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When ESG Meets Risk and Resilience: Quantile on Quantile Connectedness Across the G7, Volatility Index, and Gold Mining Sector

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Abstract: This study examines the connectedness between the G7 countries' ESG Leader indices, the CBOE Volatility Index (VIX) – an indicator of market stress – and the NYSE Arca Gold Miners Index (GDM), representing the gold-mining sector, using the Quantile-on-Quantile Connectedness approach. The analysis employs daily return data covering the period from January 2, 2019, to May 12, 2025. The findings reveal significant differences in the connectedness of G7 ESG Leader indices with VIX and GDM, varying according to market conditions and quantile levels. Results demonstrate that, under normal market conditions, ESG indices exhibit stronger connectedness with VIX. However, during periods of heightened market volatility, connectedness with GDM intensifies. Additionally, the notably high connectedness at reverse quantile levels emphasises the importance of monitoring the gold sector under varying market scenarios when assessing ESG investment performance. Furthermore, global economic and political events during the studied period – such as the COVID-19 pandemic, the Ukraine-Russia conflict, the SVB collapse, the Israel-Palestine conflict, and Trump's tariff implementations – significantly impact these connectedness measures, with the nature of the impact varying according to event type. Consequently, for ESG investors, adopting a dynamic, quantile-based monitoring strategy sensitive to market conditions is crucial. The study suggests that tracking VIX during normal market conditions and focusing on GDM during crisis periods would be more effective for portfolio diversification and risk management. The study is an original work; inclusion of GDM offers a more nuanced insight into the equity performance of gold mining companies, which frequently exhibit varying behaviours, particularly in times of financial distress. Furthermore, the integration of VIX as an indicator

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for market uncertainty enable the paper to effectively reflect the transmission of financial shocks emanating from the U.S. market.

Keywords: ESG Leader Indices; VIX; GDM; Quantile on Quantile Connectedness.

JEL classification: C32; G11; G15; Q02; Q56.

1. INTRODUCTION

Recently, various catastrophic events, including the COVID-19 pandemic, the Russia-Ukraine War, the Israel-Palestine Conflict, and the U.S.-China trade war, have led to significant uncertainties and unpredictability within the global financial markets (Sheikh *et al.*, 2024). The influence of these uncertainties and unpredictability on the financial market has become more pronounced due to growing financial and economic integration. Existing literature indicates that due to increasing financial integration, the effects of uncertainties and unpredictability can be readily observed across a wide range of financial assets, including traditional stock markets, commodities markets, and digital assets, among others (Vo and Ellis, 2018). In the quest to mitigate the adverse implications of raising volatility and uncertainties among the financial assets, as well as to explore alternative safe haven assets, numerous studies have been conducted to evaluate the level of financial interconnectedness within the traditional and evolving financial instruments. For instance, Mensi *et al.* (2021) investigated the volatility and stock market connectedness among 16 international equity markets; Bahloul and Khemakhem (2021) explored the return and volatility connectedness between commodities and the Islamic stock market; Khalfaoui *et al.* (2022) examined the connectedness and spillover effects between digital assets, green assets and the traditional equity market; Wang *et al.* (2023) explore the interconnection and risk transmission between the foreign exchange market and global stock indexes, etc. In addition to the aforementioned studies, numerous other scholars have also explored market interconnectedness and spillover effects among a range of financial assets (please see (Khalfaoui *et al.*, 2023; Hanif *et al.*, 2024; Ben Salem and El Aoun, 2025)). Most of the aforementioned studies concluded that strong market interconnectedness and spillover effects exist between several financial assets. Some studies projected that developed countries' stock markets are the net transmitter of risk, whereas some studies indicate that developing countries' stock markets are the net transmitter of risk (Mensi *et al.*, 2021). Additionally, a few studies also conclude that under specific economic conditions some commodities are immune to traditional equity market volatility and serve as potential safe haven assets (de Boyrie and Pavlova, 2024). However, some existing literature challenges this viewpoint by discounting the safe-haven potential of specific commodities in relation to traditional equity market volatility. These inconclusive outcomes and the potential to choose alternative asset classes motivated investors to explore alternative options that could boost portfolio diversification and provide a hedge against risk transmission stemming from market interconnectedness amid fluctuating economic conditions.

The quest for alternative financial assets has recently drawn investors' attention toward sustainable investment options. Among the widely available sustainable investment alternatives, Environmental, Social, and Governance (ESG) investing has surfaced as a crucial component in global financial markets, garnering increasing interest among investors, policymakers, and scholars alike. Existing literature indicates that investor interest toward environmental sustainability compelled stakeholders in financial markets to inculcate ESG

dimensions in their decision-making (Alharbi *et al.*, 2025). The integration of ESG factors into investment strategies has experienced notable expansion, especially following the post-pandemic period. Moreover, the inclusion of ESG in one of the 17 United Nations' sustainable development goals (SDGs) has significantly contributed to the substantial growth of ESG investments. This is evidenced by the current valuation of the ESG investing market at USD 27,480 billion in 2023, with projections indicating it will reach USD 130,880 billion by 2032, exhibiting a compound annual growth rate of 17.31% from 2024 to 2032. The recent expansions in the ESG investing market can also be correlated with the growth in ESG-focused indices across developed and emerging economies. Existing literature claims that investment decisions that include ESG dimensions are characterised by higher returns, lower risk during market uncertainty, foster reputation management, and have a healthy environmental and social impact (Alharbi *et al.*, 2025). Globally, ESG indices have witnessed a significant increase in sustainable investment flows. However, existing literature indicates that these indices may perform similarly to conventional investments and might be susceptible to financial shocks and economic uncertainties (Alda, 2021). The recent growing global uncertainties stemming from events like the Russia-Ukraine War, the Israel-Palestine conflict, the U.S.-China trade war and the India-Pakistan border conflict and the concern about the effect of risk transmission due to financial integration both within and from other financial markets on ESG investments warrant an investigation on the market interconnectedness of ESG investments with key financial indicators in response to the evolving global landscape.

