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APPLIED ECONOMICS OF ENERGY AND ENVIRONMENT IN SUSTAINABILITY

Information transmission in regional energy stock markets

Suha M. Alawi[1] · Sitara Karim[2] · Abdelrhman Ahmed Meero[3] · Mustafa Raza Rabbani[4] · Muhammad Abubakr Naeem[5,6]

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Abstract

Since markets are undergoing severe turbulent economic periods, this study investigates the information transmission of energy stock markets of five regions including North America, South America, Europe, Asia, and Pacific where we differentiated the regional energy markets based on their developing and developed state of economy. We employed time–frequency domain from Jan 1995 to May 2021 and found that energy stocks of developed regions are highly connected. The energy markets of North America, South America, and Europe are the net transmitters of spillovers, whereas the Asian and Pacific energy markets are the net receivers of spillovers. The results also reveal that the connectedness of regional energy markets is time and frequency dependent. Regional energy stocks were highly connected following the Asian financial crisis (AFC), global financial crisis (GFC), European debt crisis (EDC), shale oil revolution (SOR), and COVID-19 pandemic. Time-dependent results reveal that high spillovers formed during stress periods and frequency domain show the higher connectedness of regional energy stock markets in the short run followed by an extreme economic condition. These results have significant implications for policymakers, regulators, investors, and regional controlling bodies to adopt effective strategies during short run to avoid economic downturns and information distortions.

Keywords Information transmission · GFC · COVID-19 · Regional energy markets · Time–frequency

Introduction

Measuring and monitoring the information transmission and interdependence between the major financial markets is a major concern among the academic research researchers, policymakers, government institutions, investors, and business practitioners (Shen et al. 2018). It is critical to understand the information transmission mechanism in the regional energy stock market as it helps the investors, hedge funds, and insurance companies in making investment and hedging decisions (Hasan et al. 2021; Naeem et al. 2021a, b; Dagar et al. 2021). Given the globalized nature of the world economy and rapid development of the commodity market, understanding the information transmission mechanism in the energy market is not only extremely important to improve the portfolio selection and allocation strategies but

Responsible Editor: Philippe Garrigues

✉ Muhammad Abubakr Naeem
m.ab.naeem@gmail.com

Suha M. Alawi
salawi@kau.edu.sa

Sitara Karim
sitarakarim.malik@gmail.com

Abdelrhman Ahmed Meero
ar.meero@ku.edu.bh

Mustafa Raza Rabbani
mrabbani@uob.edu.bh

1 Department of Finance, King Abdulaziz University, Jeddah, Saudi Arabia

2 Department of Business Administration, Faculty of Management Sciences, ILMA University, Karachi, Pakistan

3 College of Business Administration, Kingdom University, Riffa, Bahrain

4 Department of Economics and Finance, College of Business Administration, University of Bahrain, Sakhir, Bahrain

5 Accounting and Finance Department, United Arab Emirates University, P.O. Box 15551, Al-Ain, United Arab Emirates

6 South Ural State University, Lenin Prospect 76, Chelyabinsk 454080, Russian Federation

also extremely helpful in devising best policy response for maintaining financial stability (Karim et al. 2020a, b) and avoiding any possible financial contagion. Against such a backdrop, we examine the information transmission between the regional energy stock markets by using the time–frequency domain provided by Diebold and Yilmaz (2012) and Baruník and Křehlík (2018).

The energy markets across the globe are interconnected as the shocks in the oil market substantially increase the risk in the natural gas and other energy markets (Shen et al. 2018). The regional, geographical, and political differences make it worthwhile to study the regional connectedness of the energy market (Hasan et al. 2021). Many studies have investigated the volatility spillover between the energy, stock, bond, cryptocurrency, crude oil, and commodity market including the interdependence structure between these markets (Akram et al. 2020; Ferrer et al. 2018; Naeem et al. 2020; Tiwari et al. 2020). For example, it is believed that the energy transmission across the adjacent countries is faster than the non-adjacent countries and it is expected that the energy connectedness in the regional electricity markets is higher in the closer vicinities. Similar findings are obtained by Bunn and Gianfreda (2010), de Menezes and Houllier (2015), and Xiao et al. (2019) by examining the risk transmission in the regional energy market of Europe. Xiao et al. (2019) concludes that European energy market experienced relatively high connectedness and it is easy for the regulators to identify the market with high risk of system instability. The findings obtained by de Menezes and Houllier (2015) suggest that the German market is less integrated with the adjacent markets. In contrast, the geographical and political relations are rather complex in Asian market and difficult to link the cross-border energy connectedness. For measuring the connectedness in the Asian market, it cannot be grasped by considering member countries in isolation (Cui et al., 2021; Singh et al. 2019). On the other hand, the Australian electricity markets share their geographical locations and are highly connected within a particular region due to physical interconnectors (Apergis et al. 2020; Han et al. 2020; Simshauser and Tiernan 2019). The present study aims to examine the dynamic information transmission between the regional energy stock markets. In particular, we make an attempt to address the following issues. Can the information in the European energy market help to predict the risk in the Asian energy market or any other regional energy market? Does the information interdependence structure changes over time? Is the heterogeneity present in one market representative of the other regional markets?

Since markets are undergoing severe challenges posed by information transmission, the current study is motivated to examine the risk connectedness of energy stock markets of five regions including North America, South America, Europe, Asia, and Pacific. For analysis purpose, we first construct the test statistic using the time–frequency domain to examine the information transmission among the regional energy markets. More specifically, we used the Diebold and Yilmaz (2012) and Baruník and Krehlik (2018) approach to show the time-varying connectedness between the regional energy markets. Time–frequency domain in the energy market is important because it helps the investors in devising the investment strategies, trading tools, and approaches (Caporin et al. 2021; Kang et al. 2019; Naeem et al. 2020; Murshed et al. 2021a, b; Rehman et al. 2021). The adopted method proposed by Diebold and Yilmaz (2012) in combination with the Baruník and Křehlík (2018) offers several advantages over the traditional methods. While Diebold and Yilmaz (2012) approach focuses only on the time domain, the approach developed by Baruník and Křehlík (2018) offers the information on degree and direction of spillover in the frequency domain. This approach helps to disintegrate the overall connectedness into smaller frequencies to make it possible and know the contribution of the small frequencies in the overall connectedness of a system. It also directly models the quantile and links it to the market risk, avoiding the indirect risk measure using time-varying mean and variance (Hasan et al. 2021; Tiwari et al. 2020; Zakari et al. 2021, 2022; Khan et al. 2021; Islam et al. 2021). Finally, the time–frequency connectedness uses very little distributional assumption on the underlying data generation process.

