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ORIGINAL PAPER

Dynamics of extreme spillovers across European sustainability markets

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Abstract

This study examines the asymmetric spillovers, quantile connectedness, and dynamic inter-dependence structures among the leading European Dow Jones sustainability markets (Belgium, Europe, Finland, France, Germany, Italy, the Netherlands, and Spain). We used the quantile cross-spectral approach of Barunik and Kley (Econom J 22:131–152, 2019) and the quantile connectedness analysis of Ando et al. (Manag Sci, 2022) to achieve our objectives. The results show a positive short-term dependence between European and country-level sustainability markets during bearish and bullish market scenarios. The dependence is higher in the long term than in the short and intermediate terms in bearish markets than that for bullish markets. The return spillover is higher during bearish market conditions than during bullish ones. The sustainability indices of Belgium, Italy, the Netherlands (only at lower quantiles), and Finland are net receivers in the system under bearish and bullish market conditions, whereas the remaining indices are net return transmitters in the system.

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1 Introduction

As the world population grows and the need for higher economic growth becomes inevitable, pressure on conventional energy sources has intensified the degree of global emissions. This has led to severe environmental damage, making climate change an existential threat to life and welfare across countries. Given this state of affairs, the imperative has now become to decouple economic growth from conventional energy use in pursuit of sustainability in all facets of life. For this purpose, the finance-based mechanism has proven to be a vital instrument for advancing the environmental sustainability effort (Irfan et al., 2022; Nekhili et al., 2023). In the case of the European Union (E.U.), which is the most industrialized region in the world, a recent report on greenhouse gas emission inventory revealed that the bloc's emissions in 2021 were 30% lower than those in 1990 (Europe Environment Agency, 2023). Moreover, the European Green Deal is also expected to transform the EU into a resource-efficient economy such that by 2050, there would be zero net emissions of greenhouse gases, with economic growth being decoupled from the use of dirty resources.

Many European countries are already experiencing significant sustainable innovation, green technological development, and sustainable business models. The European Green Deal seems to be the vehicle for these, as it is reportedly known to convey 12 of the 17 Sustainable Development Goals (SDGs) (European Sustainable Development Report, 2021). Except for 2020, when a decline was observed, the SDG index for EU27 rose from 62.9% in 2000 to 71.4% in 2019. One of the contributory factors to this phenomenal growth is underscored by the sustainability performance of firms characterized by environmental, social, governance, and economic (ESG) activities. However, the continuous performance of these firms and their ability to continue to mobilize funds for various sustainability adventures are significantly tied to their associated risks. This determines the level of confidence and investment bias that investors place on firms' stocks. Unfortunately, recent studies have shown that risk transmission is a significant hallmark of modern financial markets in the face of rising globalization and cross-market and cross-country integration (Adekoya et al., 2022; Fasanya et al., 2021; Lucey, 2017). This is particularly important for regional countries, such as the EU, which are characterized by similar economic fundamentals, agreements, and frameworks. In addition, global sustainability markets are still in their early developmental stages and are prone to significant volatility and cross-market shocks. Notwithstanding the special characteristics of E.U. sustainability markets that make them a worthwhile subject of study, among the most pertinent studies in the literature (see inter alia Chen & Lin, 2022: Hasan et al., 2023; Suleman et al., 2023; Wang et al., 2023), no study, to the best of our knowledge, has yet examined these markets in a manner that accounts for their evolution. That is, in a way that considers the dynamic and turbulent nature of these financial markets (Diebold & Yilmaz, 2012).

Against this background, this study aims to examine extreme risk spillovers among the sustainability markets of European countries. We extend the frontiers of knowledge to the existing literature on these three fronts. First, we examined the quantile relationship among European sustainability markets (Europe, Belgium, France, Italy, the Netherlands, Spain, Finland, and Germany) using daily sustainability data from January 2012 to August 2020. This sample period was tempestuous and included different forms of economic, energy, and political crisis/events.

Second, sustainability markets are characterized by episodes of upward and downward movements. Markets have shown asymmetric reactions to different movements due to patterns of connections among markets (Richards et al., 2012). Therefore, we examine the interaction among sustainability markets across different market periods: normal, bull, and bear. Thus, potential investors will be eager to define the position they should hold based on different market statuses.

Third, this study applies the quantile cross-spectral and quantile connectedness methods developed by Barunik and Kley (2019) and Ando et al. (2022), respectively. We consider the quantile cross-spectral approach owing to its flexibility and ability to determine the mean and extreme quantile dependence between markets across different horizons. This method can unilaterally analyze the nonlinear dependence characteristics of markets, as it focuses on the nonlinear relationships across markets through a dependency structure matrix over two, 22, and 250 days.

This study also extends the Diebold and Yilmaz (2012, 2014) approach and Baruník and Křehlík (2018) frequency domain method by incorporating analysis across different quantiles. It examines market connectedness using the traditional mean-based method in both static and dynamic contexts and explores quantile-based spillovers, particularly focusing on tail depedencies. By dopting the quantile regression framework of Koenker and Bassett (1978), VAR models are applied at both lower and upper quantiles to study network spillovers resulting from extreme asymmetric shocks (as discussed by Alomari etal., 2022 Bouri et al., 2020; Jain et al., 2023; Mensi et al., 2023a, 2023b; Rehman et al., 2023). This highlights that systemic shocks, which can be larger than aveage shocks, may have varied impacts across different magnitudes and distributions of shocks (refer to Bouri et al., 2021; Mensi et al., 2021a, 2021b, 2022, 2023c; Naeem et al., 2022; Ramham et al., 2021). The findings suggest that analyzing these extremes yields more insightful results compared to solely focusing on central quantiles through mean-based methods (Pandey & Sehgal, 2018); Meng & Huang, 2019; Bouri et al., 2021.

In the presence of frequent market turbulence, it is important to examine the connectedness among these markets by considering different market conditions and time variations. On the one hand, the quantile-based formulation of the proposed techniques helps capture the behavior of the markets when the market tends to be normal or at extremes (i.e., bearish or bullish). The analysis across different market states is further important for inferring mere risk transmission, contagion effects, and diversification advantages, all of which aid in the effective management of portfolio risks (Mensi et al., 2021c, 2023d). On the other hand, the incorporation of these approaches makes it possible to examine the relationship across different investment horizons, including short-term, medium-term, and long-term. This is another way to ensure optimal portfolio management, as investors have the right knowledge of how markets perform over time.

Foreshadowing our main results, first, the analysis shows the possibility of diversification across frequencies and quantiles. The dependence structure in sustainability markets intensifies across frequencies. Irrespective of the period, the level of the dependence structure is enhanced over longer periods, relative to what we observed in the medium and short run. Second, there are signs of non-uniformity in the connectedness pattern in the right, median, and left tails of the distribution among the European sustainability markets. Third, the shocks to the system of return spillovers around the right- and left-tail conditional distributional quantiles have a greater impact on the return spillovers compared to the shocks evaluated at both the average and 50th percentiles. This implies that spillover indices estimated at either the average or middle conditional distributions do not highlight the level of connection that is characterized by extreme asymmetric shocks. Fourth, the time-varying dynamics of the relative tail dependence (RTD) and the movements between negative and positive values suggest a possible asymmetric pattern in upper and lower tail dependence. Notably, we emphasize the significance of tail dependencies through a time-varying analysis that intensified during major crises. This is especially relevant given that several studies have found that the latest disturbance in the form of COVID-19 particularly affected financial and commodities markets (see Hasan et al., 2021, 2022; Lu et al., 2023; Mensi et al., 2023e; Naeem et al., 2023; Tiwari et al., 2022). For example, Hasan et al. (2022) found that there was a structural change in the connection between commodity markets and several financial market uncertainties during the COVID-19 pandemic.

The remainder of this paper is organized as follows. Section 2 gives a brief account of the most pertinent literature connectedness to sustainability markets. Thereafter, Sect. 3 explains the methodology used in this study. Section 4 describes the data and preliminary analyses, and Sect. 5 presents analysis of the data along with interpretation of the results. Finally, Sect. 6 concludes the study.

2 Brief literature review

Among the most pertinent studies on sustainability markets, Maraqa and Bein (2020) examine time-varying volatility spillover between stainability stock indices, international crude oil prices and major stock returns of European oil-importing and oil-exporting countries using DCC-MGARCH model. They show heterogenous interrelationships between sustainability stock indices and stock market returns. More importantly, the authors demonstrate higher correlation between sustainability stock indices and oil-importing countries whereas oil-exporting economies have higher correlation with the crude oil market. In addition, the correlation between oil and stock markets increases during and after the global financial crisis. conversely, there is insignificant volatility spillover between sustainability stock returns, international oil prices and the major stock markets of oil-importing and -exporting countries. Using a quantile VAR connectedness model, Chen and Lin (2022) examine the tail connectedness among worldwide ESG leaders' equity markets during bearish and bullish market conditions. The authors show significant spillovers among global ESG leaders' equity markets. Moreover, the spillovers among worldwide ESG leaders' equity is higher at extreme quantiles (bear and bull market statuses) than median quantile (tranquil market conditions). In addition, the E.U. and North American markets are the main shock contributors to the global ESG investment market. Finally, the cross-market spillover effects are asymmetric. Using spillover index of Diebold and Yilmaz (2012), Baruník and Křehlík (2018) and Iqbal et al. (2022) examine the asymmetric spillovers among global sustainable investments in the short and long terms. Moreover, the authors examine the impact of global risk factors such as UK and US economic policy uncertainties, US treasury market volatility, stock market volatility, and COVID-19 on the connectedness magnitude. The results reveal significant asymmetric return connectedness among market under study at both short- and long-terms. In addition, France, Germany, Netherlands, and the UK are the larger return shock transmitters in the system. The stock market volatility and COVID19 are the main influential of spillover size in the long run. The US treasury market volatility affects positively (negatively) the spillovers in the short term (long term). The US and UK Economic policy uncertainties intensify the spillover size.

Recently, Suleman et al. (2023) investigate the time and frequency connectedness among European emissions trading system (ETS) and sustainability markets using both Diebold and Yilmaz (2012) and Baruník and Křehlík (2018) spillover index. The results show high connectedness between the carbon price and sustainability index returns. Furthermore, the spillover size is higher at the short term than at the long term. On the other hand, European, France, and Germany sustainability indices are the largest return transmitter of spillover in the system while carbon market are the lowest return shock transmitter towards the system. Hasan et al. (2023) examine the spillovers between green bonds and environmental, social and governance (ESG) markets. Using the spillover index of Diebold and Yilmaz (2012), the authors show weak spillovers among markets under investigation during tranquil and turbulent periods (e.g. COVID-19 and Russia-Ukraine tensions). Using a correlation matrix and Granger causality test, Hasan and Hossain (2022) show that renewable energy consumption and power generation from renewable and waste contribute to green finance growth in Bangladesh. Hassan et al. (2022) examine the time-varying spillover effects between environment-related stocks, commodity and green bond markets. The results show, using wavelet approach, that soybean commodity (Solactive green bond) tends to move positively (negatively) with cryptocurrency environmental attention. In addition, clean energy, sustainability, and Environmental, Social, and Governance (ESG) stock indices commove positively with cryptocurrency environmental attention between 2018 and 2019 at the medium frequency bands. The spillover index results show no significant spillovers from cryptocurrency environmental attention to both commodities, green bonds, and environment-related stocks.

