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Impacts of COVID-19 on dynamic return and volatility spillovers between rare earth metals and renewable energy stock markets

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A B S T R A C T

We examine the time-frequency co-movements and return and volatility spillovers between the rare earths and six major renewable energy stocks. We employ the wavelet analysis and the spillover index methodology from January 1, 2018 to May 15, 2020. We report that the COVID-19-triggered significant increase in co-movements and spillovers in returns and volatility between the rare earths and renewable energy returns and volatility. The rare earths act as net recipient of both return and volatility spillovers, while the clean energy stocks are net transmitters of return and volatility spillovers before and during the COVID-19 crisis. The solar and wind stocks are net transmitters/receivers of spillovers before/during the pandemic. The remaining markets shift from net spillover receivers to transmitters or vice versa; evidencing the effects of the pandemic. Our results show that cross-market hedge strategies may have their efficiency impaired during the periods of crises implying a necessity of portfolio rebalancing.

1. Introduction

Rare earths metals (REMs) are a critical resource for contemporary societies. They are indispensable ingredient in modern industry with the uses in new energy, energy conservation, new materials, aerospace, environmental protection, and electronic information industries (McLellan et al., 2013; Wang et al., 2015; Zhou et al., 2022). REMs are key components of sustainability technologies such as wind turbines and electric vehicles. However, major developed economies have been experiencing severe disruptions of REMs supply, being the situation severely affected since 2019 by the US-China trade tensions relative, in particular, to the REMs outbound shipments from China. In addition, the REMs supply-demand binominal has been being adversely impacted by the ongoing COVID-19 global outbreak. Therefore, spillover patterns between the REMs and renewable energy markets as well as mechanisms at play underlying the cross-market innovations' transmission represent an important contemporary question, with a rather scarce coverage in the scientific literature. In this context, our paper investigates static connectedness and dynamic spillovers in return and volatility time-series and time-frequency co-movements between the REMs and six important renewable energy stock markets from during 2018–2020. This period covers the escalation of the trade tensions between the US and China around 2019 and the apogee of the COVID-19 crisis in the first half of 2020. As we consider the six most important sub-sectors in the domain of renewable energy production, our results are particularly capable of providing refined valuable insights to market participants and regulators in the realm of renewable energy and REMs.

Our motivation is also straightforward as such a detailed analysis, discriminating between different sectors within the renewable energy economy is important for investors and financial professionals in search for better diversification opportunities and advanced hedge strategies, workable through the periods of global crises such as COVID-19 pandemic. Moreover, our motivational drivers have their origins rooted in significant investments in renewable energy, projected for the

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Table 1
Descriptive Statistics of daily returns for rare earth and renewable energy.

	Obs.	Mean	Maximum	Minimum	Std.Dev	Skewness	Kurtosis	J.-B.
Panel A: Full Sample								
TECH	619	0.061	11.301	−14.984	1.856	−0.625	12.955	4400***
RENIXX	619	0.058	16.672	−16.486	1.811	−0.520	27.936	20000***
ECO	619	0.031	13.399	−16.239	2.135	−1.518	15.179	6200***
SPGTCED	619	0.022	11.035	−12.498	1.560	−1.762	21.202	12000***
WIND	619	−0.017	1.752	−1.754	0.381	0.125	1.956	100***
SOLAR	619	−0.017	1.749	−1.748	0.382	0.123	1.920	98***
REMX	619	−0.158	6.253	−8.116	1.681	−0.369	2.430	170***
Panel B: Pre-COVID-19								
TECH	499	0.064	5.872	−5.201	1.313	−0.497	2.501	150***
RENIXX	499	0.042	16.672	−16.486	1.429	0.029	70.384	100000***
ECO	499	0.039	6.009	−4.471	1.351	−0.095	1.164	30***
SPGTCED	499	0.031	2.882	−2.989	0.880	0.052	0.574	7.400**
WIND	499	−0.017	1.072	−1.221	0.346	0.151	0.369	4.900*
SOLAR	499	−0.017	1.070	−1.213	0.347	0.143	0.350	4.400*
REMX	499	−0.158	6.253	−4.937	1.443	0.060	1.110	27***
Panel C: COVID-19								
TECH	120	0.051	11.301	−14.984	3.267	−0.449	4.969	130***
RENIXX	120	0.125	9.419	−11.146	2.914	−0.711	3.253	67***
ECO	120	−0.006	13.399	−16.239	4.005	−1.147	4.308	130***
SPGTCED	120	−0.017	11.035	−12.498	3.066	−1.169	5.215	170***
WIND	120	−0.016	1.752	−1.754	0.504	0.073	2.270	28***
SOLAR	120	−0.016	1.749	−1.748	0.504	0.081	2.230	27***
REMX	120	−0.156	5.425	−8.116	2.442	−0.674	1.210	18***

Notes: This table reports the descriptive statistics and Jarque-Bera (J.-B.) test of the return series for the renewable energy (TECH, RENIXX, ECO, SPGTCED, WIND, and SOLAR) and the rare earths (REMX) indices. ***, **, and * represent statistical significance at 1%, 5%, and 10% levels, respectively. Pre-COVID-19 sub-sample: January 01, 2018–November 29, 2019. COVID-19 sub-sample: November 30, 2019–May 15, 2020.

Table 2
Unconditional daily returns correlation.

	TECH	RENIXX	ECO	SPGTCED	WIND	SOLAR	REMX
Panel A: Full Sample							
TECH	1						
RENIXX	0.420	1					
ECO	0.810	0.588	1				
SPGTCED	0.700	0.695	0.884	1			
WIND	−0.001	0.158	0.037	0.108	1		
SOLAR	−0.001	0.157	0.037	0.108	1.000	1	
REMX	0.431	0.491	0.514	0.599	0.155	0.155	1
Panel B: Pre-COVID-19							
TECH	1						
RENIXX	0.240	1					
ECO	0.742	0.312	1				
SPGTCED	0.557	0.470	0.748	1			
WIND	0.025	0.132	0.059	0.178	1		
SOLAR	0.023	0.133	0.058	0.178	1.000	1	
REMX	0.308	0.333	0.374	0.483	0.186	0.187	1
Panel C: COVID-19							
TECH	1						
RENIXX	0.573	1					
ECO	0.853	0.796	1				
SPGTCED	0.782	0.865	0.942	1			
WIND	−0.030	0.200	0.020	0.070	1		
SOLAR	−0.029	0.201	0.021	0.070	1.000	1	
REMX	0.569	0.686	0.668	0.746	0.103	0.101	1

Notes: This table reports the unconditional pair-wise daily returns correlations for the renewable energy (TECH, RENIXX, ECO, SPGTCED, WIND, and SOLAR) and the rare earths (REMX) indices. Pre-COVID-19 sub-sample: January 01, 2018–November 29, 2019. COVID-19 sub-sample: November 30, 2019–May 15, 2020.

near future, on the one hand, and, on the other hand, they reside in an ongoing upsurge of the rare earths in a quality of investment vehicles. More concretely, our motivation, from the applied finance point of view is three-fold. First, due to a certain opacity of the rare earths' materials and renewable energy industries, a certain lack of trust (Reboredo and Ugolini, 2020) and concerns regarding price volatility have resulted in failures of multiple projects because of insufficient investment. Second, exposures to rare earths' materials have been becoming important portfolio diversification practices, igniting attention from investment communities and requiring a better information coverage of rare earths' prices and their interrelations with other industries and markets. Third, each time wider attention to an unstoppable expansion of renewable energy facilities have resulted in a vast body of research dedicated to the connectedness and risk spillovers between renewable and conventional carbon-based energy markets. However, the literature on the rare earths and renewable energy is rather scarce and insufficient. Hence, in light of all the above discussed aspects, we are motivated, by means of our research, to provide useful insights for academy scholars, investors and market practitioners.

To better understand the linkages between the REMs and renewable energy companies, it is important to bear in mind that REMs play role of crucial inputs for manufacturing of wind dynamo machines,

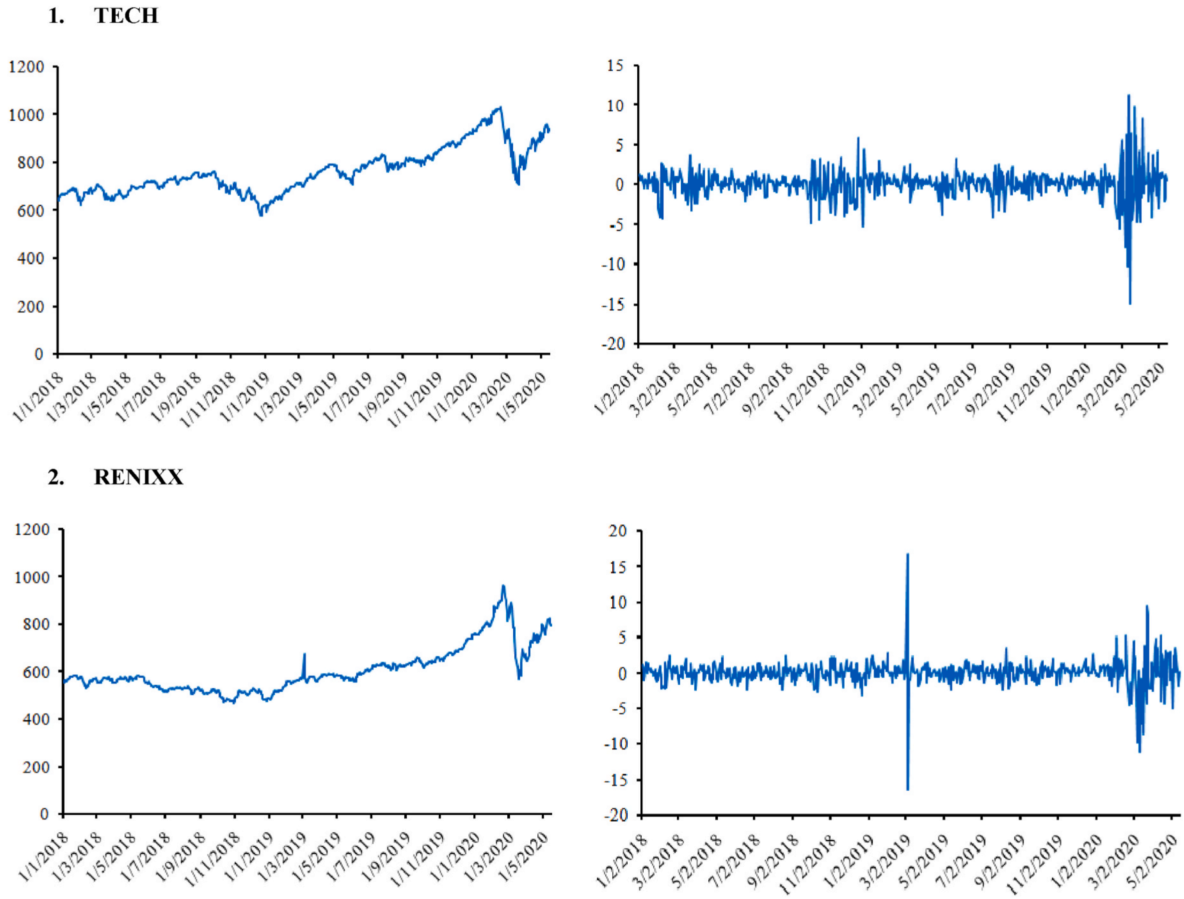


Fig. 1. Price and return dynamics.