Buidling on these arguments, the current study contributes to the existing literature in many ways. First, the study takes energy stock markets of five regions, namely, North America, South America, Europe, Asia, and Pacific. To the best of our knowledge, this is the first study which uses the data of energy companies and their stocks belonging to five regions. Second, we utilized the time-and-frequency connectedness analysis to observe whether markets are transmitting/receiving spillovers over the period of time. Third, DY[12] and BK[18] approaches are appealing in examining the interconnectedness of energy markets as the former segregates the net risk transmission/reception while the latter segregates the short- and long-run spillovers. Fourth, we found that energy markets of developed regions are highly connected among each other and transmit spillovers whereas developing regions are receiving spillovers. Hence, we compared the economic orientation of these regions and provided unique insights. Fifth, our sub-sample analysis provided robust results with full sample period indicating higher connectedness during the periods of financial distress. Finally, we framed various implications for policymakers, regulation bodies, investors, and portfolio managers.

The findings of the study reveal that North American (NAMR) and South American (SAMR) energy stock markets are the net transmitters of information spillovers. Europe (EURO) transmitted moderate spillovers whereas

Asia (ASIA) and Pacific (PACF) are the net recipients of information spillovers. Moreover, the connectedness of energy markets was high during stress periods where global economic fragility, uncertainty, and world-wide closure of business operations resulted in the formation of higher spillovers. The frequency dependent analysis showed that regional energy markets showed significant spikes in the short run whereas connectedness becomes lower in the long run. Followed by the uncertainties in the global working conditions and economic distress, the energy markets of five regions showed varying patterns of connectedness. Additionally, the sub-sample analysis also confirmed that NAMR is the net transmitter of information spillovers followed by SAMR and EURO. And, ASIA and PACF are the net recipients of the information spillovers.

The remaining study proceeds as follows. In the next section, we provide the review of relevant literature related to the regional connectedness of energy markets. In "Methodology," we provide the methodology used for the study and "Empirical results" presents the empirical analysis and findings of the study. Finally, in "Conclusion," we conclude with several policy and regulatory implications.

Literature review

The relationship and interconnectedness among the regional energy markets have been investigated and analyzed from different perspectives. Hasan et al. (2021) examined the time–frequency connectedness between the Asian electricity markets by using the Baruník and Křehlík (2018) and Diebold and Yilmaz (2012). Macroeconomic factors of the energy market such as geographical location, supply, and demand play an important role in information transmission and the connectedness of the regional energy markets (Singh et al. 2019; Muhammad and Khan 2021; Karim and Naeem 2021). Despite the economic and political differences between the countries in Asian region, a great potential for the connectedness of energy sector in the Asian region exists (Oseni and Pollitt 2016). Several efforts have been made to connect the energy sector in the Asia region in the last couple of decades and some advancements have also been made in this regard (Bhattacharyay 2010). Under the CAREC program strategy, the TAPI gas pipeline project was approved to help and improve the regional energy trade between the TAPI countries (Turkmenistan, Afghanistan, Pakistan, and India). The expansion of central Asian power system is intended to enhance the regional energy trade and connectedness of new energy markets such as Afghanistan and Turkmenistan with the central Asian markets (Zobaa and Lee 2006). These connectivity initiatives highlight towards the fact that, although the regional trade practices among the Asian nations have been low, the right steps are being undertaken to strengthen the regional energy connectedness among the Asian nations (Hasan et al. 2021).

Many scholars have focussed on the network connectedness of the energy market in Europe (Geng et al. 2021; Xiao et al. 2019). The energy market has become increasingly integrated in Europe due to the market coupling and interconnection capacity and further integration plan is expected in the early 2020s (Lockwood et al. 2017). The UK's exit strategy from European Union will have a long-term impact on the energy market integration and information transmission in the European region (Lockwood et al. 2017; Lowe 2017; Karim et al. 2021a, b). Lin and Li (2015) applied VAC-MGARCH approach to study the spillover effects across natural gas and concluded that oil and natural gas markets are co-integrated across the European market within the first and second moments. The information transmission is expected to have multiple possible impact on the energy integration including the availability and cost of finance, energy market and security of supply, nuclear power, and supply chain of all energy markets across Europe and energy efficiency policy (Egan 2019; Mayer et al. 2019).

The rest of the studies are summarized in Appendix 1 (Table 3).

Methodology

Connectedness of the regional energy markets in the time–frequency domain

Following the methodology proposed by Diebold and Yilmaz (2012, 2014), this study employed the time-based connectedness using the static VAR model of p order, as indicated in Eq. (1)

$$y_t = \Phi(L)y_t + \varepsilon_t = \psi\Phi_1 y_{t-1} + \Phi_2 y_{t-2} + \cdots + \Phi_p y_{t-p} + \varepsilon_t \quad (1)$$

The vector $y_t = (R_{1t}, \ldots, R_{nt})$ is an $n \times 1$ vector that contains the net connectedness or partial connectedness of Australian electricity markets and $\Phi(L)$ shows lagged variable. ε_t shows random error term where the mean value is zero and the matrix variance is$\sum$; we also observed no problem of serial correlation with ε_t. As indicated above, the VAR model offers static estimations in the time domain, Eq. (1) can be re-written given the infinite order of moving average process, for instance, VMA(∞), say$y_t = \psi(L)\varepsilon_t + \psi_0\varepsilon_t + \psi_1\varepsilon_{t-1} + \cdots + \psi_h\varepsilon_{t-h} + \ldots$ Here,ψ_h denotes moving average coefficient analogous to the h-th lag time. When h-th lag time is zero, the ψ_0 is adjusted to I which is the identity matrix.