Interestingly, Wang et al. (2023) use the novel interconnected multilayer network framework to account for the connectedness among global stock and foreign exchange markets. Among their primary findings is the observation that stock markets transmit greater spillovers to foreign markets. Moreover, their framework can signal the financial turbulence such as the COVID-19 pandemic. Meanwhile, Okhrin et al., (2023), using the cross-quantilogram, paired vine-based copulas and copula vine-based regression analysis, assess the asymmetric and nonlinear interconnectedness among financial and commodity markets and find that connectedness among these markets increased during the COVID-19 pandemic and the Russia–Ukraine war. Moreover, they find that there is greater dependence in the lower tail which is evidence that there is asymmetry in the connectedness. Similarly, Uddin et al. (2023) find that renewable energy companies' role in the spillover network with other energy firms intensified at the onset of the pandemic.

In consideration of the current body of work on sustainability markets, the present study advances the bounds of knowledge by paying particular attention to European sustainability markets. This is accomplished by examining the dynamic and frequency spillovers among the leading European Dow Jones sustainability markets of Belgium, Europe, Finland, France, Germany, Italy, the Netherlands, and Spain using both the quantile cross-spectral approach of Barunik and Kley (2019) and the quantile connectedness analysis of Ando et al. (2022).

3 Methodology

3.1 Quantile cross-spectral approach

We follow the quantile cross-spectral approach pioneered by Barunik and Kley (2019) to measure the dynamic inter-dependence structure among the return indices of European sustainability markets.

A quantile coherency kernel for two stationary processes X_{t,j_1} and X_{t,j_2} can be written as:

$$\mathrm{K}^{j_1,j_2}\left(\omega;\tau_1,\tau_2\right) := \frac{f^{j_1 j_2}\left(\omega;\tau_{1,}\tau_2\right)}{\left(f^{j_1,j_2}\left(\omega;\tau_{1,}\tau_2\right)f^{j_1,j_2}\left(\omega;\tau_1,\tau_2\right)\right)^{1/2}}, \tag{1}$$

where $-\pi < \omega < \pi$ and $\tau \in [0,1]$, f^{j_1,j_2} are the quantile cross-spectral densities, and f^{j_1,j_1} and f^{j_2,j_2} are the quantile spectral densities of processes X_{t,j_1} and X_{t,j_2}, respectively. These are estimated from the Fourier transform of the matrix of quantile cross-covariance kernels $\Gamma_k\left(\tau_1,\tau_2\right) := \left(\Upsilon_k^{j_1,j_2}\left(\tau_1,\tau_2\right)\right)_{j_1,j_2}$, where

$$\Upsilon_k^{j_1,j_2}\left(\tau_1,\tau_2\right) := Cov\left(\mathrm{I}\left\{X_{t+k,j_1} \le q_{j_1}\left(\tau_1\right)\right\},\mathrm{I}\left\{X_{t,j_2} \le q_{j_2}\left(\tau_2\right)\right\}\right) \tag{2}$$

for $j \in \{1,\dots,d\}$, $k \in Z$, $\tau_1,\tau_2 \in [0,1]$, and $\mathrm{I}\{A\}$ is the indicator function of event A. For continuous cases, this measure corresponds to the difference in the copula of $\left(X_{t+k,j_1},X_{t,j_2}\right)$ and the dependence copula. If $j_1 \neq j_2$, we calculate the coefficients of the cross-sectional dependence. The matrix of the quantile cross-spectral density kernels is defined as:

$$\mathcal{F}\left(\omega;\tau_1,\tau_2\right) := \left(f^{j_1,j_2}\left(\omega;\tau_1,\tau_2\right)\right)_{j_1,j_2=1,\dots,d}, \tag{3}$$

where

$$f^{j_1,j_2}\left(\omega;\tau_1,\tau_2\right) := (2\pi)^{-1}\sum_{k=-\infty}^{\infty}\Upsilon_k^{j_1,j_2}\left(\tau_1,\tau_2\right)e^{-ik\omega}. \tag{4}$$

Following Barunik and Kley (2019), the quantile coherency is obtained from smoothed quantile cross-periodograms. The estimation of quantile coherency matrices is conducted at three quantiles (0.05, 0.50, and 0.95) as well as their combinations. More specifically, three frequencies are corresponding to short-term (2 days), medium-term (22 days), and long-term (250 days).

3.2 Quantile connectedness analysis

In this study, we employ the quantile connectedness approach following Ando et al. (2022), built on the idea of Diebold and Yilmaz (2012, 2014), to examine the quantile transmission mechanism among European sustainability indices. Following Koenker and Bassett (1978), we employ quantile regression to examine the dependence of y_t on x_t at each quantile (q) of the conditional distribution of y_t/x_t. The quantile vector auto regression QVAR(p) can be expressed as:

$$y_t = c(q) + \sum_{j=1}^{p}\Phi_i(q)y_{t-i} + \varepsilon_t(q), \quad \mathrm{q} \in (0,1) \tag{5}$$

where y_t is the vector of $\mathrm{N}\times 1$ endogenous variables, p is the lag length, c(q) is the $\mathrm{N}\times 1$ mean vector, $\Phi_i(q)$ is the $\mathrm{N}\times\mathrm{N}$ QVAR coefficient matrix, and $\varepsilon_t(q)$ indicates the error term with the $\mathrm{N}\times\mathrm{N}$ variance–covariance matrix, $\Sigma(q)$. We estimate $\hat{\Phi}_i$ and $\hat{c}_i$ by assuming that the residuals follow the quantile constraint $Q_q\left(\varepsilon_t(q)|y_{t-1},\dots,y_{t-p}\right) = 0$. The population qth conditional quantile of response y is defined as

$$Q_q\left(y_t|y_{t-1},\dots,y_{t-p}\right) = \hat{c}(q) + \sum_{i=1}^{p}\hat{\Phi}_i(q)y_{t-i} \tag{6}$$

Following the original work of Ando et al. (2022), we construct quantile connectedness matrices for various quantiles. From Eq. (1), we define an infinite-order vector moving average (MA) representation of QVAR(∞) as follows:

$$y_t = \mu(q) + \sum_{i=0}^{\infty}\Psi_i(q)\varepsilon_{t-i}(q), \quad \mathrm{t} = 1,\dots,\mathrm{T} \tag{7}$$

where y_t is defined as the sum of residuals $\varepsilon_t(q)$ at every quantile q. The generalized forecast error variance decomposition (GFEVD) with a forecast horizon H was defined by Koop et al. (1996) and Pesaran and Shin (1998):

$$C_{ij}^{g}(H)=\frac{\sum(q)_{jj}^{-1}\sum_{h=0}^{H-1}\left(e_i'\Psi_h(q)\sum(q)e_j\right)^2}{\sum_{h=0}^{H-1}\left(e_i'\Psi_h(q)\sum(\tau)\Psi_h(q)'e_i\right)}, \tag{8}$$

where $C_{ij}^{g}(H)$ denotes the contribution of the jth variable to the variance of the forecast error of the ith variable at horizon H_t and e_i is a zero vector with unity at the ith position. The normalization of each element in the decomposition matrix is

$$\tilde{C}_{ij}^{g}(H)=\frac{\Theta_{ij}^{g}(H)}{\sum_{j=1}^{k}\Theta_{ij}^{g}(H)},\quad \text{where}\quad \sum_{j=1}^{k}\tilde{C}_{ij}^{g}=1\quad \text{and}\quad \sum_{i,j=1}^{k}\tilde{C}_{ij}^{g}(H)=k \tag{9}$$

Following Diebold and Yilmaz (2012, 2014), various measures of connectedness at the qth conditional quantile can be formulated using GFEVD. Specifically, the total spillover index (*TSI*) measures the total connectedness effect in the entire system at the qth quantile and is specified as follows:

$$TSI(q)=\frac{\sum_{i-1}^{k}\sum_{j=1,i\neq j}^{k}\tilde{C}_{ij}^{g}(q)}{\sum_{i-1}^{k}\sum_{j=1}^{k}\tilde{C}_{ij}^{g}(q)}\times 100 \tag{10}$$

The "TO" directional spillover index from index i to all indices j at quantile (q) is:

$$TO_{i\to j}(q)=\frac{\sum_{j=1,i\neq j}^{k}\tilde{C}_{ji}^{g}(q)}{\sum_{j=1}^{k}\tilde{C}_{ji}^{g}(q)}\times 100 \tag{11}$$

The "FROM" directional spillover index from all indices j to index i at quantile (q) is:

$$FROM_{i\leftarrow j}(q)=\frac{\sum_{j=1,i\neq j}^{k}\tilde{C}_{ij}^{g}(q)}{\sum_{j=1}^{k}\tilde{C}_{ij}^{g}(q)}\times 100 \tag{12}$$

The "NET" directional spillover index at quantile (q) is:

$$NET_i(q)=TO_{i\to j}(q)-FROM_{j\leftarrow i}(q) \tag{13}$$

A positive (negative) value of $NET_i(q)$ indicates a net transmitter (net recipient) from the other markets. Practically, the quantile connectedness index is estimated using a QVAR with a lag order of four (selected based on the Bayesian information criterion) and a forecast horizon of 10. We adopt a 200-day rolling window to estimate the dynamic connectedness at the quantiles.

4 Data and preliminary analysis

4.1 Data

This study considers the Dow Jones sustainability indices (DJSI) for European countries—Belgium, Europe, Finland, France, Germany, Italy, Netherlands, and Spain. We note that the DJSI was launched in 1999 and represents a reference for investors who have recognized that sustainable business practices are critical to generating long-term shareholder wealth and wish to reflect their sustainability convictions in their investment portfolios. The DJSI covers 20% of the 600 largest European companies in terms of sustainability. The DJSI Europe assesses the financial performance of sustainability leaders in smaller Eurozone regions. All daily sustainability data were obtained from Thomson Reuters DataStream between January 2, 2012, and August 24, 2020. The sample period is representative of studying the linkages among sustainability indices as it includes major economic and political events (e.g., the integration of Croatia in the European Union's July 2013, oil price crash in mid-2014, 2016 economic slowdowns in China, the 2016 US presidential election, Brexit in mid-2016, and the COVID-19 pandemic, among others). Figure 1 displays the time variations of the European sustainability indices. As we can see, the Europe index experiences two important structural breaks. Specifically, we observe an increase in the Europe index from 2012 to 2014, followed by a sudden drop in mid-2014 and an increase until the end of 2019; thereafter, the index decreased in early 2020 due to the effects of COVID-19. We observe a common downward pattern for all indices during the pandemic crisis as well as during the oil price crash in mid-2014.