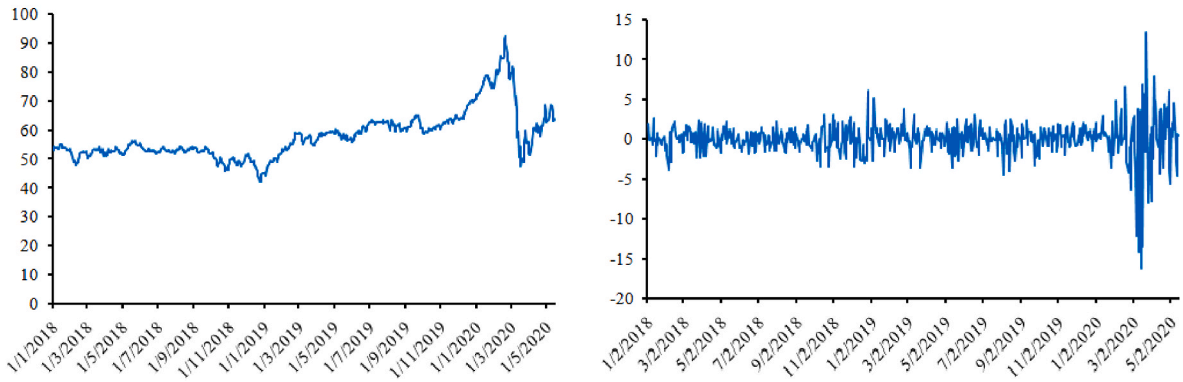
photovoltaic panels, and electric accumulators and cars, whereas a replacement of rare earths as fundamental production ingredients is seemingly hardly possible at the current state of technology development (Müller et al., 2016; García et al., 2017; Buchholz and Brandenburg, 2018). Therefore, the aspired transition to renewable energies requires an urgent evolution of the REMs markets (Elshkaki, 2021; Hodgkinson and Smith, 2021). Beyond their primary importance for the renewable energy companies, REMs are intensively required by several non-energy industries (Müller et al., 2016; Nassar et al., 2016). Therefore, to guaranty a sustainable shift to renewable energy production, a reliable supply of REMs is of an extreme importance (Elshkaki, 2021; Watari et al., 2021).

The REMs mining and production is dominated by China and, hence, REMs supply possesses serious inherent vulnerabilities (Buchholz and Brandenburg, 2018; Mancheri et al., 2019; Watari et al., 2021). The intrinsic riskiness of the REMs supply chains is responsible for large variations in their prices, which have been observed since the global financial crisis and will continue into the foreseeable future due to unstable supply, increasing demand, diverse market disruptions because of local and global crises, and unceasing geopolitical tensions (Schmid, 2019; Proelss et al., 2020). REMs evolve towards becoming a stand-alone commodity category, although remaining inherently more vulnerable to geopolitics and, hence, riskier than traditional commodities (Fernandez, 2017; Cox and Kynicky, 2018; Proelss et al., 2020). Therefore, researching the risk spillovers between the REMs market and REMs-dependent markets such as renewable energy industry is highly desirable. On the other hand, it is worth noting that the clean energies sectors have demonstrated their relative resilience vis-à-vis conventional carbon energy producers, the latter being severely impacted by a considerable decay in demand due to pandemic containment measures, including travel and mobility restrictions, lockdown policies and work-from-home practices (Kim and Karpinski, 2020).

Given the importance of this topic, several economics and financial aspects of the REMs and renewable energy markets have been addressed in the literature (McLellan et al., 2013; Baldi et al., 2014; Apergis and Apergis, 2017; Elshkaki, 2021; Watari et al., 2021). All they find that the REMs prices represent a crucial determinant for development of renewable energy capacities. We also point to a few existing scientific studies, which address interconnections between the REMs and the renewable energy companies, such as Fernandez (2017); Chen et al. (2020); Reboredo and Ugolini (2020); Bouri et al. (2021); and Song et al. (2021). However, these works while studying the nexus between the REMs and renewable energy companies, in the first place, pay attention to the REMs market. For instance, to the best of our knowledge, just one benchmark for renewable energy industry is commonly employed to describe the whole universe of renewable energy domains. Such approach overlooks the detailed description of the renewable energy subsectors and may result in over-generalized results and conclusions as the performance of one subsector may considerably differ from the other (s).

Our paper contributes to the academic literature in the two following ways. First, our study represents a contemporaneous forehanded research, based on the historical dataset covering both, the apogee of the trade tensions between US and China in 2019 and the escalation of the COVID-19 crisis with its peak in March 2020, bearing in mind that the joint influence of the mounting US-China trade tensions and of the ongoing pandemic makes highly desirable to revisit earlier empirical findings by means of analyzing a new dynamic between REMs and

3. ECO



4. SPGTCED

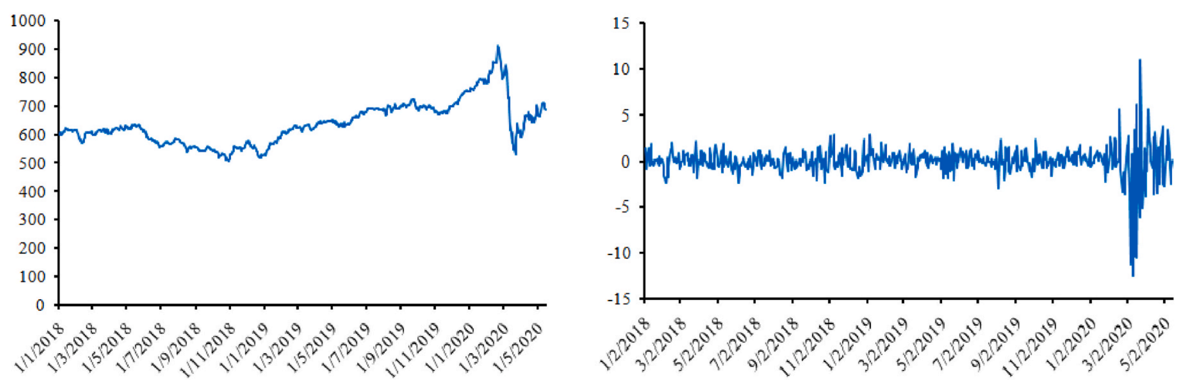


Fig. 1. (*continued*).

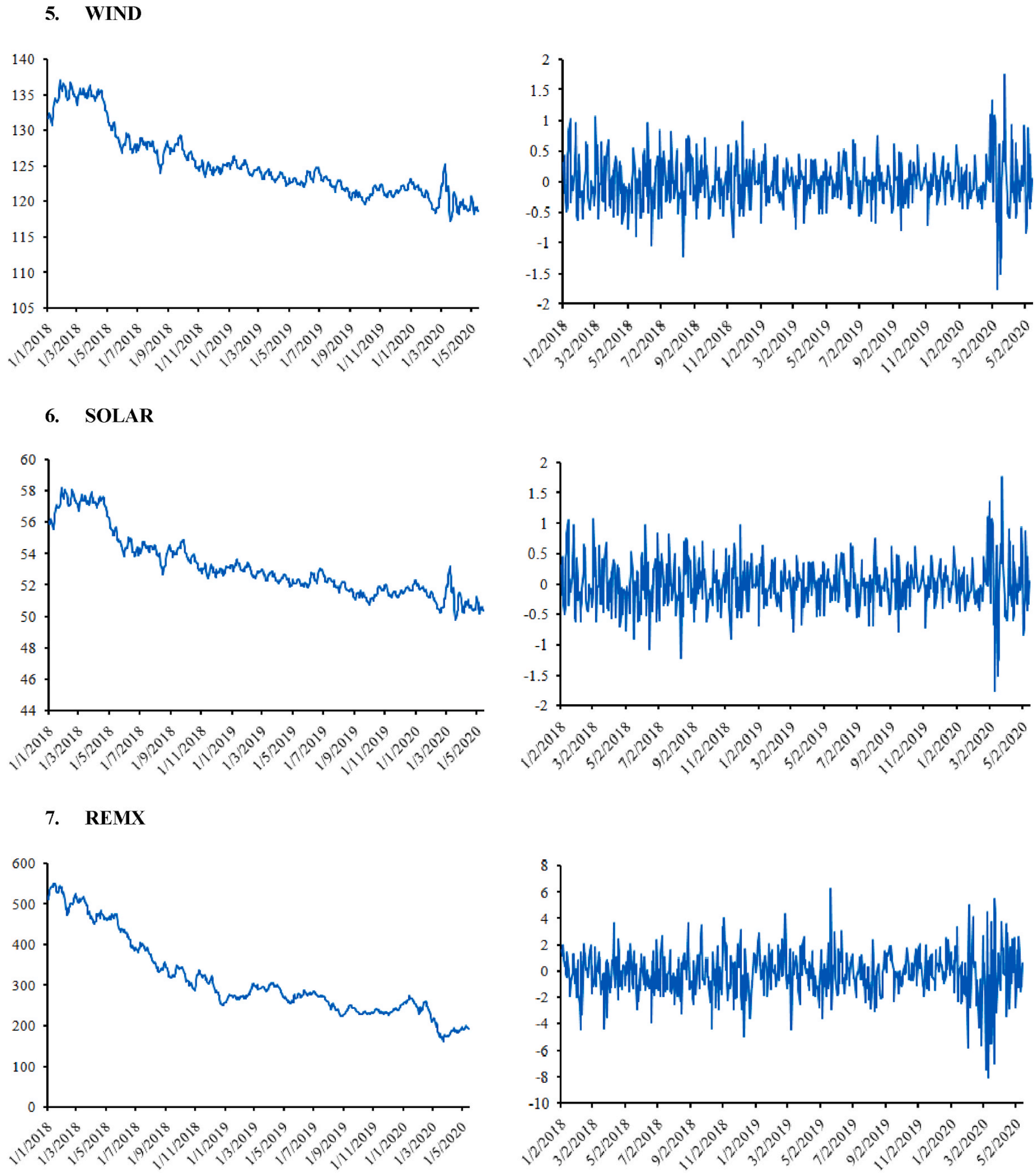
different sectors of renewable energy industry.

Second, the dynamic return and volatility connectedness of the REMs index with six renewable energy sectors indices, regarding total and net directional spillovers, is thoroughly explored and the receiver/transmitter role of each market is duly identified. We perform our connectedness analysis for the whole sample period and for the two constituent pre-COVID-19 and COVID-19 sub-periods. Thus, differing from previous research (Chen et al., 2020; Reboredo and Ugolini, 2020; Bouri et al., 2021; Song et al., 2021) focused mainly on diverse interrelations between the rare earths markets and other major asset classes, our primary focus is centered on the main renewable energy sub-industries as well as on the risk and volatility spillovers between them and the REMs market within the unique research setup shaped by COVID-19.