Recently, due to the raising trend toward ESG investments, numerous scholars have examined the interconnectedness of ESG investments with prominent conventional markets (de Boyrie and Pavlova, 2024; Naeem *et al.*, 2024; Sharma and Rani, 2025). Most of the aforementioned studies explained that ESG investment alternatives are sensitive to broader market sentiment and risk factors. However, studies exploring the dynamic connectedness of ESG indices against exclusive market volatility indices and commodity-linked assets are still in a developing state. The present study offers a novel perspective to the existing body of literature by integrating both the GDM and the VIX into the analysis of financial contagion and market linkages. While existing studies have predominantly focused on broad market indices or commodity prices such as spot gold, the inclusion of GDM offers a more detailed insight into the equity performance of gold mining companies, which frequently exhibit distinct behaviours compared to physical gold, particularly in diverse market conditions. Moreover, the integration of VIX as an indicator for market uncertainty allows the paper to effectively capture the transmission of financial shocks that stem from the U.S. market. By examining the role of VIX, this study is able to assess how investor fear and volatility in American markets potentially spill over to other asset classes and international financial systems, thereby enhancing the understanding of global risk transmission mechanisms. The incorporation of both GDM and VIX adds originality and unique dimensions, setting it apart from existing literature that often overlooks these critical elements. Additionally, most of the studies on the interconnectedness of ESG investments and conventional financial assets focus on specific market conditions (Alda, 2021). Nonetheless, with the exception of a limited number of studies, there is no existing literature that has explored the dynamic interconnectedness of ESG indices across varying market conditions. Motivated by these research gaps, this study investigates the connectedness of G7 ESG Leader indices with market stress indicators – namely, the VIX and the GDM – using the Quantile-on-Quantile Connectedness (QQC) approach.

The study contributes to the existing literature in several ways. First, unlike the existing literature, which focuses on specific ESG indices, the present study contributes by exploring the dynamic interconnectedness of G7 ESG leader indices. G7 ESG leader indices are included because the G7 countries, i.e., the U.K., the USA, Canada, France, Germany, and Italy, represent the world's largest and most advanced economies. These economies account for more than 40 percent of the global GDP and contribute around 25 percent of global greenhouse gas emissions. Their considerable economic footprints highlight their essential role in the development of a global ESG standard. Moreover, existing literature also indicates the G7 nations are the major investors in renewable and sustainable infrastructure (Erdogan *et al.*, 2023). Notably, the United States, France, Germany, the United Kingdom, and Japan rank among the top contributors to global renewable energy investment. Their contribution toward clean and sustainable infrastructure not only adds to their own goals of carbon neutrality but also serves as a model for other nations to follow. Furthermore, investigating G7 nations is crucial because the ESG market structure, investor sentiments, and market conditions differ significantly among these economies. As such, the empirical estimation of the dynamic interconnectedness in context with the G7 economies will contribute by capturing asymmetries and heterogeneous responses to hedging effectiveness and provide valuable insights for globally diversified ESG portfolios. Second, the study contributes not only by exploring the dynamic connectedness within G7 ESG leader indices but also by examining how these indices connect with VIX and GDM indices across varying market conditions. Investigating the dynamic connectedness between G7 ESG and VIX indices will offer critical insight to comprehend how sustainable investments react to global uncertainty, especially during financial distress. The VIX index, commonly referred to as the fear index, explains investor sentiments and market volatility. Investigating the time-varying nature of interconnectedness between ESG investments and VIX will contribute to unveil how ESG investments react asymmetrically to evolving volatility regimes, stable during normal periods but vulnerable under stress, which is critical for investors looking to manage risk and for policymakers attempting to construct robust sustainable finance systems. Additionally, including GDM in our empirical analysis further contributes to the existing literature, which mostly concentrates on gold as a safe haven asset. The gold mining sector exhibits sensitivity to commodity fluctuations and follows a cyclical pattern. Unlike physical gold, its performance is closely linked to operational factors, geopolitical influences, and ESG considerations, particularly given the significant environmental externalities associated with mining activities. These characteristics make GDM a relevant proxy for examining the interaction between ESG-related equity markets and commodity-linked equity exposure under different market conditions. Moreover, existing literature indicates that GDM acts as a substitute for safe havens and commodity exposure, frequently moving in a countercyclical manner relative to equities. Therefore, exploring the dynamic connectedness with G7 ESG and GDM will contribute to understand shock transmission within sustainability-focused and commodity-orientated markets, which will assist in risk management and portfolio diversification. Finally, it methodologically contributes by applying the QQC approach to assess connectedness across different market quantiles, unlike conventional VAR or TVP-VAR models, thus offering regime-specific insights into ESG market connectedness. Specifically, we applied the concept of reverse total connectedness in the context of stress conditions and direct total connectedness during normal market conditions, along with their

differential, to measure regime-sensitive spillover effects, which will assist to offer a novel insight on market connectedness under varying market conditions and quantiles.

The paper is further summarised as follows. Section 2 provides the detailed overview of existing literature. Section 3 discusses the methodology employed. Section 4 presents in detail the result and analysis, and finally, the last section encompasses the concluding remarks.

2. LITERATURE REVIEW

Due to growing financial integration, numerous studies have been conducted to model volatility, dynamic interconnectedness, spillover effects, and co-movements among traditional assets and commodity markets. However, recently, the excessive volatility of conventional assets and the rising environmental concerns have also attracted investors' interest toward ESG investment alternatives. The following sections provide a detailed overview of existing literature, focussing on dynamic interconnectedness and spillover involving traditional assets, commodities, and alternative investments, such as ESG investments.

Emphasising the significance of dynamic market interconnectedness, Syllignakis and Kouretas (2011) conducted one of the pioneering studies by investigating the dynamic conditional correlation between weekly returns of seven emerging stock markets of Central and Eastern Europe and concluded that during the financial crisis, Central European markets are closely connected with the U.S. and the German markets. However, post-crisis, there was a regime shift in the connectedness among these markets, i.e., the usual pattern of movement between markets was varied during the crisis compared to the normal period. In a similar context, Ahmad *et al.* (2013) investigated the market interdependency among the financial markets of BRICS and GIPSI countries during the Eurozone crisis period. The empirical outcome of the multivariate DCC–GARCH model indicates that the financial markets of BRICS countries are strongly influenced by the GIPSI countries during the Eurozone crisis period. Alongside the aforementioned pioneering studies on financial market interconnectedness, numerous other scholars also attempted to explore the interconnectedness among the financial markets through several dimensions and methodologies. However, the literature on financial market interconnectedness rose significantly due to the significant contribution from new models like the Diebold and Yilmaz (2014) model, which was best suited to measure how shocks spillover among different markets, indicating their direction and magnitude of interconnectedness. Using the aforementioned model, Zhang (2017) revisited the market connectedness between oil and stock market returns from the global perspective. The author concluded that the interconnectedness between the oil and stock markets is limited. However, large shocks in the oil prices have a significant influence on the global stock market's returns. Rehman *et al.* (2018), by extending the Diebold and Yilmaz (2014) framework, investigated the time-varying connectedness between oil prices and precious metals returns and concluded that during the financial crisis there was a notable increase in the time-varying effect of oil shocks on the precious metals except for gold. The author also highlighted the hedging potential of palladium against oil price shocks. Connectedness applications have also extended to energy markets. Arifoğlu *et al.* (2023), using a connectedness approach for Türkiye electricity markets, show that the relationship between intraday electricity prices, day-ahead prices, and electricity generation sources changes over time and is affected by global events. Existing literature indicates that the studies employing the Diebold and Yilmaz (2014) model, although providing intriguing outcomes, fail to capture nonlinearities or asymmetric responses under different

market conditions. Recently, this limitation has prompted the exploration of quantile-based methods, which facilitate the representation of dependence between two variables throughout their entire conditional distribution and address extreme tail behaviours that are often neglected in linear or average-based analyses.