To calculate the continuously compounded daily returns, we take the difference between the log values of two consecutive prices. Figure 2 presents the return dynamics of the sustainability indices. We find evidence of volatility clustering and fat tails, mainly in 2016 and early 2020. These stylized facts are evidence of nonlinear behavior in DJ sustainability indices. Therefore, it is more appropriate to employ nonlinear methods to investigate the linkages among the European DJSI.

4.2 Descriptive statistics

Table 1 shows the results of the descriptive statistics of the DJSI returns for European countries. A closer look at the means of sustainability returns suggests that positive average returns are indicated, except for Spain. Belgium and the Netherlands exhibited the highest returns, whereas Spain had the lowest. Finland has the riskiest returns, followed by Italy at 1.607 and 1.565, respectively, whereas Germany is the least volatile market, indicating that outlying effects do not significantly influence the mean values. Most importantly, the European market is relatively less volatile. A graphical inspection of the sustainability indices corroborates the return series plotted in Fig. 2. It is not surprising that the Jarque–Bera test rejects the null hypothesis of normal distribution for all return series, following the reports of both the skewness and kurtosis statistics. While the skewness values are asymmetric

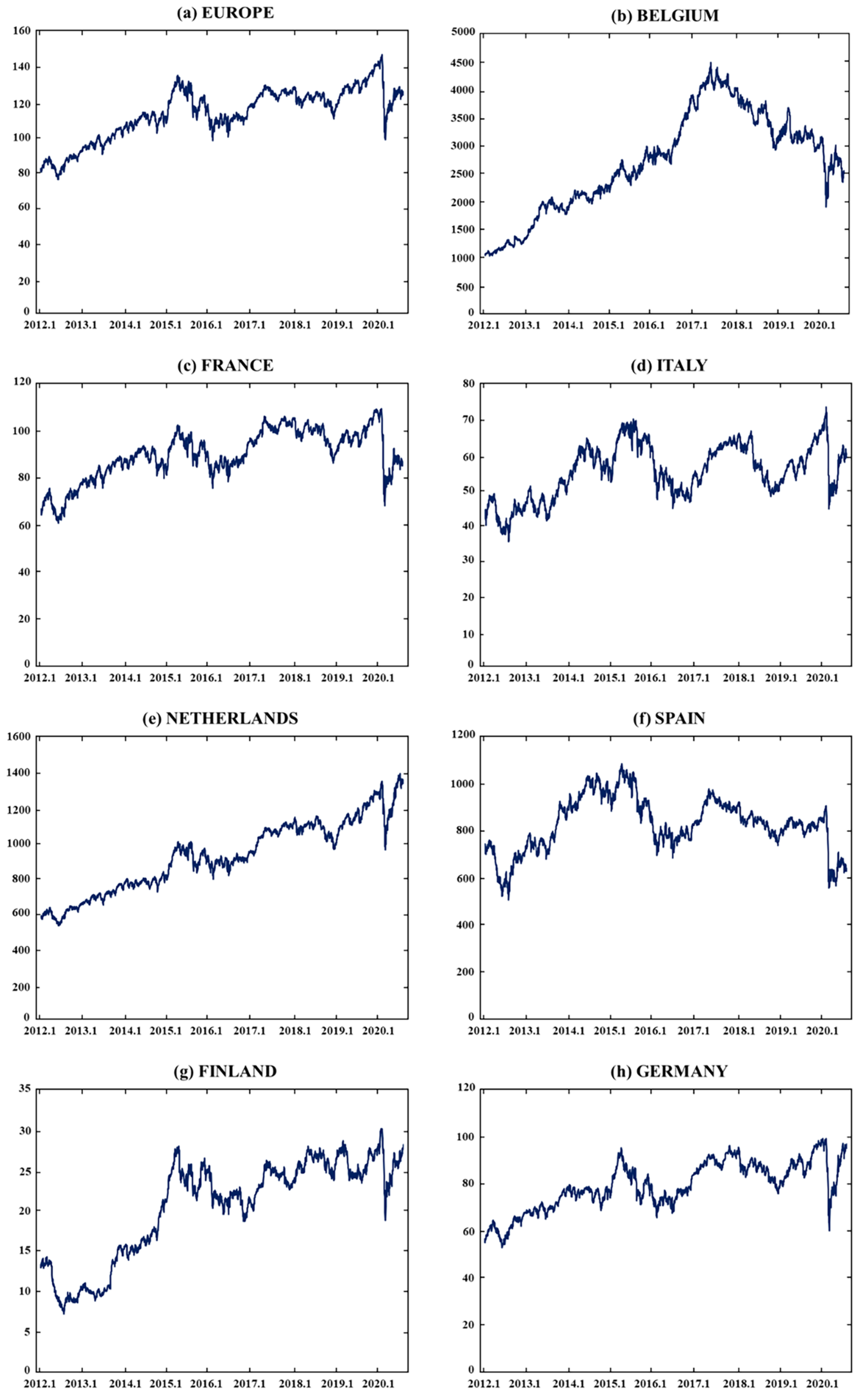


Fig. 1 The European sustainability indices

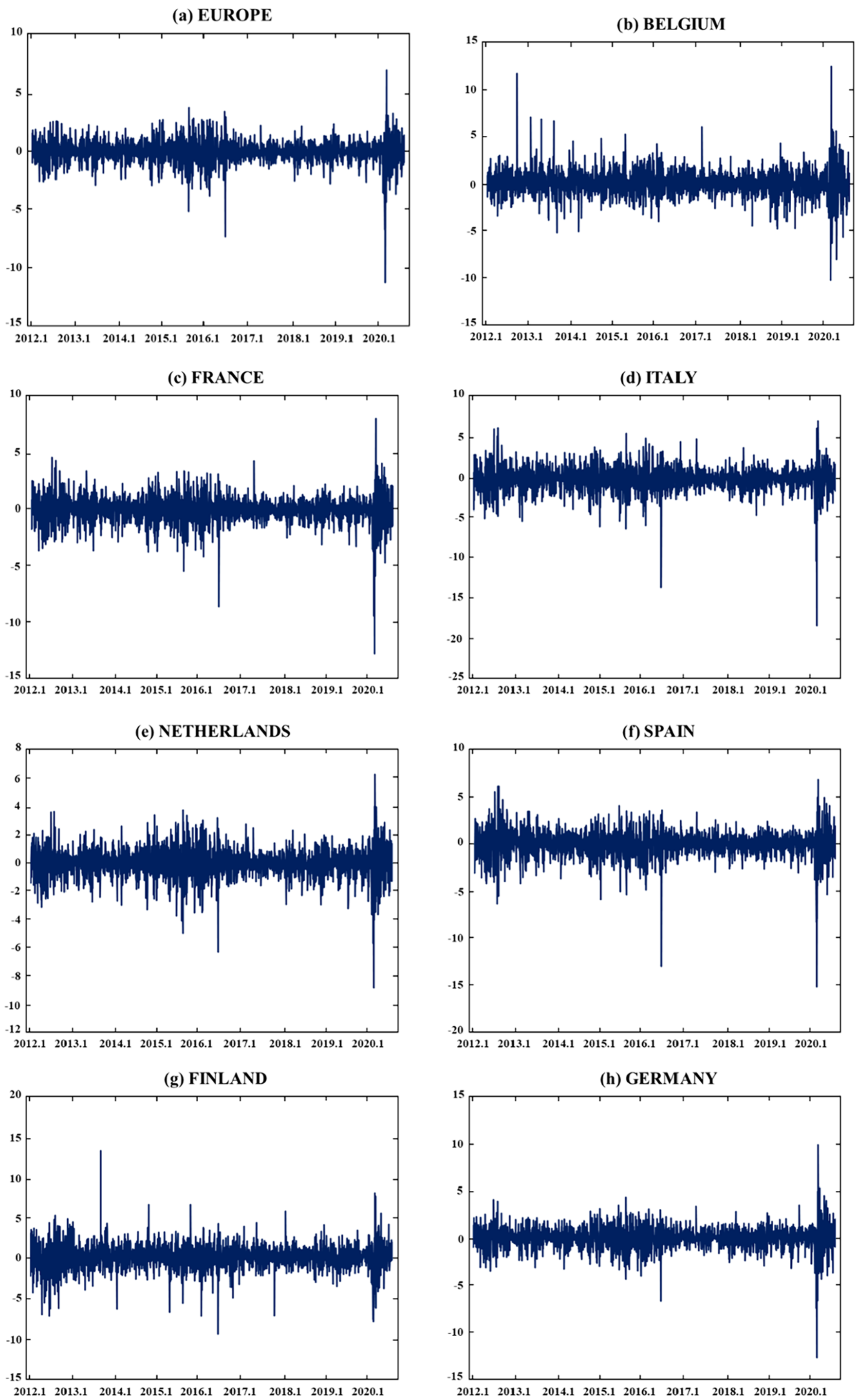


Fig. 2 Daily returns of European sustainability indices

Table 1 Summary of descriptive statistics

	Europe	Belgium	France	Italy	Netherlands	Spain	Finland	Germany
Mean (%)	0.0200	0.0404	0.0126	0.0141	0.0393	− 0.0068	0.0351	0.0256
Max	7.3737	13.156	8.6031	7.7126	6.7057	7.2252	13.921	10.447
Min	− 11.702	− 10.881	− 13.47	− 19.173	− 9.3052	− 15.845	− 10.103	− 13.471
Std. Dev	1.0107	1.433	1.2212	1.5656	1.0778	1.4253	1.6075	1.2148
Skewness	− 1.1066	0.4228	− 1.0189	− 1.2418	− 0.5223	− 1.1593	− 0.1531	− 0.7493
Kurtosis	16.15	12.52	15.15	17.90	8.559	15.89	9.402	14.89
Jarque–Bera	16,730.***	8603.4***	14,288.***	21,448.***	3007.4***	16,132.***	3862.***	13,514.***
Q (20)	45.46***	48.81***	36.98**	41.80***	26.42	40.46***	14.14	42.11***
ADF	− 26.59***	− 27.20***	− 26.65***	− 26.78***	− 26.76***	− 27.30***	− 26.67***	− 25.70***
KPSS	0.0835	0.5397	0.1102	0.0385	0.0220	0.1202	0.0819	0.0460

This table summarizes the basic statistics of sustainability stock index returns, the Ljung–Box test (Q(20)) for the autocorrelation of returns series, ADF unit root test of Dickey and Fuller (1979) and KPSS stationary test of the Kwiatkowski et al. (1992)