Our paper uses the wavelet method that allow one to obtain the results in the form of time-frequency heatmaps containing the information on both coherence and time difference of the studied pairs of indices (Torrence and Compo, 1998; Grinsted et al., 2004; Vacha and Barunik, 2012; Banović et al., 2013; Bredin et al., 2015; Umar and Gubareva, 2020). As an important aspect of the wavelet approach, the wavelet coherence analysis allows providing insights on the joint behavior of indices, not only along the dimension of time, but also over different investment time scales or so-called frequency periods, thus enabling us to study various patterns stock price movements, lead-lag relations, and co-movements. Given the importance of frequency or investment horizon dimension in the context of stock investments, we opt to employ wavelet methods. It is worth noting that the wavelet technique does not require any strong assumption such as stationarity and can be used to capture both linear and non-linear effects. This aspect is especially important while investigating abrupt market movements in the periods of crises when stationarity could be potentially compromised. All the above characterize the wavelet methodology as a robust approach, commonly employed to investigate coherence between various time series (Zaremba et al., 2019; Younis et al., 2020; Gubareva and Umar, 2020; Umar and Gubareva, 2021). To get an accurate and full picture on the relationships between rare earth stock and renewable energy markets, we employ the spillover index approach proposed by Diebold and Yilmaz (2012). This method allows us to identify the size and the direction of spillovers among assets, allowing to identify the source of contagion as it identifies the net receivers and the transmitters of returns and volatility (Umar and Gubareva, 2021).

Our results reveal a high coherence between the REMs and renewable energy markets before the pandemic at intermediate frequency. However, the co-movements increase during the pandemic irrespective of frequencies. In addition, during the pre-COVID-19 period the REMs stocks lead the renewable energy market returns, except for the wind and solar energy sectors. Furthermore, our separate return and volatility transmission study signals that both return and volatility spillovers mostly upsurge from the REMs and influence the renewable energy market with spillover intensities augmenting considerably during the pandemic. In what concerns renewable energy sectors, the clean energy index companies act as the major net transmitter of return spillovers during the whole sample. However, the high growth technology companies take a lead in net volatility transmission during the COVID-19 pandemic. Moreover, the REMs and renewable energy indices, are found to be moderately interrelated before the pandemic in both return and volatility perspective. However, they become strongly interconnected during COVID-19, transmitting return and volatility spillovers to each other, and evidencing an increased influence of the REMs companies, especially for volatility transmission.

The remaining part of the paper is structured as follows. Section 2 presents the literature review. Section 3 discusses the employed methodologies. Section 4 describes the dataset, addresses the descriptive



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sample statistics, and overviews preliminary results. Section 5 discusses the empirical results. Section 6 concludes the paper.

2. Literature review

The renewable energy sectors are heavily dependent on the REMs, implying that there exists an inherent interdependence between the renewable energy system and the companies involved in REM extraction, production and handling. Therefore, a shift towards renewable energies brings about new challenges related to interrelations between the clean energy and REM markets and to new risks emerging from their connectedness. Several researches have been addressing diverse linkages between the REM and renewable energy industries (Massari and Ruberti, 2013; Baldi et al., 2014; McLellan et al., 2014; Dutta et al., 2016; Apergis and Apergis, 2017; Cox and Kynicky, 2018; Chen and Zheng, 2019; Månberger and Johansson, 2019; Wang et al., 2019; Chen et al., 2020; Proelsset al., 2020; Watari et al., 2021; Zhou et al., 2020; Elshkaki, 2021; Hanif et al., 2021; Piarulli et al., 2021; Zheng et al., 2021; Golroudbary et al., 2022).

Several works investigate the interrelations between the REM companies and renewable energy stocks. For example, Baldi et al. (2014) find that the relationship between the selected set of REs and the clean energy index is inverse within the 2006–2012 period. In their turn, Apergis and Apergis (2017) study the joint dynamics of the REM prices and the clean energy consumption within 2004–2016 period and provide empirical evidence of a negative relationship between these two economic aggregates at both the regional and the global scales. In parallel, Fernandez (2017) analyzes historical evolution of rare earths market and finds that low correlation between REM and commodity prices may imply an existence of attractive diversification benefits. In

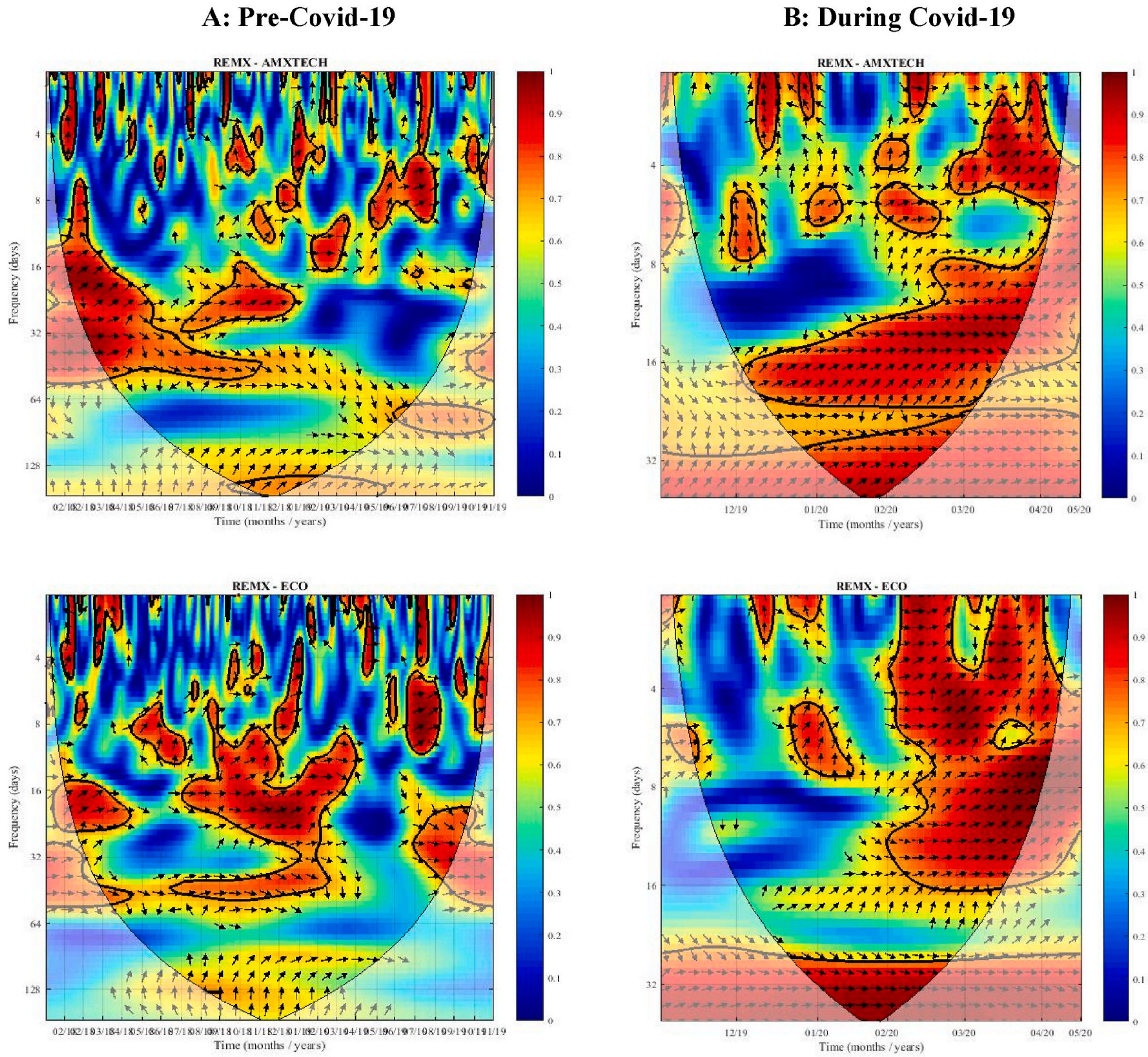
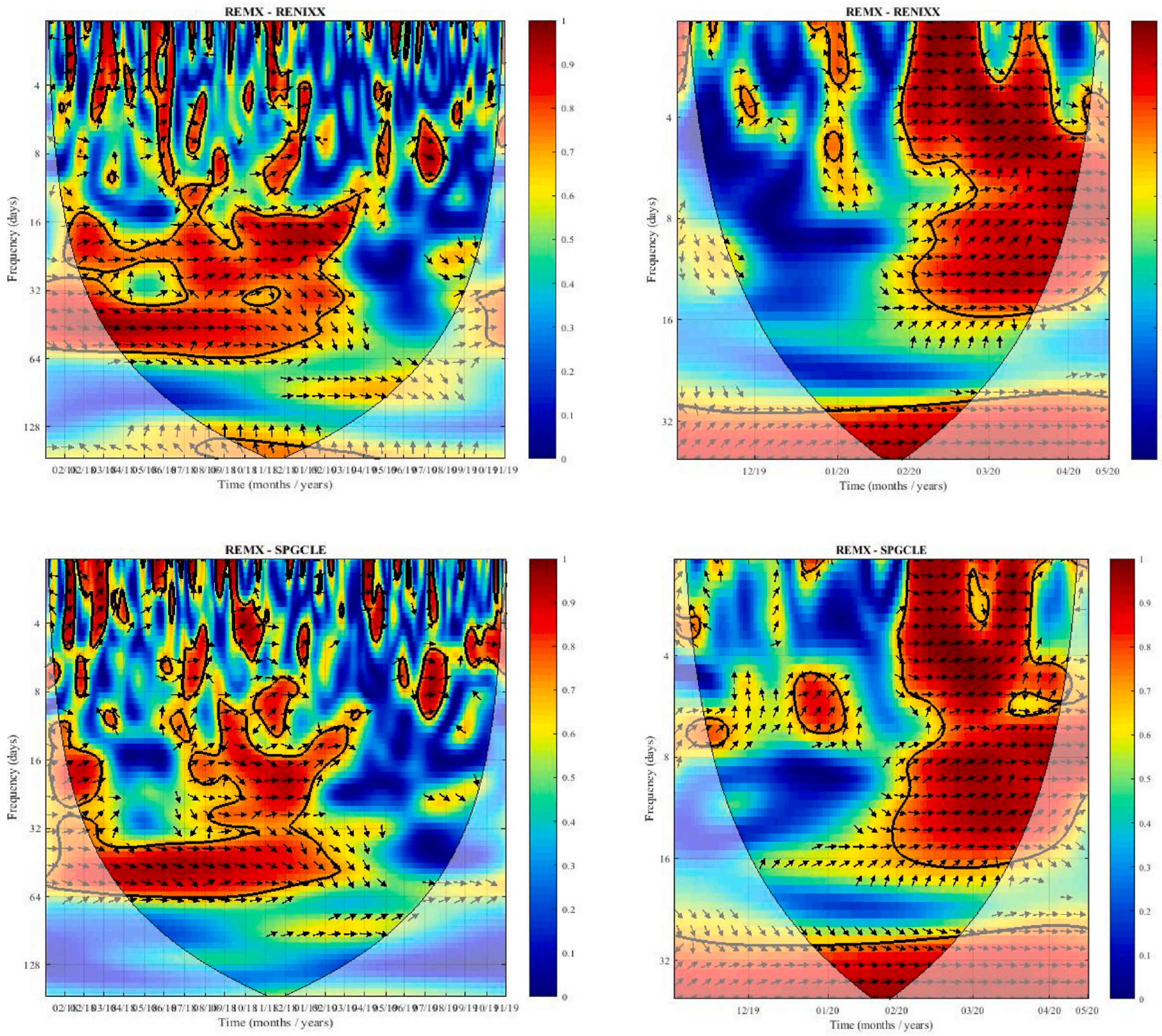


Fig. 2. Squared wavelet coherence plots, pairwise estimates.
Notes: This figure shows the SWC between rare earth metals and renewable energy stocks. The frequency (in days) and time are given on the vertical and horizontal axis, respectively. The level of significance has been ascertained in the Monte Carlo simulation (for further explanations of the SWC plot, see Bredin et al., 2015).

particular, Fernandez (2017), based on the pair-wise correlation analysis, provides empirical evidence that since 2008 to 2016 the REM indices move more in line with non-precious than with precious metals.

