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COVID-19 and time-frequency connectedness between green and conventional financial markets

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A R T I C L E I N F O

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A B S T R A C T

Against the backdrop of the exponentially growing trend in green finance investments and the calls for green recovery in the post-COVID world, this study presents the time-frequency connectedness between green and conventional financial markets by using the spillover models of Diebold and Yilmaz (2012) and Baruník and Křehlík (2018). Covering a sample period from January 01, 2008, to July 31, 2020, we aim to explore the dynamics of connectedness between conventional and green investments in fixed income, equity, and energy markets. Additionally, we determine the role of market-wide uncertainty in altering the connectedness structure by performing a subsample analysis for the ongoing COVID-19 pandemic crisis period. Our results show that competing energy investments are not connected, and there is only one-way spillovers from the conventional bonds in the fixed-income investments. Additionally, we observe a low (high) intergroup connectedness for conventional (green) investments. Moreover, the frequency-based analysis shows that connectedness between these competing markets is more pronounced during the short-run. The subsample analysis for the pandemic crisis period shows similar results except for the disconnection between bond markets in the short-run frequency. Our time-varying analysis shows peaks and troughs in the connectedness between climate-friendly and conventional investments that suggest different global events such as the Eurozone Debt Crisis and Shale Oil Revolution drives the association between alternate investments. Similarly, we observe an enhanced connectedness during the recent COVID-19 period, suggesting that financial stability would be a significant factor in determining the smooth transition to green investments.

1. Introduction

The COVID-19 pandemic is being regarded as one of the most devastating global events since the Great Depression and the 2008 global financial crisis (GFC). The economic and financial repercussions of the COVID-19 have led to a new economic and financial order worldwide, thereby posing severe challenges to the stability of conventional financial markets. Stock markets, the US stock

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market, for instance, touched circuit breaker four times in just a matter of weeks. Similarly, the pandemic has taken a toll on other stock markets worldwide, leading to growing fears and changing cross-market linkages (Zhang, Hu, & Ji, 2020). Simultaneously, energy markets, crude oil prices, for instance, plunged to under USD 20 a barrel, a historic low since the start of this century. On April 20, 2020, WTI crude oil futures suddenly dropped to an unprecedented low of -$37.63 per barrel, an event that shocked practitioners and policymakers alike. Similarly, the bond markets have shown significant liquidity problems during the COVID-19 episodes (Haddad, Moreira, & Muir, 2020; Kargar et al., 2020). Overall, the conventional financial markets have plummeted due to the lowest economic activity and heightened uncertainty, posing challenges for asset allocations, risk management, and financial stability.

Since the turn of this century, climate change has become one of the major challenges faced by humans. Due to the devastating effects of climate change on our ecosystem and human life, firms need to take substantial steps to reduce carbon emissions and fossil fuel consumption. Nowadays, green finance avenues in bonds, stocks, and commodities represent environmental-friendly financial markets that help firms tackle climate change. These avenues play an instrumental role in mobilizing the capital needed to fund the massive environment-oriented projects.

Consequently, green finance markets have emerged as an alternate asset class that has shown remarkable potential over the past decade. For instance, the green bond market has increased from a meagre USD 37bn in 2013 to USD 258.9bn in 2019 (Climate Bonds Initiative, 2019).[1] Similarly, the equity and commodity markets also show a swift transition to climate-friendly investments. The growth of green investments originates equally from the rise of socially responsible investing trends, country-level and global commitments such as the Paris climate agreement, the European green deal, and the implementation of carbon taxes. Policymakers and investors are thus concerned about how early the financial markets can recover as the ongoing recession drops off and economic growth picks up. Lately, the emphasis has shifted towards sustainable finance markets (Yoshino, Taghizadeh-Hesary, & Otsuka, 2020). Concurrently, the sustainable finance markets have performed substantially well during the pandemic (Broadstock, Chan, Cheng, & Wang, 2020). Surveys suggest that portfolios formed from environmental, social, and governance (ESG) stocks perform better than the overall market (Broadstock et al., 2020).

Green stocks are shares of firms whose essential business focuses on protecting the environment. Such firms primarily concentrate on alternative energy, recycling, energy and material efficiency, water management, clean transportation, and waste management. After the 2015 Paris Climate Agreement, the green stocks have observed an unprecedented boom by attracting massive capital flows due to environment-friendly features and lucrative potential. According to Morningstar, capital inflows of USD 51.1 billion went into US environmental, social, and governance (ESG) funds in 2020. This amount was more than double the amount invested in 2019 and represented the fifth consecutive annual record.[2] This investment is particularly remarkable given the market slump brought about by the ongoing COVID-19 pandemic. Like green bonds and green stocks, clean energy is a commodity market that also shares an environment-friendly objective and attracts investors' interest towards these low carbon instruments. Recent empirical evidence suggests that including clean energy in investment portfolios provides diversification benefits (Naeem, Peng, Suleman, Nepal, & Shahzad, 2020a, 2020b). In particular, portfolio managers holding energy commodities may include clean energy in their portfolios to fulfil diversification objectives over the long-term horizons (Naeem et al., 2020a, 2020b).

Notwithstanding the popularity and evidence for superior performance of green finance markets, little is known about how they are disentangled from conventional finance markets. Even the studies trying to answer this question have focussed only on green bonds and their linkage with other asset classes. Pham (2016) documented a positive connection between green and conventional bonds, suggesting potential benefits of forming portfolios by including the two bonds. Reboredo (2018) showed that although green, corporate, and treasury bonds are positively correlated, there are diversification gains of green bonds for energy and stock markets. Broadstock & Cheng (2019) found the time-varying correlation between green and black bonds. Some other evidence has recently emerged in the same vein (Naeem, Farid, Ferrer, & Shahzad, 2021; Naeem, Nguyen, Nepal, Ngo, & Taghizadeh–Hesary, F., 2021; Nguyen, Naeem, Balli, Balli, & Vo, 2020a, 2020b). Nonetheless, this growing body of literature ignores the possibility of a network connectedness between green and conventional finance markets. Additionally, the time-frequency aspect of such a network is also missing.

We fill this gap by arguing that the time-frequency connectedness between green and conventional financial markets provides a more holistic picture by simultaneously incorporating the cross-market linkages and investor horizons. Understanding the frequency connectedness between green and conventional finance markets is vital for investors and policymakers. Since investors are continuously looking for alternative asset classes to diversify their portfolios, it is paramount to assess the risk and return profile and hedging/safe-haven potential of green finance markets. This understanding becomes particularly important during times of market turmoil and financial crisis when investors are in dire need of safe-haven assets. Besides, the knowledge of green finance markets' interconnectedness aids investors who wish to reduce risk without slashing green assets from their portfolios. For policymakers, this may also help better comprehend the intricacies of shock transmission between green and conventional markets. This is highly insightful for policymakers, given their commitment to developing a resilient financial system that enables raising the massive amount of funds needed for environment-friendly and sustainable projects.

