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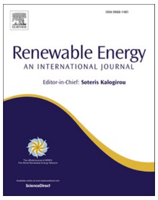

Investigating the spillovers and connectedness between green finance and renewable energy sources

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ABSTRACT

Although a few studies have analyzed the nexus of renewable energy and green finance, the literature lacks the use of renewable energy by sources. The other major failure is that it uses only annual and small data. Therefore, this study investigates the connectedness and spillovers relationship between green finance and five types of renewable energy (biofuels, fuel cell, geothermal, solar, and wind) by applying the novel TVP-VAR method of Balcilar et al. [1] to the daily indexes from July 31, 2014, to Feb 4, 2022. The results show that dynamic connectedness, both total and pairwise, is heterogeneous over time and influenced by economic events. Furthermore, wind is found to be the largest transmitter of shocks to green finance, followed by biofuels, while both fuel cell and geothermal receive the least shocks. The findings suggest that green finance is mostly a net receiver of shocks from renewable energy sources and that wind has been a net receiver of shocks during the COVID-19 pandemic. A high interconnectedness between the indexes highlights the safe-haven property for diversification purposes of green finance. Our results are important for energy policymakers, those responsible for the implementation of environmental policies, individual investors, and portfolio managers, while also shedding light on the achievement of COP26 goals.

1. Introduction

Given the environmental risks witnessed in the last decades, it is evident that imminent action is necessary to reduce carbon and greenhouse gas emissions to ensure a comfortable human existence in the coming decades. Despite the acceptance of 17 Sustainable Development Goals (SDGs), it seems very unlikely the zero-carbon target will be achieved any time soon. In order to cope with changes in climate, severe environmental disasters, and weather extremes, many countries and multilateral initiatives are taking steps to avert the negative externalities of ongoing climate change that may undermine their economic development and sustainability [1,2]. Supranational measures, such as the Conference of the Parties (COP), promote the SGDs to provide measurable goals to help countries cope with changes in the global climate. Very recently, about 200 countries attended the COP26 and agreed upon the Climate Pact, which represents a promise by countries to decarbonize the global economy [3]. The negative externalities of environmental damage to human health, agriculture, and the economy necessitate countries taking steps towards a green economy that embraces SDGs, through adapting the production process by using renewable energy [2].

Despite these efforts, there are barriers to reaching net-zero targets that are dependent on the emergence of new green technologies. The main problem with the required technologies is not limited to suspicions regarding their workability, or having been untested at scale, but the necessity of enormous injections of private capital [4]. In other words, a lack of financial resources and insufficient contributions by the private sector to renewable energy investment is the main obstacle for countries in shifting to renewable energy [5,6]. During COP 26, finance was at the core of discussions, and emerging countries emphasized their need for the transfer of finance and technology to switch to a lower carbon-emitting phase by adopting renewable energy [7]. With COP 26

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aiding poorer countries converting to net-zero, at least $100 billion over the next 10 years is assured. Yet, the huge expenditures resulting from the COVID-19 pandemic are causing many emerging and even developed countries distress. There is huge concern that the shift of expenditures from renewable energy projects to cope with the downside risks of the pandemic will result in lower commitments to environmental progress [8]. A shift to renewable energy, despite the commitments in COP 26, does not seem likely given the gigantic need for funds to finance these technologies. Still, the initiation of renewable energy technologies is inevitable for almost every energy importing country, not only because of environmental impacts but also because of increasing energy prices and supply issues. Recent developments regarding the Ukrainian-Russian war have also made it clear that maintaining sufficient energy sources, especially renewable energy sources, is a necessity to cope with unexpected shocks in energy markets, despite the huge installation costs.

The increasing financing needs for renewable energy investments has stimulated the green finance market, impacting the economy and environment favorably [9,10]. A resilient green finance market is essential to ensure the financing of renewable energy projects [11] and to solve environmental problems that stem from a lack of finance [12]. Yet, renewable energy projects are considered high-risk and low-return investments at the inception stage [13], making financing even more difficult. Nonetheless, the costs of renewable energy projects have declined considerably recently, not only because of advances in green technologies but also as a result of the lower cost of financing provided by green financing [14]. Morever, the shift from fossil fuel consumption to renewable energy could be triggered through lowering the cost of capital [15]. In fact, a transition from fossil fuel consumption to other various renewable energy sources can only be made possible through the financing sector. Pathania and Bose [16] clarified that finance and financial innovation have acted as the most significant factor in every energy transition in world history, and the transition to renewable energy adoption is no exception. They further note the significance of technological innovations, yet they stress that these innovations could only be possible by accompanying financial innovations to trigger energy transition. However, transferring the finance for investment and technological innovation in renewable energy is the major barrier experienced by many countries in climate change mitigation [6]. Renewable energy adoption will only be possible through public or private financing with the usage of innovative instruments [17].

Among green financial instruments, green bonds stand as the most popular way of financing renewable energy projects, given their lower risk and lower return nature [18]. The functioning of green bonds is akin to traditional bonds, but the funds raised by the bond should be used solely for financing projects that mitigate environmental deterioration (Madaleno et al., [19]. The global transition to clean energy and low-carbon economic activities could be financed mainly through green bonds [20]. Moreover, despite the decline in investments in renewable energy as a result of the pandemic, the issuance of green bonds is still expected to accelerate. According to the latest report of the Climate Bonds Initiative [21](2021), the issuance of green bonds is expected to reach about USD 680 billion in 2022 and exceed USD 1 trillion in 2023, assuming a modest growth rate. The significance of green bonds is so high that Glomsrød and Wei [22] note that a reasonable adoption of green bonds could result in a reduction of 4.7 Gt of carbon emissions before 2030. Gianfrate and Peri [23] also point to green bonds as being one of the key tools in achieving the carbon reduction targets of the Paris Agreement. The attractiveness of the return of green bonds outweighs traditional counterparts, and the impact of these green financing instruments on renewable energy sources is immense. In addition, although the impact might appear small, stock markets also have significant impacts on renewable energy financing since they offer financing for renewable energy projects through the listing of renewable energy stocks [24]. Thus, a direct relationship is expected between renewable energy indices and renewable energy deployment.

With the adoption of different renewable energy sources, greenhouse gas emissions will drop significantly. Thus, to ensure sustainability and meet the SDGs, it is crucial to promote them [25]. Renewable energy has various sources or types, which can be generated from solar, biomass, wind, hydro, and geothermal energy sources. Nevertheless, the types of renewable energy generated are dependent on the availability of financing sources [26]. Obtaining funds with low-cost and institutional complexities hamper the growth of renewable energy deployment [27]. Despite the existence of other channels for renewable energy adoption, such as subsidies, grants, tax allowances, and other incentives, these conventional funds and financial instruments are not adequate to fund large-scale renewable energy investments. Thus, it is necessary to attract green finance to promote renewable energy. Additionally, different types of renewable energy technologies are in diverse phases in their life cycle. They also have unique commercial value and impact [28]. Therefore, it is to be expected that the effects of green financing on these different renewable energy sources might also display diversion.

Although all supranational authorities are focused on tackling the limitations on funding for renewable energy investments, it remains a challenge for most countries, especially after the pandemic. Given these problems regarding the financing of renewable energy adoption, our analysis focuses on the relationship between green finance and renewable energy. The paper aims to characterize spillovers and connectedness between the indexes of renewable energy by types (biofuels, fuel cell, geothermal, solar, and wind) and green finance by applying the novel TVP-VAR method of Balcilar et al. [29] to the daily stock indexes from July 31, 2014, to Feb 4, 2022. The well-known method of Diebold and Yilmaz [30] is also applied for robustness.

The contribution of the paper to the literature is threefold. First, to the best of our knowledge, this is the first study that investigates the connectedness and spillovers relationship between renewable energy by types and green finance, despite the limited amount of literature on the nexus of green finance and renewable energy. The green financing provided to different sources might vary, thus, the effectiveness of green finance might be different. In that sense, the analysis of green finance - renewable energy type is crucial in measuring the success of the financing. If green finance has different impacts on different renewable energy sources, this result will be significant for both policymakers and investors. Second, the paper adopts a novel approach to the time-varying parameter vector autoregression (TVP-VAR) model. This is superior in that it is less outlier-sensitive, it does not require an arbitrarily chosen window size, and it can describe parameter changes accurately. Third, the analysis coincided with a period in which there were possible significant shocks to green finance and renewable energy consumption, such as the COVID-19 pandemic, an immense decline in non-renewable energy prices, and very low demand for energy sources and then accelerated demand for energy sources in the economic recovery period.

The next section provides a brief literature review, section 3 presents the data and methodology, section 4 explains the results of the analyses, robustness and sensitivity checks and finally, section 5 concludes.