Time-dependent connectedness

Following Pesaran and Shin (1998) for estimating time-based connectedness, a generalized forecast error variance decomposition (FEVD) to the static VMA(∞) was developed as indicated in Eq. (1). By employing the H-step ahead analysis, the contribution of realized daily returns of the j-th to the estimated error variance of the realized returns of the i-th variable is as follows:

$$\theta_{ij} = \frac{\sum_{h=0}^{H-1}\left(e_i'\Psi_h\sum e_j\right)^2}{e_j'\sum e_j \times \sum_{h=0}^{H-1} e_i'\left(\Psi_h \sum \Psi_h'\right)e_i} = \frac{1}{\sigma_{jj}} \times \frac{\sum_{h=0}^{H-1}\left(\left(\Psi_h\sum\right)_{ij}\right)^2}{\sum_{h=0}^{H-1}\left(\Psi_h\sum\Psi_h\right)_{ii}} \quad (2)$$

where the ij-th item of Σ is denoted as σ_{ij}, and the diagonal item of j-th is represented as σ_{jj}; and e_j denotes zeros conditioned that the j-th item is one. For the analysis carried out for estimating the connectedness of regional energy markets, a forecast horizon (H) of 100 days was chosen and we equally standardized the contribution across all variables in terms of ($j = 1, 2, \ldots, n$), in this way, following the Diebold and Yilmaz (2012, 2014) approach, the connectedness of regional energy markets can be computed.

Frequency-dependent connectedness

Following the Eq. (1) VMA p-order model, we initiated the estimation process to obtain frequency-dependent connectedness. After getting the VMA (∞) illustration, for instance,$\mathbf{y}_t = \boldsymbol{\psi}(L)\varepsilon_t$, the Fourier transform on the lagged coefficient element, was applied and $\boldsymbol{\psi}\left(e^{-i\omega}\right) = \sum_{h=0}^{\infty} e^{-i\omega h}\boldsymbol{\psi}_h$ was obtained where ω denotes particular frequency. Afterward, we took power spectrum of y_t as $S_y(\omega) = \sum_{h=-\infty}^{\infty} E\left[y_t y_{t-h}\right]e^{-i\omega h} = \psi\left(e^{-i\omega}\right)\sum\psi\left(e^{i\omega}\right)$. The j-th variable contribution (i.e., the connectedness of the j-th element) to the forecast error variance of the i-th variable (i.e., the connectedness of the i-th element) is as follows:

$$\vartheta_{ij}(\omega) = \frac{1}{\sigma_{jj}} \times \frac{\left|\left(\psi\left(e^{-i\omega}\right)\sum\right)_{ij}\right|^2}{\left(\psi\left(e^{-i\omega}\right)\sum\psi'\left(e^{i\omega}\right)\right)_{ii}} = \frac{1}{\sigma_{jj}} \times \frac{\sum_h^{\infty}\left(\psi\left(e^{-i\omega h}\right)\sum\right)_{ij}^2}{\sum_h^{\infty}\left(\psi\left(e^{-i\omega h}\right)\sum\psi'\left(e^{i\omega h}\right)\right)_{ii}} \quad (3)$$

Time-dependent connectedness vs. frequency-dependent connectedness

Table 1 provides the definitions of several time-dependent connectedness measures based on Diebold and Yilmaz (2012, 2014). Moreover, the table also provides definitions of frequency-dependent connectedness given by Baruník and Křehlík (2018). It can be observed that the variation in the two measures (time and frequency) only comes from the variable j related to i, i.e., the forecast error variance variable.

Following the studies of Balli et al. (2019), Naeem et al. (2020), Caporin et al. (2021), and Shahzad et al. (2021), our study also used both time and frequency domains. The use of time–frequency domains simultaneously offers two benefits. First, the directional spillovers are obtained, exhibited by a network diagram. Second, the short- and long-run components can be segregated following the frequency domain.

Empirical results

Data and preliminary analysis

This study endeavors to investigate the information transmission among five regional energy markets by employing the methodology of Diebold and Yilmaz (2012) and Barunik and Krehlik (2018) for the period encompassing January 2, 1995, to May 27, 2021. For analysis purpose, we have taken the data

Table 1 Connectedness measurements between variables in a VAR(p) system

Connectedness type	Time-dependent	Frequency-dependent
Connectedness (j to i)	$\tilde{\theta}_{ij} = \frac{\theta_{ij}}{\sum_{j=1}^{n}\theta_{ij}}$	$\tilde{\vartheta}_{ij}(\omega) = \frac{\vartheta_{ij}(\omega)}{\sum_{j=1}^{n}\vartheta_{ij}(\omega)}$
Total spillover index of the variables under consideration	$C = \frac{1}{n}\sum_{i\neq j}^{n}\sum_{j=1}^{n}\tilde{\theta}_{ij}$	$C(\omega) = \frac{1}{n}\sum_{i\neq j}^{n}\sum_{j=1}^{n}\tilde{\vartheta}_{ij}(\omega)$
Net pairwise connectedness (j to i)	$C_{ij,net} = \tilde{\theta}_{ij} - \tilde{\theta}_{ji}$	$C_{ij,net}(\omega) = \tilde{\vartheta}_{ij}(\omega) - \tilde{\vartheta}_{ji}(\omega)$
From connectedness of i (from all other variables to i)	$C_{i\leftarrow\cdot} = \frac{1}{n}\sum_{j\neq i}^{n}\tilde{\theta}_{ij}$	$C_{i\leftarrow\cdot}(\omega) = \sum_{j\neq i}^{n}\tilde{\vartheta}_{ij}(\omega)$
To connectedness of i(from i to all other variables)	$C_{i\rightarrow\cdot} = \frac{1}{n}\sum_{j\neq i}^{n}\tilde{\theta}_{ji}$	$C_{i\rightarrow\cdot}(\omega) = \sum_{j\neq i}^{n}\tilde{\vartheta}_{ji}(\omega)$
Total connectedness of variable i (scaled by 100)	$C_{i,net} = \frac{1}{n}\sum_{j\neq i}^{n}\tilde{\theta}_{ji} - \frac{1}{n}\sum_{j\neq i}^{n}\tilde{\theta}_{ij}$	$C_{i,net}(\omega) = \sum_{j\neq i}^{n}\tilde{\vartheta}_{ji}(\omega) - \sum_{j\neq i}^{n}\tilde{\vartheta}_{ij}(\omega)$

All of the definitions are sourced from Diebold and Yilmaz (2012, 2014) and Baruník and Křehlík (2018)