The connectedness across frequency bands is motivated by the notion that financial markets consist of multiple market participants, including investors such as intraday traders, pension funds, and sovereign wealth funds. Having heterogeneous investment horizons, which range from a few seconds to several years, these investors collectively drive cross-market behavior. Investors having short-term

[1] https://www.climatebonds.net/resources/reports/green-bonds-global-state-market-2019

[2] Morningstar also showed that ESG funds constitute approximately one fourth of all the investment made into the US equity and bond funds in 2020, compared to only about 1% of the share in 2014.

horizons often rely on technical information and thus are relatively more susceptible to herd behavior. In contrast, investors having long-term horizons focus more on essential information, thereby driving long-term movements (Kristoufek, 2013). Studies have shown that different economic agents (market participants) typically operate at different investment horizons – expressed in trading frequencies (Gençay, Gradojevic, Selçuk||, & Whitcher). This is related to various types of investors, trading tools, and strategies that correspond to the trading frequencies (Conlon, Cotter, & Gençay, 2016; Bredin, Conlon, & Potì, 2017). Therefore, it would seem plausible to argue that investors with divergent investment horizons would respond heterogeneously, which would translate into cross-market connectedness over short- and long-run investment horizons.

In this context, we examine the interconnectedness between conventional and green financial markets during the Covid-19 pandemic. While environmentally concerned investors have naturally been paying particular attention to green finance markets (Banga, 2019), a growing number of traditional investors have also begun to appreciate green assets' potential benefits. This is because green investments provide avenues to diversify their portfolios in conventional assets. To assess whether and the extent to which green financial assets offer diversification and hedging opportunities for conventional investors, it is paramount to investigate green and conventional financial markets' network dynamics. The interconnectedness patterns between green and conventional financial markets can help various economic agents, especially investors, for using the connectedness dynamics' direction and size to devise portfolio management strategies. Such information may also be vital for policymakers in formulating policies to safeguard and restore financial stability.

Amid the exponentially growing trend of green finance investments, we present a time and frequency-based connectedness analysis between green and conventional financial markets. We aim to explore the dynamics of connectedness between conventional and green investments in fixed income, equity, and energy markets. Additionally, we determine the role of market-wide uncertainty in altering the connectedness structure by performing a subsample analysis for the ongoing COVID pandemic crisis period. To this end, we employ Diebold and Yilmaz's (2012) network connectedness approaches to analyze the connectedness between green and conventional finance markets for the full sample and COVID sub-sample. Additionally, we use the Baruník and Křehlík (2018) method to ascertain the connectedness in short- and long-term frequencies. Our full sample results show a weakly connected network of return spillovers between conventional and green investments. However, the results' hard thresholding shows that contending energy investments are not connected, and there are only one-way spillovers from the conventional bonds in the fixed-income investments. Additionally, we observe a low (high) intergroup connectedness for conventional (green) investments. Moreover, the frequency-based analysis shows that connectedness between these competing markets is more pronounced during the short-run.

The subsample analysis for the pandemic crisis period shows similar results except for the disconnection between bond markets in the short-run frequency. Our time-varying analysis shows peaks and troughs in the connectedness between climate-friendly and conventional investments that suggest different global events such as the Eurozone Debt Crisis and Shale Oil Revolution drives the association between alternate investments. Similarly, we observe an enhanced connectedness during the recent COVID pandemic crisis period, suggesting that financial stability would be a significant factor in determining the smooth transition to green investments.

The current study offers the following contributions to the previous literature. Our first and foremost contribution goes towards studies that focus on the relationship between green finance markets and traditional markets (Pham, 2016; Reboredo, 2018; Broadstock & Cheng, 2019; Naeem, Farid, et al., 2021, Naeem, Nguyen, et al., 2021). While other studies overwhelmingly focus on how green bonds are linked to other asset markets, we offer a more holistic picture by involving green finance assets in equity, bond, and commodity markets and corresponding conventional assets. We, therefore, introduce a much broader network of two different cadres of financial markets to seek wider diversification opportunities available across stocks, bonds, and commodity markets. This is not only attractive for environment-concerned investors but also other investors. Our second contribution goes towards studies that unveil the time-frequency nexus between green and conventional markets (Nguyen et al., 2020a, 2020b). This is important because financial markets - either green or conventional – include heterogeneous groups of investors with a wide variety of preferences. Institutional investors, such as investment banks and many individual investors, invest over short-term horizons, whereas others, such as pension funds and insurance companies, invest over medium- to long-term horizons. The time-frequency analysis performed in this study is an innovative approach that considers multi-scale, cross-asset connectedness patterns that would be insightful for investors operating at different investment horizons.

The rest of the paper is organized as follows: Section 2 provides a brief introduction of the literature on the linkage between green and conventional markets. Section 3 describes the dataset and methodological details. Section 4 offers empirical findings, and Section 5 concludes.

2. Literature review

It is well-known that the linkage between green finance markets and conventional markets is gaining popularity. However, despite this popularity, not much has been done to explore the connectedness network between the two financial market cadres. The prior literature has studied mainly the linkage between green bonds and other financial markets, let alone the studies that focus only on stylized facts related to the green bond market. However, given the growth trajectory of green bonds since their introduction in 2014, the empirical evidence on green bonds is relatively scant.

While yielding mixed evidence, pioneering works in this strand of literature assess whether green bonds carry any premium vis-a-vis their conventional counterparts. For instance, recent studies (Baker, Bergstresser, Serafeim, & Wurgler, 2018; Ehlers & Packer, 2017; Febi, Schäfer, Stephan, & Sun, 2018; Gianfrate & Peri, 2019; Zerbib, 2019a, 2019b) document that green bonds carry a negative premium, implying that investors buying green bonds tend to trade off lower returns on these bonds for environmental benefits. On the other hand, some studies (Kanamura, 2020; Karpf & Mandel, 2017) find a positive yield differential on green bonds, while others

(Flammer, 2021; Hachenberg & Schiereck, 2018; Larcker & Watts, 2020) witness an essentially zero-premium on green bond. Another strand of literature demonstrates that bother investors (Baulkaran, 2019; Tang & Zhang, 2020; Wang, Chen, Li, Yu, & Zhong, 2020a, 2020b) and issuers (Lebelle, Lajili Jarjir, & Sassi, 2020) can benefit from issuing green bonds.

An emerging strand of literature has focussed on the connectedness between green and ordinary bonds. For example, a seminal work by Pham (2016) studied the nexus between green and conventional bond markets, finding a positive relationship across these markets and portfolio benefits for combining the two bonds. More recently, Broadstock & Cheng (2019) assessed the correlation co-movement between the green and black bonds and realized their correlation's time-varying feature. In another recent work, Naeem, Farid, et al. (2021), Naeem, Nguyen, et al. (2021) compare the efficiency of green bonds and conventional bonds via asymmetric multifractal investigation, showing green bonds to be more inefficient, particularly during market downturns. Ahmad (2017) indicates that technology stocks and oil prices play crucial roles in improving green energy value and oil price results. Ferrer, Shahzad, López, and Jareño (2018) discussed the time, and frequency dynamics of renewable energy supplies, crude oil prices, and other financial instruments are discussed to the degree that it may suggest an interrelationship with other market factors overall market efficiency. A lot of the returns and volatilities tied to those traders are produced in the short term. e.g., moves up to five days. The long term plays a minor role.