Nonetheless, research, dedicated to studying interrelations between the REM and renewable energy stocks such as Reboredo and Ugolini (2020), Bouri et al. (2021), Song et al. (2021), commonly uses only one benchmark index for proxying the renewable energy industry, namely, the Wilder Hill Clean Energy Index (Bloomberg ticker: ECO Index). Such approach allows for an aggregate, though eventually biased view of the renewable energy system, as it does not permit to duly discriminate between different sub-sectors and lines of businesses of the companies involved into the transition towards cleaner energies. To the best of our knowledge, there exist no previous studies considering the interrelations between the REM and solar energy industry, between the REM and wind energy companies, and so on, and so forth.

Chen et al. (2020) investigate the nexus of crude oil, new energy and rare earth in China, focusing in particular, on spillovers in volatility series among three renowned benchmarks, namely the Brent crude oil price, Mainland new energy index, and the rare earth industry index. They document a high interdependency between new energy and rare earths industries. In addition, Chen et al. (2020) conclude that the China's rare earth industry is the major transmitter of volatility spillovers. Reboredo and Ugolini (2020) investigate price transmission between REM companies' stocks and related stock markets, including base metals, clean energies, gold, oil and general stock markets. The authors employ a Markov-switching vector-autoregressive (VAR) model to distinguish between the high- and low-volatility regimes. The authors find that in a low-volatility regime the REM stocks are weakly connected to clean energy stock market, while in a high-volatility regime, they observe an increase in REM price co-movements with price changes in the clean energy sector. Overall, the Authors conclude that the REM stock market always acts as a net recipient of price spillovers with null/limited capacity to originate price spillovers under low-volatility/high-volatility conditions. Their findings provide relevant insights regarding downside risk hedging of REM exposures by investing in stocks of clean energy companies. Using a quantile-based connectedness approach Bouri et al. (2021) explore the connectedness in returns and volatility between return and volatility connectedness between the RE stock index and both clean energy, aerospace and defense, consumer electronics, telecommunications, and healthcare equipment. The authors show that the relationships between these markets are asymmetric during extreme (lower and upper) quantiles. More importantly, the



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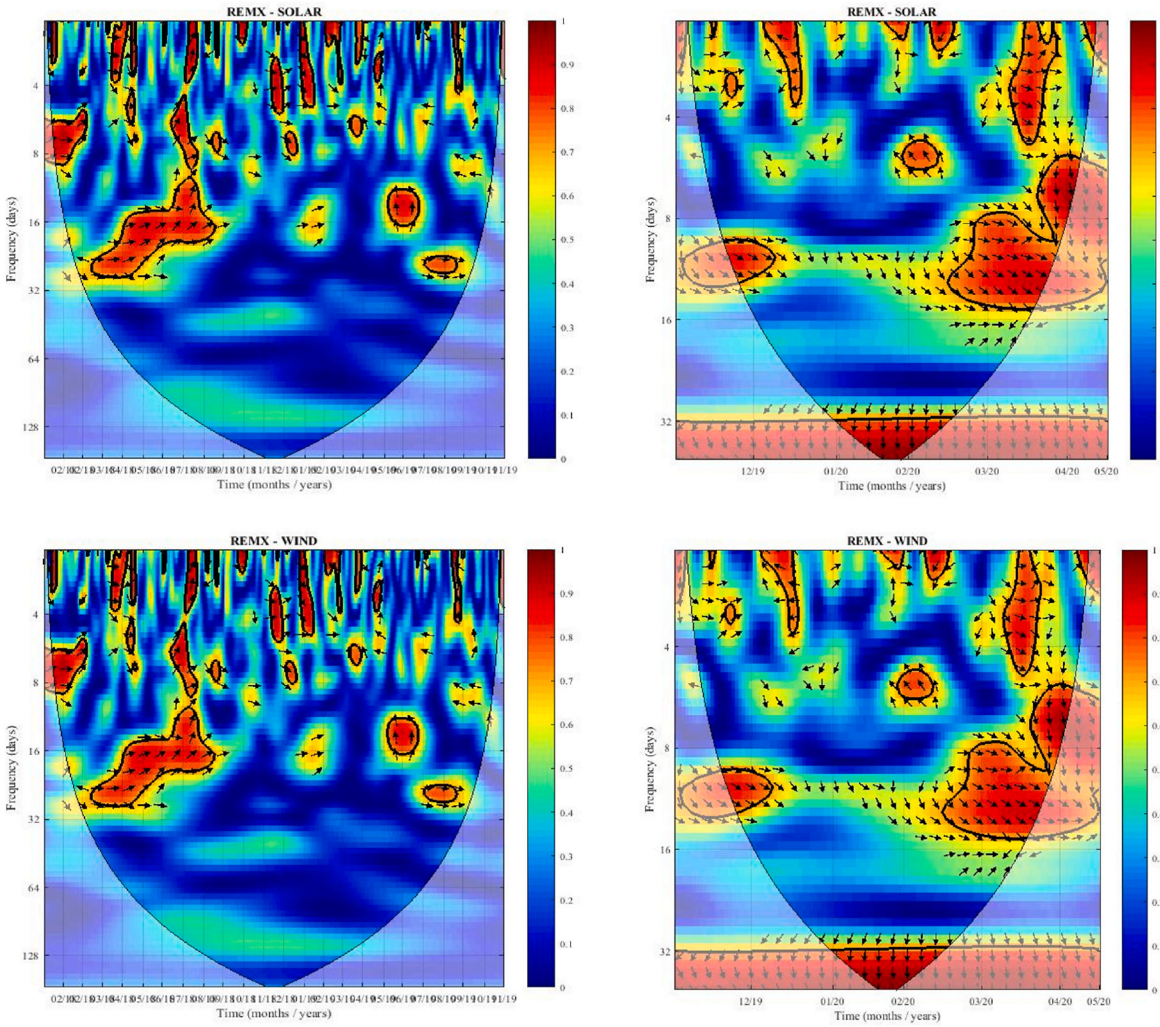
authors find a higher interdependence during the pandemic crisis. Conversely, the U.S.-China trade embargo has insignificant effects on the spillovers between the considered markets. Song et al. (2021) find that rare earth stock market are net receivers of both returns and volatility from both clean energy, world equity, global base metals, global gold, and global oil indexes. The rare earth stock market plays a significant role during the pandemic spread. Hanif et al. (2021) find significant spillovers and nonlinear dependence between renewable energy indices and European emission allowance.

Focusing on Chinese economy and using Chinese firms' data, Zheng et al. (2021), study asymmetric connectedness and dynamic spillovers between renewable energy and rare earth markets. Authors highlight that there exists potential risk transfer between renewable energy and rare earth sectors of economic activity. Their results demonstrate that at firm level the patterns of risk transmission between renewable energy and rare earth markets alter among firms and along the time. Moreover, employing the methodology of asymmetric spillover measure, authors reveal pessimistic mood, which dominates both markets during the sample period 2012–2020, thus, indicating insufficient confidence in the financing channel of the considered industries. Authors argue that their findings provide useful insights for investors and shareholders in what concerns the adequately informed decision-making about investing in the renewable energy and rare earth production facilities.

Being interested in a worldwide, rather than regional, context, Golroudbary et al. (2022), analyze the global environmental cost of using rare earth elements in green energy technologies. Authors claim that generation of green energy must be analyzed through the prism of global perspectives bearing in mind a broad environmental scenario. Their results based on the dataset covering the period 2010–2020, permit to conclude that an increase of green energy production by 1% causes 0.18% depletion of rare earths' reserves and increases greenhouse gas emissions in the exploitation phase by 0.90%. Therefore, authors claim that new approaches to decarbonization are extremely necessary to assure sustainability of this process. Their outcomes underscore an urgency to develop and implement diverse metrics, which would allow increasing the recycling of rare earths materials and eventually substituting them by other materials by means of innovative technologies to be fostered in the nearest future. Authors argues that these metrics would help to design appropriate strategies for decarbonization and environmentally sustainable development of renewable energy technologies.

The above literature survey evidences the two lacunas, existing in the previous research. The first shortcoming is related to the fact that while studying the nexus between the REM and renewable energy stock markets, the main emphasis is paid to the REM companies. Therefore, to the best of our knowledge, solely one benchmark is used to describe the whole spectrum of business diversity within the renewable energy industry. Such approach seems to lack a capacity to provide the detailed description of the renewable energy subsectors and may result in somewhat biased results, hence, not appropriate for designing elaborate



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hedge strategies. For instance, we believe that research financial community will benefit from the possibility to have a more granular information, e.g., on the interrelations between the REM and solar energy industry, between the REM and wind energy companies, among other subsectors of the contemporary renewable energy system. Our research aspires to fill this gap, as we employ six different benchmark indices to proxy the renewable energy subsectors in our quest to decipher intricate interrelations between the variety of renewable energy companies and REM stocks.

The second gap is related to a usually observed reliance on a single chosen methodology, which predominantly is the forecast-error variance decomposition based on VAR techniques. However, this approach ignores the perspective of investment horizons. Given the importance of frequency or investment horizon dimension in the context of stock investments, we opt to employ wavelet time-frequency analysis as a complementary methodology to provide confirmation to our results obtained within the VAR-supported variance decomposition framework and vice-versa. It is worth noting that the wavelet technique does not require any strong assumption such as stationarity and can be used to capture both linear and non-linear effects. This aspect is especially important while investigating abrupt market movements in the periods of crises when stationarity could be potentially compromised. Hence, our paper provides a cross-confirmation of our results, serving as a robustness check and allowing for deeper insights due to availability of the two distinct perspectives.

3. Methodology

3.1. Wavelet analysis

We examine the time-frequency dynamics of rare earth metals stock and renewable energy stock markets before and during the covid-19 using Grinsted et al. (2004)'s wavelet squared coherence (WTC) approach. This technique allows us to securitize the lead-lag relationship between rare earth metals stock and renewable energy stock markets before and during the COVID-19. The concept of WTC is similar to the traditional correlation coefficient (i.e., R^2). The east- and west-facing arrows show positive and negative correlations, respectively. Further, they indicate the lead-lag and in-out phase relationship. The level of significance has been ascertained through Monte Carlo simulations.

The smoothed wavelet power spectrum is calculated as:

$$R_n^2(S) = \frac{\left|S\left(s^{-1}W_n^{xy}(s)\right)\right|^2}{S\left(s^{-1}\left|W_n^x(s)\right|^2\right).S\left(s^{-1}\left|W_n^y(s)\right|^2\right)} \tag{1}$$

Where S is a time and scale smoothing operator. Convolution in time and scale is used to achieve smoothing.

$$S(W) = S_{scale}(S_{time}(W_n(S))) \tag{2}$$

Where S_{scale} and S_{time} are smoothing operator along with the wavelet scale axis and time, respectively (Torrence and Compo, 1998).

