic ESG signals during periods of regional policy intensification, such as the rollout of mandatory ESG reporting for ACE Market-listed issuers and Bursa Malaysia's enhanced sustainability framework. This dual role is empirically novel for the Malaysian context and complements evidence on ESG implementation in financial institutions (Alessandro et al., 2023; Sin et al., 2025).

Total Connectedness and Climate-Finance Integration
The TCI evidence of a rise from approximately 4% in late 2023 to above 8% by mid-2025 indicates a structural deepening of climate-finance integration. The pattern is consistent with Armeanu et al. (2025), Mnif et al. (2025), and Zeng et al. (2025), who document intensifying connectedness between sustainable assets and broader financial systems under recent crises. The sharp dip in late 2023, followed by a sustained increase, coincides with the period of recalibration in global climate policy, including the operationalization of the EU's Carbon Border Adjustment Mechanism, the acceleration of clean-technology incentives under the U.S. Inflation Reduction Act, and renewed COP-level commitments on transition finance. These external developments increased the policy intensity of TRI and reinforced the role of CELS as a transmission channel, lifting overall connectedness with F4GBM.

From an investor perspective, the rise in TCI implies that diversification benefits across green, transition-risk, and ESG assets are shrinking, requiring more sophisticated hedging strategies that incorporate transition-risk indicators directly into portfolio construction (Cocca et al., 2024; Yousfi & Bouzgarrou, 2024). From a policy perspective, the upward trend supports calls by Calvin et al. (2023) and Gaies (2025) for stronger macroprudential climate-finance frameworks, since the same connectedness that channels green capital also channels systemic risk. The findings also resonate with Yuan et al. (2023), who argue that financial roles in green investment vary across quantiles and time, implying that any climate-finance governance framework must be state-contingent rather than static.

Implications for Malaysia's ESG Market

For Malaysia specifically, the findings have three implications. First, the F4GBM's evolving net spillover position implies that ESG market resilience cannot be assumed: as integration deepens, domestic sustainability assets become more exposed to global climate-policy and clean-energy shocks. Second, the role of transition risk as a major receiver suggests that Malaysian regulators must closely monitor international policy developments, including the EU's Carbon Border Adjustment Mechanism, the U.S. Inflation Reduction Act's clean-technology subsidies, and ASEAN's evolving sustainable-finance taxonomy, because these external policy shifts feed into domestic ESG pricing through TRI. Third, the implementation of sustainable finance and ESG in Malaysian financial institutions (Alessandro et al., 2023; Maheresmi et al., 2023; Sin et al., 2025) implies that strengthening firm-level ESG disclosure can help reduce information asymmetry and dampen the amplification of external shocks. The combination of stronger disclosure, clearer green taxonomies, and adaptive macroprudential policy is necessary to ensure that Malaysia's growing integration into global green finance contributes to resilience rather than fragility.

Theoretical and Practical Implications

Theoretically, the study contributes to the literature on climate finance, sustainable investing, and emerging-market integration by demonstrating that the transmission of sustainability risk is hierarchical, time-varying, and asymmetric. Global clean-energy markets behave as systemic sources of sustainability volatility; transition-risk indicators serve as policy-sensitive transmitters and receivers; and country-level ESG markets, such as F4GBM, operate as adaptive channels whose net role depends on macro-financial regimes. This finding refines the climate-finance integration hypothesis by introducing a directional and time-varying dimension absent from earlier static frameworks (Mensi et al., 2018; Zhang et al., 2022).

In practical terms, the findings have direct implications for three stakeholder groups. For institutional investors, the persistent transmitter role of CELS and the rising TCI suggest that integrating CELS- and TRI-linked volatility forecasts into risk-parity and ESG-tilted portfolios can improve tail-risk management, especially for funds with exposure to ASEAN equities. For regulators in Malaysia and across ASEAN, the evidence supports embedding transition-risk monitoring into macroprudential stress tests and aligning national green taxonomies with the ASEAN Taxonomy for Sustainable Finance to reduce regulatory arbitrage. For corporate issuers, especially F4GBM constituents, the results underscore the value of high-quality ESG disclosure aligned with IFRS S1/S2 and the recommendations of the Task Force on Climate-related Financial Disclosures, as lower information asymmetry attenuates the transmission of externally driven volatility.