Overall, the abovementioned studies clarify that the prior literature emphasized green bond's key characteristics and how it is connected to other conventional markets. However, simultaneous, network-based, time-frequency analysis of multiple green assets and conventional markets was missing to date. Our study fills this gap in the existing literature.

3. Methodology

The basic notion is to explore within a network framework whether green and conventional financial markets constitute two separate asset classes despite having several common features or whether, on the contrary, they exhibit resemblance with each other. The network framework has a flexible and powerful tool to uncover any complex system by clearly specifying nodes and edges for shock transmission. There is a vast body of literature indicating that network analysis provides a suitable framework to highlight similarities and differences among distinct asset classes, especially when it comes to price movements (Ahmad, 2017; Chi, Liu, & Lau, 2010; Ji, Bouri, & Roubaud, 2018; Mantegna, 1999).

Another general facet of both conventional and green markets is that they encompass multiple market participants, including investors, who have heterogeneous investment horizons, varying from a few seconds to several years. Investors operating at diverse investment horizons collectively dictate market-wide and cross-market behavior. Studies have shown that different economic agents (market participants) typically operate at different investment horizons – expressed in trading frequencies (Gençay et al., 2010). This is related to various types of investors, trading tools, and strategies that correspond to the trading frequencies (Conlon et al., 2016; Bredin et al., 2017). It, therefore, seems plausible to argue that market participants with divergent horizons behave differently, and their distinct behaviors are reflected in the cross-market network of asset markets.

Motivated by the above, the most appropriate empirical methods seem to be the network-based frequency model. Our methodology hinges upon Diebold and Yilmaz's (2012) connectedness framework to undercover the connectedness dynamics between conventional and green finance markets. Subsequently, the connectedness patterns are decomposed into short- and long-term components by employing Baruník and Křehlík's (2018) framework. This model helps us decipher the behavior of cross-market connectedness into various time horizons.

Diebold and Yilmaz (2012) resort to the generalized vector autoregressive (VAR) setting for computing the connectedness computations. The VAR framework produces forecast error variance decompositions (FEVD), leading to the connectedness estimates. To this end, a covariance-stationary VAR (p) model for N-financial market series, including both conventional and green markets, is constructed as $y_t = \sum_{i=1}^{p}\phi_i y_{t-i} + \varepsilon_t$, where $\varepsilon_t \sim N(0, \Sigma)$. Consequently, a moving average (MA) depiction driven from the VAR model, therefore, results in an MA (∞) process, $y_t = \sum_{i=0}^{\infty}\psi_i\varepsilon_{t-i}$, where ψ_i is a coefficient matrix of order $N \times N$, which is recursively computed through $\psi_i = \phi_1\psi_{i-1} + \phi_2\psi_{i-2} + \ldots + \phi_p\psi_{i-p}$, where ψ_0 is the identity matrix.

Subsequently, we follow Koop, Pesaran, and Potter (1996) and Pesaran and Shin (1998) to achieve orthogonality through the generalized framework. Hence, a given series j's contribution to another series i's H-step-ahead generalized forecast error variance is represented by ξ_{ij}(H), and estimated by:

$$\xi_{ij}(\mathrm{H}) = \frac{\sigma_{jj}^{-1}\sum_{h=0}^{H-1}\left(\Im_i^{'}\psi_h\sum\Im_j\right)^2}{\sum_{h=0}^{H-1}\left(\Im_i^{'}\psi_h\sum\psi_h^{'}\Im_i\right)^2} \tag{1}$$

Where $\sum$ and σ_{jj} represent the covariance matrix of errors and the j^{th} component of the standard deviation's diagonal, respectively. For an i^{th} component, $\Im_i$ takes a value of one, and zero otherwise. In the non-orthogonalized VAR's infinite MA representation, ψ_h represents a coefficient matrix with the multiplication of h-lagged errors.

Accordingly, the pairwise connectedness from series j to series i is given by:

$$\Omega_{i\leftarrow j}^{H} = \xi_{ij}(\mathrm{H}) \tag{2}$$

Consequently, we can capture the total directional connectedness to (from) other series to series j (i). According to Diebold and Yilmaz (2012), it can be obtained by dividing the off-diagonal sum of columns (rows) by the sum of all elements. It is represented by:

$$\Omega^{H}_{i\leftarrow\bullet} = \frac{1}{N}\sum_{\substack{j=1\\ j\neq i}}^{N} \xi_{ij}(\mathrm{H}) \quad (3)$$

$$\Omega^{H}_{\bullet\leftarrow j} = \frac{1}{N}\sum_{\substack{i=1\\ i\neq j}}^{N} \xi_{ij}(\mathrm{H}) \quad (4)$$

Similarly, we can obtain the total or system-wide connectedness. According to the authors, it can be computed by dividing the sum of to others (from others) elements by the sum of all its elements:

$$\Omega^{H} = \frac{1}{N}\sum_{\substack{i,j=1\\ i\neq j}}^{N} \xi_{ij}(\mathrm{H}) \quad (5)$$

Next, we estimate the cross-market connectedness over short- and long-term horizons. To this end, we resort to Baruník and Křehlík's (2018) frequency connectedness model. The model decomposes the variance into spectral components and allows us to compute the connectedness over short- and long-term horizons.

Accordingly, the Fourier transform of the coefficients Γ_k, for $i = \sqrt{-1}$, helps us ascertain the frequency response function, $\Gamma(\Im^{-i\Theta k}) = \sum_k \Im^{-i\psi k}\Gamma_k$. At a given frequency band, Θ, the Fourier Transform for MA(∞) processes defines AB's spectral density and is given by:

$$T_{XY}(\Theta) = \sum_{k=-\infty}^{\infty} E(XY_t XY'_{t-k})\Im^{-i\Theta k} = \Upsilon(\Im^{-i\Theta})\sum \Upsilon'(\Im^{+i\Theta}) \quad (6)$$

where $T_{XY}(\Theta)$ is the power spectrum which maps the distribution of XY_t's variance for each ψ. There is also an alternative way of describing frequency domains through covariance's spectral decomposition. It is expressed as follows: $Exp(XY_t, XY'_{t-k}) = \int_{-\varphi}^{\varphi} T_{\phi}(\Theta)\Im^{ifk}d\Theta$.