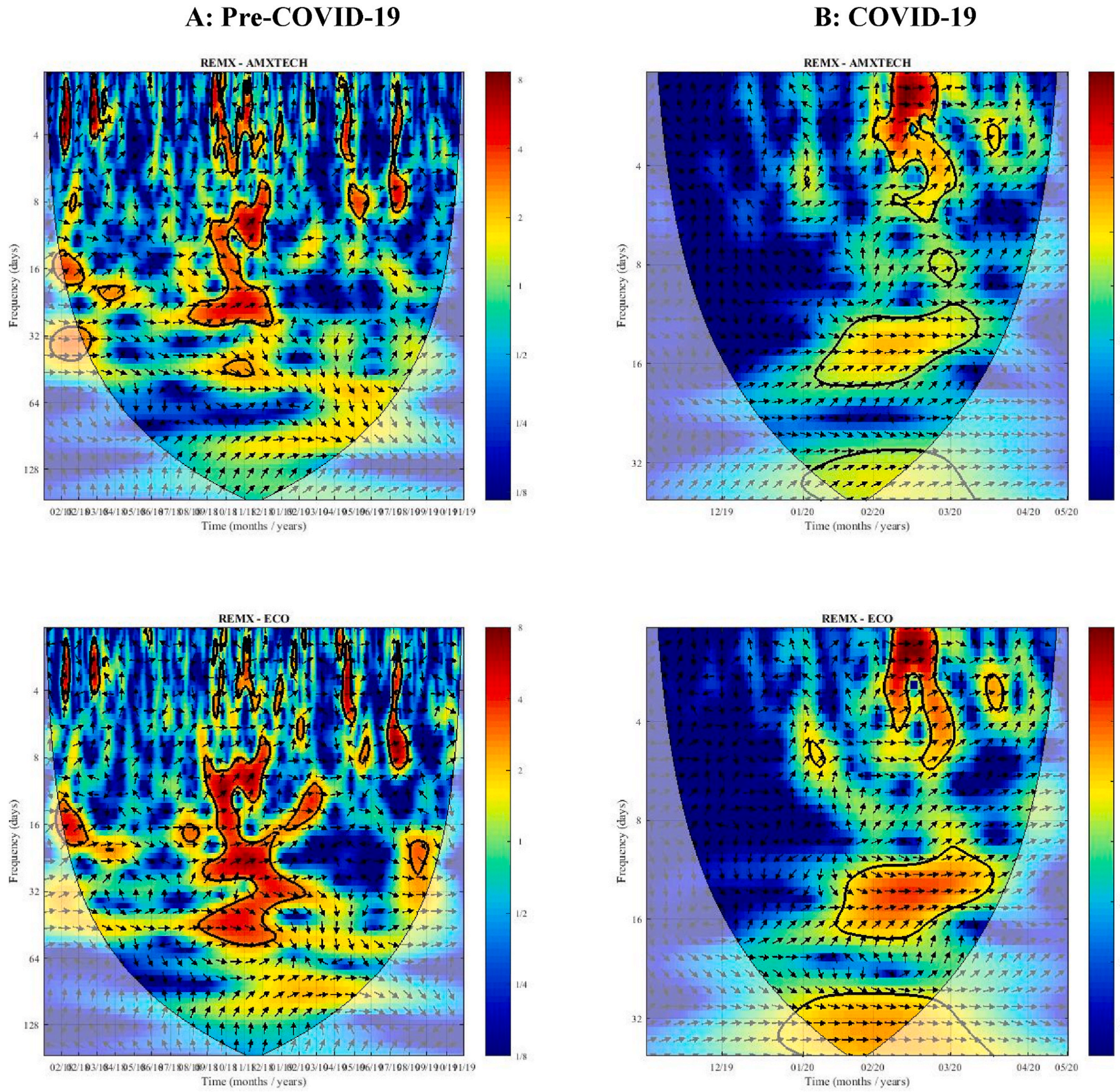

Fig. 3. Cross wavelet transform plots, pairwise estimates.

Following the Morlet wavelet, the smoothing power can be written as:

$$S_{time}(W) = \left(W_n(s) * c_1^{\frac{-t^2}{2s^2}}\right) and\ S_{time}(W)_s = \left(W_n(s) * c_2^{\Pi}(0.6s)\right)_s \quad (3)$$

Where Π is the rectangle function. c_1 and c_2 donate the normalization constants. The wavelet coherence coefficient between two stationary series at each scale, which varies between $R_n^2(s)\varepsilon\,[0,1]$. The phase for wavelet coherence is described as:

$$\varnothing_n^{XY} s = tan^{-1}\left(\frac{I\{S(S^{-1}W_n^{XY}(s))\}}{R\{S(S^{-1}W_n^{XY}(s))\}}\right) \quad (4)$$

where I and R is imaginary and real parts of smooth power spectrum.

Finally, we define the cross wavelet transform for the two time series $x(t)$ and $y(t)$ with the continuous transforms $W_x\,(u,s)$ and $W_y\,(u,s)$ as:

$$W_{xy}\,(u,s) = W_x\,(u,s)W_y^*\,(u,s), \quad (5)$$

In equation (5), u and s are position index and scale, respectively. The sing * indicate the complex conjugate.

3.2. Spillovers index

To examine the return and volatility spillovers between rare earth metals index and renewable energy stocks, we apply the Diebold and Yilmaz (2012) approach. This approach describes the H-step ahead generalized forecast-error variance decomposition as:

$$\varnothing_{ij}^{g} H = \frac{\sigma_{ij}\sum_{h=0}^{H-1}\left(e_i^{'}\sum e_i\right)^2}{\sum_{h=0}^{H-1}\left(\acute{e}_i A_h \sum e_i A_h^{'} e_i\right)} \quad (6)$$

where σ_{ij} is the standard deviation of the error term for the *jth* market and $\sum$ is the variance matrix of the error vector. e_i, on the other hand, is the selection vector. Finally, we must ensure that the selection vector e_i has one component for the *ith* component and zero for the other components. To ensure that each row of the variance decomposition matrix has a unit total, we normalize each entry by row sum, which is written as

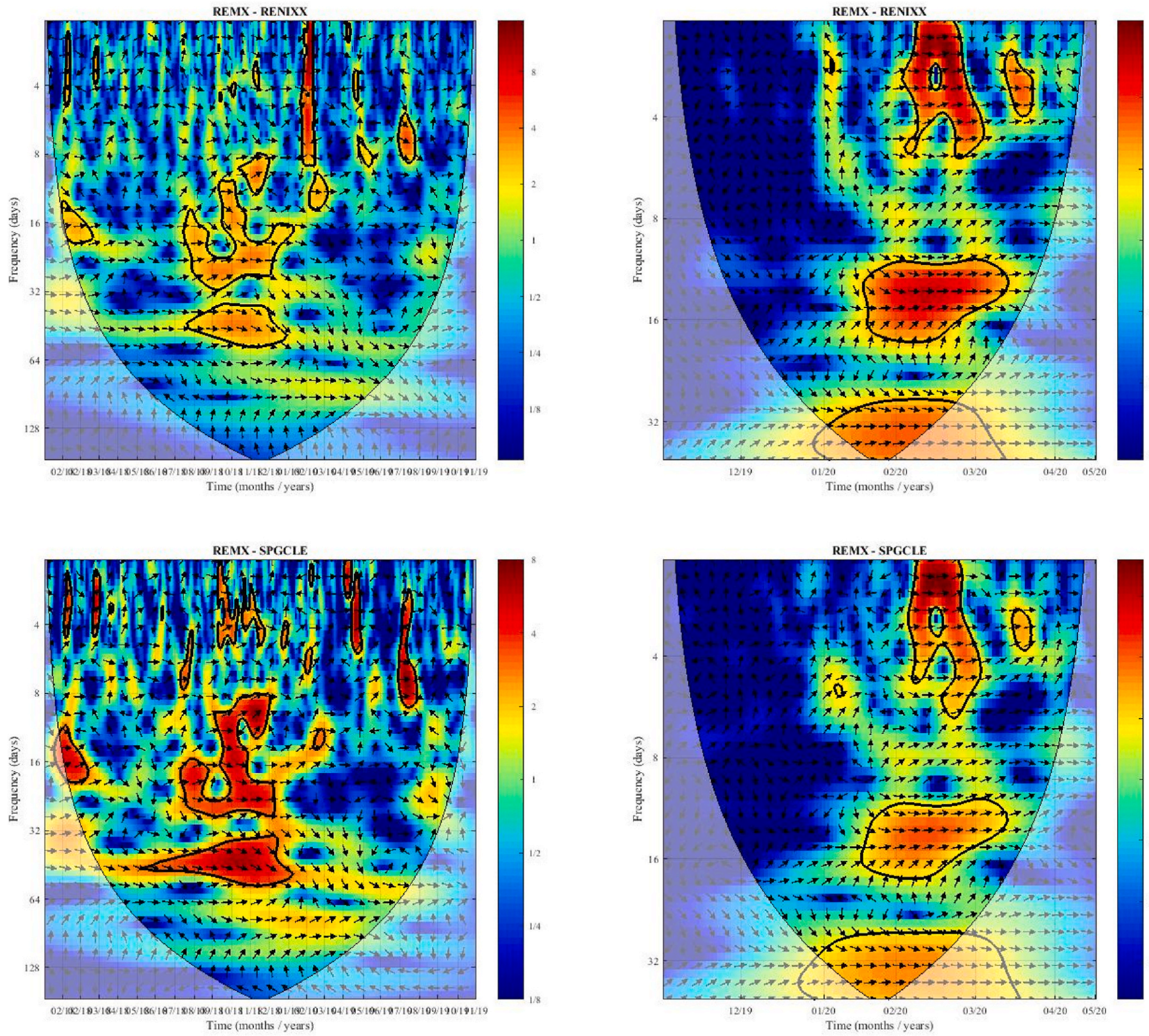

Fig. 3. (*continued*).

$$\varnothing_{ij}^{\sim g} = \frac{\varnothing_{ij}^{g} H}{\sum_{j=1}^{N} \varnothing_{ij}^{g} H} \tag{7}$$

where, $\sum_{j=1}^{n} \varnothing_{ij}^{\sim g}(H) = 1$ and $\sum_{ij=1}^{n} \varnothing_{ij}^{\sim g}(H) = n$. However, we can calculate the total spillover index across all markets as follows;

$$S^{g}\ (H) = \frac{\sum_{i,j=1,j\neq 1}^{N} \varnothing_{ij}^{\sim g}(H)}{\sum_{i,j=1}^{N} \varnothing_{ij}^{\sim g}(H)} \text{ x } 100 = \frac{\sum_{i,j=1,j\neq 1}^{N} \varnothing_{ij}^{\sim g}(H)}{N} \text{ x } 100 \tag{8}$$

The directional spillovers received by the market *i* from all other variables *j* can be measured as follows:

$$S_{i}^{g}(H) = \frac{\sum_{j=1,i\neq j}^{N} \varnothing_{ij}^{\sim g}(H)}{\sum_{j=1}^{N} \varnothing_{ij}^{\sim g}(H)} \text{ x } 100 = \frac{\sum_{i,j=1,i\neq j}^{N} \varnothing_{ij}^{\sim g}(H)}{N} \text{ x } 100 \tag{9}$$

Similarly, the directional spillovers from variable *i* to and from all other variable *j* is described as:

$$S_{i}^{g}(H) = \frac{\sum_{j=1,i\neq j}^{N} \varnothing_{ij}^{\sim g}(H)}{\sum_{j=1}^{N} \varnothing_{ij}^{\sim g}(H)} \text{ x } 100 = \frac{\sum_{i,j=1,i\neq j}^{N} \varnothing_{ij}^{\sim g}(H)}{N} \text{ x } 100 \tag{10}$$

Finally, we can calculate the net directional spillover by subtracting Eq. (9) from Eq. (10) which can be written as:

$$S_{i}^{g}(H) = S_{i}^{g}(H) - S_{i}^{g}(H) \tag{11}$$

In the concrete case of our current study, a 100-day rolling window and a 10-step-ahead forecast horizon are used to calculate the total spillover/connectedness index.