2. Literature review

Green finance encompasses the financial instruments that provide funds to support firms or projects that address climate change and environmental benefits. Green loans, securities, insurance, and environmental and sustainable investments not only provide funds for environmentally-friendly firms or projects but also create an ecologically minded society [31]. Green finance has an impact on environmental outcomes through its effects on capital support, resource allocation, and technological innovation [32]. The way in which it supports capital suggests that green finance can direct accumulated funds to firms that are low-carbon emitters or to projects that are related to renewable energy production [2]. With regard to resource allocation, green finance can increase the efficiency of capital allocation from low-efficiency and high polluting firms to higher-efficiency, low polluting firms and lead to better environmental outcomes and high-efficiency industry structure [33,34]. Fan et al. [35] show that green credit regulation increases the cost of capital for non-compliant companies, reduces the amounts loaned, and raises the difficulty of accessing loans, compared to green firms. The technological innovation effect explains how green finance impacts environmental quality through the provision of credit to firms that focus on green technology innovations that will eventually reduce environmental damage and pollution (Li and Jia, 2015; [31].

The literature investigates various aspects of green finance. One strand considers the relationship between green finance and renewable energy. Sadorsky [36] undertook one of the pioneering studies by investigating the relationship between clean energy stocks and technology stocks. He reports that clean energy companies display higher dynamic conditional correlations with technology companies than those of oil prices. From an investor's perspective, we see that investors are more inclined to energy products recently, creating transmission and spillovers between energy and finance [37]. Wang and Zhi [38] relate the success of renewable energy technologies to the development of finance for these projects and further note that progress in solar technology is restricted by a lack of financing. The availability of green financing and green financial systems should also be regulated by governments; otherwise, the impact of green financial development might diminish the efficiency of renewable energy investments [9]. Streimikiene and Kaftan [39] stress the significance of policies that are shaped by sustainable environmental goals to adapt to carbon-free and environmentally friendly approaches. They also point to green loans, green bonds, and green mortgages as effective policy tools to achieve sustainability. The study by Taghizadeh-Hesary et al. [40] notes the facilitative function of the green bond market to maintain green financing for renewable energy in the Asia and Pacific regions. Ye et al. [41] consider COVID-19 both as a challenge and an opportunity, since production in many economic sectors was halted, but the pandemic put extreme pressures on renewable energy sources. They report that green credit, green investment, and green securities, followed by corporate social responsibility reporting, yield a positive, statistically significant relationship with renewable energy investment in Pakistan. Some of the literature also emphasizes that developments in renewable energy investments boost industrialization, trade liberalization, economic development, and additional elements that indirectly influence green finance [42]. Kutan et al. [24] investigate the role of stock markets and forward direct investment in BRICS countries and associate a positive link between the former and renewable energy consumption.

Hu et al. [31] also associate green credit policy significantly with green patents for high-polluting companies. Dogan and Seker [43] investigate European Union countries that are representative of the largest renewable energy users and report a link between effective reduction of domestic carbon dioxide emissions and financial development. Meo and Karim [44] consider the top ten economies supporting green finance and their quantile-on-quantile regression analysis results suggest that green finance causes carbon dioxide emissions to decline. Zhou et al. [33]; Zhou et al. [45] calculate a green finance development index and relate it with emissions, such as industrial smoke dust, solid waste, and carbon dioxide. Their findings show the positive contribution of green finance to environmental outcomes in 30 provinces in China with varying degrees of economic development. Zhao et al. [46] report conflicting results, for example that financial depth development reduced sulfur dioxide and solid waste, whereas financial efficiency increased these two waste types. A positive impact of financial development on industrial wastewater [47] and nitrogen oxide [48] has also been reported. Rasoulinezhad and Taghizadeh-Hesary [49] investigate the green energy index and green finance and their relationship with carbon dioxide emissions and energy efficiency in the top ten economies supporting green finance. Their results indicate that green bonds are an effective method for financing green energy projects and diminishing carbon emissions.

Another line of research considers the risk-return characteristics of renewable energy investments, focusing on Capital Asset Pricing Models (CAPM). Renewable energy investments possess lower non-diversifiable but higher firm-specific risk than other financial assets [50], suggesting a diversification opportunity for investors [51]. Martinez-Fernandez et al. [52] analyze a CAPM framework and emphasize that small and large hydro and offshore wind projects contribute positively to the efficiency of portfolios. They further note that to minimize the cost and risk of the portfolio, all available renewable technologies should be reflected to benefit from diversification. Inchauspe et al. [53] ascertained from their proposed state-space multi-factor asset pricing model that renewable energy stock risk-adjusted stock returns provided negative returns from 2009 to 2013. They also argue that these stocks did not recover from losses incurred during the global financial crisis, with the possible reason being the lower oil price and subsidy limits by governments.

Another stream of literature investigates the relationship between green financial instruments and other classes of financial asset. Hammoudeh et al. [54] focus on the relationship between green bonds, US conventional bonds, the clean energy index, and carbon dioxide emission allowance prices and find a significant Granger causality from clean energy index returns to green bonds. Tiwari et al. [55] investigate the dynamic connectedness between green bonds and solar, wind, and clean energy stocks. Mensi et al. [56] explore dynamic and frequency spillovers between global Green Bonds, WTI oil, and G7 stock markets and note that the spillovers are crisis-sensitive. Green bonds are found to provide better diversification opportunities than oil in G7 stock markets and are a net recipient of spillovers. Kamal and Hassan (2022) consider the impact of the cryptocurrency environment attention index (ICEA) on clean energy stocks and green bonds and report a diversification benefit for clean energy stocks and green bonds in a portfolio against the ICEA in bearish market conditions. Umar et al. [57] investigate the volatility connectedness between clean energy stocks and crude WTI, natural gas, gas oil, and fuel oil by adopting time-domain and frequency-domain approaches. The results reveal weak volatility connections between those groups. Madaleno et al. [19] reflect on the nexus of clean energy, green finance, environmental responsibility, and green technology. The results of their recursive evolving and rolling window algorithms point to bidirectional causality between the variables, but that the significance of the relationship faded during the pandemic period. Interestingly, the results suggest a causality running from clean energy to green finance, but not the other way around. Despite the recent development of green finance literature, work on a thorough analysis of finance and renewable energy sources appears to be non-existent. Nevertheless, an understanding of the possible difference in the relationship between green finance and renewable energy sources has significant implications.

3. Data and methodology

This study employs a time-varying parameter vector autoregression extended joint connectedness model. The variables are the S&P Green Bond Index, used as a proxy for green finance, and five types of renewable energy: NASDAQ OMX BioFuels Index, NASDAQ OMX Fuel Cell Index, NASDAQ OMX Geothermal Index, NASDAQ OMX Solar Index and NASDAQ OMX Wind Index. The span of all the daily datasets is from August 1, 2014, to February 4, 2022. All the data are taken from DataStream (https://www.refinitiv.com/en/). The graphical illustration of the time series and the returns (the natural logarithmic of index values between time t and t-1, daily) is depicted in Figs. 1 and 2. The descriptive statistics with some preliminary tests are tabulated in Table 1. From the Table 1 results, we may infer that the solar index presents the highest mean but not the highest volatility, which is attributed to the fuel cell index. The lowest mean and variance are from the green finance index. These results lead us to infer that green finance is less volatile than the five representatives of renewable energy. This could be the result of the fact that green finance has a significant association with economic

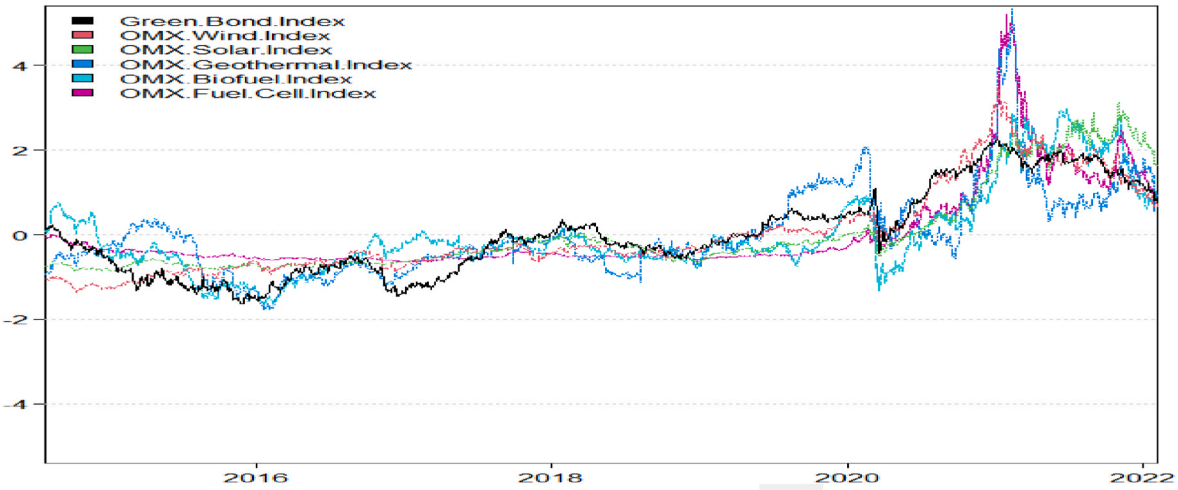

Fig. 1. Time series plot of the variables.

Table 1
Summary statistics.