In this context, several studies have recently applied the QQR approach to ascertain the dynamic market connectedness between a wide array of financial assets. For instance, Dong *et al.* (2022) investigated the time-varying connectedness and asymmetric effect of the Covid-19 pandemic on global stock sectors. The empirical estimate indicated that during COVID-19, there was a sharp increase in the time-varying connectedness of the global stock sector. However, this effect was not uniform across all sectors, and the daily volatility in stock returns exhibited variations corresponding to the daily fluctuations in Covid-19 cases and fatalities. In a similar vein, Shang and Hamori (2024) examined the quantile time frequency connectedness between crude oil, gold, financial markets, and macroeconomic indicators within the United States and the European Union. The empirical outcome reveals that oil is the primary source of shocks within both regions, whereas gold sends only long-term shocks. The study also indicates that the U.S. market volatility varies as per the bullish and bearish trends, whereas the EU markets exhibit greater balance and stability. Similarly, Chen *et al.* (2024) examined the dynamic connectedness between commodity and financial markets and also explored how various forms of uncertainties like EPU, VIX and GPR interact with this connectedness. The findings indicate that a strong time-varying connectedness exists between commodities and the conventional financial markets. Additionally, the selected uncertainties, i.e., EPU, VIX, and GPR, alter this connectivity depending on market conditions and investment horizons. In addition to the aforementioned studies, several other authors also attempted to examine the dynamic connectedness between various forms of financial assets across diverse market conditions (Afşar *et al.*, 2025; Singh *et al.*, 2025). Recent quantile-based network methods have extended connectedness analysis toward directionality, simultaneity, and network heterogeneity. Quantile Granger causality is useful for examining predictive links across distributional tails (Karpman *et al.*, 2022), whereas DNQR and TGNQ-type models are more suitable for predetermined or high-dimensional network structures (Liu *et al.*, 2024; Xu *et al.*, 2024). The approaches mentioned are complementary to the current study; however, our objective extends beyond simply estimating a high-dimensional ESG network or testing formal quantile causality. Instead, this research focuses on the pairwise cross-quantile connectedness between each G7 ESG Leader index and VIX/GDM. Therefore, QQC is better suited to distinguish between direct and reverse quantile spillovers in this study.

Conclusively, the aforementioned literature review indicates that from time to time numerous studies have investigated the nature and dynamics of financial market connectedness under varying market conditions using a diverse range of methodologies and financial assets. Nevertheless, the review of existing literature indicates that most of the aforementioned studies are centred around conventional stock markets, mostly oil prices, digital assets, and a few selected precious metals. Most of the above studies concluded strong market interconnectedness and spillover among the conventional stock indices. Additionally, the studies reported that market connectedness among the conventional stock indices is volatile and subject to variations in market conditions, such as bullish and bearish trends. A few studies also suggested strong market interconnectedness and risk transmission from the conventional stock indices to commodities markets and vice versa. A strand of literature exhibits strong risk transmission from the commodities to the conventional stock market

returns, whereas few studies reported contradictory outcomes. Recently, in pursuit of improved investment alternatives that can offer enhanced hedging and risk diversification compared to conventional assets across fluctuating market conditions and in light of increasing environmental concerns, researchers have also started to explore the potential of ESG investments relative to traditional assets. For instance, Ferrer *et al.* (2018) investigated the time-varying interconnectedness between ESG stocks and oil prices and suggested that oil price is not the significant driver for ESG stocks. On the contrary, Saeed *et al.* (2021) indicated that energy stocks are the net transmitters of shocks to the oil markets. Cagli *et al.* (2023) examined the dynamic connectedness between ESG investing and commodity markets and concluded the ESG investment alternatives are the net transmitters of shocks, whereas all the selected commodities except crude oil are the net shock receivers. Also, Celik *et al.* (2025) examine asymmetric interconnectedness among green, sustainable, and environmental markets and show that connectedness varies according to the direction of shocks, with negative shocks during turbulent periods increasing dynamic connectedness among these markets. Additionally, scholars also attempted to explore the performance of ESG investments against conventional stock indices; for instance, Wang *et al.* (2023) employed a TVP-VAR model to examine the return and volatility transmission between ESG leader indices and G7 traditional equity markets. In a related sustainable-finance setting, Demir (2024) examines the dynamic connectedness between investor sentiment indicators and U.S. conventional and green bond markets using a Q-VAR framework and reports that VIX and MOVE act as volatility transmitters, while the bond market indices are positioned as volatility receivers. The empirical estimates indicate a significant level of connectedness between ESG and traditional equity markets, and ESG leader indices are the net transmitters of return and volatility spillover to the conventional equity markets. However, there are few authors who have contradicted the above outcome (de Boyrie and Pavlova, 2024; Alharbi *et al.*, 2025).

The aforementioned literature review indicates that the literature on ESG investment alternatives is in a developing phase, and most of the existing literature focuses on exploring the dynamic connectedness of ESG investments in context to conventional stock indices and selected commodities. As per the author's knowledge, there is no specific study that has examined the dynamic connectedness of ESG investments against systemic risk indicators such as the VIX. Additionally, although a limited number of studies have examined the interconnectedness of ESG investments with commodities, including gold, there is no specific study that has examined the interconnectedness and risk spillover of ESG investments with real, financial, and commodity-linked assets, such as GDM under extreme market conditions. The inclusion of GDM adds a novel dimension to the existing literature, as it exhibits the performance of gold mining equities, which are influenced not only by fluctuations in gold prices but also by macroeconomic and geopolitical risks, thus providing a sector-specific perspective on investor sentiment during times of stress. Additionally, the inclusion of VIX as a measure of U.S. financial stress and uncertainty permits us to analyse how disturbances in the American market influence ESG-related assets on a global scale. The incorporation of both the aforementioned measures facilitates a more detailed exploration of tail-risk dependencies and asymmetric spillover effects across varying market conditions, an area that continues to be inadequately addressed in the existing research. Moreover, the literature also indicates that most of the existing literature on ESG investments focuses on specific ESG-related stocks or country-specific ESG indices; there is a dearth of literature on ESG investments, which evaluate a comprehensive and a well-diversified and developed ESG market. Therefore, against this

backdrop, the present study attempts to investigate the dynamic connectedness of G7 ESG leader indices with VIX and GDM indices under varying market conditions. The study adds to the existing literature on ESG investment by bridging two different but similar risk alternatives, that is, volatility shocks and safe-haven dynamics. Furthermore, unlike most of the existing literature on ESG investments, which employs linear and mean-based techniques, the present study also adds to it by employing non-linear and distribution-sensitive methods to capture the behaviour of the aforementioned assets under varying market conditions. The applications of QVAR and the reverse and direct total connectedness approach will assist to comprehend how connectedness varies across different distributions and market conditions, which will have direct implications on asset allocation, hedging and policy formulation within the realm of sustainable finance and risk management. The subsequent section provides a detailed explanation of the data description and methodology employed.