Table 2 Descriptive statistics

Market	Symbol	Mean	Maximum	Minimum	Std. Dev	Jarque–Bera
Asian energy sector	ASIA	0.007	8.337	– 12.017	1.280	15,515.58***
European energy sector	EURO	0.016	13.704	– 15.493	1.497	36,036.96***
North American energy sector	NAMR	0.019	14.859	– 23.425	1.617	87,172.68***
Pacific energy sector	PACF	0.020	13.819	– 14.591	1.418	19,302.99***
South American energy sector	SAMR	0.022	16.203	– 28.473	2.145	36,495.95***

***indicates 1% level of significance

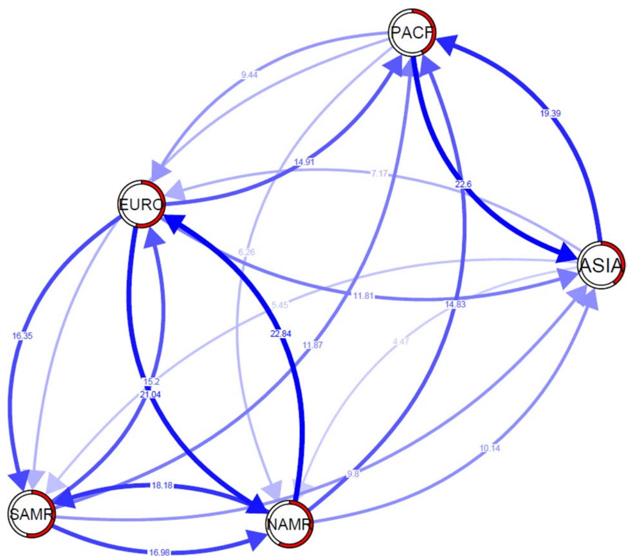


Fig. 1 Network connectedness using Diebold and Yilmaz (2012). This figure indicates the full sample connectedness among regional energy markets using Diebold and Yilmaz (2012) with 100 days ahead forecast error variance and lag 1 using SIC criteria

of regional energy sectors: Asian energy sector (ASIA), European energy sector (EURO), North American energy sector (NAMR), Pacific energy sector (PACF), and South American energy sector (SAMR). The data have been sourced from DataStream of the relevant energy sectors. Table 2 illustrates the descriptive statistics of markets under study where highest average values are reflected by SAMR, PACF, and NAMR followed by EURO. ASIA yield the least average returns for the complete sample period. The highest variability of average returns is indicated by SAMR followed by NAMR while EURO and PACF depicted comparable exposure to risk. Finally, ASIA exhibited lowest variability in the average returns among the rest of the regional energy sectors. The Jarque–Bera test of normality indicates that values are substantially higher and there is abnormality in the average returns.

Network connectedness of regional energy markets

This study attempts to investigate the information transmission of five regional energy markets, namely, North American region (NAMR), South American region (SAMR), European region (EURO), Asian region, (ASIA), and Pacific region (PACF). The information transmission has been estimated through time and frequency dependence structure provided by Diebold-Yilmaz (2012) and Barunik-Krehlik (2018) approaches respectively. Figure 1 presents the network connectedness of five regions based on Diebold-Yilmaz (2012) method, where two distinct clusters are formed. The first cluster reveals connectedness between NAMR, SAMR, and EURO regions where markets are highly connected with each other and transmit spillovers to other markets. We argue that NAMR, SAMR, and EURO are developed regions and due to strong economic and financial stability, these regions are transmitting spillovers to developing regions. Accordingly, PACF and ASIA form the other cluster and are highly connected with each other. The network diagram displays NAMR and SAMR which are the net transmitters of spillovers whereas ASIA and PACF are the net recipients of spillovers. The connectedness among the regional energy markets is evident for the regions which are adjacently located with each other. The geographical proximity of these markets makes the information transmission feasible and easily accessible resulting in the higher connectedness of the energy regions. The findings are in line with the arguments of Han et al. (2020), Manner et al. (2019), and Yan and Truck (2020) who also reported similar findings claiming higher connectedness of markets of closer vicinities. Meanwhile, we also segregate the regions of energy stock markets based on their developed and developing economic stature.

Figure 2 illustrates the connectedness of regional energy markets in the short and long run following Barunik-Krehlik (2018) approach. Figure 2a presents the spillovers of information transmission in the short run which reiterate the formation of two main clusters. The information spillovers are higher among NAMR, SAMR, and EURO in the short run. And, these regions show higher connectedness in the short run and are net transmitters of information spillovers. On the other hand, PACF and ASIA regions form second cluster of connectedness and are the net recipients of information spillovers. Meanwhile, the short-run analysis points to the crisis periods where majority of the regional markets are highly connected following the uncertain economic downfall