	Green Finance	Wind	Solar	Geothermal	Biofuels	Fuel Cell
Mean	0.002	0.044	0.080	0.020	0.010	0.045
Variance	0.105	2.810	4.767	3.525	4.463	12.420
Skewness	−0.503***	−0.743***	−0.627***	0.568***	−1.026***	0.515***
Excess Kurtosis	5.237***	6.608***	7.552***	13.375***	10.842***	6.345***
JB	2163.922***	3490.658***	4458.963***	13709.575***	9263.159***	3143.695***
ERS	−15.400***	−11.363***	−18.641***	−9.018***	−13.458***	−17.658***
Q(20)	32.424***	17.680**	61.067***	43.714***	80.096***	23.260***
$Q^2(20)$	445.740***	151.333***	1110.718***	256.477***	1525.185***	401.719***

Notes: ***, **, and * show significance at 1%, 5%, and 10%, respectively; Skewness: D'Agostino [59] test; Kurtosis: Anscombe and Glynn [60] test; JB: Jarque and Bera [61] normality test; ERS: Stock et al. [62] unit-root test with constant; Q(20) and $Q^2(20)$: Fisher and Gallagher [63] weighted portmanteau test.

growth and environmental variables [58]. We find that all series are significantly left-skewed, except the geothermal index and the fuel cell index, and leptokurtic distributed. Based on the Jarque-Bera normality test, which considers both the skewness and excess Kurtosis at the same time and reveals the normality of the data (the said test holds the null hypothesis of skewness and excess Kurtosis being zero), we may conclude that all series are statistically non-normally distributed at a 1% significance level.

From the rest of the tests presented in Table 1, we note that all series seem to be stationary, autocorrelated, and exhibit ARCH/GARCH error at 1% significance levels. Therefore, all these statistics seem to support our choice of modeling interrelationships among variables using a time-

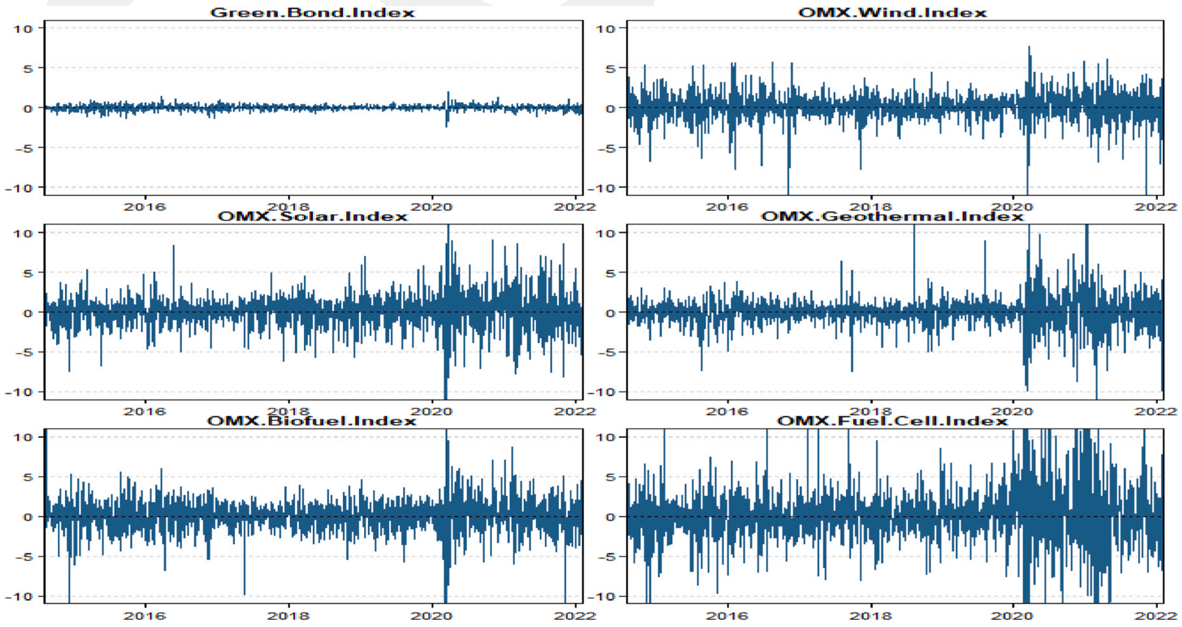

Fig. 2. Returns plot of the variables.

varying parameter vector autoregression (TVP-VAR) model, as in Tiwari et al. [55]; Kang et al. [64]; Madaleno et al. [19]; Zhao et al. [65]; Balcilar et al. [29]; and Li et al. [66].

Fig. 1 presents the time series plot of all the 6 variables under study. Here we can observe intense fluctuations in the price series of all indexes under examination throughout the entire period of analysis. Fig. 2 presents the same plots for each series of returns. It is possible to see that variations in both prices and returns (we converted each series into first difference log levels) were even more pronounced during economic events, such as the recent COVID-19 pandemic. Multiple volatility clusters are evident for all series except for the green bond index/green finance, leading us to conclude that this can be considered a safe-haven asset, protecting investors from fluctuations in energy markets, while building their asset investment portfolios.

3.1. Methodology

Balcilar et al. [29] based on Antonakakis et al.'s [67] time-varying parameter vector autoregression (TVP-VAR) model established a more extended connectedness approach. In particular, they combined the TVP-VAR connectedness framework of Antonakakis et al. [67] with the joint connectedness approach of Lastrapes and Wiesen [68] and proposed a novel TVP-VAR extended joint connectedness method.

TVP-VARs have become popular for the analysis of macroeconomic time series. This is because TVP-VARs differ from the traditional linear VAR model by allowing coefficients to vary over time. For that, we just need to specify a law of motion [69]. Additionally, TVP-VARs include stochastic volatility, allowing the error processes variance affecting the VAR to change over time. On the assumption that time series usually exhibit some form of nonlinearity (faster rise/decrease of the series at the start/end of a recession than its decline/rise at the onset of the recovery/decline; time series which exhibit occasional periods where volatility rises considerably), these need to be captured by the model, once this time series behavior has potentially different underlying structural causes. This behavior can only be captured through TVP-VARs with stochastic volatility, it being a more flexible framework. Moreover, using a simple time-series VAR model only permits explaining the joint evolution of economic and financial series using their lags. Applying TVP-VAR preserves this structure, allowing also to model coefficients as stochastic processes. For that, coefficients are assumed to follow random walks, specifically the intercepts, the lagged coefficients, and variances and covariances of the error term, providing a flexible functional form to capture various nonlinearity forms [69].

In a nutshell, Lastrapes and Wiesen (L&W) (2020) constructed a scaling parameter λ_t to calculate the joint connectedness equivalent of $S^{gen,to}_{i\rightarrow\cdot,t}$. The computational definition of this scaling parameter λ_t is as follows:

$$g\widetilde{SOT}_{ij,t} = \lambda_t gSOT_{ij,t} \tag{1}$$

where

$$\lambda_t = \frac{jSOI_t}{\frac{1}{K}\sum_{i=1}^{K}\sum_{j\neq i}^{K} gSOT_{ij,t}} = \frac{jSOI_t}{gSOI_t} \tag{2}$$

Subsequently, we can get the total directional connectedness (TDC), and estimating the TDC, we get the net total directional connectedness (NTDC), respectively. These definitions can be given as follows:

$$calculation\ of\ TDC\ => S^{jnt,to}_{i\rightarrow\cdot} = \sum_{j=1,i\neq j}^{K} g\widetilde{SOT}_{ij,t} \tag{3}$$

$$calculation\ of\ NTDC\ => S^{jnt,net}_{i,t} = S^{jnt,to}_{i\rightarrow\cdot,t} - S^{jnt,from}_{i\leftarrow\cdot,t} \tag{4}$$

Nonetheless, the aforementioned estimated models of L&D (2020) could not calculate the net directional pairwise spillovers. Consequently, Balcilar et al. [29] overcame this issue by constructing the TVP-VAR model through an extended joint connectedness approach. Briefly, they generalized the scaling parameter λ_t of L&D (2020). Now, this scaling parameter λ_t can be calculated as follows:

$$\lambda_i = \frac{S^{jnt,from}_{i\leftarrow\cdot,t}}{S^{gen,from}_{i\leftarrow\cdot,t}} \tag{5}$$

$$\lambda = \frac{1}{K}\sum_{i=1}^{K}\lambda_i \tag{6}$$

Now, according to Balcilar et al. [29] the net total and pairwise directional connectedness can be estimated as below:

$$S^{jnt,net}_{i,t} = S^{jnt,to}_{i\rightarrow\cdot,t} - S^{jnt,from}_{i\leftarrow\cdot,t} \tag{7}$$

$$S^{jnt,net}_{i,t} = gSOT_{ji,t} - gSOT_{ij,t}. \tag{8}$$

4. Empirical findings

The methodology employed allows for the summarizing of complex nonlinear transmission and propagation mechanisms, permitting a comparison of different relative impacts. Thus, the shock in one variable will be observable in another variable's forecast error variance with the other, once the feedback loops of the entire network are considered [29]. Moreover, the methodology can be utilized to monitor and evaluate spillovers, while mitigating adverse effects by adjusting economic and political strategies [29,55]. To read about the multiple issues overcome as compared to the original connectedness approach, we suggest reading Balcilar et al. (2021, p.8). In this section, we set out the averaged joint connectedness results (Table 2) and the dynamic total connectedness results (Fig. 3). Also, net total and pairwise dynamic directional connectedness are explored (Fig. 4 and 5, respectively). It should be noted that all findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

Average results regarding connectedness are presented in Table 2. The main diagonal elements refer to the series' contributions and all off-diagonal elements to contributions either from or to other series. Rows refer to each index's contribution to the forecast error variance of one specific index in the system, while columns correspond to the effect one specific index has on all other indexes separately. There are substantial variations in the magnitude of shocks transmitted across indexes. For all the analyzed indexes, green finance is found to transmit the lowest value of shocks to other indexes (7.87%). Even so, it is higher than the values reported by Tiwari et al. [55] considering solely carbon price index, solar, wind, and clean energy (2.246%; [55]; p.10). The highest shock spillovers originate from biofuels to solar (12.14%) followed by the propagation from solar to fuel cell.