4. Data

This study considers daily prices of one rare earth index (REMX Index) and six renewable energy indices: SuperTech Index, World Renewable Energy Industrial Index, WilderHill Clean Energy Index, S&P Global Clean Energy Index, NYSE Bloomberg Global Wind Energy Index, and NYSE Bloomberg Global Solar Energy Index. The choice of the renewable energy sector indices is based on their representativeness and use by research and financial community.

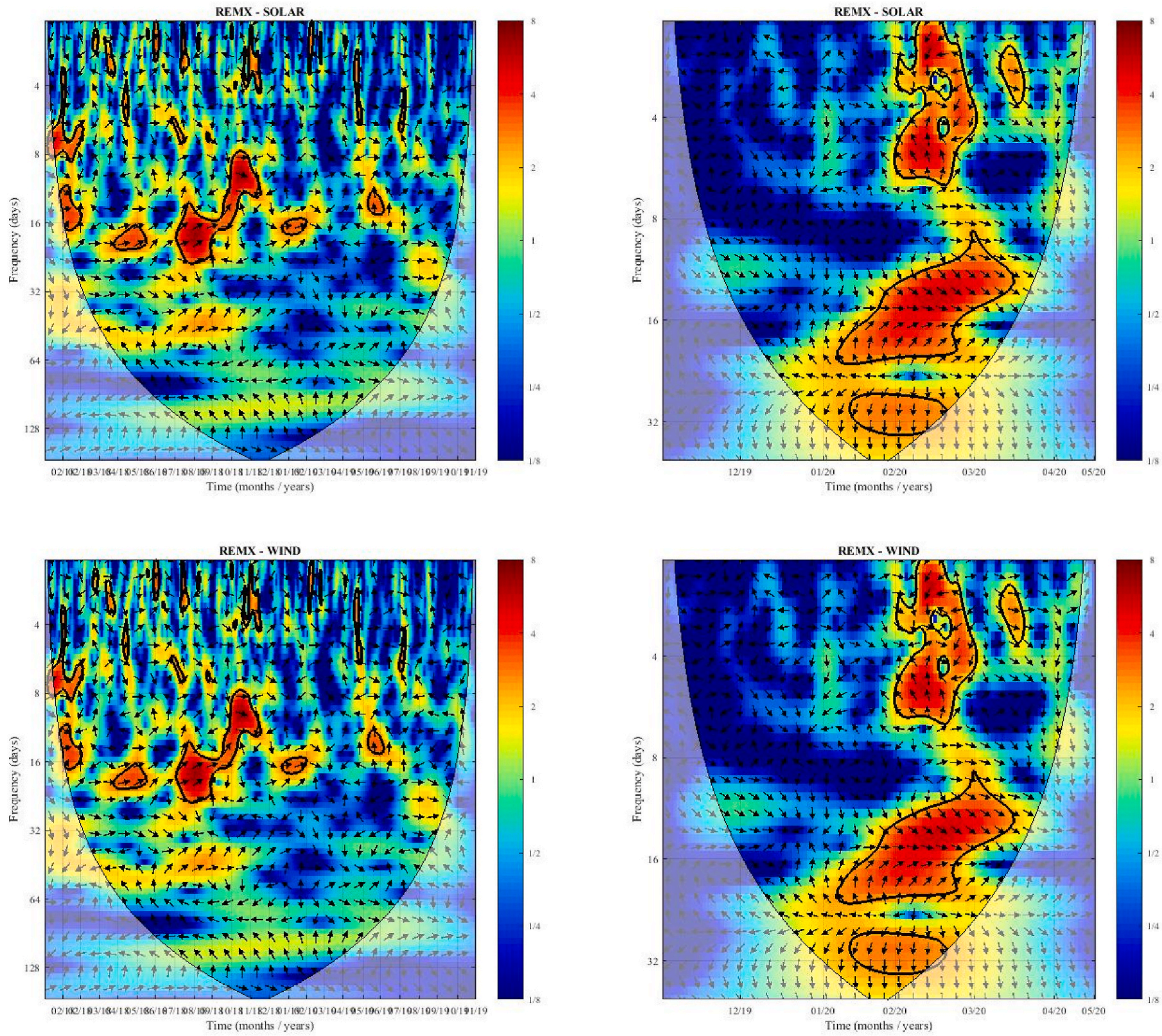

Fig. 3. (*continued*).

(i) Super Tech Index (Bloomberg ticker: TECH Index) represents companies engaged in high-growth technology, media, and manufacturing industries that focus on providing internet-enabled, electronic devices or services to consumers. As the clean energy companies are largely dependent on the most advanced technologies including electronic devices and internet-based activation of products and services we include the Super Tech index in our dataset as a relevant benchmark.
(ii) World Renewable Energy Industrial Index (Bloomberg ticker: RENIXX Index) is the first global stock index, which comprises the performance of the world's 30 largest companies of the renewable energy industry whose weighting in the index is based on the market capitalization.
(iii) Wilder Hill Clean Energy Index (Bloomberg ticker: ECO Index) is a modified equal dollar weighted index comprised of publicly traded companies whose business's stand to benefit substantially from societal transition toward the use of cleaner energy and conservation.
(iv) S&P Global Clean Energy Index (Bloomberg ticker: SPGTCED Index) provides liquid and tradable exposure to 30 companies from around the world that are involved in clean energy related businesses. The index is comprised of a diversified mix of Clean Energy Production and Clean Energy Technology and Equipment Providers companies.
(v) NYSE Bloomberg Global Wind Energy Index (Bloomberg ticker: WIND index) is an investable modified market cap weighted index made of companies active across the wind energy value chain including the manufacture of wind energy equipment and the financing, development and operation of wind projects.
(vi) NYSE Bloomberg Global Solar Energy Index (Bloomberg ticker: SOLAR index) is an investable modified market cap weighted index comprised of companies active across the solar energy value chain including the manufacture of solar energy equipment and the financing, development and operation of projects.

At this point we deem important to provide a succinct description of the MVIS Global Rare Earth/Strategic Metals Index (Bloomberg ticker: REMX Index) used as benchmark to track the stock market value of RE companies. This index covers the largest and most liquid companies, which are active in the rare earth/strategic metals sector. The index is reviewed on a quarterly basis. It is float market capitalization weighted, and its rules estipulate that the maximum component weight does not exceed 8%. REMX index covers at least 90% of the investable universe, includes companies generating at least 50% of their revenues from REs and strategic metals or that have ongoing mining projects that have the potential to generate at least 50% of the company's revenue from rare earth and strategic metals. The members-constituents of this index are stocks of the companies based in China (35%), Australia (24%), Japan (9%), Canada (7%), Netherlands (4.6%), South Africa (4.5%), USA

Table 3
Total directional return spillovers.

	TECH	RENIXX	ECO	SPGTCED	WIND	SOLAR	REMX	From
Panel A: Full Sample								
TECH	35.79	9.50	22.73	18.85	1.34	1.34	10.44	64.21
RENIXX	10.95	38.84	19.09	21.11	0.95	0.95	8.10	61.16
ECO	19.80	12.94	30.62	24.31	1.15	1.14	10.04	69.38
SPGTCED	14.91	16.52	24.18	30.71	1.03	1.02	11.64	69.29
WIND	0.88	1.32	2.06	1.70	46.52	46.5	1.02	53.48
SOLAR	0.87	1.32	2.07	1.70	46.52	46.52	1.00	53.48
REMX	13.07	9.21	15.57	16.16	0.86	0.85	44.27	55.73
Directional to Others	60.48	50.82	85.69	83.84	51.86	51.81	42.24	426.73
Directional Including Own	96.28	89.66	116.31	114.55	98.37	98.33	86.51	**60.96%**
Directional Connectedness	−3.72	−10.34	16.31	14.55	−1.63	−1.67	−13.49	
Panel B: Pre-COVID-19								
TECH	48.01	4.46	26.25	14.60	0.79	0.80	5.10	51.99
RENIXX	8.19	58.79	11.97	14.33	0.93	0.93	4.85	41.21
ECO	22.70	5.63	41.13	22.63	0.84	0.84	6.22	58.87
SPGTCED	12.97	10.07	23.80	40.97	1.84	1.85	8.49	59.03
WIND	0.21	0.97	0.47	1.47	47.60	47.59	1.68	52.40
SOLAR	0.22	0.97	0.48	1.49	47.57	47.59	1.68	52.41
REMX	12.16	4.85	14.77	14.67	2.36	2.35	48.85	51.15
Directional to Others	56.45	26.95	77.74	69.18	54.34	54.37	28.03	367.05
Directional Including Own	104.45	85.74	118.87	110.15	101.94	101.96	76.88	**52.44%**
Directional Connectedness	4.45	−14.26	18.87	10.15	1.94	1.96	−23.12	
Panel C: COVID-19								
TECH	26.66	14.41	18.88	18.23	5.16	5.16	11.49	73.34
RENIXX	13.64	27.59	20.37	20.56	4.09	4.13	9.62	72.41
ECO	17.59	18.01	23.63	21.77	3.70	3.72	11.57	76.37
SPGTCED	15.83	19.84	21.80	23.81	3.29	3.30	12.12	76.19
WIND	4.40	5.95	6.26	5.08	38.25	38.22	1.85	61.75
SOLAR	4.35	5.92	6.26	5.08	38.29	38.28	1.82	61.72
REMX	13.94	11.57	15.66	15.60	4.49	4.49	34.25	65.75
Directional to Others	69.75	75.71	89.23	86.32	59.03	59.01	48.48	487.54
Directional Including Own	96.41	103.3	112.86	110.13	97.28	97.29	82.73	**69.65%**
Directional Connectedness	−3.59	3.30	12.86	10.13	−2.72	−2.71	−17.27	

Notes: This table reports the static volatility spillovers for the renewable energy (TECH, RENIXX, ECO, SPGTCED, WIND, SOLAR) and the rare earths (REMX) indices. The pre-COVID-19 period spans from January 01, 2018 to November 29, 2019 whereas the COVID-19 period covers November 30, 2019 until May 15, 2020.

(4.4%), UK (4.1%), France (4%), and Brazil (2.5%). The index includes refineries, recyclers, and producers of rare earth and strategic metals and minerals.

The sample period spans from January 1, 2018 to May 15, 2020, yielding the 620 daily observations. Our sample period covers the rapid expansion of Covid-19 virulent disease in early 2020 becoming the pandemic and causing the health and economic crisis around the globe. The choice of daily data is justified by our focus on abrupt market movements caused by the rapid advancement of the COVID-19 pandemic outbreak crisis. Our data sample allows investigating pair-wise coherence and co-movements of the analyzed markets as well as modeling the connectedness and spillovers between rare earth metals and renewable energy stocks before and during the COVID-19 pandemic. The whole period is subdivided into two sub-periods: pre-COVID-19 sub-sample: January 1, 2018, to November 29, 2019, the COVID-19 sub-sample: November 30, 2019, to the end of the sample period. The selection of the sub-periods is based on the first reported COVID-19 case in Wuhan, Hubei, People's Republic of China, in November 2019.