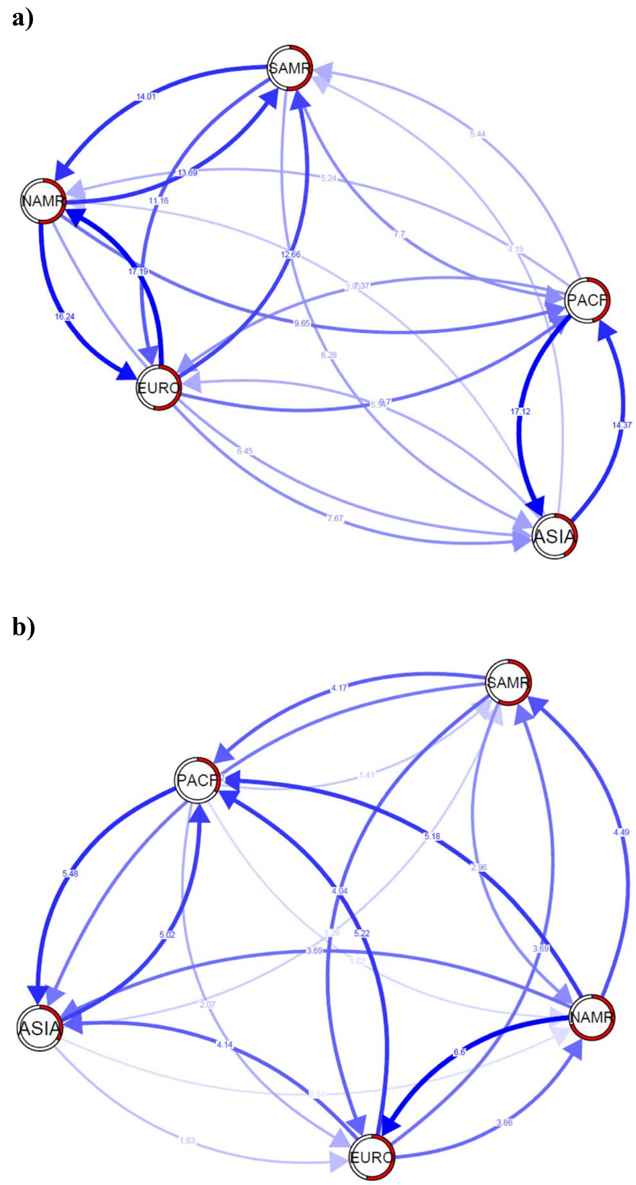


Fig. 2 Network connectedness using Barunik and Krehlik (2018). **a** Short run (1–5 days). **b** Long run (> 5 days). This figure indicates the full sample connectedness among regional energy markets using Barunik and Krehlik (2018) with 100 days ahead forecast error variance and lag 1 using SIC criteria

and disruptions in the information transmission. For this reason, our findings corroborate Balli et al. (2019) who argue that various commodities, like energy commodities, form high spillovers in the short run following a particular crisis.

Correspondingly, Fig. 2b presents the connectedness of regional energy markets in the long run which illustrates that NAMR and SAMR are transmitting spillovers to other energy regions. EURO region is transmitting moderate spillovers to PACF and ASIA regions. Meanwhile, PACF and ASIA are the net recipients of information spillovers in the long run. The nodes on the regional energy markets

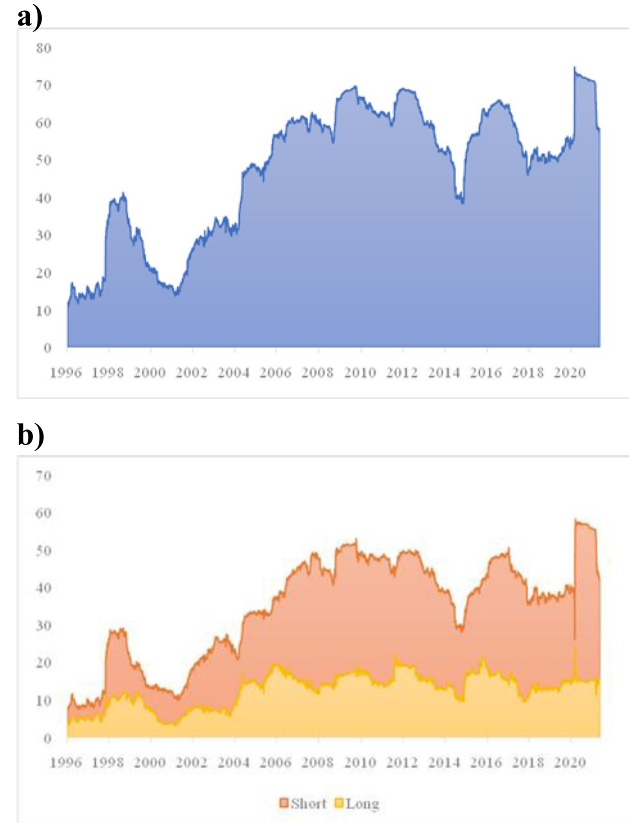


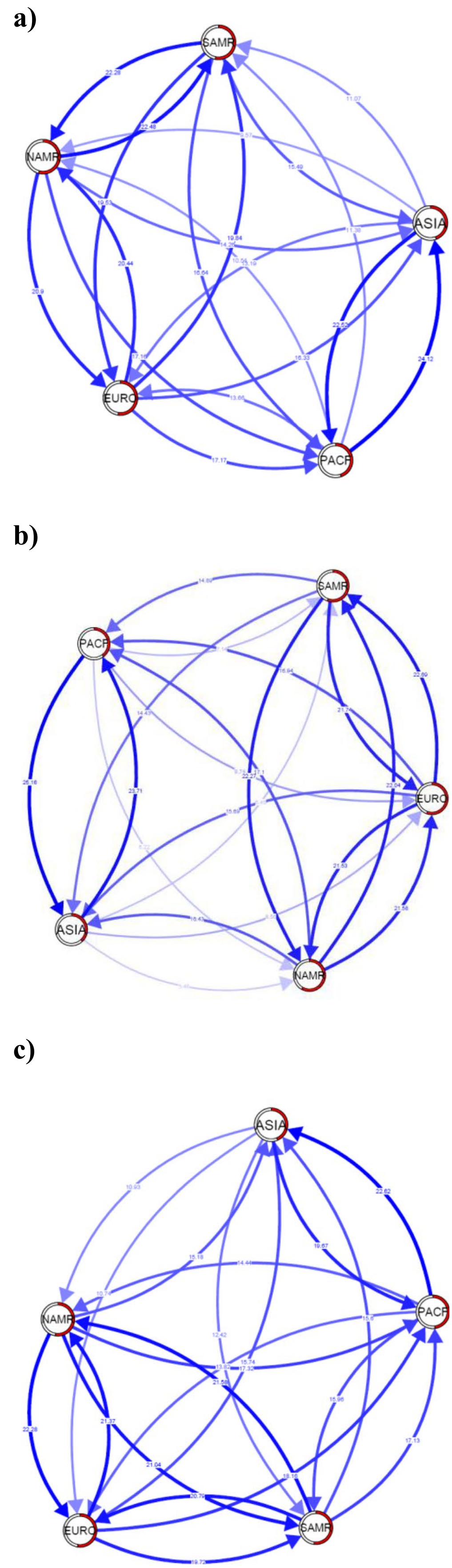
Fig. 3 Time-varying connectedness. **a** Diebold and Yilmaz (2012). **b** Barunik and Krehlik (2018). This figure indicates the time-varying connectedness using a rolling window (260 days) among regional energy markets. Panel **a** indicates Diebold and Yilmaz (2012) and Panel **b** indicates Barunik and Krehlik (2018) with 100 days ahead forecast error variance and lag 1 using SIC criteria

(highlighted with red) determine the net transmitting and net receiving capacity of spillovers. In this way, it is suggested that the regional energy markets which are sharing their geographies are highly connected to each other whereas the energy markets which are located at distant places tend to show disconnection with other energy regions. The other significant takeaway of the analysis reveals that the energy regions of developed economies are highly connected with each other and transmit information spillovers to the energy regions of developing economies. Thus, regional energy markets of developed economies are net transmitters of spillovers whereas energy markets of developing economies are net recipients of spillovers.