Following Baruník and Křehlík (2018), the cross-spectral density of the interval, $l = (c, d) : c,\ d \in (-\varphi, \varphi),\ c < d$, is estimated and given by:

$$\sum_{\Theta}\widehat{\Gamma}(f)\widehat{\sum}\widehat{\Gamma}'(\Theta) \quad (7)$$

for $\Theta \in \left\{\lfloor cK/_{2\pi}\rfloor, \dots, \lfloor dK/_{2\pi}\rfloor\right\}$, where

$$\widehat{\Gamma}(\Theta) = \sum_{k=0}^{K-1}\widehat{\Gamma}_k\Im^{-2i\varphi\Theta/K} \quad (8)$$

(and) $\widehat{\sum} = \widehat{\varepsilon}'\widehat{\varepsilon}/_{(\Omega - y)}$ where y represents adjustments that correspond to the loss of degrees of freedom, which strictly depends on the VAR framework.

Consequently, a frequency-based decomposition of the impulse response is given by $\widehat{\Gamma}(l) = \sum_f \widehat{\Gamma}(\Theta)$, where the generalized FEVDs are calculated as:

$$\left(\widehat{\Re}_l\right)_{j,m} = \sum_f \widehat{\rho}_j(\Theta)\left(\widehat{P}(\Theta)\right)_{j,m} \quad (9)$$

where $\left(\widehat{P}(\Theta)\right)_{j,m} = \widehat{\delta}_{ll}^{-1}\left(\left(\widehat{\eta}(\Theta)\widehat{\sum}\right)_{j,m}\right)^2 / \left(\widehat{\Gamma}(\Theta)\widehat{\sum}\Gamma'(\Theta)\right)_{j,j}$ and $\widehat{\Re}_j(\Theta) = \left(\widehat{\Gamma}(\Theta)\widehat{\sum}\Gamma'(\Theta)\right)_{j,j}/(f)_{j,j}$ denote the estimates for the generalized causation spectrum and the weighted fraction, respectively; where f can be computed from $\sum_f \widehat{\Gamma}(\Theta)\widehat{\sum}\widehat{\Gamma}'(\Theta)$. Finally, the frequency connectedness estimates are achieved by substituting $\left(\widehat{\Re}_k\right)_{j,m}$ into the abovementioned connectedness metrics.

4. Data, sample and empirical analysis

4.1. Data and sample

We use representative indices from debt, equity and energy markets that reflect the market performance of green and conventional investment across different financial markets. Existing studies use these indices for green and conventional financial markets' representation. For details, see; Arif, Naeem, Farid, Nepal, and Jamasb (2021); Naeem, Farid, et al. (2021), Naeem, Nguyen, et al. (2021); Ferrer, Benítez, and Bolós (2021). Specifically, our sample includes S&P Green Bonds Index, S&P Global Clean Energy Index, and Dow Jones Sustainability Index that represent the green investments. Besides, Barclays Bloomberg Global Treasury Index, S&P GSCI Energy Index, and MSCI World Index represent the conventional investments. We use the Bloomberg database to extract the data for conventional and green indices. Our data spans from 01/012/2008 to 31/07/2020. We transform index prices into logarithmic first difference (returns).

4.2. Descriptive statistics

Table 1 presents the descriptive statistics for green and conventional investments. Equity indices from both green and conventional financial markets exhibit the highest average returns followed by fixed-income investments. On the other hand, the energy investments from both types of markets show the lowest average returns. Additionally, these investments also show the highest return variability, indicating that commodity investments from both green and brown energy markets are risker and sensitive to market-wide fluctuations. Further, the negative skewness values for equity and commodity investment reveal that these investments mostly experienced positive returns and few large negative returns during the sample period. Additionally, the high kurtosis values suggest the presence of heavy tails in the sample investments. The last two columns of Table 1 show Jarque-Berra (JB) and Augmented Dicky-Fuller (ADF) test statistics. Highly significant test statistic values of these tests confirm that the time series under investigation are non-normal and stationary.

4.3. Network-based connectedness

Fig. 1a presents the full sample return connectedness network between green and conventional investments in fixed income, equity, and commodity markets. We observe spillovers running to and from each asset to other assets except for the global treasury bond that sends (receive) spillovers only to (from) S&P green bond index. Moreover, we apply hard thresholding (the values smaller than the average of the first 100 largest partial derivatives are set to be 0) to identify significant and economically substantial spillovers between sample investments. Fig. 1b shows the post-thresholding connectedness network that only displays two-way spillovers between equity investments and one-way spillovers from the global treasury to the green bond index. This observation specifies that sizeable connectedness is either limited to homogenous asset classes or non-existent in the connectedness network. These findings indicate the presence of potential diversification opportunities within and across asset classes. For example, the non-connectedness of clean energy index with conventional commodity index and other asset classes qualifies them as potential diversification investments for energy and equity and fixed-income investments.

Further, we employ BK2018 to explore the connectedness between sample investments in different time frequencies in i-e short- and long-run. Fig. 2 (a-b) presents the short-run connectedness results with and without thresholding. These figures show a very similar connectedness structure within and across asset classes as full sample analysis, indicating that short-run connectedness drives the spillovers between sample investments. Moreover, the long-run analysis presented in Fig. 2 (a-b) exhibits considerable connectedness only among equity investments i-e sustainability and conventional stock indices. The frequency-based connectedness analysis indicates that connectedness between green and conventional investments is influence by time horizons. These observations present significant implications for short- and long-run investors in terms of adjusting their investment strategies to make most of the opportunities available in these markets.

Overall, the network-based analysis offers insightful findings concerning the connectedness between sustainable and conventional investments and the diversification opportunities that green investments offer. Regarding the connectedness between conventional and green equity investments, our findings agree with Lundgren, Milicevic, Uddin, and Kang (2018) and Ferrer, Benítez, and Bolós (2021) that report a strong connectedness between green stocks and conventional equity investments. Additionally, our results corroborate with Ferrer, Benítez, and Bolós (2021) regarding the connectedness between fixed-income investments in green and conventional financial markets. Moreover, our findings also pinpoint the diversification avenue available to investors due to the weak or no connectedness between green investments such as green bonds and conventional financial investments. Although at a varying scale, existing literature also reports diversification opportunities offered by green investments. For example, using global green bond indices, Reboredo (2018) and Arif et al. (2021) report sizeable diversification benefits of green bonds investments against equity and

Table 1
Descriptive statistics.

Market	Code	Mean	Max	Min	Std. Dev.	Skewness	Kurtosis	JB	ADF
S&P Green Bonds	SPGB	0.003	6.815	−3.782	0.535	0.938	21.710	44699.13***	−55.919***
S&P Clean Energy	SPGC	−0.009	11.794	−12.800	1.623	−0.490	11.414	9070.185***	−51.747***
Dow Jones Sustainability	DJSI	0.027	7.694	−10.604	1.087	−0.632	12.710	12121.92***	−52.586***
Bloomberg Barclays Global Treasury	BBGT	0.012	3.746	−2.336	0.386	0.212	9.797	5863.561***	−52.041***
S&P GSCI Commodity	GSCI	−0.052	15.983	−30.169	2.150	−1.315	25.729	66183.72***	−55.961***
MSCI World	MSCI	0.031	8.406	−10.441	1.023	−0.915	16.367	23011.59***	−17.930***

Note: JB and ADF represent the Jarque-Bera test of normality and the Augmented Dickey-Fuller test of stationarity, respectively. *** indicates significance at 1%.

