

## Article

# Rare Earth Market, Electric Vehicles and Future Mobility Index: A Time-Frequency Analysis with Portfolio Implications

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**Abstract:** This study investigates the co-movements between the Solactive Electric Vehicle and Future Mobility Index (EVFMI) and multiple rare earth elements (REEs). We applied a TVP-VAR model and bivariate wavelet coherence approach to capture co-movements both in the time and frequency domain considering short-, medium- and long-term investment horizons. Using daily returns from 1 June 2012 to 4 June 2021, the results of the TVP-VAR model show that individual REEs and the EVFMI have strong return connectedness and are heterogenous over time. The bivariate wavelet coherence approach reveals that Dysprosium, Neodymium, Praseodymium and Terbium returns have positive co-movement (in-phase) with the EVFMI in the medium-term and long-term. In contrast, Cerium, Europium, Lanthanum and Yttrium returns have negative co-movements (out-phase) with the EVFMI in the medium-term and long-term. We find strong positive co-movements between the MVIS Global Rare Earth/Strategic Metals Index (MVREMX) and EVFMI at multiple wavelet scales. Following the lead/lag relationship, Cerium, Europium and Lanthanum, Yttrium returns are leading the EVFMI, and Neodymium, Dysprosium, Praseodymium, Terbium and MVREMX returns are lagging to the EVFMI. This study, therefore, suggests heterogenous hedging and diversification properties of REEs over time and investment horizons. Specifically, Cerium, Europium, Lanthanum and Yttrium act as strong hedges in long-term investment horizons and Neodymium, Dysprosium, Praseodymium and Terbium are weak hedges or diversifiers in short-term investment horizons. These results may be of particular interest to investors and relevant to policymakers considering multiple investment horizons.

**Keywords:** electric vehicles; future mobility; rare earths; hedge; diversifier; TVP-VAR; wavelet coherence



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## 1. Introduction

United Nations (UN) has adopted the agenda of 17 sustainable development goals (SDGs) to achieve a sustainable and better future for all (Naeem et al. 2021; Ul Haq et al. 2022). According to sustainable development goal 13, nations must take appropriate actions to combat climate change and its impacts. The world cannot restrict carbon footprints with the current unsustainable transport systems. Therefore, investments in green technologies (Naeem et al. 2022), electric vehicles (Alves Dias et al. 2020; Nastasi et al. 2022) and sustainable mobility firms (Hopkins 2020) can help to achieve sustainable mobility and sustainable

development goals around the globe. However, the unavailability of rare earth elements is crucial and can restrict the green and digital transition in these (Alves Dias et al. 2020).

The concept of future mobility is emerging and several recent technological developments and revolutions in electrification, automation and share mobility have got the attention of scholars and practitioners (Pan et al. 2021). Solely, a vehicle's electrification can reduce omissions by up to 75% and save up to 50% petroleum. It benefits USD 5500 million annually to the USA (Pan et al. 2021). The targeted automobile electrification can be accomplished through four different ways, simple hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) (Li et al. 2019).

Importantly, these four routes are highly dependent upon the usage of rare earth elements (REE) (Li et al. 2019). REEs are critical resources for electric vehicles around the world (Castilloux 2019; Henderson 2020; Riba et al. 2016) because technology applications are dependent upon permanent magnetics, especially in the digital economy, which improve energy efficiency (Filippas et al. 2021; Song et al. 2021). Indispensably, permanent magnetics rely on REEs. Filippas et al. (2021) conclude a huge future usage of permanent magnetics in HEVs, PHEVs, BEVs and FCEVs. They will increase the future consumption of REEs. In particular, a total rise of 189% and 168% in Neodymium (Nd) and Dysprosium (Dy) is expected, respectively (Filippas et al. 2021). Hundreds of technologies are using rare earth elements in small amounts (Castilloux 2019) which include battery alloys, catalysts, ceramics, glass polishing, metallurgy, permanent magnetics, phosphors and others. According to Bloomberg, around 90% to 93% of traction vehicles are using permanent magnetics synchronous motors (Alves Dias et al. 2020). Moreover, a recent report by Adamas Intelligence forecasted that the sale of electric vehicles will grow from 4.3 million units in 2019 to 12.5 million in 2025 and 32.0 million by the end of 2030 (Adamas 2019). Additionally, the usage of permanent magnets is projected to rise by 80%, which will lead to an increase in the demand and consumption of rare REEs by up to 350% for electric vehicles (Adamas 2019). In an overview, electric vehicles are believed to become an important end-user of rare earth elements by 2050 (Habib and Wenzel 2014). Although companies are exploring alternatives to replace REEs, still no viable rare earth magnetics have been introduced that may competitively replace rare earth magnetics (Alves Dias et al. 2020).<sup>1</sup>

China's monopolistic control over REEs' exploration and production has become a big threat to its supply chains (Song et al. 2021). The inherent volatility in REEs is reflected in financial markets. The prices of REEs have undergone huge fluctuations in the past and will continue to do so in the future (Proelss et al. 2020). There are several predictors of these fluctuations such as demand growth (Filippas et al. 2021; Schmid 2019), supply constraints (Bouri et al. 2021; Z. Chen et al. 2021; Haq et al. 2021b) and geopolitical risk (Proelss et al. 2020). The current strategic importance of the REEs makes them a potential commodity asset class, despite being volatile (Proelss et al. 2020). Current US–China trade war puts extra stress on REEs, electric vehicles and future mobility. Notably, the COVID-19 outbreak makes the subject more critical because individual and institutional investors are looking to diversify their supply chains away from China (Song et al. 2021).