3. METHODOLOGY AND DATA

3.1. Quantile on Quantile Connectedness

This study investigates the relationship between the ESG Leader indices of the G7 countries, the VIX – a market uncertainty and stress indicator – and the GDM – an indicator for the gold mining sector. The methodology applied in this research is the Quantile-on-Quantile Connectedness approach developed by Gabauer and Stenfors (2024), an extended version of the Quantile Connectedness method proposed initially by Chatziantoniou *et al.* (2021), which allows connectedness to vary simultaneously across different quantiles. This method enables a dynamic analysis of G7 ESG Leader indices, VIX, and GDM relationships across varying market conditions and quantile levels. Thus, interactions can be comprehensively captured not only in normal market states but also during periods characterized by high volatility – such as when ESG indices, VIX, and GDM are increasing or decreasing simultaneously or moving inversely to each other (e.g., ESG indices rising/falling while VIX and GDM are falling/rising).

$$Q_t = \mu(\tau) + \sum_{l=1}^{p} B_l(\tau) x_{t-j} + u_t(\tau) \tag{1}$$

The vector and its lagged form are defined as endogenous variable vectors of dimension. The symbol represents quantile levels within the interval [0,1], whereas p indicates the selected lag order for the QVAR model. Additionally, is the conditional mean vector of dimension , and is a coefficient matrix of dimension associated with the QVAR framework. Furthermore, refers to the error vector with dimension , possessing an accompanying variance-covariance matrix, , also of dimension .

To facilitate the calculation of the generalized forecast error variance decomposition (GFEVD), as introduced by Koop *et al.* (1996), we convert the QVAR model into a QVMA representation by employing the Wold decomposition theorem. This yields the following transformation:

$$Q_t = \mu(\tau) + \sum_{l=1}^{p} B_j(\tau) Q_{t-l} + u_t(\tau) = \mu(\tau) + \sum_{k=0}^{\infty} A_i(\tau) u_{t-k}(\tau) \quad (2)$$

The H-step ahead GFEVD subsequently captures the influence of shocks originating from variable on variable . This relationship is formally expressed using an indicator vector, defined as an vector of zeros except for a single unit at the “”th position:

$$\phi^{g}_{k\leftarrow l,\tau}(H) = \frac{\sum_{h=0}^{H-1} \left(\boldsymbol{e}_i' \boldsymbol{A}_f(\boldsymbol{\tau}) \boldsymbol{F}(\boldsymbol{\tau}) \boldsymbol{e}_j\right)^2}{\boldsymbol{F}_{kk}(\boldsymbol{\tau}) \sum_{h=0}^{H-1} \left(\boldsymbol{e}_i' \boldsymbol{A}_f(\boldsymbol{\tau}) \boldsymbol{F}(\boldsymbol{\tau}) \boldsymbol{A}_f(\boldsymbol{\tau})' \boldsymbol{e}_k\right)} \; g\mathrm{SOT}_{k\leftarrow l,\tau}(H) = \frac{\phi^{g}_{i\leftarrow l,\tau}(H)}{\sum_{l=1}^{n} \phi^{g}_{k\leftarrow l,\tau}(H)} \quad (3)$$

Since the rows of the GFEVD, denoted , do not sum to one, Diebold and Yilmaz (2014) propose normalization by dividing each element by its respective row sum. The resulting normalized measure is termed the scaled GFEVD, symbolized as .

This scaled GFEVD constitutes the core of the connectedness analysis. It is employed in calculating directional connectedness measures, specifically the total directional connectedness TO (FROM) other variables. The TO measure indicates the aggregate impact exerted by series on all other series in the system, whereas the FROM measure captures the cumulative effect of all series on series . Formally, these measures can be defined accordingly.

$$C^{\text{gen,to}}_{k\rightarrow,\tau} = \sum_{n=1,k\neq l}^{N} gSOT_{n\leftarrow k,\tau} \quad (4)$$

$$C^{\text{gen,from}}_{k\leftarrow,\tau} = \sum_{n=1,k\neq l}^{N} gSOT_{k\leftarrow n,\tau} \quad (5)$$

The difference between total directional connectedness TO and FROM yields the NET directional connectedness for series.

$$C^{\text{gen,net}}_{k,\tau} = C^{\text{gen,to}}_{k\rightarrow,\tau} - C^{\text{gen,from}}_{k\leftarrow,\tau} \quad (6)$$

A positive net directional connectedness, implies that series k acts predominantly as a transmitter of shocks to other variables, while a negative net directional connectedness, indicates that series k is predominantly a recipient of shocks from others.

Ultimately, an adjusted total connectedness index (TCI), ranged within [0,1], is computed. This index provides a succinct measure of the extent of interconnectedness within the network. A higher TCI indicates greater market risk, reflecting elevated systemic interconnectedness (Gabauer and Stenfors, 2024):

$$TCI_{\tau}(H) = \frac{N}{N-1}\sum_{n=1}^{N} C_{n\leftarrow,\tau}^{\text{gen,from}} \equiv \frac{N}{N-1}\sum_{n=1}^{N} C_{n\leftarrow,\tau}^{\text{gen,to}} \quad (7)$$

In the empirical implementation, separate country-specific bivariate QQC-QVAR systems are estimated. For each G7 country c, two systems are considered: (ESG_c, VIX) and (ESG_c, GDM), and the reported TCI values should be interpreted as pairwise connectedness measures. The lag length is selected automatically according to the Bayesian Information Criterion, and the baseline specification uses a 200-day rolling window and a 20-step-ahead forecast horizon.

3.2. Data

In this study, we use daily return data covering the period from January 2, 2019, to May 12, 2025, for the G7 countries' ESG Leader indices (USA, CAN, UK, FRA, GER, ITA, JAP), the VIX, and the GDM. VIX is also expressed as a return series to focus on changes in implied-volatility conditions and to maintain consistency with the return-based ESG and GDM series. The G7 ESG Leader indices data are obtained from msci.com, while VIX and GDM data are sourced from investing.com. Table no. 1 presents the descriptive statistics for the dataset.