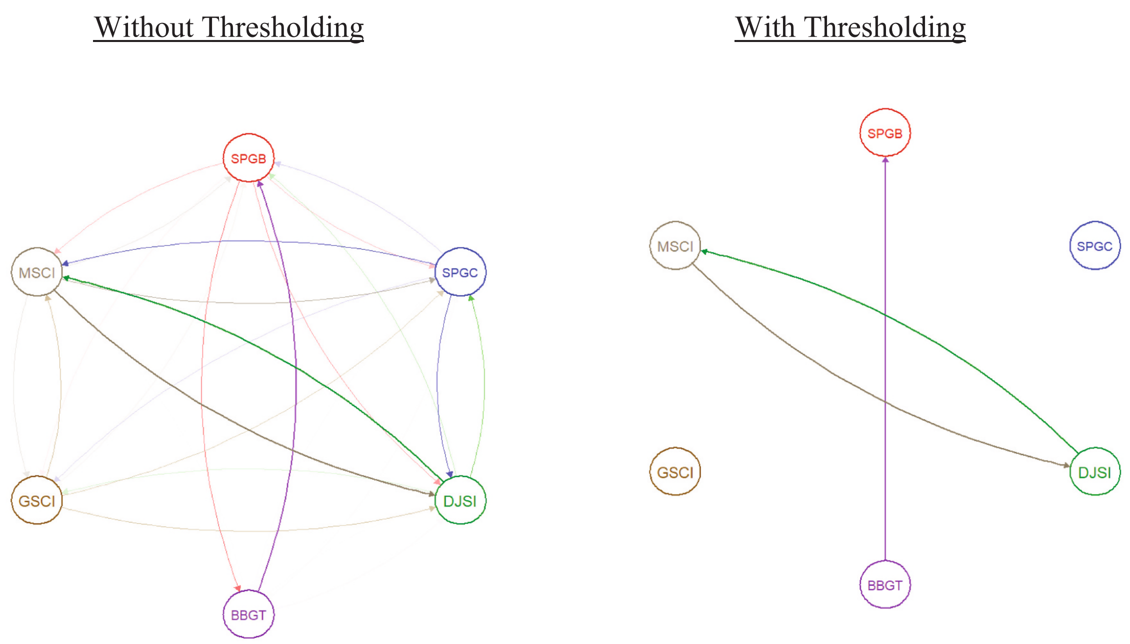

Fig. 1. Full sample network diagram of connectedness table.
Note: This network graph illustrates the degree of total connectedness in a system that consists of debt, equity and energy investments. Total connectedness is measured using the Diebold-Yilmaz framework. The width of the arrows and size of node refers to the strength and magnitude of connectedness.

energy commodity investments. Additionally, using a diverse group of commodities, Naeem, Farid, et al. (2021), Naeem, Nguyen, et al. (2021) report considerable diversification and hedging benefits of green bond's inclusion in commodity portfolios. Reboredo, Ugolini, and Aiube (2020) report diversification possibilities for green bond investors against corporate bonds, stock and energy assets in the EU and US financial markets. In addition to green bonds, our observation that clean energy investments offer potential diversification avenues for conventional energy investors in short- and long-run investment horizons corroborates with (Ferrer et al., 2018).

4.4. Dynamic connectedness

The network approach offers a static analysis of the connectedness between green and conventional financial markets. However, Reboredo (2018) identified a dynamic dependence structure between green bonds and other financial assets and found lower tail-dependence between green bonds and equity and energy markets. Besides, Ferrer et al. (2018) report time-varying connectedness between renewable energy stocks, conventional energy (oil and gas) prices, and treasury bonds. Moreover, sustainable equity indices also exhibit dynamic connectedness with different financial market risk indicators such as VIX volatility index, US economic policy uncertainty (EPU) index, Chicago Board Options Exchange (CBOE) volatility index and US 10-year Treasury bond yield (Umar, Kenourgios, & Papathanasiou, 2020).

Owing to existing evidence concerning the dynamic association between green and conventional investments, we estimate the time-varying connectedness between study variables by employing a full sample and frequency-based time-varying connectedness analysis. Accordingly, Fig. 3 presents the graphical representation of the full sample time-varying spillovers index using a rolling window length of 260 days. Fig. 3 reveals a highly volatile connectedness pattern between study variables. We observe a higher connectedness (around 60%) at the beginning of the sample period that coincides with the post-GFC period when the overall financial market experienced the highest connectedness (Kang & Lee, 2019). After easing of the GFC effects, the spillovers index shows a decline of around 10% just before it rose again and peaked in early 2012. This high connectedness period coincided with the escalation of the European sovereign debt crisis (ESDC) when many countries, including Greece, Spain, and Portugal, requested bailout packages.

Further, one can see a steady decline (25% compared to the peak) in connectedness between green and conventional investments for the post-EDSC period with the spillovers index reaching its lowest point in early 2014. The lower connectedness during this period could be attributed to the smooth functioning of financial markets. However, the spillovers index started to rise again in the latter part of 2014 and sustained this trend until early 2016. During the 2014–2016 period, two important events took place that produced higher uncertainty in the financial markets. First, the shale oil revolution increased the volatility transmission in the energy markets, including renewable energy (Nguyen et al., 2020a, 2020b). Second, the slowdown of the Chinese economy during 2015–2016 that increased the overall market uncertainty. Most recently, the spillovers index shows another spike after a relative calm period. The current escalation in the connectedness concurs with the onset of pandemic crisis that has caused havoc in the social as well as financial and economic spheres around the world—consequently causing extreme contagion in the equity, commodity and debt markets