*** and ** indicate that the significance at the 1% and 5% levels, respectively

Table 2 BDS impudence test

Dimension	Europe	Belgium	France	Italy	Netherlands	Spain	Finland	Germany
2	0.0231*** (0.0020)	0.0147*** (0.0018)	0.0183*** (0.0020)	0.0171*** (0.0019)	0.0157*** (0.0019)	0.0194*** (0.0019)	0.0142*** (0.0019)	0.0118*** (0.0019)
3	0.0445*** (0.0032)	0.0298*** (0.0029)	0.0392*** (0.0032)	0.0314*** (0.0030)	0.0324*** (0.0031)	0.0396*** (0.0031)	0.0257*** (0.0029)	0.0262*** (0.0031)
4	0.0619*** (0.0039)	0.0373*** (0.0034)	0.0568*** (0.0038)	0.0433*** (0.0035)	0.0477*** (0.0037)	0.0556*** (0.0037)	0.0337*** (0.0035)	0.0390*** (0.0037)
5	0.0716*** (0.0041)	0.0398*** (0.0035)	0.0677*** (0.0039)	0.0500*** (0.0037)	0.0567*** (0.0038)	0.0661*** (0.0039)	0.0384*** (0.0036)	0.0466*** (0.0038)
6	0.0758*** (0.0039)	0.0397*** (0.0034)	0.0725*** (0.0038)	0.0533*** (0.0039)	0.0605*** (0.0037)	0.0706*** (0.0038)	0.0403*** (0.0035)	0.0506*** (0.0037)

***Significance at the 1% level

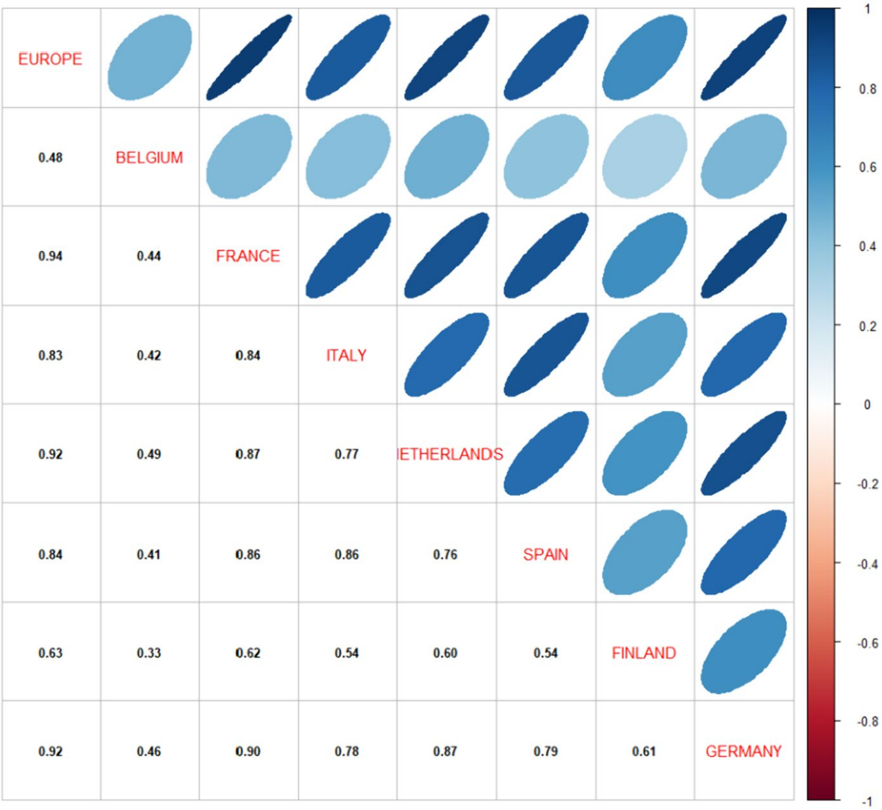


Fig. 3 Pairwise correlation among European sustainability returns

except for Belgium, their kurtosis estimates are leptokurtic and exceedingly larger than the standard threshold. This suggests the presence of extreme fluctuations in European sustainability markets, justifying the need to study extreme connectedness

Fig. 4 Cross-quantile coherency matrix. Notes: This Fig. presents the quantile coherence matrices for **a** the short term (2 days), **b** the medium term (22 days), and **c** the long term (250 days). Coherence appears to intensify from the short term to the long term, showing stronger dependencies among assets in the long term

and consider any form of nonlinearity in these return spillovers. Interestingly, we observed stationarity in the returns according to the conventional ADF unit root test (1979) and the stationarity test of the KPSS (1982). There is evidence of serial correlation for almost all the return series.

We present the results of the BDS test developed by Brock et al. (1996) to investigate the possible non-linearity in the time series. From Table 2, we observe that all the sustainability markets are non-linear. We are therefore justified in using quantile-based methodologies.

Furthermore, Fig. 3 shows the pairwise unconditional correlation between the returns of the sustainability indices. As shown in the matrix, it is evident that the correlations among the European sustainability markets are positive, with the Europe–France pair, which characterizes the highest association with the Belgium–Finland pair, exhibiting the least degree of correlation. The degree of association within country sustainability indices is relatively high, except for the pairing of Belgium and other European countries, where we find a moderate positive correlation between Belgium and other European sustainability markets, indicating opportunities for diversification. The upper-right quadrant in Fig. 3 corresponds to intergroup correlations, indicating an association that is non-significant among the sustainability markets, implying potential evidence of portfolio diversification.

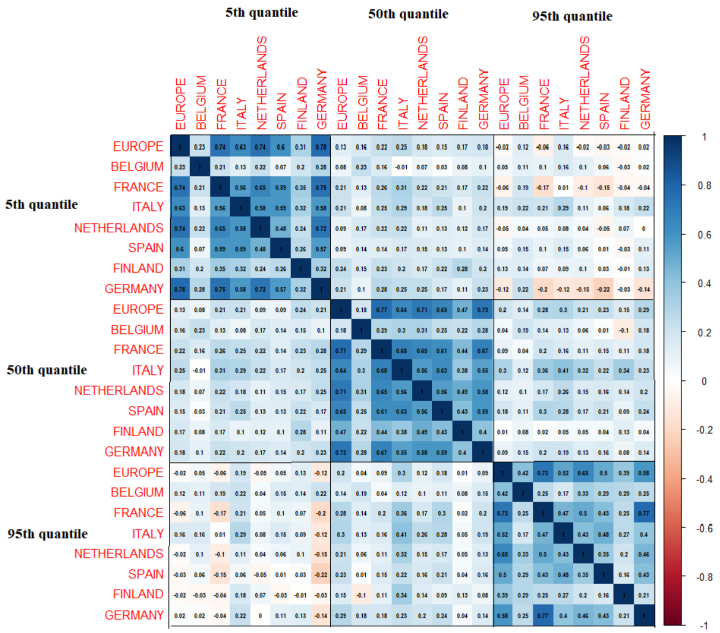
5 Empirical results

5.1 Quantile cross-spectral analysis

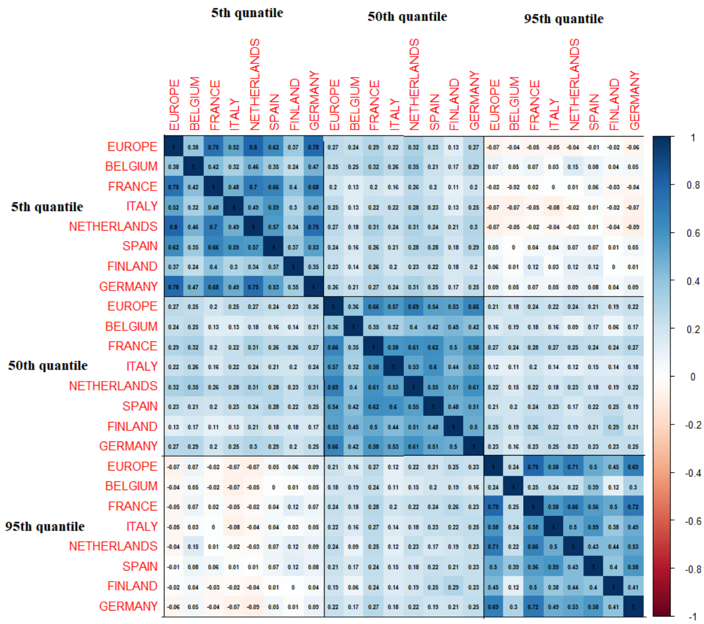
The quantile relationships among European sustainability markets are estimated through the quantile cross-spectral framework across three sets of quantiles (5th, 50th, and 95th) under three different time periods: short term (2 days), medium term (22 days), and long term (250 days). To allow for asymmetries across European sustainability markets, this framework extracts information on the dependence structure between extremely positive and negative sustainability market returns. We characterize the results for three different time horizons in relation to each range of quantiles in Fig. 4a–c, respectively.

A closer inspection of the quantile coherency matrices shows that they are symmetrical in nature. For example, as shown in Fig. 4a, the short-term quantile cross-spectral dependence of 0.18 between Italy and Finland sustainability markets in the upper-right submatrix, which characterizes the Bullish-Bearish market region (0.95|0.05 quantiles), is similar to that of the Bearish-Bullish market space in the lower-left submatrix (0.05|0.95 quantiles), as both submatrices are consistent with the connection between the extreme negative market returns for Italy and

(a) Short-term



(b) Medium-term



(c) Long-term

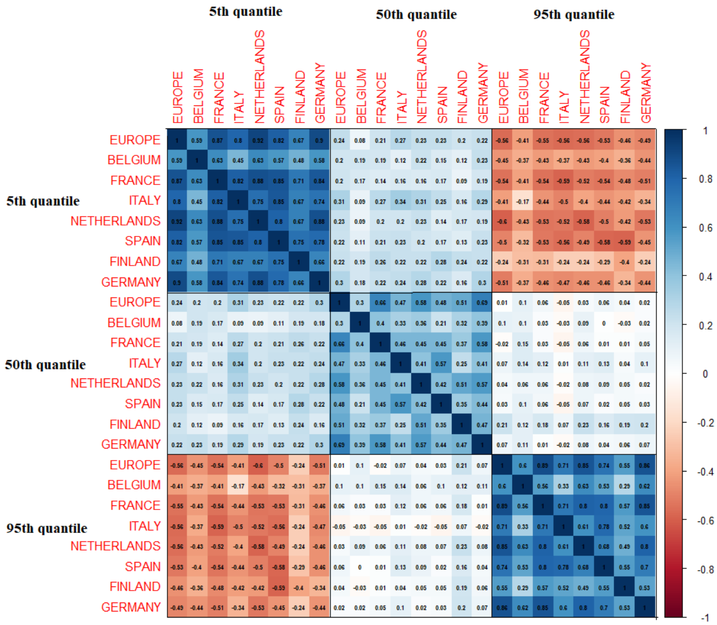


Fig. 4 (continued)

the extreme positive market returns for Finland. At a more specific level, the short-term quantile coherency matrix shows a positive dependence between Europe and the country-level sustainability markets in both the lower tail (0.05| 0.05 quantiles) and the upper tail (0.95| 0.95 quantiles). Interestingly, there is a high correlation between Europe and country-level markets; however, there is a higher dependence in the lower quantile relative to the upper quantile, with the exception of Belgium and Finland, suggesting evidence of contagion effects and the recoupling hypothesis (Mensi et al., 2021b). In addition, we observe a symmetric connection with coherency of 0.56 and 0.47 between France and Italy with extreme negative and positive returns respectively. Therefore, the French market was not a good candidate for the Italian market. This is a result of both markets being highly dependent and integrated into the larger European market, likely due to the homogeneity of both markets. In addition to the connectedness between the French and Italian markets across Europe, there are other eye-catching findings. First, other European markets share joint co-movement. Under the pairwise correlation among European sustainability returns, we find a high correlation between the Netherlands and Germany (0.87). Similarly, when both the Netherlands and Germany record extreme negative returns (0.05|0.05 quantiles), the coherency is 0.72. When both record extreme positive returns (0.95|0.95 quantiles), coherency is 0.46. In the median dependence (0.50|0.50 quantiles), coherency was 0.58. Thus, these two sustainability markets are connected to some extent in the short term irrespective of the current market situation. Another interesting observation is that all markets are positively dependent on one another during bear, normal, and bull market periods, suggesting that all markets crash simultaneously. The findings show that market pairs move in the same direction across quantiles. This explains the transmission effect from Europe to individual markets and corroborates the contagion effects that may likely exist among European sustainability markets. Intuitively, when market volatility increases, other markets also rise. This finding has implications for portfolio investors.