Table no. 1 – Descriptive Statistics

	USA	CAN	UK	FRA	GER	ITA	JAP	VIX	GDM
Mean.	0.0006	0.0004	0.0003	0.0003	0.0004	0.0005	0.0003	0.0031	0.0007
Med.	0.0005	0.0005	0.0005	0.0007	0.0007	0.0010	0.0002	-0.0071	0.0003
Max.	0.0992	0.1226	0.0932	0.0898	0.1018	0.0833	0.0895	0.7404	0.1452
Min.	-0.1212	-0.1302	-0.1241	-0.1389	-0.1325	-0.1825	-0.0955	-0.3575	-0.1057
Std. Dev.	0.0131	0.0127	0.0121	0.0135	0.0138	0.0147	0.0126	0.0839	0.0199
Skew.	-0.2851	-0.8498	-0.6820	-0.6175	-0.3481	-1.4475	-0.0111	2.1390	0.1634
Kur.	16.3744	25.6566	15.7490	13.9696	13.4977	21.1149	11.2584	15.1900	7.1384
JB	12148.33*	34994.82*	11144.74*	8260.92*	7503.553*	22814.05*	4623.504*	11314.28*	1168.274*
LB Q^2 (5)	1149.57*	978.531*	278.409*	214.838*	166.007*	144.924*	417.698*	62.5841*	518.292*
LB Q^2 (10)	1840.94*	1501.31*	717.532*	443.187*	410.765*	190.492*	459.326*	69.2038*	722.357*
LB Q^2 (20)	2157.37*	1697.66*	800.689*	514.328*	478.923*	209.922*	464.09*	74.4247*	941.016*
ADF	-12.4303*	-13.9185*	-14.8294*	-40.0081*	-14.6981*	-26.5253*	-44.3234*	-42.8816*	-34.892*
Correlations	**USA**	**CAN**	**UK**	**FRA**	**GER**	**ITA**	**JAP**		
VIX	-0.7143	-0.5522	-0.3247	-0.3655	-0.3694	-0.3823	-0.0770		
GDM	0.2788	0.4058	0.3000	0.2818	0.2993	0.2718	0.2035		

All series display positive average returns. The series with the highest standard deviation is VIX, followed by GDM. JB (Jarque-Bera) test statistics indicate non-normality for all series, while ADF (Augmented Dickey-Fuller) tests confirm stationarity across all variables. LB (Ljung-Box) test results on squared residuals also reveal autocorrelation, implying heteroskedasticity within the return series. Furthermore, Pearson correlation coefficients illustrate a negative correlation between the G7 ESG Leader indices and VIX, whereas correlations with GDM are positive. Given that the observation period of this study encompasses significant global economic, health-related, and political events such as COVID-19 (March 2020), the Ukraine-Russia conflict (February 2022), the Silicon Valley Bank (SVB) collapse (March 2023), the Israel-Palestine conflict (October 2023), and Trump's tariff implementations (April 2025), interactions among these series are expected to be influenced by these events and may exhibit temporal variability. Consequently, employing a dynamic modelling approach becomes crucial.

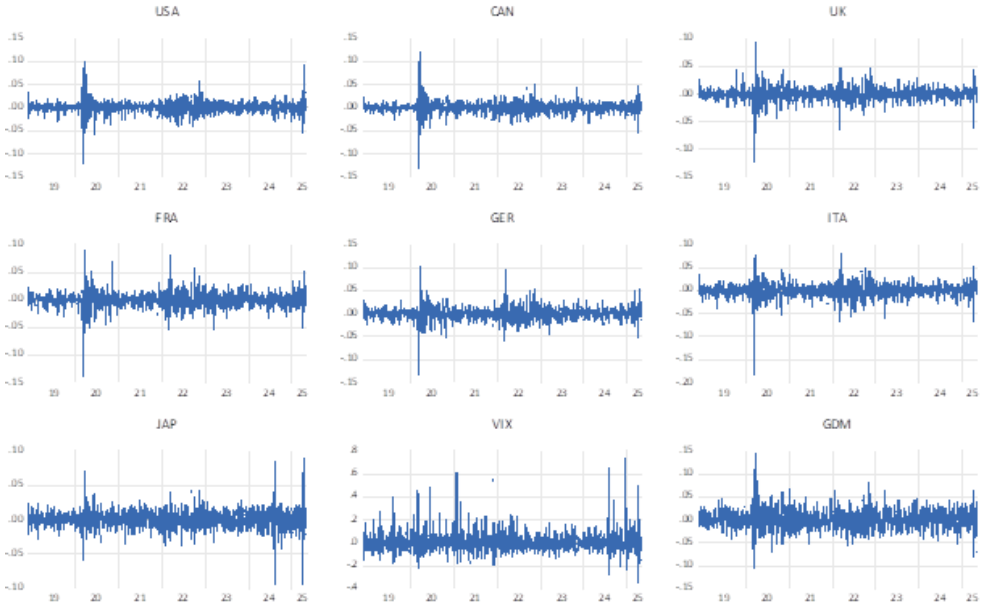

Figure no. 1 – Time Series Graphs of Return Series

Figure no. 1 displays the time-series plots of the analyzed series, highlighting their variability and volatility over time. Notably, periods of increased volatility in the series align closely with the aforementioned global events. The onset of COVID-19 (March 2020) and Trump's tariff implementations (April 2025) demonstrate notably pronounced common impacts across all series. Furthermore, the initiation of the Ukraine-Russia conflict (February 2022) has significantly affected the UK, FRA, GER, and ITA series, while the 7.6-magnitude earthquake in Japan in August 2024 distinctly impacted the JAP and VIX series.

4. EMPIRICAL RESULTS

This part of the study presents empirical findings related to Quantile-on-Quantile Connectedness measures. We illustrate static and dynamic pairwise connectedness between the G7 ESG Leader indices, GDM, and VIX across various market conditions and cross-quantiles to achieve this. Table no. 2 provides the average total connectedness between the G7 ESG Leader indices and GDM and VIX at different quantile levels.

The total connectedness results show that overall pairwise connectedness between G7 ESG Leader indices, GDM, and VIX is generally higher in extreme same-quantile states (0.05-0.05 or 0.95-0.95) and reverse-tail states (0.05-0.95 or 0.95-0.05) compared to normal market conditions (0.5-0.5). The intermediate quantiles (0.25 and 0.75) further indicate that connectedness is not uniformly distributed across the quantile grid, with stronger spillover patterns remaining concentrated in tail and reverse-tail combinations. However, total connectedness varies according to both VIX and GDM, as well as by individual ESG Leader indices.