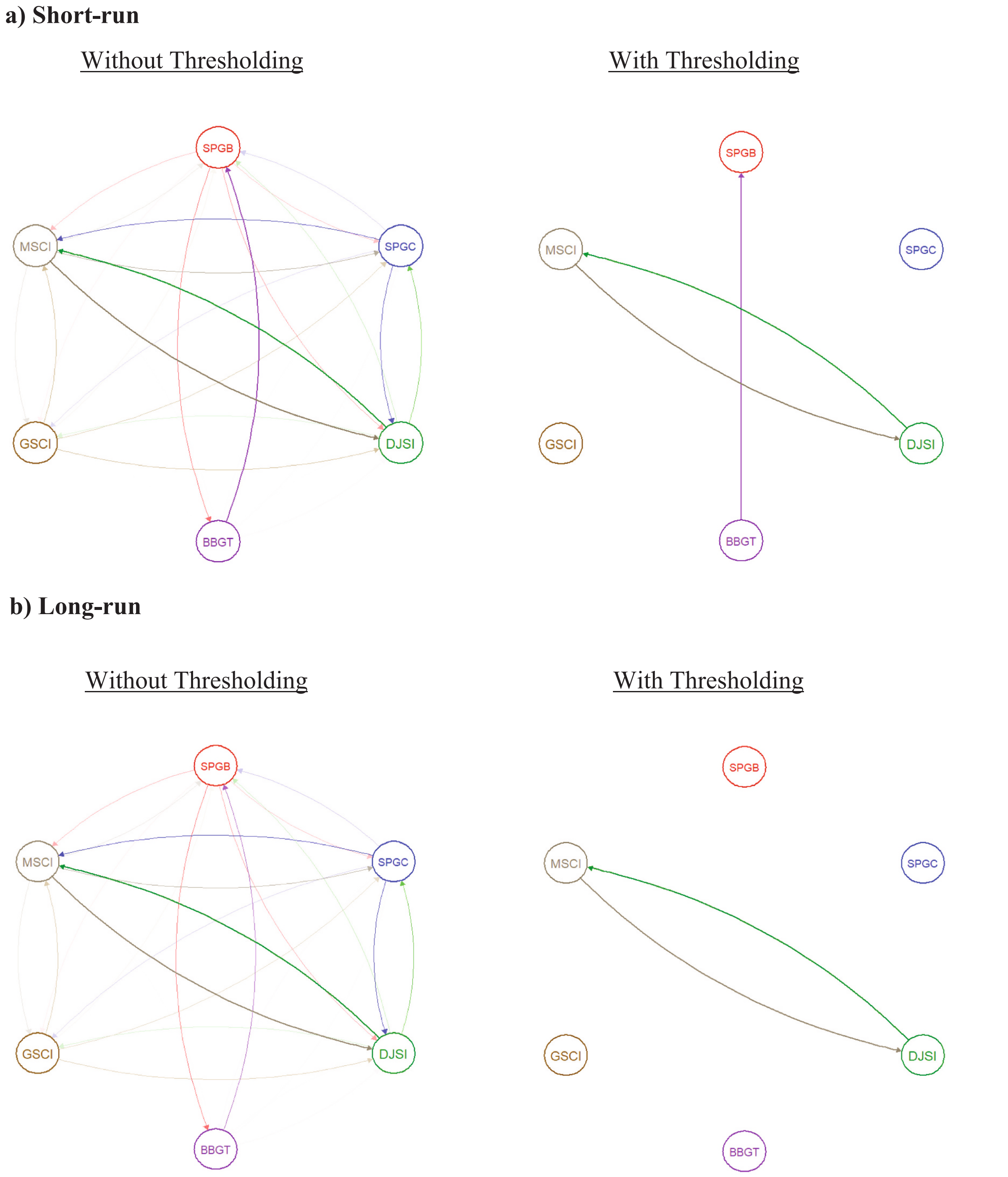

Fig. 2. Frequency-based network diagram of connectedness table.
Note: These network graphs illustrate the degree of total connectedness in a system that consists of debt, equity and energy investments. Frequency based connectedness is measured using the Baruník-Křehlík framework. The width of the arrows and size of node refers to the strength and magnitude of connectedness.

(Akhtaruzzaman, Boubaker, & Sensoy, 2020; Hernandez, Kang, Shahzad, & Yoon, 2020; Umar et al., 2020). To confirm the robustness of our results under different window lengths, we estimate the dynamic connectedness index using 200, 260, and 300 days rolling windows in Fig. 4. The dynamic connectedness indexes show a very similar pattern of connectedness under different rolling-window lengths, indicating that the choice of rolling-window length does not disturb the robustness of connectedness results.

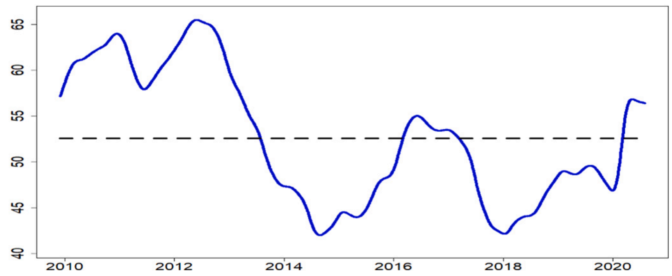

Fig. 3. Full sample dynamic connectedness graph.
Note: This graph illustrates the degree of total dynamic connectedness between debt, equity and energy investments.

Besides, we also estimate the dynamic connectedness for short and long-run time frequencies. The results presented in the Fig. 5 show that short-run market conditions, such as heightened uncertainty and unpredictable economic conditions, drive the magnitude of spillovers between conventional and green financial markets. Additionally, the short-run frequency shows a relatively higher variation in the spillovers index than the long-run frequency, signifying that the heightened connectedness between the conventional and green financial markets is a short-lived phenomenon. Thus, investors with a longer investment horizon might access the diversification benefits that green investments offer in cross-asset classes. For example, the disassociation between the green bond and conventional assets except the global treasury bond offer substantial diversification benefits for passive investors.

4.5. Network-based connectedness– Pandemic crisis

Next, we turn to a subsample analysis in order to capture the connectedness pattern between green and conventional investment during the ongoing pandemic crisis. Recent studies share concerns about the long-term impact of the Covid-19 crisis on green finance transition due to the lower oil prices, shrinking financial reserves of the organisations and government policies to save some of the sinking non-sustainable businesses (Cojoianu et al., 2020; Gillingham, Knittel, Li, Ovaere, & Reguant, 2020; Steffen, Egli, Pahle, & Schmidt, 2020). The concerns raised by these studies suggest that green investments may suffer more in the future if the stakeholders do not take appropriate actions. On the other hand, studies concerning the global financial crisis (GFC) showed heightened connectedness between green and conventional investments, indicating that financial contagion might intensify the association between these alternative investments (Ahmad, 2017; Ferrer et al., 2018).

Our pandemic crisis analysis presented in the Fig. 6 shows similar results as of full sample, indicating that the pandemic crisis did not cause much of an effect on the connectedness structure between green and conventional investments. We still observe significant two-way spillovers between equity investments and only one-way spillovers transmission from global treasury index to green bond index. Additionally, despite the considerable variation in the price of crude oil during the early phases of the pandemic crisis, the energy investments did not show any significant connectedness within themselves and across other investments, signifying the diversification potential of energy investments in times of high financial market turbulence.