Considering the renewable energy shocks, it is observable that wind is the largest transmitter of shocks to green finance (5.93%), followed by biofuels (3.71%). The finding of connectedness between green finance and renewable energy markets is in agreement with the results of both Tiwari et al. [55] and Liu et al. [70]. In the same vein, green finance transmits 3.88% of shocks to wind and 1.87% of shocks to biofuels. Both fuel cell and geothermal receive the least shocks from green finance (0.42% and 0.70%, respectively). In general, it is renewable energy indexes that transmit more shocks to green finance than vice versa. The gross directional spillovers transferred to other assets range from 7.87% for green finance to 41.33% for solar, which implies that about 41.33% of all others' forecast error variance can be explained by solar energy. The specific network of renewable energy markets can explain developments within the network itself to a moderate extent, provided the average value of TCI is 27.56%. Thus, around 20% of the forecast error variance within this network of variables can be regarded as the product of cross-market innovations, and idiosyncratic effects account for around 72% of the forecast error variance of the system. So, renewable

Table 2
Averaged joint connected results [29].

	Green Finance	Wind	Solar	Geothermal	Biofuels	Fuel Cell	FROM
Green Finance	85.65	5.93	2.06	1.44	3.71	1.20	14.35
Wind	3.88	72.78	8.25	4.50	5.88	4.71	27.22
Solar	1.00	7.96	60.02	8.33	12.14	10.55	39.98
Geothermal	0.70	4.36	8.08	75.82	6.49	4.53	24.18
Biofuels	1.87	5.87	12.13	6.38	67.06	6.70	32.94
Fuel Cell	0.42	4.21	10.80	4.51	6.75	73.31	26.69
TO	7.87	28.33	41.33	25.16	34.97	27.70	165.36
NET	−6.47	1.11	1.34	0.98	2.03	1.01	TCI
NPDC	0.00	1.00	3.00	3.00	5.00	3.00	27.56

Notes: Results are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

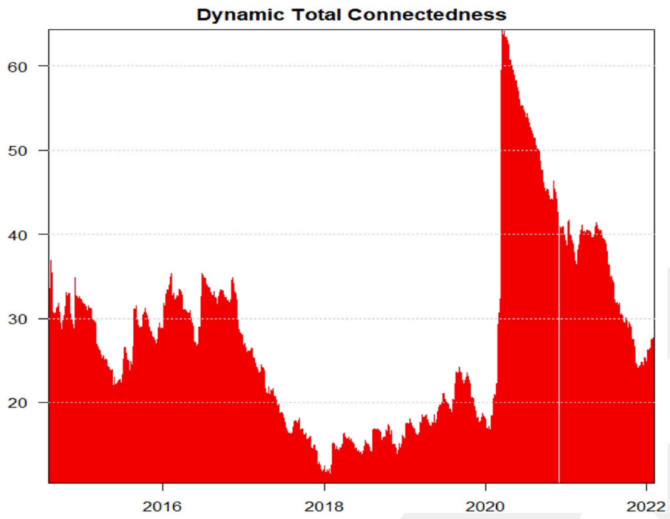

Fig. 3. Dynamic total connectedness [29].
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The red shaded area represents the joint connectedness results.

energy sources and green finance co-move moderately. On average terms, the most important transmitters appear to be solar energy, biofuels energy, and wind energy. By implication, green finance is a net receiver of respective shocks (−6.47%).

From the obtained results, it is clear that green finance has a marginal effect on other renewable markets, partially following the results of Hammoudeh et al. [54] and Tiwari et al. [55]. The former found no significant causality running from green bonds to clean energy assets. The latter found that green bonds receive more shocks from other markets, including solar, wind, and clean energy than it transmits to them. Attending to the diagonal elements of Table 2, it is worth noticing that for green finance, 85.65% of index evolution is driven by index shocks/behavior, with only 14.35% of index movement attributed to network connections. Also, index movements across renewable energy stocks driven by network connections are high compared to movements in green finance, a finding also reported by Tiwari et al. [55]. Broadstock et al. [71] found that about 40% of US green bond price is driven by network connections, whereas Tiwari et al. [55] found a value of 5.7906%, with our results pointing to 14.35%. Even so, we need to agree with Tolliver et al.'s [72] results, suggesting that green bond markets are expanding precipitously, with proceeds being increasingly allocated to renewable energy. Moreover, Wang et al. [73] conclude that green finance and renewable energy promote sustainable growth. Streimikiene and Kaftan [39] argue that green finance could be an effective tool for environmental sustainability, which is also corroborated by Zhou et al. [45] who note that green finance promotes environmental sustainability, while depending upon economic conditions. Furthermore, renewable energy dominance stocks could be related to the growing trend in renewable energy investments, supported by the correct policies being pursued [55]. It would be interesting to see the evolution of this in the future considering the COP26 directions extrapolated in Glasgow, the 1.5 °C commitment, and public engagement.

The reported average results can only give a narrow perspective, since they potentially mask major events happening during the study period which have relevant impacts over the network. Therefore, it is better to rely upon the dynamic analysis, which allows for a better understanding of the evolution of the connectedness of this network over time. Fig. 3 presents the dynamic total connectedness. Considering a dynamic framework is useful in accounting for the evolution of the total connectedness index (TCI) over time, simultaneously demonstrating changes in time in the role of specific variables within the network. The shaded area in Fig. 3 represents the joint connectedness results. Observables are the TCI values varying considerably across the study period, with very large values in specific periods, as in the early 2020s reflecting the COVID-19 pandemic period. Relatively high values mean that there are high spillovers between green finance and renewable energy stocks (a peak of around 65%). Ji et al. [74] found evidence that certain commodities acted as safe-haven assets for investments during the pandemic. Also, Balcilar et al. [29] report relevant peaks and troughs connecting major economic events to higher levels of uncertainty emerging from these. Moreover, strong connectedness may suggest that the risk relating to green finance and renewable energy is upward equivalent, a sign of comparative market confidence.

Fig. 3 denotes two major crisis events. The first can be associated with the Brexit referendum period in 2016 and the second with the COVID-19 pandemic. The magnitude of the connectedness for the entire period varies considerably, ranging from below 10% in 2018 (as reported by Tiwari et al. [55]; although with a higher connectedness percentage and associated with a normal period stage), to around 65% at the beginning of 2020. Thus, the magnitude of connectedness is high during volatile market periods as compared to normal periods. Also, Liu and Liu [75] conclude that the dynamic connectedness between green bonds and renewable energy is high and significant only during crises or turbulent periods. Similar findings are reported by Tiwari et al. [55] and for commodity markets by Balcilar et al. [29]. Fig. 4 presents the results of the dynamic net connectedness results. This graphical analysis allows for easier classification of the various indexes into net transmitting or receiving, whereas the dynamic approach allows us to identify potential shifts between the two roles (where series can be either transmitters or receivers of shocks). Fig. 5 presents also the pairwise net connectedness, where, similar to Balcilar et al. [29]; we can investigate pairs of an index between green finance and renewable energy. The goal is to see if their interrelation has evolved regarding these two potential roles. Note that positive values are associated with the net transmitting role and negative ones with the net receiving role.