Table no. 2 – Averaged pairwise dynamic quantile-on-quantile total connectedness

		0.05		0.25		0.5		0.75		0.95	
		VIX	GDM	VIX	GDM	VIX	GDM	VIX	GDM	VIX	GDM
0.95	USA	47.69	77.14	38.86	54.04	62.62	47.32	42.33	55.45	56.54	76.02
	CAN	51.65	82.68	34.49	64.38	54.9	58.06	38.44	65.49	57.3	81.7
	UK	57.19	78.23	34.48	55.34	44.84	47.77	35.2	56.88	61.26	77.43
	FRA	53.38	76.99	32.88	54.81	45.68	46.71	35.2	55.93	59.07	76.78
	GER	55.37	77.72	34.28	54.99	47.33	47.39	36.22	56.5	59.16	76.73
	ITA	54.94	75.83	34.5	53.62	48.03	45.13	37.4	54.6	60.7	75.02
	JAP	68.24	75.8	44.89	50.78	42.06	42.17	45.12	52.13	74.22	74.66
0.75	USA	35.27	57.05	26.44	33.95	50.2	27.23	29.9	35.36	44.12	55.93
	CAN	32.55	66.31	15.4	48.01	35.81	41.69	19.36	49.13	38.2	65.32
	UK	31.61	57.72	8.9	34.83	19.27	27.26	9.62	36.37	35.68	56.92
	FRA	30.45	55.57	9.96	33.39	22.76	25.29	12.28	34.51	36.15	55.36
	GER	31.3	57.43	10.2	34.7	23.25	27.09	12.14	36.21	35.08	56.43
	ITA	29.5	24.78	9.06	33.27	22.59	24.78	8.19	32.55	35.26	54.68
	JAP	47.65	53.85	24.53	30.18	21.47	20.23	24.53	30.19	53.63	52.72
0.5	USA	56.42	48.34	47.59	25.24	71.35	18.52	51.06	26.65	65.27	47.22
	CAN	49.45	58.57	32.29	40.27	52.7	33.95	36.24	41.38	55.09	57.59
	UK	40.38	50.07	17.67	27.18	28.04	19.62	18.39	28.72	44.45	49.27
	FRA	40.14	47.01	19.65	25	32.44	16.73	21.97	25.95	45.84	46.8
	GER	41.8	48.95	20.7	26.22	33.75	18.61	22.64	27.73	45.58	47.95
	ITA	40.38	46.29	19.95	24.08	33.48	15.59	22.85	25.06	46.15	45.49
	JAP	45.91	44.62	22.56	19.6	19.73	10.99	22.79	20.95	51.9	43.48
0.25	USA	32.69	55.36	23.86	32.26	47.62	25.54	27.33	33.67	41.54	54.24
	CAN	30.76	65	13.61	46.7	34.02	40.38	17.56	47.81	36.41	64.01
	UK	34.99	57.32	12.28	34.42	22.05	26.86	13	35.97	39.06	56.52
	FRA	30.79	54.8	10.3	32.62	23.1	24.52	12.62	33.74	36.49	54.59
	GER	33.31	55.88	12.22	33.15	25.26	25.54	27.11	33.15	37.09	54.88
	ITA	28.62	54.75	8.19	32.55	21.71	24.05	11.08	33.52	34.38	53.95
	JAP	49.82	52.68	26.47	27.66	23.64	19.06	26.7	29.01	55.8	51.55
0.05	USA	42.02	78.22	33.19	55.12	56.95	48.4	36.66	54.82	50.87	77.1
	CAN	46.18	83.41	28.93	65.11	49.44	58.79	32.98	66.22	51.83	82.42
	UK	52.67	79.07	29.97	56.19	40.33	48.62	30.69	57.73	56.74	78.27
	FRA	49.15	76.88	28.66	54.69	41.45	46.59	30.98	55.81	54.85	76.66
	GER	49.1	77.98	28.01	55.25	41.06	47.64	29.95	56.76	52.89	76.98
	ITA	47.32	76.54	26.89	54.34	40.41	45.85	29.79	55.32	53.08	75.74
	JAP	64.2	76.97	40.85	51.95	38.02	43.34	41.08	53.3	70.19	75.83

Note: The results are based on separate country-specific bivariate QQC-QVAR systems. For each country, two pairwise systems are estimated: (ESG_c, VIX) and (ESG_c, GDM). The row quantile refers to the ESG Leader index, while the column quantile refers to VIX or GDM. The baseline specification uses a 200-day rolling window, an automatically selected lag length based on BIC, and a 20-step-ahead forecast horizon. The quantile grid is (0.05,0.25,0.50,0.75,0.95). The magnitude of the TCI values increases progressively from light blue to dark blue. All TCI values are reported in percentage terms.

Connectedness values with GDM are generally higher compared to those with VIX, particularly in tail and reverse-tail quantile states. However, the median same-quantile state (0.5-0.5) displays a different pattern: VIX-related connectedness is higher than GDM-related connectedness across the G7 ESG Leader indices, with particularly high values for the USA and Canada. Thus, while G7 ESG Leader indices exhibit stronger connectedness with VIX under normal market conditions, connectedness with GDM is higher in extreme and reverse-tail market conditions. This suggests that, under stress-related and reverse-tail scenarios, G7 ESG Leader indices have closer relationships with the gold mining sector, whereas VIX remains more informative under normal market conditions. This finding implies that ESG

investors in G7 countries should adjust their performance-tracking strategies based on market conditions. Specifically, while monitoring market stress indicators might be more effective under normal conditions, focusing on GDM during extreme rises or falls in the gold sector may offer better insights for ESG market tracking. Furthermore, the weaker connectedness with GDM under normal conditions indicates that gold-mining equities may offer diversification potential for ESG-inclusive portfolios in calmer market states. However, these benefits may diminish during periods of significant market volatility.

Connectedness between the G7 ESG Leader indices and GDM is especially pronounced at extreme same-quantile states (0.05,0.05 and 0.95,0.95) and reverse-tail states (0.05,0.95 and 0.95,0.05), while intermediate quantile combinations generally display more moderate spillovers. Hence, monitoring GDM during extreme market conditions and periods when ESG indices and GDM move in opposite directions could serve as an effective ESG Leader index performance evaluation risk-assessment strategy. Conversely, lower connectedness with VIX during extreme or cross-market conditions implies that, under regular market circumstances, VIX might provide a more effective benchmark for ESG Leader index tracking. Nevertheless, excluding the USA and CAN ESG Leader indices, connectedness with VIX in non-normal market conditions and opposite quantile levels tends to be higher compared to normal market conditions. Thus, although focusing on GDM may generally be more beneficial during changing market conditions, tracking VIX can also offer valuable contributions in monitoring the movements of G7 ESG Leader indices.