The behavior of the European sustainability markets in the medium term is characterized in Fig. 4b as the dependence between the markets increases for almost all market pairs relative to what we observed in the short term. In the 0.05|0.05 quantiles, the dependence between Europe and the country's markets is significantly positive in both time horizons; however, the Italian and German sustainability markets show otherwise. In the Italian market, timing significantly affects the dependence structure by 0.11 while no significant changes are observed in the German sustainability market. A similar result is observed at the (0.95|0.95 quantiles) where the distributions are positive and increase for both periods except for Belgium (decrease) and Spain (constant). In addition, the time factor has been observed to be a major determinant of the mode of dependence between sustainability markets. There is greater evidence for diversification strategy options for the markets in bull-bear quantiles between Europe and the other markets compared to the short term, where Belgium, Italy, and Germany are positive under this submatrix. This indicates that all markets that exhibit extreme positive returns in Europe are negatively connected with the extreme negative returns of individual countries' sustainability markets. Hence, diversification strategies are always an option for risk-loving or medium-term spectators.

The long-term quantile cross-spectral result is displayed in Fig. 4c, which shows the dependence structure between the European sustainability markets for 250 days. Coherence appears to intensify from the short term to the long term, showing stronger dependencies among European sustainable markets in the long term. The upper-right submatrix (0.95|0.05 quantiles) and the space at the lower-left submatrix (0.05|0.95 quantiles) are much more colorful, that is, from a longer-term perspective, more coherencies are significant. These submatrices are full of negative coherencies, indicating that the relationships are symmetric between the sustainable markets and that the association between the two extreme (positive and negative) returns of the markets is inversely related. Similar to the short- and medium-term quantile matrices, the dependence structure between the sustainability markets over the long term is positive across the diagonals of the quantiles (bear-bear, normal-normal, bull-bull) and, interestingly, for the two cross diagonals on bear-normal quantiles. In addition, we observe independence between Spain and Belgium in a bull-normal market state, and since there is a symmetric relationship, the same exists along the normal-bull market matrix for both sustainable markets. In contrast, the dependence between Europe and each country's markets is greater in the longer horizon than in the short and medium time horizons, irrespective of the market states. This is expected given that various centralized policies may have the effect of preventing any drift in the long term even if there are deviations among the countries in the short term. We also observe a superior dependence among the sustainability market pairs in the long term around the (0.5|0.95 quantiles) market than in the (0.05|0.95 quantiles) state. For this reason, long-term oriented portfolio managers, investors, and market spectators may need to meticulously monitor the bull-bear (upper right quadrant)/ bear-bull (lower left quadrant) quantile coherence structure and where negative inter-dependence is observed. This provides evidence of diversification options among sustainable market pairs when extremely low returns are negatively associated.

5.2 Analysis of time domain and quantile total connectedness index

5.2.1 Conditional mean spillover

Our analysis starts with Diebold and Yilmaz (2012, 2014), connectedness model, calculated at the condiitional mean. Table 2, panel A, details return spillovers for sustainability indices using an 8-variable, second order VAR with 10-step-ahead forecasts over the entire sample period. France emerges as the most influential country in terms of contributing to the forecast error variance of Europe's sustainability returns, with a sigificant figure of 18.81, followed by Germany at 15.16. This suggests that shocks originating in France are more impactful on European sustainability returns that those from other key sustainability markets in Europe. Conversely, Belgium shows the least impact on other European sustainability markets with the smallest contribution of 26.9 to overall spillovers and the highest proportion of sustainability returns being self-explained at 57.5. In contranst, Europe, France, and Germany exhibit the highest levels of return spillovers from other markets, marked at 82.2, 81.1, and 81 respectively. With the exception of Belgium and Findland, which have negative net spillover values of -30.6 and 24.1 respectively, all other sustainability indices are net contributors of returns, indicating their roles as net transmitters. The Total Spillover Index (TSI) noted in Panel A of Table 2 is 76.4%, highlighting that over three-quarters of the total variance in forecast errors is due to inter-index shocks, with the remaining 23.6% attributed to individual shcoks. The high values in both total and directional spillover indices underline the significant presence of return spilovers across thes European sustainablily markets.

5.2.2 Quantile connectedness analysis

Panel B of Table 3 presents the estimated quantile spillover measures for the 50th percentile (q = 0.5). This result, along with the conditional mean spillover, is used as a point of reference in comparing the spillover results at the 5th and 95th quantiles. In Panel B, there is evidence of a high degree of connectedness in network spillovers among the sustainability markets, which is relatively similar to the spillover index of mean-based connectedness in Panel A. Overall, the total spillover index of the conditional mean remains at 76.40%, which is marginally higher than the 75.23% observed for the conditional median. To this end, we examine the system of return

Table 3 Total spillover table based on the DY spillover index and the quantile VAR methods

	Europe	Belgium	France	Italy	Netherlands	Spain	Finland	Germany	FROM
Panel A: DY spillover method									
Europe	17.8	4.09	15.81	12.38	14.95	12.71	7.1	15.16	82.2
Belgium	9.9	42.51	8.53	7.83	10.18	7.43	4.48	9.13	57.5
France	16.2	3.61	18.24	12.83	13.82	13.35	7	14.94	81.8
Italy	14.38	3.77	14.51	20.69	12.41	15.22	6.31	12.7	79.3
Netherlands	16.32	4.66	14.72	11.67	19.43	11.32	7.07	14.82	80.6
Spain	14.71	3.49	15.08	15.2	12	20.6	6.15	12.78	79.4
Finland	12.38	3.25	11.95	9.43	11.34	9.33	30.61	11.71	69.4
Germany	16.19	4.07	15.57	11.7	14.5	11.79	7.19	19	81
TO	100.1	26.9	96.2	81	89.2	81.1	45.3	91.2	611.1
All	117.9	69.4	114.4	101.7	108.6	101.7	75.9	110.3	**TSI: 76.40%**
NET	17.9	− 30.6	14.4	1.7	8.6	1.7	− 24.1	10.2	
Panel B: Quantile (median quantile q = 0.5)									
Europe	19.23	5.49	15.66	11.18	14.5	12.21	6.75	14.99	80.77
Belgium	10.52	37	9.75	8.05	10.68	8.5	5.96	9.55	63
France	16.2	5.31	19.99	11.56	13.47	12.68	6.39	14.41	80.01
Italy	13.62	5.02	13.44	23.89	11.77	14.87	5.78	11.61	76.11
Netherlands	16.06	6.15	14.37	10.51	21.07	11.17	6.59	14.08	78.93
Spain	14.24	5.15	14.2	14.23	11.96	22.35	5.92	11.95	77.65
Finland	11.87	5.53	10.67	8.23	10.35	8.85	33.75	10.76	66.25
Germany	16.36	5.49	15.09	10.43	13.99	11.13	6.64	20.88	79.12
TO	98.87	38.13	93.17	74.18	86.7	79.41	44.03	87.35	601.85
All	118.1	75.13	113.15	98.07	107.78	101.76	77.78	108.23	**TSI: 75.23%**
NET	18.1	− 24.87	13.15	− 1.93	7.78	1.76	− 22.22	8.23	
Panel C: Quantile (lower quantile q = 0.05)									
Europe	14.66	10.68	13.44	11.98	12.67	12.34	10.6	13.64	85.34
Belgium	12.66	15.97	12.31	11.83	11.84	11.98	10.9	12.51	84.03
France	13.7	10.81	14.46	12.18	12.14	12.57	10.48	13.67	85.54
Italy	12.68	11.2	12.87	14.96	11.85	13.05	10.47	12.92	85.04
Netherlands	13.68	10.92	12.96	11.96	14.02	12.27	10.75	13.44	85.98
Spain	12.97	10.97	12.89	12.69	12.11	15.11	10.33	12.94	84.89
Finland	12.47	11.33	12.5	12	11.69	12.26	14.98	12.78	85.02
Germany	13.44	11.09	13.2	11.96	12.39	12.21	10.76	14.95	85.05
TO	91.6	77	90.16	84.6	84.68	86.68	74.28	91.89	680.9
All	106.25	92.97	104.62	99.56	98.7	101.79	89.26	106.84	**TSI: 85.11%**
NET	6.25	− 7.03	4.62	− 0.44	− 1.3	1.79	− 10.74	6.84	

Table 3 (continued)

	Europe	Belgium	France	Italy	Netherlands	Spain	Finland	Germany	FROM
Panel D: Quantile (upper quantile q = 0.95)									
Europe	14.47	10.9	13.13	11.63	13.04	12.42	10.93	13.5	85.53
Belgium	11.8	17.14	11.74	11.31	12.17	12.12	11.48	12.23	82.86
France	13.19	11.08	14.49	11.77	12.65	12.61	10.88	13.34	85.51
Italy	12.5	10.93	12.41	15.25	12.39	13.25	10.75	12.5	84.75
Netherlands	13.05	11.55	12.52	11.63	15.12	12.43	10.83	12.85	84.88
Spain	12.57	11.32	12.7	12.67	12.31	15.26	10.58	12.6	84.74
Finland	12.34	11.27	11.8	11.2	12.39	11.98	16.61	12.41	83.39
Germany	12.98	11.21	12.88	11.53	12.84	12.24	10.73	15.59	84.41
TO	88.45	78.24	87.18	81.74	87.8	87.05	76.18	89.43	676.06
All	102.91	95.39	101.67	97	102.92	102.31	92.79	105.02	**TSI: 84.51%**
NET	2.91	− 4.61	1.67	− 3	2.92	2.31	− 7.21	5.02	

The bold letter "TSI" is Total Spillover Index

Total spillover table is estimated by a DY spillover method and a quantile VAR model with lag length of order 1 (BIC) and a 10-step-ahead forecast

spillovers in both the lower and upper tails to differentiate between extreme positive and negative shocks.