We note from Fig. 4 that none of the analyzed indexes have been solely net receivers or net transmitters over the studied period. We might, even so, argue that green finance has been solely a net transmitter in normal periods of short duration. Moreover, whereas green finance and wind were net receivers at the start of the analyzed period (2014

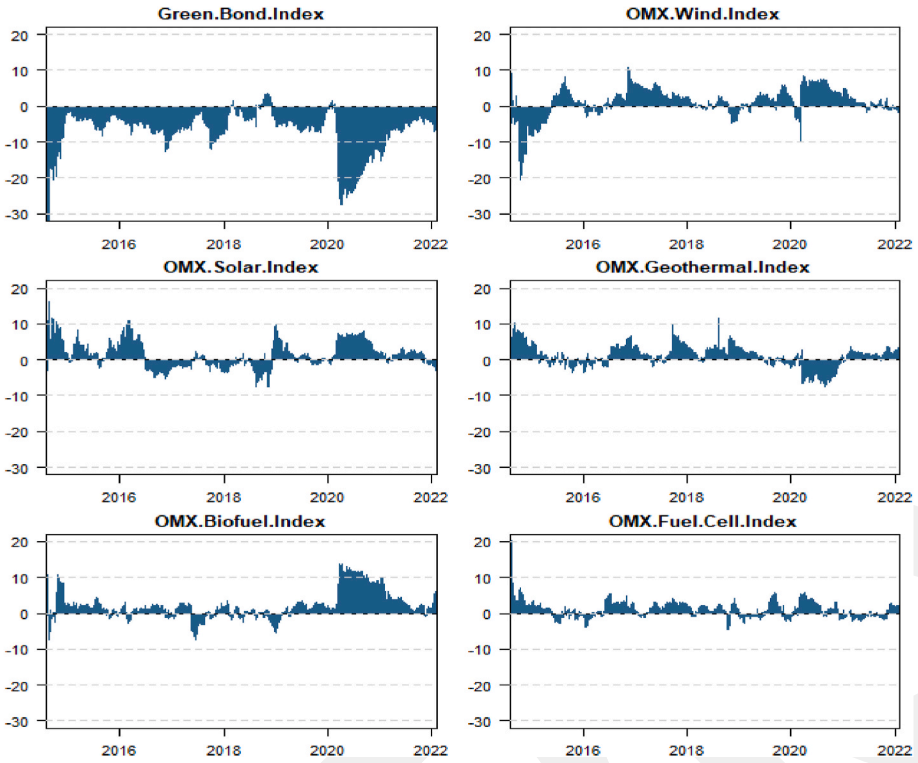

Fig. 4. Dynamic net total directional connectedness [29].
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The blue shaded area represents the joint connectedness results.

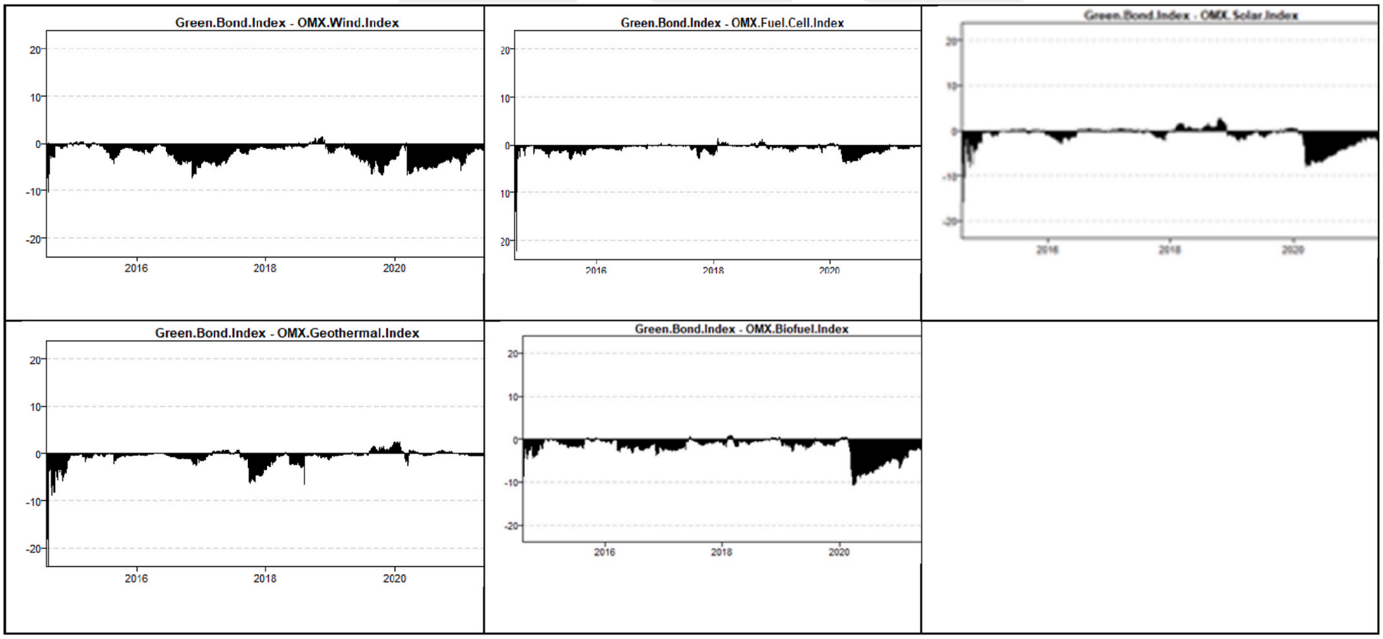

Fig. 5. Dynamic net pairwise directional connectedness [29].
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The black shaded area represents the joint connectedness results.

mostly), all the other renewable energy series are reported as net transmitters. Over the two identified crisis periods (2016 and 2020), the green bond index/green finance behaved as net receivers in the same way as geothermal, though this was not true for wind, solar, and biofuels. Overall, green finance appears to be an important net receiver of shocks almost throughout the period. In general, renewable energy sources do not seem to play a considerable role (being neither net transmitters nor net receivers) for the entire period. The exception is the COVID-19 pandemic that started in 2020, where we may identify green finance and geothermal as clear net receivers of shocks, whereas wind, solar, biofuels, and fuel cells were net transmitters during that period. Recent literature reinforces some of these results, even if not strictly with regard to the same issues. For example, Madaleno et al. [19] report that the nexus between clean energy, green finance, environmental responsibility, and green technology faded during the pandemic period. Causality exists in this period but only from clean energy to green finance. Tiwari et al. [55] found that clean energy acts as a transmitter of shocks to other markets for the entire period, and the observable magnitude of the shocks of their green bond index is very small, contradicting partially the results we are presenting in this paper, both in magnitude and time reported results. However, we agree with the authors, for other series except for green finance, that the variables observed in each asset over time suggest a constantly evolving intensity associated with each market's role.

Looking at the net pairwise connectedness results presented in Fig. 5, we will focus attention on the spillover effects of green finance, this being the important stock index series within our network with the renewable energy series. The first thing we note is that green finance assumes mostly the role of a net receiver with all other renewable energy indexes. As compared to the individual analysis, we can also state that in net terms, the magnitude of spillover activities for green finance remains low. This means that in most situations, green finance not only affects the other renewable energy stock index but is also equally responsive to innovations that take place in renewable markets. This may also validate the findings of Umar et al. [57]; who report weak volatility between clean energy stocks and fossil fuels, since green finance is used for non-fossil energy sources, as our results show. Previously, Hammoudeh et al. [54] found a significant Granger causality from clean energy index returns to green bonds. Green finance stock evidence a strong dynamic net pairwise receiving role directional connectedness at the beginning of the 2020s with wind, solar, and biofuels. Therefore, green finance and renewable energy stocks are highly interconnected, being preferable to perform dynamic portfolio management (as suggested for commodity markets by Ref. [29]. As also reported by Mensi et al. [56]; spillovers are crisis-sensitive and green bonds offer improved diversification opportunities. Polzin et al. [51] also found that renewable energy investments are a diversification opportunity for investors.

Wind has been an important transmitter of shocks to green finance, as green finance has been a net receiver of spillovers from wind, solar, and biofuels, especially during turbulent periods (higher magnitude). We also note that there are periods where green finance transmits shocks to wind and solar in small quantities during normal market conditions. As also reported by Tiwari et al. [55]; the pattern of dynamic net pairwise spillovers reveals production and complimentary relationships between green finance and renewable energy stock indexes.

4.1. Robustness checks

To present robustness checks over our results, we will present here the original connectedness approach following Diebold and Yilmaz [30]. There is no specific economic theory able to justify the ordering of a particular variable in the exploration of the interrelationship across green finance and renewable energy stocks. Thus, we employ the generalized connectedness approach as suggested by Balcilar et al. [29]. The generalized spillover table, whose results are presented in Table 3, is fundamental to multiple spillover average summary measures. The net total directional connectedness (NTDC) is one of the central metrics of the connectedness approach of variable i, demonstrating whether variable i influences the network more than is influenced by it. Once more, the total connectedness index (TCI) presenting a low value indicates low market risk. Thus, in this case, shocks in one variable are mainly its future values, and do not influence others, and this is important from the portfolio diversification point of view. Below, we will concentrate our analysis on the main reported differences.

Table 3 presents lower diagonal element values for all stocks. But TCI is now higher (32.77%) meaning the specific network of commodity markets can explain developments within the network itself to a greater extent than previously (27.56%). So, idiosyncratic effects account now for approximately 67% of the forecast error variance of the system. Moreover, while in previous results all renewable energy stocks were net transmitters of shocks in the particular system, now only wind, solar, and biofuels (1.72%, 6.96%, and 3.16%, respectively), on net terms, tend to influence other markets rather than being influenced by others.