It is crucial to demonstrate connectedness dynamically to understand the impact of global economic events on connectedness and examine how these connectedness measures evolve. For this purpose, we dynamically illustrate the total connectedness between the G7 ESG Leader indices and VIX and GDM under normal market conditions, the total connectedness in reverse quantiles, and the differences between these two measures. Examining connectedness at opposite quantile levels is particularly significant, as total connectedness at opposite quantiles becomes higher during periods when series are negatively correlated. Hence, investigating reverse quantile connectedness reveals the influence of market risks on connectedness measures (Gabauer and Stenfors, 2024; Lin *et al.*, 2024). Figure no. 2 shows the time-varying graphs of direct connectedness, reverse TCI and the differences between these two measures for the G7 ESG Leader indices and VIX.

The direct, reverse, and reverse-direct TCI measures between the G7 ESG Leader indices and VIX display notable variation over time. Generally, for ESG Leader indices other than the USA, the total connectedness at the reverse quantile level is higher. The reverse-direct TCI is predominantly negative for the USA and CAN indices but positive for the remaining G7 ESG Leader indices. Thus, for ESG Leader indices excluding USA and CAN, higher reverse connectedness than direct connectedness implies stronger linkages when ESG Leader indices are in the lower-tail state while VIX is in the upper-tail state. Conversely, focusing on direct TCI appears more effective for USA and CAN. Despite Pearson correlation results in Table no. 1 indicating the highest negative correlation with VIX for the USA and CAN series, the observation of higher reverse connectedness values in other ESG indices emphasizes the importance of evaluating different quantile levels – and especially reverse quantiles – when analyzing connectedness to capture maximum interactions between variables.

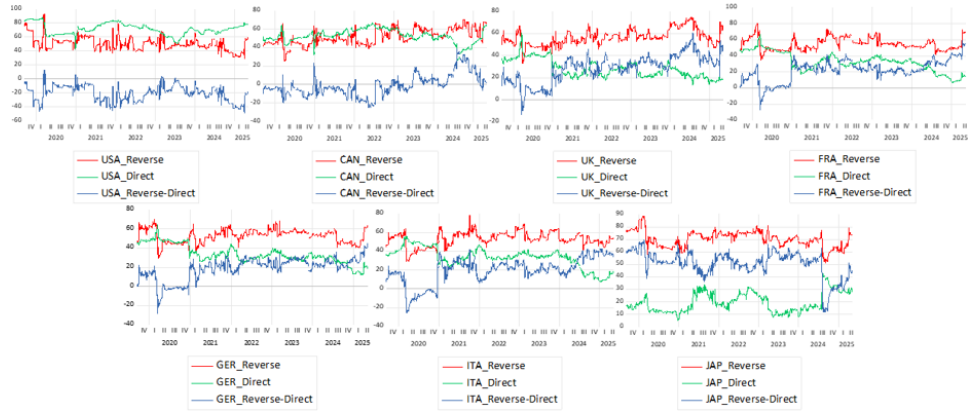

Figure no. 2 – Dynamic Reversely-Related and Directly-Related Quantiles Total Connectedness between G7 ESG Leaders Indices and VIX

Note: The Reverse TCI captures periods when the G7 ESG Leaders indices are in decline (at the 0.05 quantile level) and the VIX is exhibiting an upward trend (at the 0.95 quantile level). The Direct TCI reflects conditions where both the G7 ESG Leaders indices and the VIX are under normal market conditions (at the 0.5 quantile level), while the Reverse-Direct TCI represents the differential between the two.

Extreme fluctuations in direct, reverse, and reverse-direct TCI values generally coincide with global economic events. Specifically, direct and reverse TCI between VIX and nearly all G7 ESG Leader indices reach their peak during the onset of COVID-19 (March 2020). Additionally, early 2021, marked by high volatility in VIX (as observed in Figure no. 1), coincides with increased fluctuations in TCI due to announcements and concerns over COVID-19's delta and other variants. The rise in direct TCI for USA, CAN, UK, FRA, GER, and ITA, along with declines for JAP, aligns closely with the initiation period of the Ukraine-Russia conflict. Other events, such as the SVB collapse in March 2023, the earthquake in Japan in August 2024, and Trump's tariff adjustments in April 2025, also visibly impact total connectedness. Consequently, these globally significant events substantially influence TCI measures, highlighting that ESG investors would benefit from incorporating direct and reverse connectedness into their strategic positioning decisions during these periods. Figure no. 3 illustrates the dynamic evolution of direct connectedness, reverse TCI and the differences between the G7 ESG Leader indices and GDM.

The direct TCI, reverse TCI, and their differences between the G7 ESG Leader indices and GDM vary over time; however, reverse TCI values are consistently higher throughout the entire period than direct TCI values. This finding indicates that total connectedness is stronger when ESG Leader indices decline and GDM trends upward, suggesting reverse connectedness should be monitored together with direct connectedness when assessing ESG–GDM linkages, especially under stress-related market conditions. Additionally, while the Pearson correlation findings in Table no. 1 indicate positive correlations between GDM and the ESG Leader indices, the reverse connectedness values remain higher. This result aligns with previous findings and highlights the importance of considering multiple quantile levels, especially reverse quantiles, for more effective market forecasting.

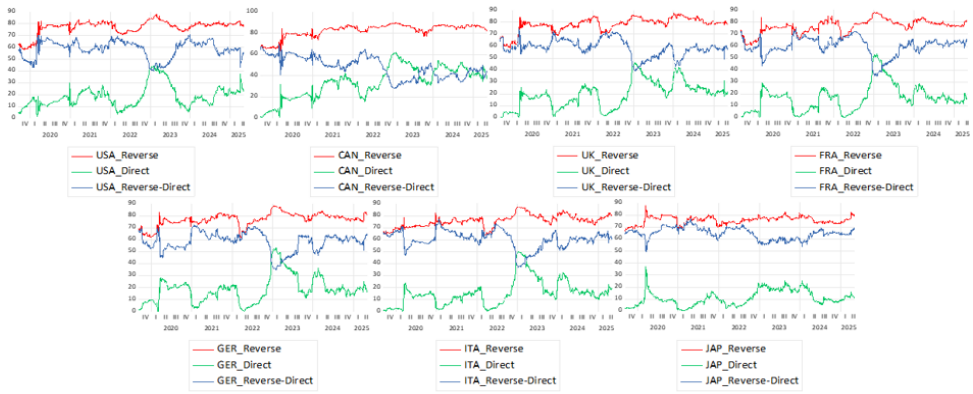

Figure no. 3 – Dynamic Reversely-Related and Directly-Related Quantiles Total Connectedness between G7 ESG Leaders Indices and GDM

Note: The Reverse TCI captures periods when the G7 ESG Leaders indices are in decline (at the 0.05 quantile level) and the GDM is exhibiting an upward trend (at the 0.95 quantile level). The Direct TCI reflects conditions where both the G7 ESG Leaders indices and the GDM are under normal market conditions (at the 0.5 quantile level), while the Reverse-Direct TCI represents the differential between the two.