Nevertheless, our frequency-based connectedness results reveal that equity investments exhibit significant connectedness in the short-run (Fig. 7a), suggesting that investors in the equity market react swiftly to financial market contagion. In a similar vein, Umar et al. (2020) report enhanced connectedness between responsible equity investment (MSCI ESG) indices and macroeconomic and financial variables during the early period of the COVID-19 pandemic crisis. More generally, Akhtaruzzaman et al. (2020) report severe

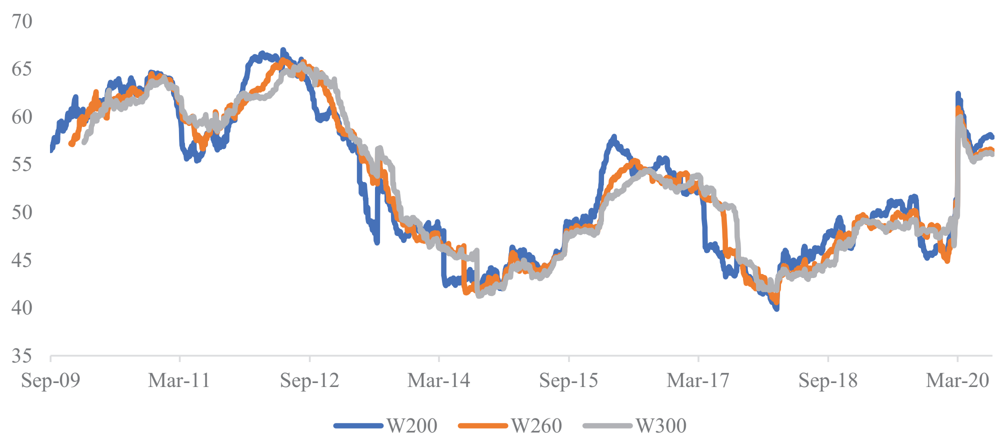

Fig. 4. Robustness test – Dynamic connectedness.
Notes: This figure shows the results for each other combination of window-length $w \in \{200; 260; 300\}$.

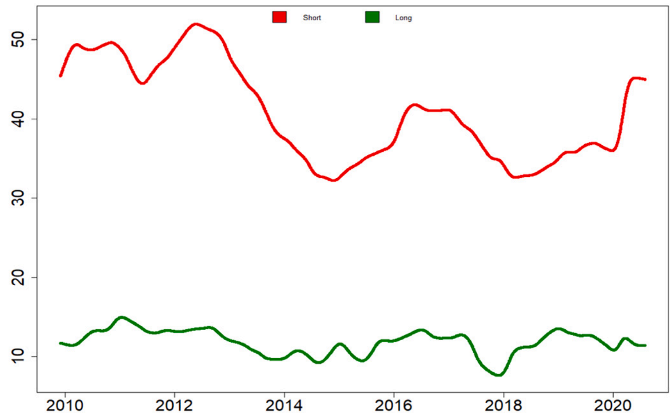

Fig. 5. Frequency-based dynamic connectedness graph.
Note: This graph illustrates the degree of frequency-based dynamic connectedness between debt, equity and energy investments.

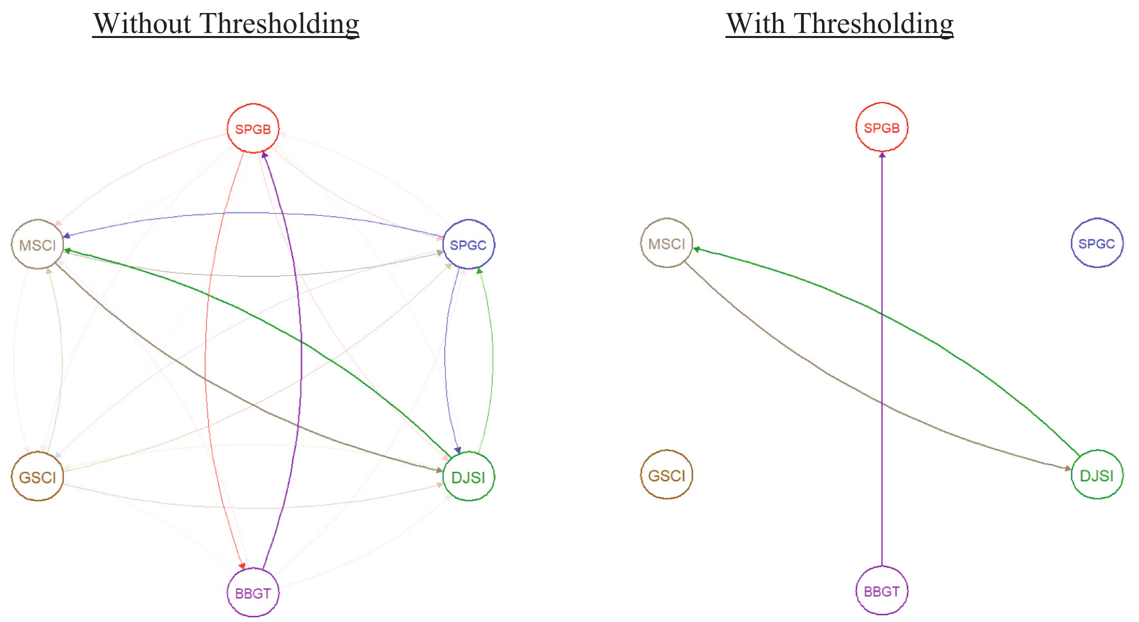

Fig. 6. COVID-19 sample network diagram of connectedness table.
Note: Refer to Fig. 1.

contagion among China and G7 countries' equity markets. On the other hand, we observe a significant connectedness between fixed-income investments during the long-run (Fig. 7b) that indicates slow transmission of the contagion effect in the low-risk assets such as global treasury and green bonds. Our finding of the heightened dependence between the green bond and global treasury indices during the pandemic crisis corroborates with existing studies that find a higher correlation between these investments during the time of the European debt crisis and the COVID-19 crisis (Ferrer, Benítez, & Bolós, 2021; Nguyen et al., 2020a, 2020b; Reboredo & Ugolini, 2020).

Mainly, the pandemic period analysis offers useful insights into the association between green and conventional financial markets. First, the weakly connected clean energy markets offer diversification avenues for and conventional energy investors during the turbulent period. Second, the long (short) run disassociation between equity (fixed income) investments offers diversification opportunities for investors with short and long investment horizons. Lastly, there are cross-asset diversification opportunities for investors who invest in multiple asset classes i.e., equity, bond, and commodities.