The return spillovers of tail connectedness for both the lower quantile (q = 0.05) and upper quantile (q = 0.95) are reported in Table 3 under Panels C and D, respectively. We observe that the spillover indices in the 5th and 95th quantiles are relatively greater than those in the average and middle quantiles. The TSI for the left (q = 0.05) and right (q = 0.95) tails of the conditional distribution are 85.11% and 84.51%, respectively, compared with only 76.40% for the conditional mean and 75.23% for the middle quantile. These findings show a greater effect of extreme negative/positive shocks on the connectedness matrix. Specifically, it is clear that the contributions to and from the others in the lower and upper quantiles are stronger than those of the median quantile and conditional mean. In addition, the givers and receivers of shocks are similar across the quantile connectedness except for the Netherlands market with a net receiver in the lower quantile, but different from the conditional mean results in Panel A. Interestingly, the Belgium and Finland sustainability markets are both net receivers across all connectedness measures. We observe stronger connectedness at the 5th quantile than at other quantile horizons, as expected, because stronger connectedness is observed among financial markets during financial tensions relative to calm periods (Ang & Bekaert, 2002). However, the variation in the TSI between the left/right tails and the conditional median (Fig. 5) shows evidence of high connectedness in both the 5th (0.05) and 95th (0.95) quantiles, indicating that the degree of network spillovers increases with the magnitude of the shock for both signs (positive/negative) of extreme shocks. This corroborates the findings of Londono (2019) on contagion in extreme events in both

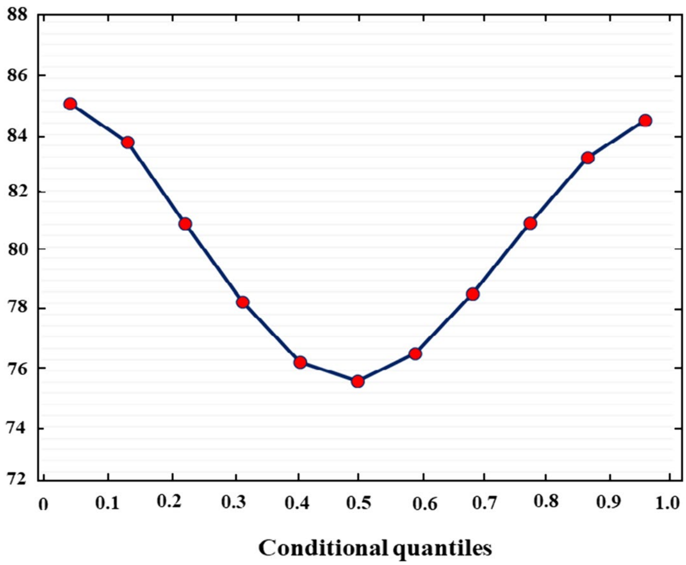


Fig. 5 Variation in the total spillover index across various conditional quantiles

the right- and left-tail quantile distributions. From this perspective, Fig. 5 highlights that larger shocks affect the system of spillovers, and the interaction among the sustainability indices increases the propagation of risk spillovers in sustainability markets. Along the different percentile points, the TSI for 0.05, 0.1, 0.09 and 0.95 reaches 85.11%, 83.84%, 83.45%, and 84.51%, respectively. The variation in TSI between the extreme left and right tails appears symmetric in nature; however, this may not be true in every scenario. This can be captured in our next section through the rolling window analysis, which supports previous findings that larger shocks are stronger than smaller shocks (Dendramis et al., 2015).

5.3 Analysis of time-varying connectedness analysis

In this section, we analyze the time-varying characteristics of return spillovers among European sustainability markets using quantile VAR-based rolling window analysis for a fixed window length of 200 days and a 10-step forecast horizon. This is used to analyze the variation in time across the connectedness spillovers over different forms of conditional distribution ranging from the mean, median, and the two extreme (upper/lower) quantiles. We have previously shown evidence of non-uniformity in the degree of connectedness across different quantiles, especially between the right/left tails and the median quantiles. The implication is that connectedness indices estimated at the conditional distribution of either the average or middle quantile do not highlight the level of connection that is characterized by extreme positive and negative shocks (Bouri et al., 2020, 2021; Mensi et al., 2021a, 2021b). Pictorial results for the time-varying TSI for both the mean and median distributions

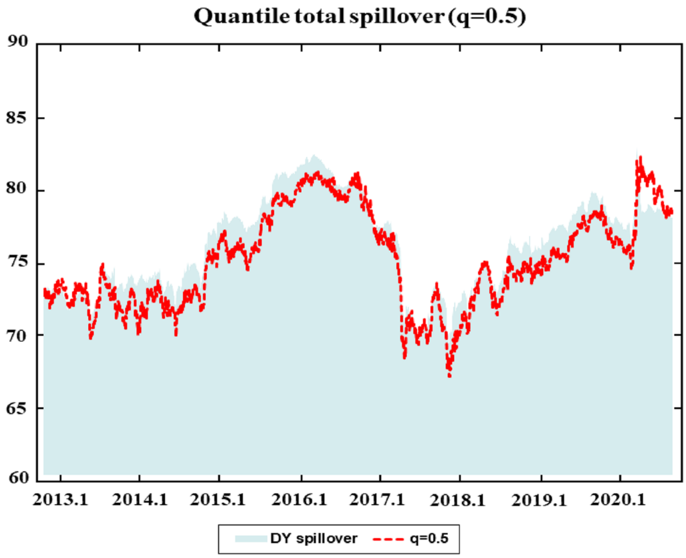


Fig. 6 DY spillover and quantile VAR methods (median quantile q = 0.5). Notes: The dynamics of the total spillover index (TSI) are computed based on a rolling window of 200 days and 10 step-ahead forecast horizon

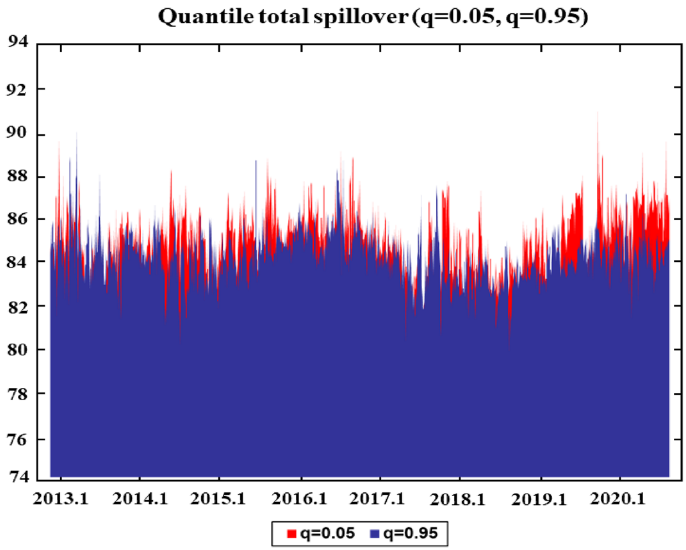


Fig. 7 Total spillover in the quantile VAR (extreme lower quantile q = 0.05 and extreme upper quantile q = 0.95)

are shown in Fig. 6. Both indices follow similar patterns and vary considerably, ranging from 67 to 82%. Meanwhile, the TSI for both the 95th and 5th quantiles, as shown in Fig. 7, is much higher but fluctuates less, ranging between 80.5 and 91%.

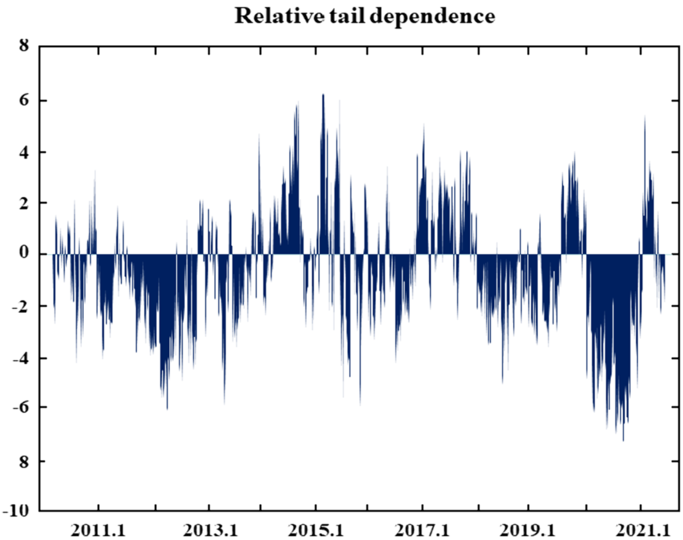


Fig. 8 Relative tail dependence ($TSI_{q=0.95} - TSI_{q=0.05}$). Notes: This figure shows the RTD, calculated as the difference between the TSI at the 95th and 5th quantiles. A negative (positive) value indicates a strong dependence on the lower (upper) quantile

The uniformity in the large degree of connectedness in the TSI at both the right and left tails suggest an increase in the sensitivity of the sustainability indices to both extreme positive and extreme negative shocks. Intuitively, the extremity of the shock is uniquely vital during normal market conditions and does not matter significantly during extreme market conditions. This corroborates the findings of Betz et al. (2016), which reiterates that the significance of network and tail dependencies in extreme risks is more relevant than simple (mean) correlations in the surveillance and regulation of financial systems. We observe that possible positive (negative) changes along the right-tail connectedness correspond to positive (negative) changes in the left-tail connectedness.

Next, we evaluate the potential asymmetry in the lower and upper quantiles, as shown in Fig. 8, by estimating the relative tail dependence RTD ($TSI_{q=0.95} - TSI_{q=0.05}$). This measure reflects the degree of connectedness, with positive values indicating stronger connectedness and negative values indicating weaker connectedness. The time-varying analysis of the RTD and the movements between negative and positive values suggest a possible asymmetric pattern in upper and lower tail dependence. We observe spikes in the value of the RTD, which characterizes strong dependence in the upper quantile (positive/good spillovers) prevailing around 2014, slightly in mid-2015, and conspicuously between 2017 and early 2018. Positive values suggest that the strength of dependence is higher in the upper quantile than in the lower quantile. An increase in relative tail dependence implies a greater sign of connectedness fragility (Bouri et al., 2021). Nevertheless, evidence of weaker connectedness (bad spillovers) coincides with major crisis periods around the European debt crisis (2011–2013), the global oil crisis, and the Brexit