Changes (increases and decreases) in direct TCI and reverse TCI and the differences between G7 ESG Leader indices and GDM over time are consistent and coincide closely with global economic events. However, the impact of global economic events on total connectedness differs depending on the nature of the event. For example, at the onset of COVID-19 and during the Silicon Valley Bank (SVB) collapse, significant increases in direct (more prominently) and reverse TCI are observed. In contrast, a clear decrease occurs during the initial phase of the Ukraine-Russia conflict. This finding illustrates that while global economic events significantly influence TCI measures, the direction and magnitude of this impact differ according to the type of event. While increased asset interconnectedness is generally expected during periods of rising risk, one of the primary uncertainties triggered by the Ukraine-Russia conflict was related to energy supply. Concerns about meeting fossil fuel energy demands heightened awareness of renewable energy sources and underscored the importance of ESG investments. Thus, energy supply risks at the onset of the Ukraine-Russia conflict had distinct implications for energy prices and the ESG sector beyond general economic uncertainty, potentially explaining the reduced connectedness observed between ESG and GDM during this period.

The findings demonstrate that VIX and GDM provide different information across market regimes. VIX appears more informative under normal market conditions, while GDM-related connectedness becomes more pronounced in tail and reverse-tail states. This suggests that ESG-related risk monitoring should be regime-sensitive rather than based on a single indicator. In particular, VIX may be useful for tracking central-market volatility conditions, whereas GDM may provide additional information during stress-related or cross-quantile states.

Additionally, reverse and direct TCI values are more positively pronounced for GDM compared to VIX. Although correlations between ESG Leader indices and VIX are negative, they are positive with GDM. This indicates that while correlations reflect the strength of co-movements among assets, connectedness measures may not always align with correlation results. Therefore, examining connectedness across different quantiles, particularly reverse connectedness, offers greater potential effectiveness for market monitoring. This finding aligns with those of Gabauer and Stenfors (2024); Lin *et al.* (2024).

5. CONCLUSION AND POLICY RECOMMENDATIONS

Recently, due to the raising trend toward ESG investments, numerous scholars have examined the interconnectedness of ESG investments with prominent conventional markets. However, studies exploring the dynamic connectedness of ESG indices against exclusive market volatility indices and commodity-linked assets are still in a developing state. In view of the aforementioned literature void, the study examines the G7 ESG Leader indices in connection with two significant systemic indicators, the VIX and GDM, employing a comprehensive quantile-on-quantile connectedness analysis. The inclusion of GDM provides a nuanced understanding of the equity performance of gold mining companies, which demonstrate unique behaviours in contrast to physical gold, particularly across varying market conditions. Moreover, the integration of VIX as an indicator for market uncertainty enables the study to accurately reflect the propagation of financial shocks originating from the U.S. market. The inclusion of VIX assists to assess how investor fear and volatility in American markets potentially spill over to other asset classes and international financial systems, thereby enhancing the understanding of global risk transmission mechanisms. The results demonstrate that connectivity patterns are markedly affected by the state, showing substantial differences across quantile levels and economic regimes. The VIX exhibits a stronger connectedness with ESG indices during periods of market stability, particularly within the North American context, encompassing both the USA and Canada. Conversely, the GDM exhibits a stronger connectedness with ESG indices during periods of significant market downturns, particularly when ESG indices demonstrate movements that are contrary to market risk indicators. The data indicates that connectivity increases during global crises such as the COVID-19 pandemic and the SVB collapse. This phenomenon can be attributed to an increase in systemic risk coupled with a reduction in the advantages typically associated with diversification. Conversely, specific geopolitical occurrences such as the Ukraine-Russia conflict yield distinct repercussions, illustrating the intricate ways in which energy dynamics and ESG consciousness influence asset interdependence. Furthermore, it is observed that reverse quantile connectedness consistently surpasses direct connection, particularly in the context of GDM. This indicates that gold and associated sectors are increasingly significant for ESG portfolio hedging in periods of market volatility. These findings enhance our comprehension of asset movement in ways that traditional correlation or linear VAR frameworks fail to reveal. The findings underscore the significance of utilising quantile-based and time-varying connectivity models to accurately depict interconnections within financial markets, particularly in relation to investments centred on ESG considerations.

In light of the aforementioned conclusion, the study proposes the following policy recommendations. In context with ESG portfolio managers, it is recommended that investment plans incorporate quantile-on-quantile connectivity to assess tail risk and portfolio sensitivity across varying market conditions. Given the persistent correlation between GDM and ESG indices during extreme market conditions, GDM may serve as a useful monitoring indicator for ESG-related risk during stress-related market states. Managers may monitor GDM more closely under tail and reverse-tail states, while VIX remains informative under normal market conditions. From the perspective of the regulators, it is recommended that regulators must advocate for enhanced risk disclosures that account for the interplay between tail risk and systemic indicators such as VIX and GDM. Moreover, supervisory frameworks should integrate scenario-based stress testing that includes quantile-based connectivity. This technique holds

particular significance for identifying vulnerabilities during systemic events. The ramifications of the Ukraine-Russia conflict demonstrate the urgent need to align energy security policies with emerging trends in ESG investments. Such alignment will contribute to maintaining investor confidence and stability within ESG markets. Although the present study shares a comprehensive and intriguing insight into the quantile connectedness between G7 ESG Leader indices in connection with two significant systemic indicators, the VIX and GDM, the study has certain limitations, which serve as a potential avenue for future research. Since the present study focuses on connectedness measurement rather than formal portfolio optimization, the portfolio implications should be interpreted as risk-monitoring implications. Future research may extend the analysis by incorporating hedge ratios, hedging effectiveness, or minimum-connectedness portfolio strategies. Another limitation is that daily data may not fully eliminate non-synchronous trading effects across markets, particularly for Japan relative to US-based VIX; future research may address this issue using market-close-adjusted or intraday data. Additionally, examining the interactions between various sectors or regions may provide valuable insights into the behaviour of ESG assets across diverse economic conditions.

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AI Use Declaration

AI-assisted tools, including GPT and Grammarly, were used solely for language editing and grammatical correction. These tools were not used for data analysis, interpretation of results, or the generation of the study's scientific content.

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