Net receivers of respective shocks are green finance, geothermal, and fuel cell. In sum, a shock in one variable spills over to all others now to a greater extent (32.77%) than previously (27.56%). Focusing on the contribution to other assets, the gross directional spillovers transmitted to other assets from each of the individual assets under examination range from 13.06% for green finance, to 48.25% for renewable energy solar, higher than previously (7.87%–41.33%). As such, 48.25% and 40.91% of the forecast error variance is caused by solar and biofuels, respectively, whereas, once again, despite its higher percentage, green finance has a marginal effect on other renewable energy markets, transmitting only about 13.06% of the forecast error variance to other markets. Concerning the dynamic total connectedness, the results presented in Fig. 6, once again, allow us to observe two distinct crisis periods, although the magnitude is higher. For example, values now range from 15% (in normal periods such as 2018) to around 75% (in crisis periods such as in 2020). Also, during Brexit (2016), the magnitude is higher, around 50%, being previously in the order of 35%. Once more, the examined markets are more highly connected during turbulent periods than during normal states.

Fig. 7 presents the dynamic net total directional connectedness, whereas Fig. 8 shows the dynamic pairwise directional connectedness following the original of Diebold and Yilmaz [30]. Again, none of the series can be considered a net transmitter or receiver of spillover shocks for the entire period. In the two crisis periods, we see that type of behavior once again. While green finance, geothermal, and the fuel cell stock index are net receivers of spillover shocks in both the 2016 and 2020 periods, wind, solar, and biofuels renewable stocks are clear net transmitters of shocks during the COVID-19 pandemic. Next, we will explore results solely for this period to see how the series are interrelated in this turbulent period, provided the magnitude of connectedness is even higher than previously reported.

Now, by looking at the net pairwise connectedness results presented in Fig. 8, with a focus on the spillover effects of green finance, we may

Table 3
Averaged joint connected results [30].

	Green Finance	Wind	Solar	Geothermal	Biofuels	Fuel Cell	FROM
Green Finance	80.46	7.15	3.74	1.86	4.88	1.92	19.54
Wind	5.32	67.23	9.33	5.26	7.03	5.82	32.77
Solar	1.96	8.33	58.71	8.30	12.27	10.44	41.29
Geothermal	1.62	6.03	9.98	67.53	8.68	6.16	32.47
Biofuels	3.10	7.13	12.94	7.15	62.25	7.43	37.75
Fuel Cell	1.06	5.85	12.26	5.55	8.06	67.23	32.77
TO	13.06	34.49	48.25	28.11	40.91	31.77	196.59
NET	−6.48	1.72	6.96	−4.36	3.16	−1.00	TCI
NPDC	0.00	4.00	5.00	1.00	3.00	2.00	32.77

Notes: Results are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

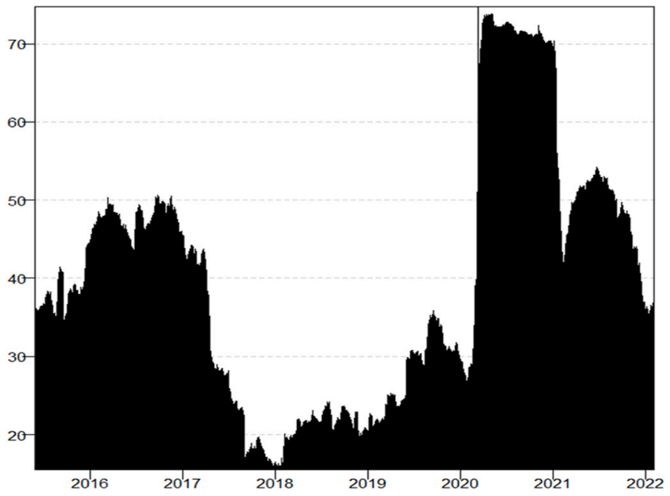

Fig. 6. Dynamic total connectedness [30]
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The black shaded area represents the joint connectedness results.

observe that green finance may assume roles of both net transmitter and net receiver of shocks over time with all other renewable energy stock indexes. Green finance receives high levels of spillovers during the pandemic from wind, solar, and biofuels, being a net transmitter in this period to geothermal. Once more, magnitudes are revealed to be higher under the more traditional Diebold and Yilmaz [30] connectedness method, and during the remainder of the periods, green finance has been both transmitter and receiver of shocks from renewable energy.

Obtaining funds with reduced cost and institutional complexities make the implementation and growth of renewable energies more difficult [27], which may justify some of these results. Moreover, financial markets promote the financing of renewable projects through these assets' inclusion in market indexes [24]. However, green energy is of extreme relevance once green financial instruments provide funds for environmental-friendly firms and an ecologically concerned society [31] making it necessary to revisit market and financing priorities to conform with COP26 goals.

4.2. *Sensitivity checks*

In this subsection, and considering the dynamics described previously during the COVID-19 pandemic period, for robustness purposes, we provide additional analysis on the magnitude of connectedness among the assets examined in the study. The sample period selected for the analysis covers January 2020 until February 2022. Table 4 contains the averaged joint connectedness results during COVID-19. During this period, wind, besides green finance, emerges as a net receiver of shocks and not a transmitter like all other renewable stock indexes (which was explored while presenting the results of Table 2). Even using the Diebold and Yilmaz [30] method (see Table 3), renewables, such as wind, kept being net transmitters in the same way that green finance remained as a net receiver. Moreover, in Table 3, both geothermal and fuel cells became net receivers. We also notice that the elements in the main diagonal of Table 4, corresponding to own-variable shocks (idiosyncratic) increased, except in geothermal and fuel cells, as compared to the values presented in Table 2. This highlights that during the pandemic, a lower percentage of index movement in green finance, wind, solar, and biofuels was driven by network connections. These results contradict those presented by Tiwari et al. [55]. In fact, we cannot even state that the pandemic fuelled intense volatility for all indexes once the magnitude of the shocks was transmitted across assets, as shown in Table 4, as this was not always greater than those we observe in Table 2. The reason may be due to the selected period and series analyzed. Now the TCI average value is 30.67%, higher than that reported in Table 2, but even so, lower than the one reported in Table 3. Thus, 30.67% of the forecast error variance within this network of variables can be regarded as the product of cross-market innovations, and around 69% of the forecast error variance of the system is accounted for by idiosyncratic effects.

Fig. 9, the dynamic total connectedness during this turbulent period,

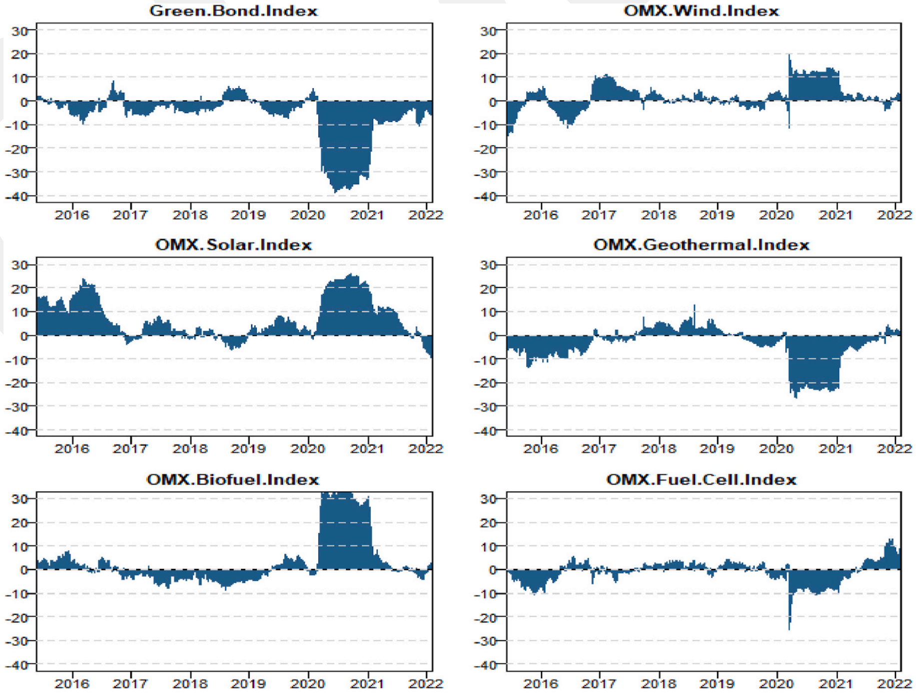

Fig. 7. Dynamic net total directional connectedness [30]
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The blue shaded area represents the joint connectedness results.