CONCLUSION

This study examined the dynamic connectedness and volatility spillovers among the NASDAQ Clean Edge Green Energy Index (CELS), the Transition Risk Index (TRI), and Malaysia's FTSE4Good Bursa Malaysia Index (F4GBM) over 2019-2025, applying a hybrid DCC-GARCH and Diebold–Yilmaz framework. The main empirical findings are that CELS acts as a persistent net transmitter of volatility, TRI behaves as a policy-sensitive net receiver, and F4GBM alternates between absorbing and transmitting shocks. The total connectedness index rises from approximately 4% in late 2023 to above 8% by mid-2025, signaling intensifying climate-finance integration between global green markets and Malaysia's ESG segment. Pairwise network analysis further indicates that bilateral net flows run from F4GBM to TRI and from TRI to CELS, complementing the aggregate hierarchy of transmission.

From a policy perspective, several specific recommendations emerge. First, Bank Negara Malaysia and the Securities Commission of Malaysia should integrate transition-risk indicators, such as TRI and CELS volatility, into macroprudential climate stress tests, building on existing supervisory expectations for climate-risk management. Second, Bursa Malaysia should accelerate the harmonization of F4GBM constituent disclosure with IFRS S1/S2 and the ASEAN Taxonomy for Sustainable Finance, particularly regarding Scope 1-3 emissions and transition-plan disclosure, to reduce information asymmetry that amplifies external shocks. Third, the green-bond and green-sukuk frameworks should be expanded with explicit transition-finance categories so that capital flowing into the F4GBM constituents is more clearly aligned with measurable decarbonization outcomes. Fourth, a coordinated regional transition-risk monitoring dashboard, jointly maintained with the central banks, would allow early detection of cross-border sustainability shocks transmitted through CELS and TRI. For investors, the evidence supports integrating transition-risk indicators into diversification and hedging strategies, particularly for portfolios with material exposure to Malaysian ESG assets, and motivates using dynamic rather than static risk-budget allocations. Overall, the findings support the view that sustainable finance can simultaneously catalyze green innovation and transmit systemic risk; the policy challenge lies in ensuring that deeper integration is matched by stronger climate-risk governance and ESG disclosure infrastructure.

LIMITATION

This study has several limitations that suggest avenues for future research. First, the empirical analysis is restricted to three indices, CELS, TRI, and F4GBM, which capture global clean energy, transition risk, and Malaysia's ESG market, respectively, but do not include other sustainability-linked instruments such as green sukuk, carbon-credit prices, or sector-specific ESG sub-indices. Second, the analysis is country-specific to Malaysia and therefore cannot be directly generalized to other ASEAN economies with different regulatory structures and disclosure regimes. Future studies may extend this framework to ASEAN-level ESG indices to compare regional diffusion patterns, integrate green sukuk and carbon markets, and apply quantile, wavelet, or time-varying parameter VAR methods to capture asymmetric and tail-dependent spillovers

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DECLARATION OF CONFLICTING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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ABOUT THE AUTHOR(S)

1st Author
Rinda Siaga Pangestuti is a faculty member at the Faculty of Business, President University, Jababeka Education Park, Cikarang, Bekasi, Indonesia.
Email: rinda.pangestuti@president.ac.id
ORCID ID: https://orcid.org/0009-0004-5989-2688

2nd Author
Roszy Non is a faculty member at the Faculty of Business and Accountancy, Selangor University, Shah Alam, Malaysia.
Email: roszynon@unisel.edu.my
ORCID ID: https://orcid.org/0009-0001-6768-6882

3rd Author
Erwin Susanto Sadirsan is a faculty member at the Faculty of Economics and Business, Pertamina University, South Jakarta, Indonesia.
Email: erwin.susanto@universitaspertamina.ac.id
ORCID ID: https://orcid.org/0000-0002-0459-0883