Time-varying connectedness of regional energy markets

Figure 3 presents the time-varying connectedness of regional energy markets based on Diebold-Yilmaz (2012) and Barunik-Krehlik (2018) models. The time-varying connectedness of regional energy markets suggests that

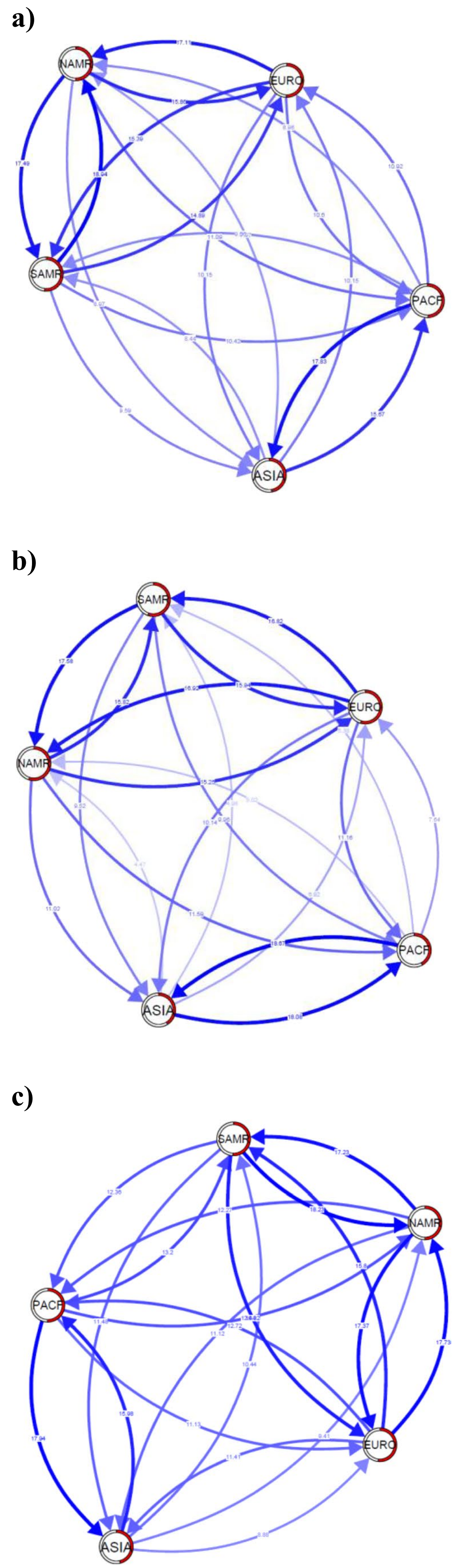
Fig. 4 Sub-sample analysis using Diebold and Yilmaz (2012). ▶ **a** Global financial crisis (GFC). **b** Shale oil revolution (SOR). **c** COVID-19 crisis (COV). These figures indicates the sub-sample connectedness among regional energy markets using Diebold and Yilmaz (2012) with 100 days ahead forecast error variance and lag 1 using SIC criteria



connectedness among the markets is time-varying and patterns of spillovers vary based on different time periods. Figure 3a presents the time-varying connectedness based on DY[12] model with significant spikes and troughs highlighting various time-periods of economic uncertainty and stress. The first spike is observed during Asian financial crisis (1997–1998) where regional energy markets showed higher connectedness as the crisis period resulted in information asymmetry and several markets shared information to overcome the drastic impact of the crisis. Hence, the graph depicts high spillovers during Asian financial crisis period. Soon after the crisis, markets tend to normalize and regained their normal working conditions illustrating the decline in the connectedness of the markets in the graph. Regional energy markets revealed spikes during global financial crisis (GFC) for the period 2007–2008 where high spillovers were formed among the markets. Reiterating, the energy markets of five regions were highly connected during the period of economic fragility. Concurrently, markets revealed high spillovers during 2010–2012 indicating the European debt crisis (EDC) where markets were significantly influenced by the anti-inflation policy from the European Central Bank (Blundell-Wignall 2012). Similarly, a spike during 2014–2016 points to the shale oil crisis where US oil markets suffered crisis during the shale oil revolution (SOR). The higher connectedness among regional energy markets revealed that asymmetrical information patterns and crisis led the markets to form high spillovers. Correspondingly, the spike during 2019–2020 highlights the current COVID-19 pandemic which significantly influenced the economic status around the globe. The higher connectedness of regional energy markets shows that spillovers were high during the crisis period and economic stress. Our findings are in line with Greenwood-Nimmo et al. (2016) and Sehgal et al. (2017) arguing that spillovers get intense during the period of economic severity and when markets are stabilized, the connectedness becomes lower.

Figure 3b reveals frequency dependent connectedness of regional energy markets following the model of Barunik-Krehlik (2018) where short run is highlighted with orange and long run is presented by yellow. Similar to Fig. 3a, the graph shows substantial spikes and troughs. The initial spike in the short-run points towards Asian financial crisis (1997–1998) where energy markets of five regions showed higher connectedness followed by a market-wide contagion. As the aftermaths of the shock disappeared, markets started to stabilize and connectedness

Fig. 5 Sub-sample analysis using Barunik and Krehlik (2018) — ▶ Short-run. **a** Global financial crisis (GFC). **b** Shale oil revolution (SOR). **c** COVID-19 crisis (COV). These figures indicates the short-run sub-sample connectedness among regional energy markets using Barunik and Krehlik (2018) with 100 days ahead forecast error variance and lag 1 using SIC criteria



becomes lower. The spike during 2006–2008 shows higher spillovers during global financial crisis where majority of the financial markets collapsed. Soon after GFC, markets showed higher connectedness during 2010–2012 pointing to the European debt crisis (EDC) where markets formed high spillovers revealing economic uncertainty and fragility. Correspondingly, the shale oil crisis during 2014–2016 depicted a spike in the graph where energy markets are significantly impacted by the shale oil revolution. The final spike in the graph highlights the ongoing pandemic condition generated due to COVID-19 signifying higher connectedness of regional energy markets where emergency situation of global lockdowns and closure of business operations has formed high spillovers of energy markets. The spikes in the short run mainly reveal that frequency connectedness of regional energy markets is affected in the short run and lasts for a shorter period of time (Londono 2019). Conversely, the connectedness of regional energy markets in the long run suggests that markets remain disconnected in the long run as it highlights normal market and economic conditions (Bouri et al. 2020).