Table 1 reports the summary statistics for the daily returns of the renewable energy and REM stocks. We observe that average returns are positive only for the two indices, namely, SuperTech (TECH) Index and World Renewable Energy Industrial (RENIXX) Index. We also note that the wind energy (WIND Index) and solar energy (SOLAR Index) stocks as well as stocks of the RE companies (REMX Index) consistently exhibit negative return mean for the whole sample as well as for each of the sub-samples. The downtrend in returns of the RE stocks along the whole sample period could be attributed to the mounting tensions between the US and China with the RE minerals in the center of the US-China trade war, which caused the reduction in outbound shipments of rare earths from China in 2020. Another factor of slowdown in production and downstream operations is related to the changes in international market demand due to the COVID-19 pandemic.

As per standard deviation, along the whole sample period the RE stocks (1.68) are in between the most volatile, - ECO (2.14), TECH (1.86), and RENIXX (1.81), - and the least volatile, - SPGTCED (1.56), SOLAR (0.38), and (WIND (0.38), - indices. However, under the pre-COVID-19 presumably normal market conditions the RE stocks are found to be the most volatile, with the highest standard deviation of 1.44. We ascribe this volatility to the US-China trade war tensions.

Only two indices, TECH and RENIXX, are consistently negatively skewed. In their turn, the RE stocks switch from low but still positive pre-COVID-19 skewness of 0.06 to negative skewness of −0.67 during the COVID-19 sub-sample period. Based on the kurtosis values we notice that there exist two distinct types of stock. The four indices, - TECH, RENIXX, ECO, and SPGTCED, - are characterized by excess kurtosis, suggesting leptokurtic distributions with fat tails, while the other three, - REMX, WIND, and SOLAR, - exhibit kurtosis values below 3, implying that their return distributions may be closer to the normal distribution function. We associate this kurtosis-wise similarity between the RE and the wind and solar industries to the heavy dependence of the two latter on the former. However, further research of the mechanism at play are highly desirable. Nonetheless, the null hypothesis of normality is rejected for all series at the 1% level, as indicated by the results of Jarque-Bera test statistics.

We present the correlation coefficients in Table 2. It is worth noting that during the pre-COVID-19 period all the correlations are positive. However, during the COVID-19 the correlation coefficients between the SuperTech stocks, on the one hand, and the solar and wind companies' equities, on the other hand become negative, presumably due to the decaying price of crude oil turning the two letter sectors economically uncompetitive. Moreover, for all the three samples, the REM companies'

Table 4
Total directional volatility spillovers.

	TECH	RENIXX	ECO	SPGTCED	WIND	SOLAR	REMX	From
Panel A: Full Sample								
TECH	32.81	10.26	24.54	22.92	0.88	0.87	7.71	67.19
RENIXX	12.03	37.78	16.39	23.71	0.32	0.32	9.45	62.22
ECO	21.21	13.00	29.08	28.38	0.70	0.70	6.92	70.92
SPGTCED	18.46	14.27	24.78	33.39	0.68	0.68	7.75	66.61
WIND	2.47	5.23	2.34	6.41	41.26	41.25	1.03	58.74
SOLAR	2.44	5.32	2.32	6.36	41.22	41.31	1.02	58.69
REMX	15.55	14.7	16.61	23.05	0.73	0.74	28.62	71.38
Directional to Others	72.18	62.77	86.99	110.83	44.55	44.55	33.89	455.75
Directional Including Own	104.98	100.55	116.06	144.22	85.80	85.86	62.51	**65.11%**
Directional Connectedness	4.98	0.55	16.06	44.22	−14.20	−14.14	−37.49	
Panel B: Pre-COVID-19								
TECH	49.02	2.97	27.02	14.69	0.27	0.27	5.76	50.98
RENIXX	3.73	81.36	3.27	6.28	1.31	1.34	2.71	18.64
ECO	30.18	5.30	38.44	20.85	0.22	0.24	4.76	61.56
SPGTCED	18.28	6.06	22.63	45.56	0.39	0.38	6.70	54.44
WIND	0.12	0.19	1.22	0.02	49.08	49.22	0.14	50.92
SOLAR	0.11	0.23	1.20	0.02	49.02	49.28	0.13	50.72
REMX	18.46	6.97	12.82	12.89	0.33	0.33	48.20	51.80
Directional to Others	70.89	21.72	68.17	54.76	51.54	51.78	20.20	339.06
Directional Including Own	119.91	103.08	106.61	100.32	100.63	101.06	68.40	**48.44%**
Directional Connectedness	19.91	3.08	6.61	0.32	0.63	1.06	−31.60	
Panel C: COVID-19								
TECH	29.77	17.84	16.39	18.64	2.68	2.59	12.10	70.23
RENIXX	18.59	25.07	12.01	20.08	2.16	2.17	19.92	74.93
ECO	20.06	19.58	17.70	19.81	4.85	4.79	13.20	82.30
SPGTCED	21.97	21.03	15.80	21.83	3.17	3.09	13.10	78.17
WIND	22.81	15.13	11.32	10.33	18.41	18.50	3.49	81.59
SOLAR	22.43	15.29	11.19	10.30	18.57	18.72	3.52	81.28
REMX	13.67	20.11	9.22	19.02	2.09	2.09	33.80	66.20
Directional to Others	119.53	108.97	75.93	98.18	33.53	33.23	65.35	534.72
Directional Including Own	149.30	134.03	93.63	120.01	51.94	51.95	99.15	**76.39%**
Directional Connectedness	49.30	34.03	−6.37	20.01	−48.06	−48.05	−0.85	

Notes: This table reports the static volatility spillovers for the renewable energy (TECH, RENIXX, ECO, SPGTCED, WIND, SOLAR) and the rare earths (REMX) indices. The pre-COVID-19 period spans from January 01, 2018, to November 29, 2019 whereas the COVID-19 period covers November 30, 2019 until May 15, 2020.

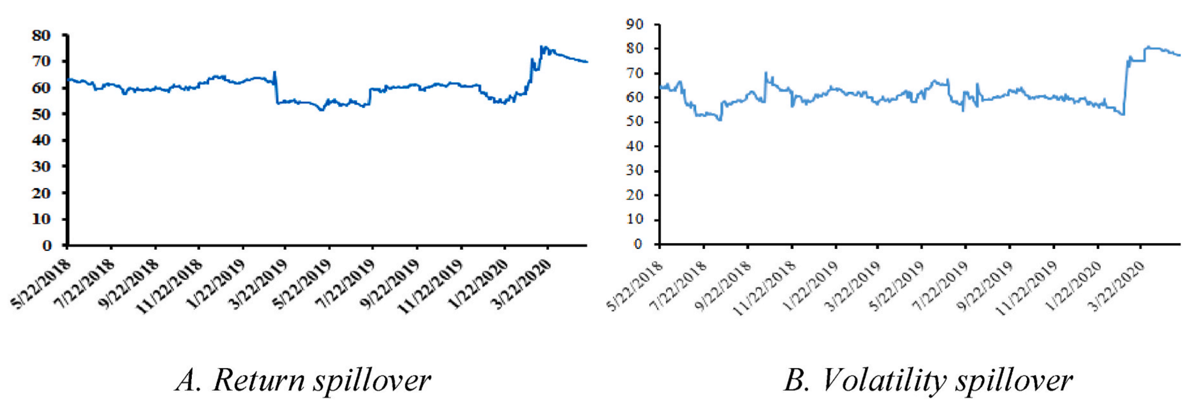

Fig. 4. Time-varying return and volatility spillover before and during COVID-19.
Notes: This figure shows the time-varying return (Panel A) and volatility (Panel B) spillover/connectedness between rare earth metals and renewable energy stocks before and during COVID-19. A 100-day rolling window and a 10-step-ahead forecast horizon are used to calculate the total spillover/connectedness index.

stocks are the most strongly correlated with the SPGTCED index. We observe the correlation coefficient values of 0.60, 0.48, and 0.75 for the full sample, pre-COVID-19 times, and COVID-19 period, respectively. Rather unexpectedly and strangely enough we document the weakest association of the REM stocks movements with solar and wind industry stocks. Further investigation of the causes of the observed phenomena may prove potentially beneficial for better understanding of the mechanism at play underlying the results of our correlation analysis.

The left column of Fig. 1 provides plots of six renewable energy indices and the REMX index used as benchmark for the REM stock market. The side or lateral trends of the four renewable energy indices, except for the wind and solar sector indices, appear to represent a certain upside prior to the COVID-19-triggered market meltdown in March 2020 (Gubareva, 2021). However, the wind and solar sector indices, contrasting the four other renewable energy aggregates, exhibit downtrend along the whole sample period. The REMX index, which is our benchmark for the REM companies' stocks, also exhibits downtrend along the whole period. In all the seven returns' plots we observe an abrupt decay followed by the bouncing back dynamics, with the lowest point being March 23, 2020, being this the apogee of the pandemic caused meltdown of the global financial markets. For the six renewable energy indices we see a negative spike-like behavior, while spike features are rather absent in the case of REMX index. We ascribe this divergence to the fact that the REM market has been being heavily depressed due to the proper market structure and demand-supply-risk conjuncture, to the point that event COVID-19 has not been able to further worsen the situation in a considerable manner. We posit, that a rather long-term nature of the REM contracts and a considerable time elapsed for outbound shipment time from China to the Western economies have been smoothing the price dynamics of the companies involved in this business. However, towards the end of the sample, all the indices, expect the wind and solar industries' stocks, exhibit upward trends associated with the recovery from the COVID-19 crisis lows.

The influence of the outbreak is also noticeable while observing the right column of Fig. 1, which depicts the return dynamics. We clearly see that the solar, wind and REM indices are notably more volatile than the four first renewable energy stocks described by the TECH, RENIXX, ECO, and SPGTCED indices. If analyzed more closely, one easily concludes that the most volatile time interval for all the seven indices is related to the influence of the COVID-19 pandemic. In this manner, by our empiric analysis we expect corroborate this insight that the pandemic outbreak has adversely affected both the renewable energy and the REM companies' valuations and to quantify the impact of the COVID-19 crisis on the return and volatility spillovers between the considered stock markets.

5. Empirical results

In line with the sequence of the presentation of the employed methodologies, we present our empirical results following the same order, i.e., starting with the squared wavelet coherence results and the cross wavelet transform analysis and, then, continuing with the results from the forecast-error variance decomposition approach applied to investigate the static and dynamic connectedness and spillovers both in returns and volatility. We argue that such order allows first to get an overall helicopter-like view of the situation based on the wavelet heatmaps, and then to analyze the relationships in more detail my means of return and volatility spillovers metrics presented in the form of tables as well as make use of time varying connectedness charts.

5.1. Squared wavelet coherence analysis

Fig. 2 displays the twelve pairwise SWC plots indicating the extent of correlations between REM companies' stocks and six major benchmarks used to prosy the performance of the stocks of the renewable energy sectors. The concept of SWC is similar to the square of the traditional correlation. That is, the squared correlation values lie between 0 and 1, where 0 indicates no correlation and is shown by the blue color on the SWC plot, whereas1 denotes high correlation and is shown by the red droplets on the SWC plot. The arrows in coherence plot represent the lead/lag and in-phase/anti-phase relationships. The east- and west-facing arrows show positive and negative correlations, respectively. The frequency is covered in days.