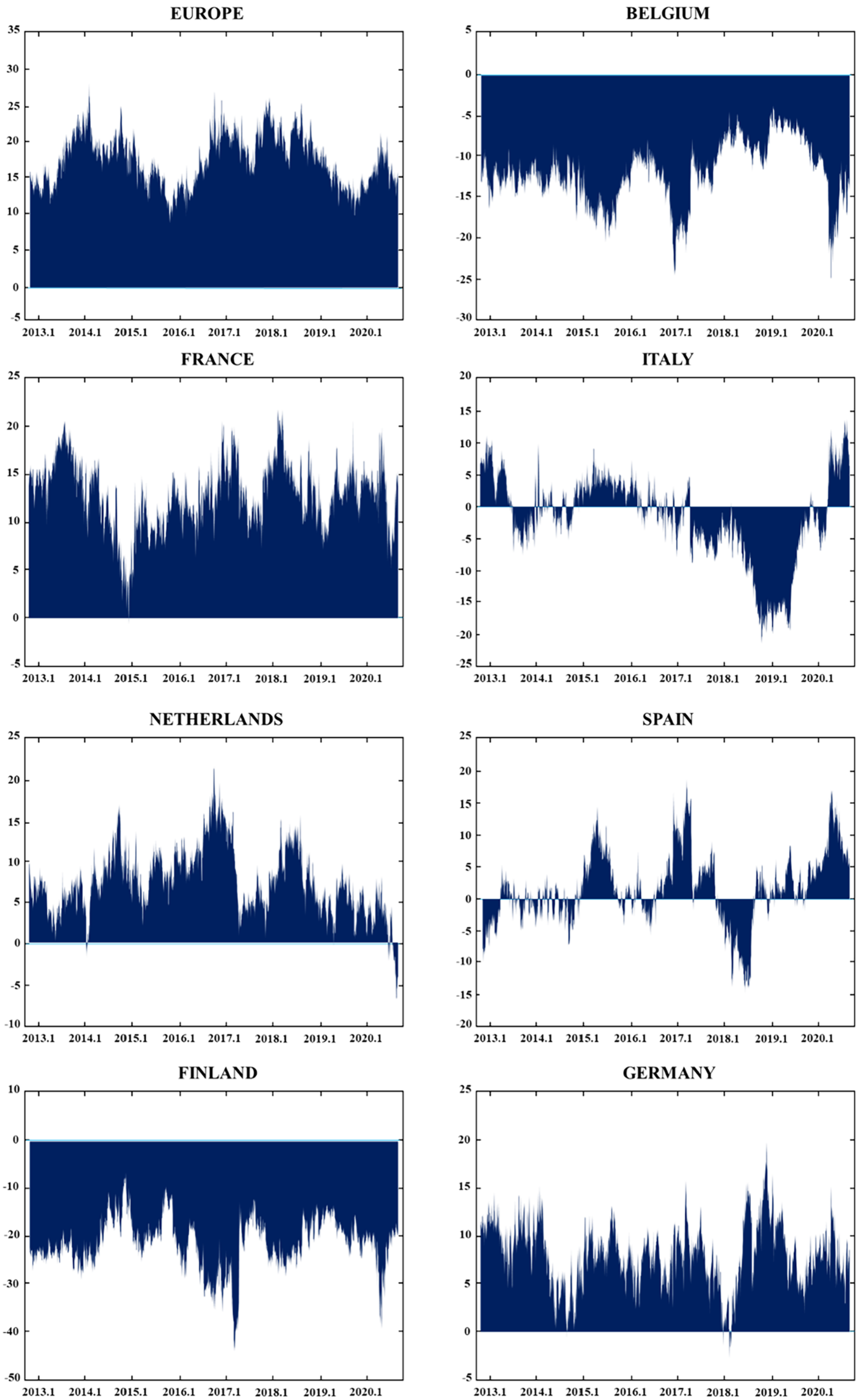


Fig. 9 Net spillovers in quantile VAR (median quantile q = 0.5)

referendum (late 2018–2019, which corresponds to the second half of the crises), and it becomes more prominent around 2020–2021 which defines the COVID 19 global pandemic. Unlike positive values, a reduction in connectedness fragility indicates that the strength of dependence is weaker in the upper quantile than in the lower quantile. After the troughs, the RTD switched between positive and negative values at the end of the sample period. Notably, periods of rising fragility, related to strengthening the propensity for negative shocks to dissipate, are also periods of increased tendency for the dissipation of positive shocks, and vice-versa. This may be due to the behavior of investors and other market participants. Investors and participants in sustainability markets rely on the propagation of extreme events at both the upper and lower quantiles by focusing on other events happening in that quantile with reference to happenings in other quantiles.

Figure 9 presents the results for the net spillovers in the quantile VAR estimates at the conditional median. Taking a closer look at spillover patterns, we observe three categories of sustainability markets. The first category highlights the predominant net transmitters (givers) of returns, indicating positive net spillovers for the entire sample period, such as Europe, France, Netherlands, and Germany. The second set indicates sustainability markets that are primarily net receivers of return spillovers such as Belgium and Finland. The third group reflects markets that switch intermittently over the sample period; they are often displayed as net givers (transmitters) of return connectedness, and at other periods act as net receivers in the system of connectedness spillovers. For example, we observe that the Italian sustainability market was a net recipient of spillovers from 2016 to 2020, which coincides with the oil crisis and Brexit and the early part COVID 19 pandemic crisis, before becoming a shock transmitter to the other markets within the zone after 2020. However, there were periods of switching between positive and negative spillovers across the sample period. The other market that falls into this category is the Spanish market, which happens to be a net transmitter of return spillovers for most of the sample period with the exemption of some periods of net recipients of spillovers that correspond with the European debt crisis of 2011–2013, the oil market crisis, and the Brexit referendum of 2016–2019. Interestingly, it is worth noting that the Spanish market transmitted shocks to other markets in most parts of the 2020 global health crisis. This is consistent with the dominance of Spain as a contributor of rising COVID-19 cases in 2020, with news such as the Financial Times' September 10th 2020 article which highlighted that Spain was harder hit in comparison with the rest of Europe (see Dombey, 2020). The effect of sentiment (arising from good or bad news) on financial markets is well established (see for example Bai et al., 2023). Insights from the predominant transmitters of return spillovers can be useful if monitored adequately by potential investors and other relevant market actors as long as the observed patterns of connectedness at the conditional middle quantile persist over time.

The time-varying net return spillovers for the right and left tails are presented in Fig. 10, with red and blue for both the left and right tails, respectively. Unlike the net directional spillovers for the conditional median, the patterns of net return spillovers for the extreme quantiles (upper and lower) are mixed given that there are no well-defined net spillover recipients or transmitters over the sample period. From Fig. 10,

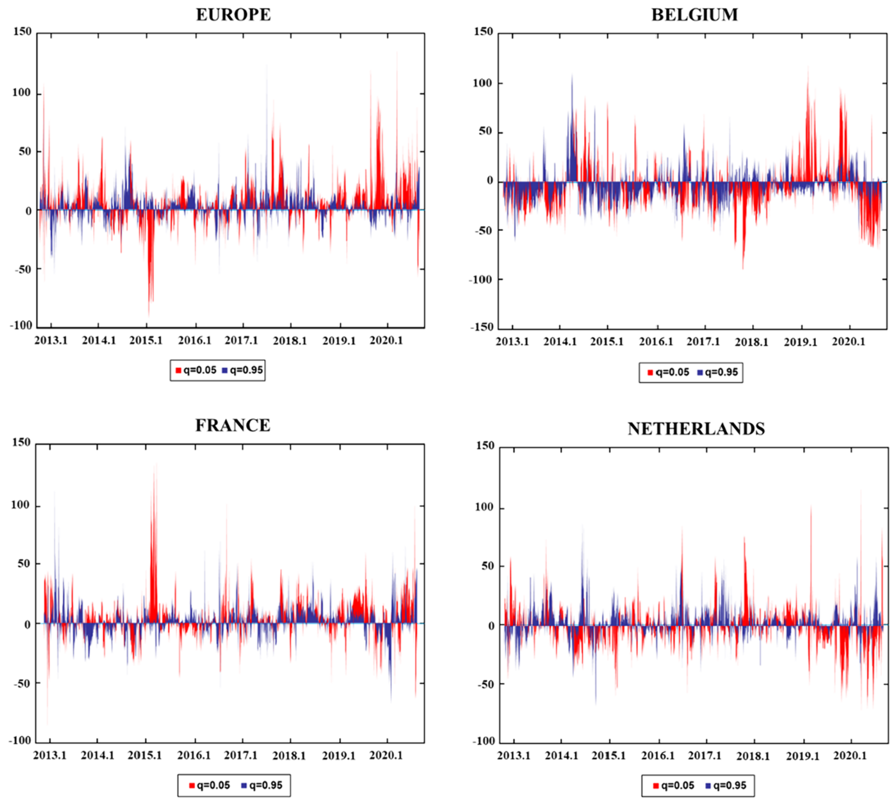


Fig. 10 Net spillovers in quantile VAR (q = 0.05, q = 0.95)

we observe that in some periods, most of the sustainability markets act as net recipients and, at other times, as net transmitters of return spillovers of extreme events. To this end, the behavior of these markets under extreme events makes them potential candidates for monitoring by portfolio investors and market regulators, particularly if their behavioral trend characterized by the system of spillovers extends into the future. The above findings extend the frontiers of knowledge on the propagation of extreme return shocks within the system of connectedness in European sustainability markets. There is evidence of nonlinearity and excess in the system of spillover networks during extreme events relative to the middle quantile and conditional average. This result reconciles the mixed findings of the contagion literature.

5.4 Network connectedness analysis

Thus far, we have analyzed the dynamic return spillovers among European sustainability indices. In this section, we provide pertinent information regarding the market transmitters or receivers of shocks along with the strength of spillovers through

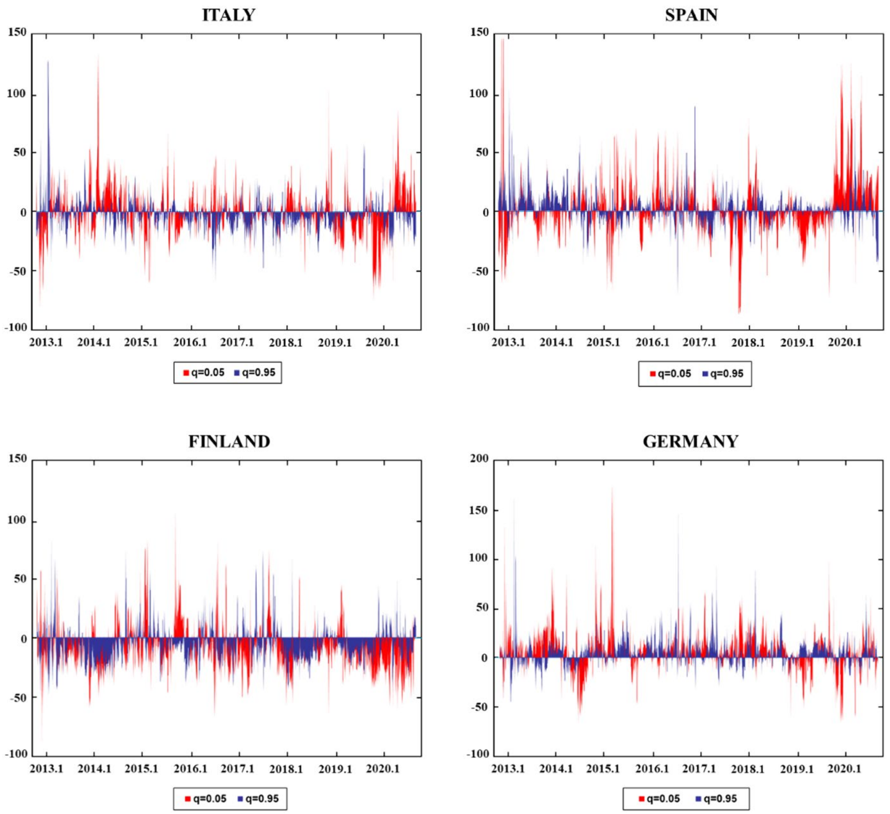


Fig. 10 (continued)

the network visualization of the net pairwise directional spillovers at the right, left, and middle conditional distributions in Fig. 11a–c, based on Table 3 (Panels A–D). Node sizes depict the magnitude of the net transmitter or receiver of spillovers in each market. The red color of a node indicates that the market is a net transmitter of spillovers, whereas the green color indicates a net receiver of spillovers. Comparing the network diagrams in Panels (a)–(c), we observe that the quantile of shocks is crucial for characterizing the connection among markets in terms of the direction and degree of connectedness. Figure 11a depicts the network visualization among the markets at the median quantile; Europe and France are the leading net contributors of return spillovers, followed by Germany and marginally Netherlands, respectively. This observation is consistent with Stoupos and Kiohos (2022) who find that, within the Euro Area, stock market integration is greatest among Germany and core-member states. The Belgium and Finland sustainability indices are the two markets that receive the least from the network of return connectedness, with Italy being a major receiver of shocks from other markets in the network.