Sub-sample analyses

Figure 4 illustrates sub-sample analysis of regional energy markets using Diebold-Yilmaz (2012) approach for three crisis periods, namely, global financial crisis (GFC), shale oil revolution (SOR), and COVID-19 crisis (COV). The connectedness among the regional energy markets shows similar patterns in all of the crisis periods where NAMR, SAMR, and EURO are net transmitters of the spillovers and show higher connectedness whereas ASIA and PACF are the net recipients of the information spillovers and show lower connectedness with other energy markets. Our findings recall the arguments of Hasan et al. (2021) on connectedness among Asian electricity markets, who reported that the connectedness of energy markets becomes high during a crisis period. Moreover, the regional markets of developed economies are net transmitters and vice versa.

Figure 5 illustrates sub-sample analysis using Barunik-Krehlik (2018) approach for three crises periods in the short run. Figure 5a, b, and c show that regional energy markets formed moderate spillovers and there is moderate connectedness among the regional energy markets. However, NAMR, SAMR, and EURO are marked as the net transmitters of information spillovers whereas ASIA and PACF are the net recipients of spillovers. Given the short-run period, the regional energy markets of closer borders tend to show

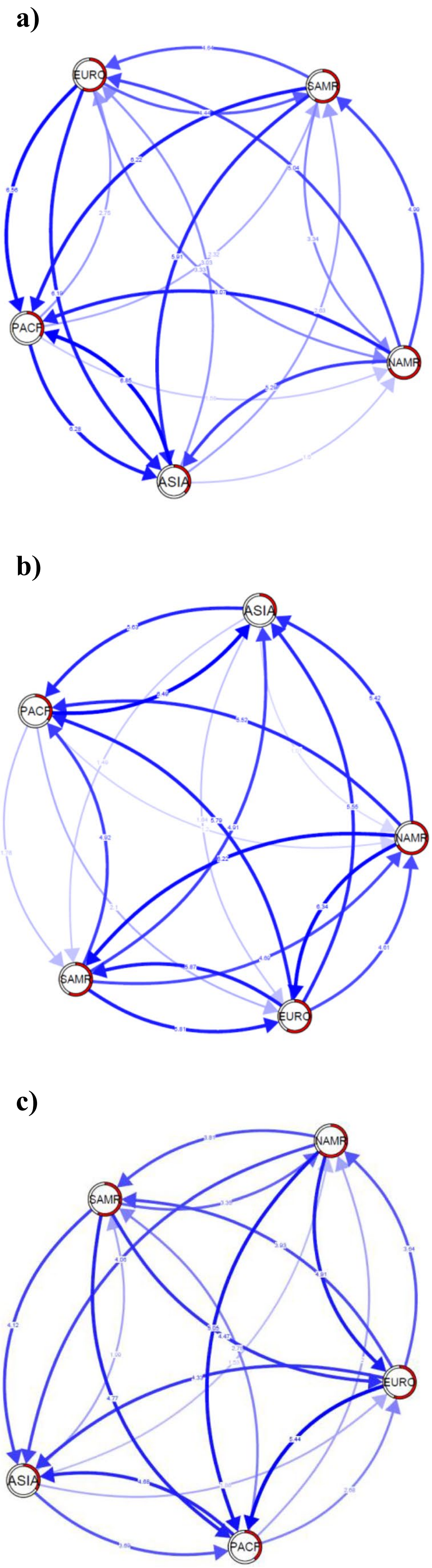


Fig. 6 Sub-sample analysis using Barunik and Krehlik (2018) — Long-run. **a** Global financial crisis (GFC). **b** Shale oil revolution (SOR). **c** COVID-19 crisis (COV). These figures indicates the long-run sub-sample connectedness among regional energy markets using Barunik and Krehlik (2018) with 100 days ahead forecast error variance and lag 1 using SIC criteria

higher connectedness during the crisis periods. In line with various studies of connectedness (Naeem et al. 2021a, b; Karim and Naeem 2021; Karim et al. 2022a, b, c), we report that spillovers are fashioned based on the development of the regional economic and financial power. Thus, markets are connected when there are distressed times and are weakly connected during stable times.

Figure 6 gives the analysis of sub-sample using Barunik-Krehlik (2018) model in the long run for three significant crises periods, i.e., GFC, SOR, and COV. For the results in each sub-sample, Fig. 6a, b, and c reveal higher connectedness of regional energy markets where NAMR is the net transmitter of spillovers followed by SAMR and EURO. Contrarily, ASIA and PACF are the net recipients of spillovers in the long run for each sub-sample. Our findings recall the studies of Naeem et al. (2021b), Elsayed et al. (2020), Le et al. (2021), and Salisu and Vo (2020), and it is asserted that the crisis period, driven by the market sentiment of fear, spreads across the globe that resulted in higher spillovers among the energy markets.

Overall, our findings illustrate that information transmission among the regional energy markets showed spillovers differentiated into developed regions' energy markets and developing regions. Notably, the connectedness among the markets was higher during the periods of economic stress and fragility followed by uncertain global financial condition and unstable business operations.

Conclusion

This research presented the information transmission of regional energy markets using the Diebold and Yilmaz (2012) and Barunik and Krehlik (2018) models of time-and-frequency-dependent structures. The time-based connectedness of five regional energy markets showed NAMR and SAMR as the net transmitters of information spillovers. EURO transmitted moderate spillovers whereas ASIA and PACF are the net recipients of information spillovers. We segregated the spillovers based on the financial and economic strength of five regions. We documented that developed regions (NAMR, SAMR, and EURO) are transmitting spillovers while developing regions (ASIA and PACF) are receiving spillovers. Moreover, the connectedness of energy markets was high during stress periods where global economic fragility, uncertainty, and world-wide closure of business operations resulted in the formation of higher spillovers. The frequency-dependent analysis showed that regional energy markets experienced significant spikes in the short run whereas connectedness becomes lower in the long run. Followed by the uncertainties in the global working conditions and economic distress, the energy markets of five regions showed varying patterns of connectedness. Additionally, the sub-sample analysis also confirmed that NAMR is the net transmitter of information spillovers followed by SAMR and EURO. And, ASIA and PACF are the net recipients of the information spillovers.