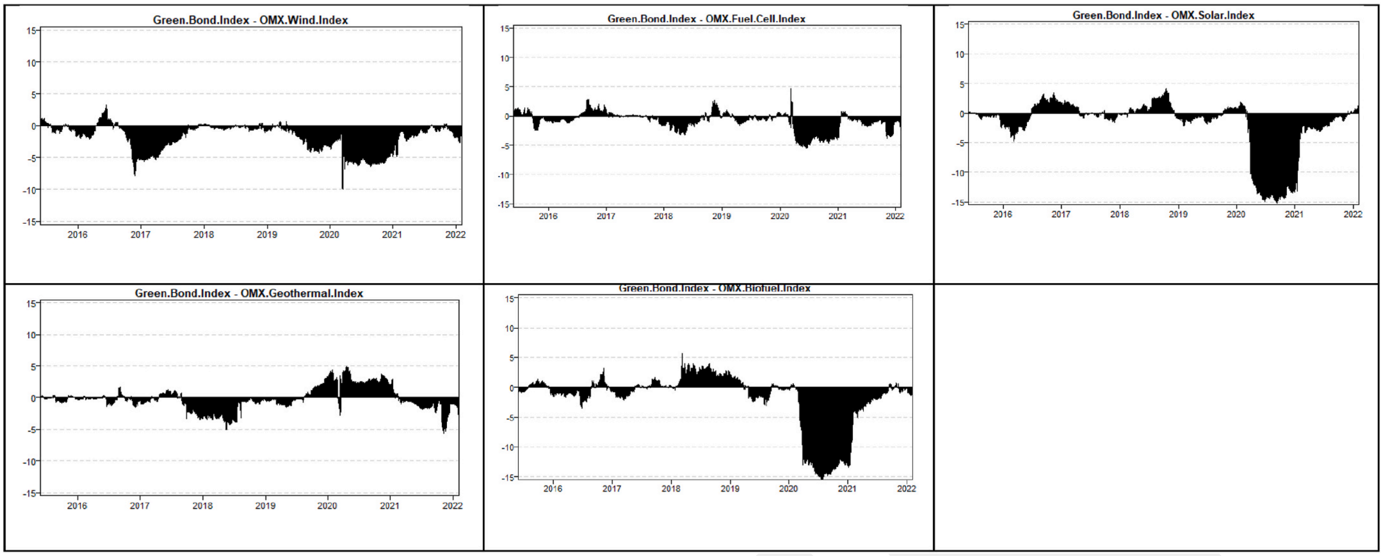

Fig. 8. Dynamic net pairwise directional connectedness (Diebold & Yilmaz,2012)
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The black shaded area represents the joint connectedness results.

Table 4
Averaged joint connected results during COVID-19.

	Green Finance	Wind	Solar	Geothermal	Biofuels	Fuel Cell	FROM
Green Finance	87.18	4.92	1.45	2.64	1.88	1.94	12.82
Wind	4.04	74.32	7.67	2.66	2.20	9.11	25.68
Solar	1.09	7.08	66.25	7.50	7.74	10.34	33.75
Geothermal	1.17	2.32	7.86	66.10	9.14	13.41	33.90
Biofuels	1.01	2.27	7.87	9.19	67.70	11.96	32.30
Fuel Cell	1.12	7.24	11.14	13.93	12.13	54.44	45.56
TO	8.44	23.82	35.99	35.92	33.09	46.76	184.02
NET	−4.38	−1.87	2.24	2.01	0.79	1.20	TCI
NPDC	0.00	2.00	5.00	4.00	2.00	2.00	30.67

Notes: Results are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition.

shows the intertemporal evolution of the TCI, which was very high (around 37%) during March and August 2020. It then decreased subsequently until the end of the year, to increase more at the beginning of 2021, but at much lower magnitudes. Thus, the safe-haven properties of green finance and/or renewable energy stocks vanish quickly, leaving investors unprotected against market fluctuations from these turbulent periods onwards. As such, dynamic hedging strategies should have been followed by investors while building these based solely on green finance or renewable energy stock. These results conform to those of Polzin et al. [51] who note that renewable energy investments are a diversification opportunity for investors. They also validate those of Mensi et al. [56]; who report that green bonds offer improved diversification opportunities.

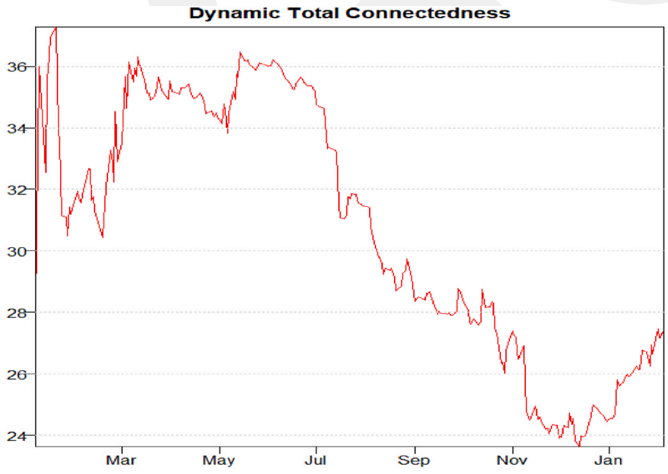

Fig. 9. Dynamic total connectedness during COVID-19 [29].
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The red line represents the joint connectedness results.

Finally, we present the dynamic net total directional connectedness during COVID-19 in Fig. 10 and the dynamic net pairwise directional connectedness during COVID-19 in Fig. 11. Very interesting results emerge for this specific period. This time, green finance is seen as a net receiver of spillover shocks with higher intensity or magnitude for the entire period until April 2020. Similarly, solar, geothermal, and fuel cell indexes assumed a net transmitting role, with wind assuming a net receiving role from April 2020 onwards. Biofuels seem to have assumed both roles over time, although clearly, its net transmitting role is rather more evident. Thus, it is evident that during turbulent periods, it is a clear net receiver from renewable energy stock indexes, as also proved in the pairwise connectedness representation in Fig. 11.

The first thing to note is that considering solely this period, green finance assumes a clear net receiving role with all other renewable series. Also clear is the fact that this high interconnection between green finance and the renewable stock index is superior to the shock or surprise of the event happening. The higher negative connectedness results are more evident at the beginning of 2020, when the entire world had to

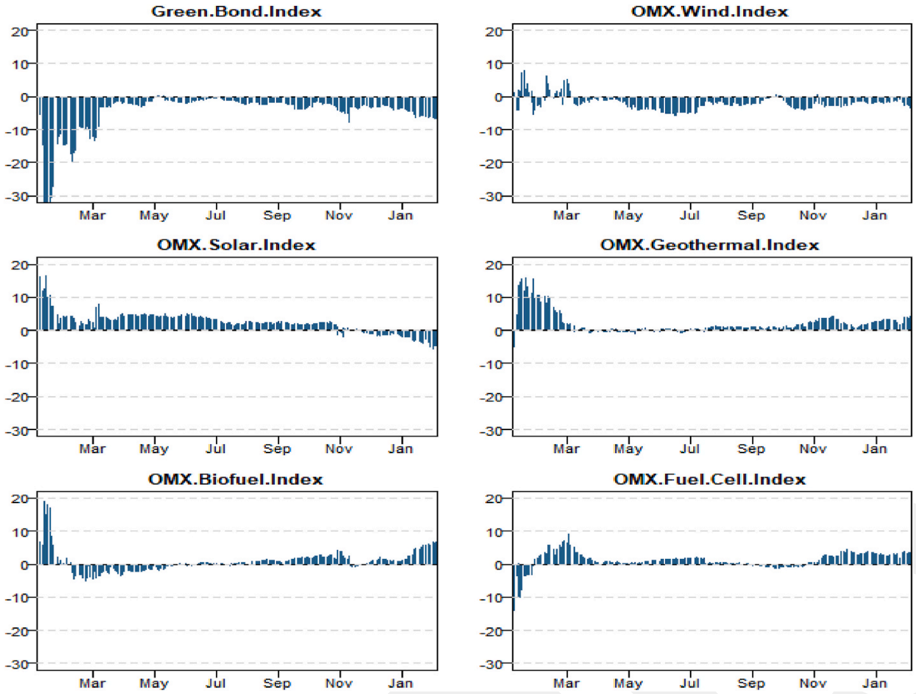

Fig. 10. Dynamic net total directional connectedness during COVID-19 [29]
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The blue shaded area represents the joint connectedness results.