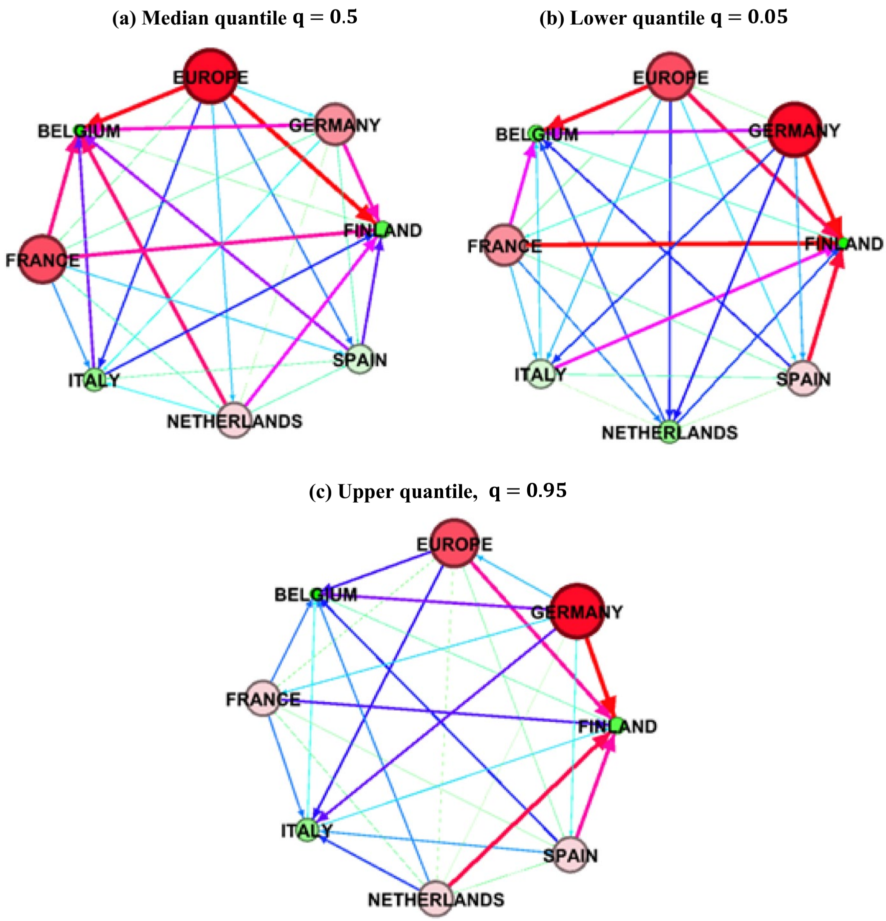
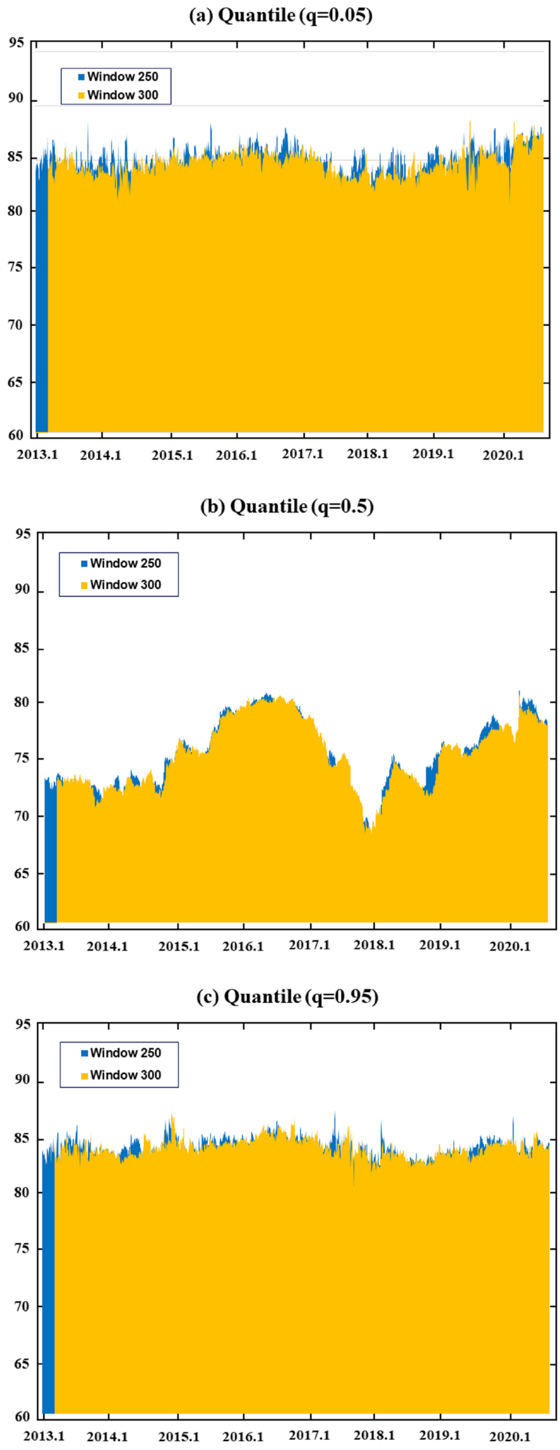


Fig. 11 Net pairwise directional connectedness network at different quantiles

The network visualizations at the left and right tails are shown in Fig. 11b and c, respectively. As expected, we observe similar patterns at the two extreme tails relative to the median quantiles. At both the upper and lower quantiles (see Fig. 11b, c), there is a greater degree of connectedness, which is in accordance with the spillover results shown in Table 3 (Panels (c) and (d)). The pattern of the network system at the extreme left shows that Germany is a major transmitter of shocks in the framework, followed by Europe and, to a lesser extent, France. Unlike the median quantile, the Netherlands market is a major recipient of shocks, while Finland receives the least shocks from other market participants in this quantile. Notably, we observe that both the Spanish and Italian sustainability markets share the spoil in the network, with Spain being more a transmitter than a receiver of shocks and Italy being more of a receiver than a contributor of shocks. The net pairwise directional spillovers at the upper quantile are shown

Fig. 12 Robustness test for quantile spillovers. Quantile spillovers are estimated using 250- and 300-day rolling windows with a forecast horizon of 10 days.



in Fig. 11 (Panel c). The findings are closer to the lower quantile network characterization, except that Italy is a conspicuous recipient of shocks with Finland, Belgium, France, Netherlands, and Spain give more than what they receive in system-wide connectedness.

5.5 Sensitivity analysis

To validate our analysis, we tested the sensitivity of our quantile spillover by considering alternative daily rolling windows. Until now, our analyses have focused on using a window length of 200 days and a forecast horizon of 10 days. In this section, we consider robustness tests for the 250- and 300-day rolling window estimates with a forecast horizon of 10 days. The analysis was performed to characterize the behavior of the conditional median, upper, and lower quantiles relative to our previous window length of 200 days. The result documented in Fig. 12b for the middle quantile shows that there is no significant difference in the pattern of the return spillover index for both the 250- and 300-day rolling window estimates as against what we presented with a window size of 200 days. In reaffirming our evidence of non-uniformity in the connectedness spillovers between the extreme lower and upper tails and the conditional median, we conduct robustness analyses for both the right and left tails at new window sizes of 250 and 300 days. The results presented in Fig. 12a and c show that the pattern of the return spillovers in the right and left tails is not affected by changes in the size of the window. Notably, there is evidence of significant dependence in both the left and right tails; hence, the system of spillovers estimated at the middle quantiles does not show the strength of the return spillovers connected with extreme shocks. Overall, our results are insensitive to the window size and forecast horizon.

6 Conclusion

The findings of this study demonstrate the possibility of diversification across frequencies and quantiles using the quantile cross-spectral approach at different time horizons and market conditions. The dependence structure in sustainability markets intensifies across frequencies. In the short term, there is a high correlation between Europe and country-level markets; however, the dependence is higher in bearish markets than in bullish markets, except for Belgium and Finland, suggesting evidence of contagion effects and the recoupling hypothesis. In the medium term, the dependence between markets increases for almost all market pairs. There is greater evidence for diversification strategy options for the markets at the Bullish-Bearish quantiles between Europe and the other markets than in the short term, where Belgium, Italy, and Germany are positive under this market. This indicates that all markets that exhibit extreme positive returns in Europe are negatively associated with the extreme negative returns of individual countries' sustainability markets. Coherence appears to intensify from the short term to the long term, showing stronger dependencies among European sustainable markets in the long term. The dependence between Europe and each country's markets is higher in the longer horizon than in the short and medium time horizons, irrespective of market state.

Moreover, the results show evidence of non-uniformity in the connectedness pattern in the upper, median, and lower quantiles of the distribution among European sustainability markets. Essentially, the network of connectedness or return shocks is more pronounced at extreme tails than the conditional mean or median. Therefore, more focus should be on monitoring extreme news and events by relevant policymakers and regulators; otherwise, paying attention to mean shocks and the middle quantile within the network of connectedness may produce a bias and less optimal results and may mislead regulators in the formulation, application, and stabilization of policies during extreme news and events. To this end, adequate knowledge of the degree and direction of connectedness, as well as the magnitude and direction of the return spillovers among the sustainability markets, can be helpful to investors and regulators in forming suitable policy tools and surveillance mechanisms to manage potential adverse effects emanating from extreme risk spillovers in the sustainability market. There are also relevant insights for investors and regulators for making decisions concerning short- or long-term positions in sustainability indices in extreme markets. That is, in either bearish or bullish market conditions. Future research may be able to apply the analysis of this study to other economic/regional blocs like SADC, BRICS, and ECOWAS among others. This will be particularly insightful as the countries comprising these blocs are markedly different from those in the European Union.

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Data availability Data is avaiable upon the request.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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