Our findings draw significant implications for policymakers, investors, financial institutions, financial markets, regulatory bodies, and global market players. Policymakers can evaluate their policies and reformulate certain strategies to avoid the drastic effects of crises coming in their way of progress and development. Meanwhile, policymakers of each region can redevelop their policies pertaining to energy stock markets and encourage their affiliates to invest in the stocks of energy companies as they are reportedly performing well than the developing regions. Investors can assess their risk portfolios by adding a blend of commodities and financial instruments to diversify their risks in the face of economic downfall. Moreover, for investors, we recommend investing in the energy stocks of developing regions as they are diversifiers among developed energy stock markets. Hence, drawing useful strategies from the study can help the investors to mitigate their risk during turbulent time periods. Regulatory bodies can redevelop their strategies to provide sufficient safety to the investments of the investors particularly during crisis times. In this way, crisis periods provide substantial insights for financial markets to consider those financial instruments and commodities which provide shelter to their mainstream investments. As future research avenues, the study recommends to include various other regions and their energy stock markets to provide a comprehensive analysis on portfolio diversification and risk assessment. Following this, our study is of particular importance to upcoming researchers, practitioners, and decision-makers to relish the findings of the study in a meaningful way.

Appendix 1

Table 3 Summarized literature review

No	Author(s)	Method(s)	Sample period	Findings
1	Naeem et al. (2021a)	Cross-Quantilogram	2008–2019	There is an asymmetric relationship between green bonds and commodities and hedging and diversification benefits are highlighted
2	Saeed et al. (2021)	Quantile VAR	2012–2019	The return connectedness of clean energy, green bonds, crude oil, and energy stocks is mainly pronounced in the left and right tails
3	Naeem et al. (2021b)	Time–frequency analysis; hedge ratios and hedge effectiveness	2013–2020	Green bonds reveal a significant weight in the overall network and are strongly connected with the USD and bond index. Green bonds can act as hedgers for some assets and can provide safe-haven features during tumbled periods
4	Shahzad et al. (2021)	Quantile generalized forecast error variance decomposition	2001–2020	The system-wide connectedness of different classes of assets shows varying behavior across multiple financial markets
5	Ferrer et al. (2021)	Wavelet Analysis	2010–2020	Green bonds are strongly related to treasury and investment-grade bonds whereas green stocks are strongly connected with general stocks. There is no linkage between green bonds and green stocks
6	Liu et al. (2021)	Conditional value-at-risk (CoVaR) and delta CoVaR	2011–2020	Green bonds and clean energy markets have positive time-varying average and tail dependence
7	Le et al. (2021)	Time–frequency analysis	2018–2020	There is very high connectedness among green bonds, fintech, and cryptocurrencies. And volatility transmission is higher in the short run than in the long run
8	Naeem et al. (2021c)	Time–frequency analysis; spillover network	2008–2020	Green bonds and crude oil are strongly connected. Green bonds act as succor for risk transmission during crisis times
9	Pham and Huynh (2020)	Diebold-Yilmaz and VAR approach	2014–2019	Investor attention can vary the green bond returns and volatility but the relationship is time-varying
10	Han et al. 2020	01 January 2010 to 31 December 2017 Daily electricity price volatility data from NEM	Connectedness using Diebold and Yilmaz (2009–2012)	The local factors influence the regional market price volatility. All five regions of NEM receive and transmit the volatility effects

Appendix 2

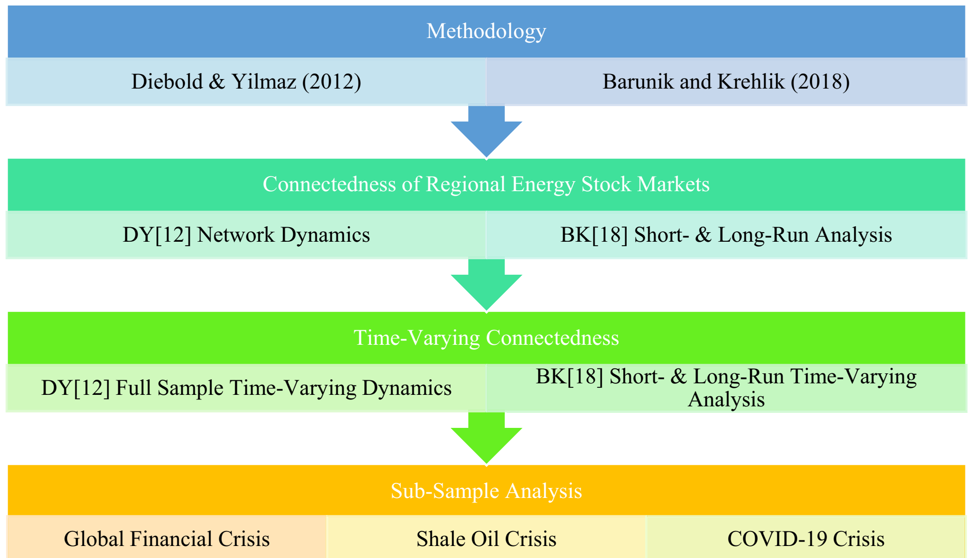


Fig. 7 Graphical illustration of methodological approach

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Author contribution Sitara Karim: writing — review & editing, methodology, software, formal analysis, original draft.

Muhammad Abubakr Naeem: conceptualization, data curation; methodology, software, visualization, writing — review & editing.

Mustafa Raza Rabbani: writing — review & editing, original draft.

Abdelrahman Ahmed Meero: writing — review & editing, original draft.

Suha M. Alawi: writing — review & editing; supervision.

Data availability The data and material for this study are made available upon request from the corresponding author.

Declarations

Ethics approval Not applicable.

Consent for participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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