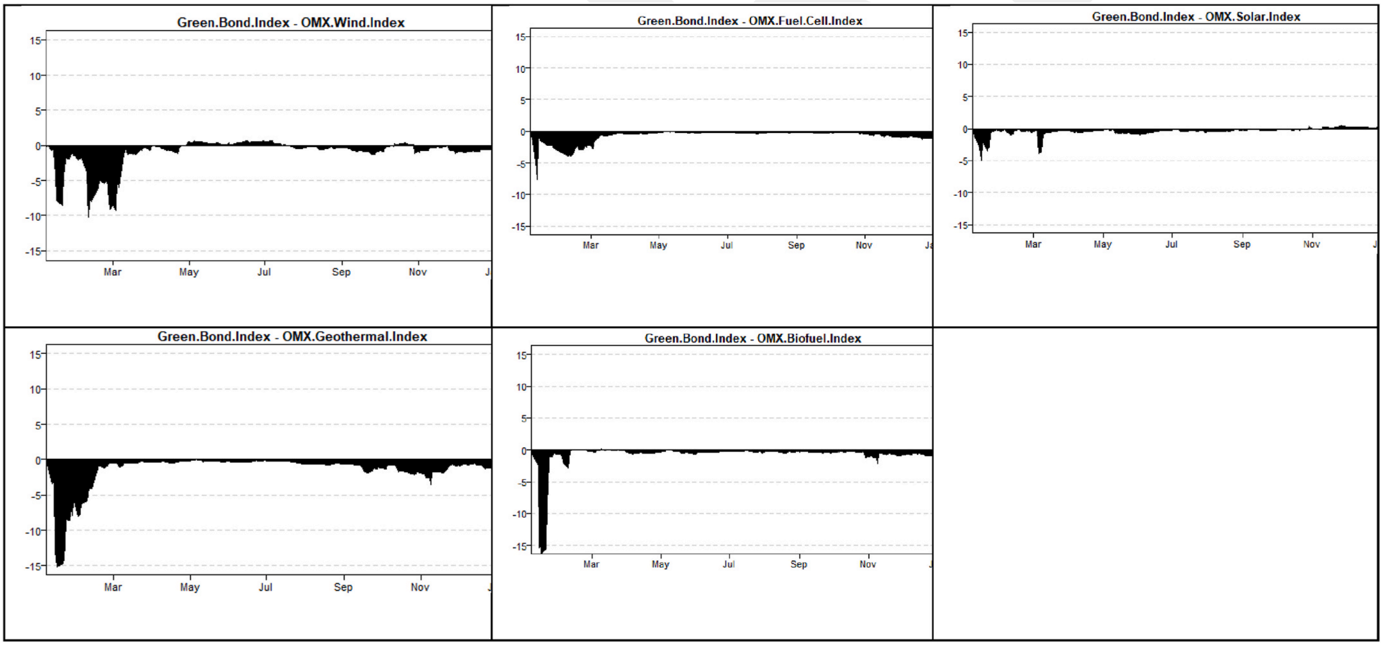

Fig. 11. Dynamic net pairwise directional connectedness during COVID-19 [29]
Notes: Findings are based on a TVP-VAR model with a lag length of order one (BIC) and a 20-step-ahead generalized forecast error variance decomposition. The black shaded area represents the joint connectedness results.

react to a new unknown event, affecting all economic activity sectors at once. Therefore, it is the surprise of shocks that justify the dynamic portfolio management in turbulent periods and may redirect investors and investments to more ecological, green, and environmentally friendly investments in financial markets. Following the findings of He et al. [32]; green finance leads to increased environmental benefits through capital support, resources allocation, and technological innovation [31], the latter promoting decreases in firms' environmental damages and pollution (Li and Jia, 2015). Ye et al. [41] state that the pandemic put extreme pressure on renewable energy sources, noting that green financing sources exerted a positive influence on renewable energy investments, conforming to our results.

Undoubtedly, the world assisted in a decrease in CO2 emissions, and lower pollutant levels, but these environmental improvements were obtained at the expense of lower economic and financial growth. It is known in the literature that green finance causes carbon dioxide emissions to decline [44]. Our results provide evidence, even if indirectly, that this is true. A positive contribution of green finance to environmental outcomes is also stated by Zhou et al. [33]; Zhou et al. [45]. Additionally, the results of Razoulinezhad and Taghizadeh-Hesary [49] show that green bonds are a convenient and significant method for financing green energy projects and decreasing carbon emissions.

5. Conclusion and policy implications

This paper aims to characterize spillovers and connectedness between the indexes of renewable energy by types (biofuels, fuel cell, geothermal, solar, and wind) and green finance by applying the novel TVP-VAR method of Balcilar et al. [29] from July 31, 2014, to Feb 4, 2022. The well-known method of Diebold and Yilmaz [30] is also applied to test for robustness. Full sample results show that green finance and the indexes of renewable energy sources are moderately interconnected, and even more so during turbulent periods, such as 2016 and 2020. This is evidenced by the total connectedness index (TCI) which is approximately 28%, being higher under the traditional method (33%), and during the pandemic period (31%). Thus, the network is exposed to moderate market risk.

Overall, the system-wide dynamic connectedness is heterogeneous over time and driven by market economic events like the Brexit referendum and the COVID-19 pandemic. Results from the empirical evidence allow us to state that green finance is a net receiver of shocks from renewable energy stocks, but pairwise connectedness maintains that green finance not only affects renewable energy markets but is also equally responsive to innovations that take place in most of these markets. Since the empirical results demonstrate sizable connections between green finance and renewable energy, they underscore the potential of higher, or lower, systematic risk, or diversification possibilities for investors in these financial markets. These are more pronounced given the magnitude of connectedness during market downturns, such as the Brexit referendum and the COVID-19 pandemic, the latter checked carefully for robustness. The results show the impact a shock in one of the assets has on the network, and any portfolio manager would be aware that a shock in green finance is not isolated. Green finance was clearly a net receiver shock, especially in economic crises. Policymakers who are entrusted with designing environmentally-friendly policies can use these findings to see the impact of potential spillovers of a change in renewable energy markets on green finance. This might be a safe-haven asset during turbulent events, especially those that lessen the effects of pollution, thereby improving air quality, such as during the COVID-19 pandemic. Streimikiene and Kaftan [39] point out that green loans, bonds, and mortgages are effective tools to achieve sustainability. However, green finance should be regulated by governments, otherwise, its development will decrease renewable energy investment efficiency [9].

Additionally, we find that green finance transmits the lowest value of shocks to other markets, followed by geothermal, irrespective of the technique used for estimating it. Concerning the period under analysis, namely the pandemic period, besides green finance, wind is also a lower transmitter of shocks. The highest spillovers are transmitted from biofuels to solar (12.14%) using the Balcilar et al. [29] technique, from solar to biofuels (12.94%) under the Diebold and Yilmaz [30] traditional technique, and from geothermal to fuel cell (13.93%) during the COVID-19 pandemic period. Generally, renewable energy stocks transmit more shocks to green finance compared to vice versa. Green finance can direct accumulated funds to firms that are low-carbon emitters or to projects of renewable energy production [2]. The cost of capital is increased and loan amounts decreased when accessing credit for non-compliant firms [35]. Thus, green finance increases the efficiency of capital allocation, moving the capital from non-compliant companies to low-polluting firms [33,34]. There is also evidence in the literature that clean energy and technology stocks are more correlated than clean stocks and oil prices [36]. The evidence in the present work is clear that there are spillovers between energy and finance, as concluded by Ma et al. [37]. From our results, among all the renewable stocks considered, wind is the one transmitting higher shocks to green finance. Green finance has a marginal effect on renewable energy stocks, since it only accounts for 7.87% of shocks to other markets (13.06% under Diebold and Yilmaz's [30] technique, and 8.44% during the pandemic period). Even so, these amounts are much higher than those found by Tiwari et al. [55]; at 2.246%.

The fact that green finance receives more shocks from renewable markets compared to what it transmits to them is also a point to be discussed. Using the newest TVP-VAR technique, we note that green finance is the only asset having negative net spillover values, being a net receiver of shocks. Considering the more traditional technique, both green finance, geothermal, and fuel cell present net negative spillover values. During the pandemic, both green finance and wind seem to be the largest receivers of shocks. The largest net transmitter in terms of magnitude in the sample was solar energy, except using the Balcilar et al. [29] technique, wherein this situation occurred with biofuels.

Important factors relating to green finance policies can be derived from our results, supporting renewable energy investments. Public funding can have an impact on renewable energy companies, whenever renewable energy stocks move up or down jointly with green finance. Policy decisions based on the transition of energy to a decarbonized economy should account for these effects on green finance, which is also critical for the achievement of COP26 goals. Thus, policymakers should consider green finance stocks and renewable energy stocks as interrelated assets. Finally, market participants may also use our results for diversification purposes in their portfolio compositions, especially during turbulent periods, as discussed in the results section.

The heterogeneous impact of green finance stock over renewable energy stocks is also an important point for discussion, since they are markets that fluctuate substantially. In particular, sudden extreme events have significant effects on market volatility interactions [46]. Since extreme events can bring shocks to market interactions, emergency measures to measure these extreme event shocks and market risks must be strengthened. Recently, Madaleno et al. [19] concluded that green finance investments are promoted and apportioned by the need for clean energy. In the present work, the interrelationships have been explored and the net transmitting and receiving roles of shocks between green finance and renewable energy markets highlighted. Rasoulinezhad and Taghizadeh-Hesary's [49] results show that green bonds are suitable assets to promote green energy projects and reduce emissions, as Madaleno et al. [19] suggest. This occurs through the funding of green technology for successful energy transition and the achievement of sustainable development goals. It could be harder to obtain the necessary funds to finance green projects during crisis periods [49], but our results highlight clear interactions and magnitudes of interrelationships among green finance and renewable energy stocks that should be considered by both policymakers and portfolio investors, especially during a crisis.

This study has some limitations that we can easily convert into future research directions. In the future, we recommend the inclusion of geopolitical risk and the more recent turbulent period in energy markets caused by the invasion of Russia to Ukraine. Including carbon stock in the spirit of Tiwari et al. [55] would be beneficial to carbon-related-policies assessment. It would also be important to include fossil fuel to see the magnitude of the impacts to and from green finance to follow the achievement of COP-26 goals. Moreover, larger data periods would provide more insights into the effects of financial policy supports, clean energy supports, carbon markets effects, and other relevant economic and financial crisis events. Finally, it would be relevant to perform country analysis and comparisons since different findings would certainly be found depending on a country's development level, the renewables stake in the energy mix, and socio-economic-political difficulties faced.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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