5. Conclusion and policy implication

The green finance market has emerged as an alternate financial market that has shown remarkable growth in the past decade. Green investments' growth originates equally from the rise of socially responsible investing trends, country-level, and global commitments

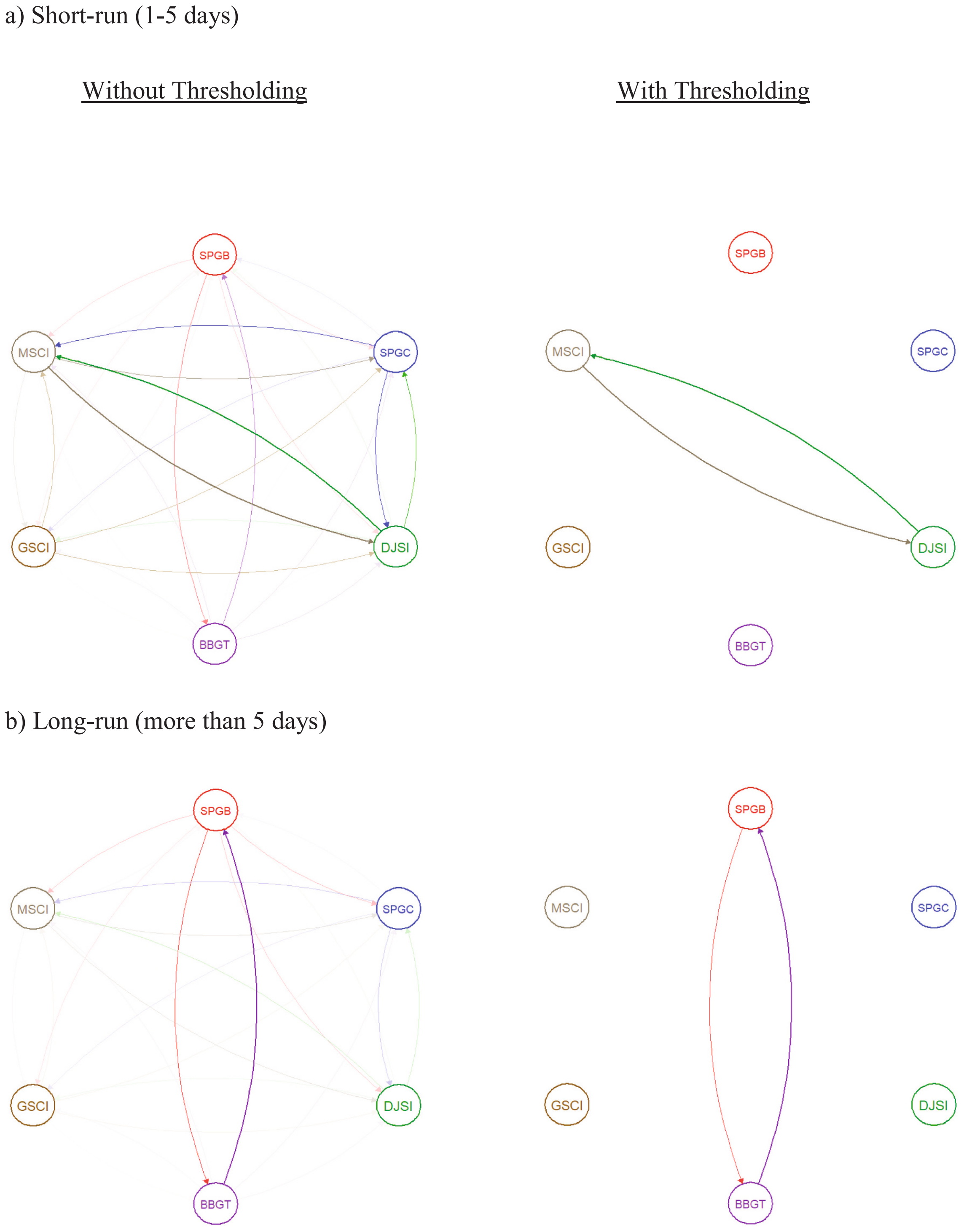

Fig. 7. COVID-19 sample frequency-based network diagram of connectedness table.
Note: Note: Refer to Fig. 2.

such as the Paris climate agreement, the European green deal, and the implementation of carbon taxes. Against this backdrop, this study presents a time and frequency-based connectedness analysis between green and conventional financial markets returns. We aim to explore the connectedness dynamics between conventional and green investments in fixed income, equity, and energy markets. Additionally, we perform a subsample analysis for the ongoing COVID pandemic crisis period to ascertain the role of market-wide uncertainty in connectedness patterns. To this end, we employ Diebold and Yilmaz (2012) and Baruník and Křehlík (2018) network connectedness approaches to analyze the connectedness between green and conventional finance markets for the full sample and different frequencies. Moreover, we study the time-varying properties of connectedness between these competing investments to unearth market events that enhance/diminish this relationship.

Our full sample results show that contending energy investments are not connected, and there is only one-way spillovers from the conventional bonds in the fixed-income investments. Additionally, we observe a low (high) intergroup connectedness for conventional (green) investments. Moreover, the frequency-based analysis shows that connectedness between these competing markets is more pronounced during the short-run. The subsample analysis for the pandemic crisis period shows similar results except for the disconnection between bond markets in the short-run frequency. Furthermore, our time-varying analysis shows peaks and troughs in the connectedness between climate-friendly and conventional investments that suggest different global events such as the Eurozone Debt Crisis and Shale Oil Revolution drives the association between alternate investments. Similarly, we observe an enhanced connectedness during the recent COVID pandemic crisis period, suggesting that financial stability would be a significant factor in determining the smooth transition to green investments.

The findings of this study have important implication for different economic agents. First, our findings provide important implications for investors operating in different financial markets and investment horizons. Our findings indicate that numerous diversification and hedging opportunities are available for conventional investors in the green financial markets, especially in green bonds and energy investments. Additionally, based on the lower connectedness between green bonds and green stocks, our findings reveal that environmentally conscious investors can diversify their portfolios into different asset classes without compromising their sustainability objectives. Additionally, owing to lower connectedness between equity and fixed income investments under different investment horizons, our frequency-based analysis suggests that long-run (short-run) investors can diversify into competing equity (fixed income) investments.

Second, our findings concerning the connectedness between green and financial markets during the COVID-19 crisis suggest that due to an increasing connectedness between green and financial investments, a smooth transition to a green economy depends on overall financial stability and robust financial markets. Therefore, policymakers on one hand need to ensure the stability of conventional financial markets through robust and inclusive financial policies. While on the other hand there is a need to promote the development of green financial instruments and a green financial ecosystem that meet the financial needs of different investors and boost the confidence of issuers and investors. Lastly, the resilience of green fixed-income investments during turbulent market times provides issuers with a starting point to focus their attention on building fixed income green financial instruments. Consequently, these investments can prove to be a catalyst in bridging the gap between the economic recovery agenda and transition into a green financial ecosystem during the post-COVID times.

Our study has some limitations that open the doors for future studies. We limit our analysis to broader green and conventional indices in fixed income, equity, and commodity markets. Future studies can extend this sample to include regional and country-specific indices. Moreover, future studies can also use sectoral indices for a comprehensive enquiry into the dynamics of conventional and green financial investments. Such analysis may provide more explicit findings of the interdependence between green and conventional investments at the regional/sectoral level. Moreover, we restrict our analysis at the identification of diversifiers and hedgers, future studies may take this investigation one step further by quantifying the diversification and hedging benefits of green financial investments against the conventional counterparts.

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Declaration of Competing Interest

None.

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