In the left-hand column of Fig. 2 we provide the six pairwise SWC plots for the pre-COVID-19 period, while in the right-hand column the six pairwise SWC plots for the COVID-19 pandemic are presented. The right down or left up pointing arrows signify that the first series, i.e., the REM market is leading, while the right up or left down pointing arrows show that the second series (in our case one of the renewable energy stock indices) is leading. During the pre-COVID-19 period, for the 1-to-2-month frequency range, we document that the REMX index predominantly leads the stocks of the companies active in renewable energy industry, except for the solar and wind sector stocks, which lag behind by the REM companies' stocks. In addition, during the 2018, for the 2-to-8-week frequency range we observe for each of the six plots the red regions, implying the high coherence between the analyzed time series. We attribute this integration between the markets to the common cause being it the mounting China-US tensions regarding the REMs and being in the very center of the China-US trade war. However, in 2019 the overall tonality becomes colder with diminishing red and growing blue zones. It is also worth noting that among the pre-COVID-19 heatmap, the REMX-SOLAR and REMX-WIND panels are predominantly blue colored along the whole pre-COVID-19 period, signaling a low coherence between the time-series, and, hence, evidencing attractive diversification benefit subjacent to joint investment in these pairs of the respective sectors of economic activities.

In what concerns the COVID-19 period, as per Fig. 2, for the below-2-week frequency range, since February 2020 onwards we see the well-defined red regions evidencing high levels of the pairwise coherence for all the analyzed sectorial pairs. This high coherence phenomenon is clearly related to the impact of the COVID-19 market meltdown in February–March 2020. Our empirical findings on SWC between REM companies' stocks and renewable energy sector stocks provide relevant insights for potential investors in REM companies. For instance, under relatively normal market conditions, such as observed during the pre-COVID-19 period, investors holding positions in REM companies may harvest hedging benefits from attractive diversification opportunities provided by join investment in the REM and the low-integrated with REM renewable energy stocks. Still, as we evidence by our analysis, such hedging strategies may become not feasible in the periods of global crises, as during the COVID-19 pandemic their efficiency has been impaired by high levels of pairwise coherence between all the analyzed equity markets.

5.2. Cross wavelet transform analysis

For an in-depth analysis, we turn to consideration of the cross wavelet transform. The advantage of this technique is that it preserves the information about the phase. It is worth noting that arrows indicating phase information help us to better comprehend the relationships between the analyzed pairs of markets. Fig. 3 presents twelve cross-wavelet transform heatmaps; six in the left-hand column for the pre-COVID-19 and six in the right-hand for the COVID-19 periods. We clearly see a certain similarity of the patterns within each of columns. In the left-hand pre-COVID-19 column, we observe that though there is positive covariance or in-phase relationship it is localized within the 1-to-8-week frequency band and is reasonably well concentrated along the time scale around the end of 2018/the beginning of the 2019.

However, in the right-hand COVID-19 column we see that the regions of positive covariance or in-phase relationship starts from the 1-day frequency and are especially well-defined for the 1-to-3-week frequency range. Our results allow us to conclude the following. Even if there is significant covariance between the different time series, under the relatively normal pre-COVID-19 market conditions, it substantially varies between the shorter and longer cycles. During the COVID-19 pandemic, the covariance patterns become more homogeneous, indicating significant covariance between the REM and renewable energy stocks across the whole range of considered frequencies, alerting in this way of diminishing diversification opportunities during global crisis events such as the ongoing COVID-19 outbreak. In order to validate our findings based on the wavelet analysis, we now turn to alternative but complementary approach based on forecast-error variance decomposition.

5.3. Return spillovers: static analysis

In Table 3, we present the results of the static spillover analysis of the return series in the system composed of the six renewable energy stock indices (TECH, RENIXX, ECO, SPGTCED, WIND, and SOLAR) and the stock index for the REM (REMX) for the three analyzed time intervals: full sample, pre-COVID-19 and COVID-19 periods. We find that overall moderate connectedness in the system during the pre-COVID-19 period (52.44%) increases to a considerably higher level (69.65%) during the COVID-19 times. While comparing the pre-COVID-19 and COVID-19 sub-samples, we observe that the diagonal elements of own variance are diminishing, becoming all below 40% during the latter period.

Therefore, the contribution to each index's variance during COVID-19 is more affected by the return spillovers form other indices than by its own variance, implying that the overall connectedness in the system increases.

In addition, in Table 3, we show that for all the three periods the largest contributions to the system are originated from the Clean Energy (ECO) index companies' stocks being, respectively, 85.69, 77.74, and 89.23 percent. This finding also holds for pre-COVID-19 and COVID-19 sub-samples regarding the influence of the ECO index at REMX index: 14.77 and 15.66 percent, respectively. Coming back to the row "Directional to Others" we document that, for the three analyzed periods, the REM companies' stocks are those that less contribute to system (42.24%, 28.03%, and 48.48%). Moreover, analyzing the "Directional Connectedness" row we see that for all the three periods the REMX index acts as a net receiver of influence from the system: 13.49%, −23.12%, and −17.27%. This is a rather unexpected result as the REMX index members-constituents produce the basis inputs for the renewable energy industries. Hence, further research into this subject is highly desirable. In general lines, these our findings evidence that in time of financial turmoil, such as COVID-19-triggered meltdown, the return of the stock indices exhibit higher levels of connectedness and corroborate with the conclusions of Reboredo and Ugolini (2020) and Song et al. (2021). However, considering six benchmarks for the renewable energy companies' performance, we provide more details on interrelations of the REM stocks with renewable energy stocks, ignored in the former study and proxied just by one Clean Energy (ECO) index in the latter.

5.4. Volatility spillovers: static analysis

Table 4 presents the results of the static connectedness analysis of the volatility series in the system for the three time-intervals: full sample, pre-COVID-19 and COVID-19 periods. As shown in this table, we find that overall moderate connectedness in the system during the pre-COVID-19 period (48.44%) increases to a much higher level (76.39%) during the COVID-19 times. It is worth noting that volatility connectedness is lower (higher) that return connectedness during the pre-COVID-19 (COVID-19) period: 48.44% < 52.44% during the pre-COVID times and 76.39% > 69.65% during the COVID-19 pandemic). In line with the returns' series case, while comparing the pre-COVID-19 and COVID-19 sub-samples, we observe that the diagonal elements of own variance are diminishing, becoming all below 40% during the latter period. Therefore, the contribution to each index's variance during COVID-19 is more affected by the volatility spillovers form other indices than by its own variance, implying that the overall connectedness in the system increases.

In addition, in Table 4, we see that for the whole sample period the largest contribution from the system is directed to the REMX index companies' stocks (71.38%) while the same REMX index transmits the lowest influence to system (33.89%). Notable the REMX index appears as the least important receiver of the volatility shocks from the system during the COVID-19 period (66.2%). This is somewhat expected result as the REMX index members-constituents produce the basis inputs for the renewable energy industries, and hence, should not be so sensitive to the volatility of the results of their customers. Our findings regarding volatility connectedness, based on six benchmarks for the stocks of the renewable energy companies, considerably enhance previous studies, namely, Reboredo and Ugolini (2020) and Song et al. (2021), as the former does not address the volatility connectedness at all, and as the latter uses just one Clean Energy (ECO) index for benchmarking the renewable energy stock performance, ignoring the existing variety within the renewable energy industries.

5.5. Return and volatility spillovers: dynamic analysis

Fig. 4 presents the dynamic variations of the total return (Panel A) and volatility (Panel B) connectedness between rare earth and renewable energy indices. As per Fig. 4, the total volatility connectedness for both varies within the range [50%, 80%]. The major values are observed in the late March 2020, the apogee of the COVID-19 slowdown. We observe that the respective indices exhibit higher levels of connectedness during the period of global crises. Our finding is in line with those of Reboredo and Ugolini (2020) and Song et al. (2021). We conclude that an abrupt increase in March 2020 signals of the increased level of integration among the return series (Panel A) as well as among the volatility series (Panel B). We ascribe this increased connectedness to unprecedented uncertainty, affected the global economy and financial markets through the worldwide implementation of lockdown policies, which resulted in disruptions of the supply chains of the renewable energy industries (Kim and Karpinski, 2020; Gubareva, 2021; Gubareva et al., 2022).

6. Conclusion

This study investigates the frequency comovements and spillovers (in returns and volatility) between one rare earth index (REMX Index) and six important renewable energy indices namely SuperTech Index, World Renewable Energy Industrial Index, WilderHill Clean Energy Index, S&P Global Clean Energy Index, NYSE Bloomberg Global Wind Energy Index, and NYSE Bloomberg Global Solar Energy Index. The wavelet-based approach and the spillover index methodology from January 1, 2018 to May 15, 2020 are used to achieve the objectives.

The results of the wavelet analysis provide empirical evidence that during the COVID-19 pandemic, the covariance patterns become more homogeneous, indicating significant increase in covariance between the REM and renewable energy stocks across the whole range of considered frequencies. Thus, our results alert investors of diminishing diversification opportunities during global crisis events such as the ongoing COVID-19 outbreak. In its turn, the forecast-error variance decomposition approach allows us to conclude that the REM stocks always, for all the considered periods, remain net recipient of innovation from the system for both the return and volatility time-series, with a limited capacity to transmit respective spillover effects to the system independently of the analyzed period. Nonetheless, we document a considerable increase in transmission of return and volatility shocks by the REM stocks during the pandemic. In particular, for both, return and volatility series, it is found that the contribution to each index's variance during COVID-19 is more affected by the respective spillovers form other indices than by its own variance, implying that the overall connectedness in the system increases. In addition, the dynamic return and volatility spillover indices allow us to conclude that the COVID-19-triggered market meltdown in February–March 2020 caused an abrupt from 50% to 80% increase in time varying connectedness in the system, both in returns and volatility. Therefore it is evidenced that the turbulent market conditions, such as during the COVID-19 pandemic, result in increasing integration of the REM and renewable energy markets.

Our results offer relevant insights for investors in stocks of the REM and renewable energy companies. In particular, holders of the stocks of the REM companies may wish harvest hedging benefits from attractive diversification opportunities provided by join investment in the REM and the low-integrated with REM renewable energy stocks. Still, as we evidence by our analysis, such hedging strategies may become not feasible in the periods of global crises, as during the COVID-19 pandemic, their efficiency has been impaired by high levels of pairwise coherence between all the analyzed equity markets.

The evolving return and volatility spillovers reveals a necessity for investors to consider adopting dynamic hedge strategies to mitigate the risk spillovers between the REM and renewable energy stock exposures as scarcer opportunities for diversification by means of joint investments in these two markets remain in the periods of crisis. Hence, in response to our newly reported findings, a pursuit of innovative downside-risk hedge strategies for REM and renewable energy stock exposures might represent new lines for future investigation, which may be potentially useful for investors as well as market regulators and resources policy makers.

CRediT (contributor roles taxonomy) authors statement

Waqas Hanif: Conceptualization, Methodology, Investigation, Formal analysis, Data Curation, Visualization, Writing - Original Draft, Writing - Review & Editing; **Walid Mensi**: Conceptualization, Methodology, Investigation, Formal analysis, Data Curation, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing; **Mariya Gubareva**: Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Validation, Project administration, Funding acquisition; **Tamara Teplova**: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Validation, Resources.

Data availability

Data will be made available on request.

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