From the above discussion emerges two observations. First, the dynamic connectedness between REEs and the Solactive EVFM Index was ignored in the risk-management domain. Second, studies are limited to explore the relationship theoretically using primary data. However, rare studies have investigated the co-movement between REEs and the Solactive EVFM Index, considering investment horizons. Therefore, our research answers the following key research questions timely, especially in light of COVID-19 and US–China trade war. Firstly, do REEs lead (lag) the Solactive EVFM Index in the short-, medium- and long-term? Secondly, do REEs act as hedges or diversifiers with the Solactive EVFM Index over short-term, medium-term and long-term investment horizons?

This study follows the definitions of Baur and Lucey (2010) to define hedge and diversifier. The definition of (weak/strong) hedge and diversifier corroborate with (Bouri et al. 2017a, 2017b; Iqbal 2017). They define that a strong (weak) hedge is an asset that is negatively cor-

related (uncorrelated) with another asset or a portfolio in a normal economic and financial period on average. A diversifier is any asset that has a positive correlation with another asset or a portfolio, but not a perfect positive correlation. On the basis of the current definition, this research has two research objectives. The primary objective is to investigate the leading/lagging behavior between the Solactive EVFM Index and REEs. The secondary objective is to explore the hedging and diversification opportunities between the rare earth market and Solactive EVFM Index.

Wavelet coherence analysis has several practical advantages for individual and institutional investors. Bivariate wavelet coherence captures the association between two financial markets or time series in terms of both time and frequency scales (Ul Haq et al. 2022). In this way, investors can make investment decisions and design portfolio strategies considering co-movements across multiple investment horizons, i.e., short-term, medium-term and long-term investments horizons (Bouri et al. 2020). In addition, investors can take a short or long position in the market to earn maximum returns (Qiao et al. 2020). Second, the wavelet coherence method determines the lead/lag relationship between series through directed arrows toward several directions (Jiang and Yoon 2020; Nguyen et al. 2021). The lead/lag relationship is crucial for investors, policymakers and regulators in terms of avoiding potential losses, portfolio selection and designing regulations and policies to restrict the financial contagion effect transmitting from other financial markets. Finally, our objectives corroborate with the purpose of wavelet coherence. Hence, the bivariate wavelet coherence approach is a suitable method for the paper.

In using a bivariate wavelet coherence approach, the output produces intriguing empirical evidence considering the co-movement across multiple investment horizons. Neodymium, Dysprosium, Praseodymium and Terbium returns showed positive co-movement with the Solactive EVFM Index in a long-term investment horizon. Notably, wavelet coherence revealed the most significant and strong positive co-movements between the MVIS Global Rare Earth/Strategic Metals Index and Solactive EVFM Index across wavelet components or investment horizons. The lead/lag relationship showed that Neodymium, Dysprosium, Praseodymium and Terbium returns are leading the Solactive EVFM Index long-term investment horizon. However, the MVIS Global Rare Earth/Strategic Metals Index is leading the Solactive EVFM Index across investment horizons. Considering the hedging and diversification perspective, Neodymium, Dysprosium, Praseodymium and Terbium can act as weak hedges in the short-term, however, they failed to act as hedges in the long-term investment horizon. In contrast, we uncovered the negative connectedness of Yttrium, Cerium, Europium and Lanthanum returns with the Solactive EVFM Index. In particular, these negative associations were more pronounced in medium-term and long-term investment horizons from 2014 to 2015 and 2019 to 2021. Meanwhile, Yttrium, Cerium, Europium and Lanthanum returns were lagging to the Solactive EVFM Index, indicating that REE returns were not predicting returns for the Solactive EVFM Index alone, but the Solactive EVFM Index behaved similarly and also predicted REE returns. Overall, we discovered a mixed dependence structure between the returns of REEs and the Solactive EVFM Index. In addition, the co-movement follows time-varying features at multiple frequency scales. Our results corroborate with (Haq et al. 2021b; Reboredo and Ugolini 2020; Song et al. 2021) who find that REEs are a potentially volatile commodity asset class, and hence require specific attention to hedge or diversify the volatility in the rare earth market.

This paper contributes in a few ways to the existing body of knowledge. First, it is a rare study that reveals the co-movements between individual REEs and the Solactive EVFM Index in short-, medium- and long-term investment horizons. Second, we find heterogeneous dependence between REEs and the Solactive EVFM Index. It brings a novel contribution to the extant literature because no such study has investigated the return dependence in both the time and frequency domains. Third, our findings contribute toward the hedge and diversifier literature (Y. Chen et al. 2020; Haq et al. 2021b; Song et al. 2021) where individual REEs have strong (weak) hedging properties against the Solactive EVFM

Index in (short-term) medium-term and long-term investment horizons. Finally, this research makes a methodological contribution to the previous research by using a bivariate wavelet coherence approach. Previous studies considered the dynamic conditional correlation model (DCC) (Y. Chen et al. 2020; Haq et al. 2021b) and Baba Engle Kraft Kroner (BEKK) model (Y. Chen et al. 2020), quintile regression with variance at risk (VAR) and multifactor analysis (Baldi et al. 2014), and a cross-quintilogram (Uddin et al. 2019) and MS-VAR model (Reboredo and Ugolini 2020). However, this study examined the association between eight individual REEs and the MVIS Global Rare Earth/Strategic Metal Index in both time and frequency domains.

The remainder of the article is organized as follows: Section 2 reviews related research. Section 3 presents the material and methods employed for estimation. Section 4 covers the results and the discussion part. Finally, Section 5 concludes the paper.

## 2. Review of Related Studies

The rare earth market has evolved as a volatile commodity asset class (Song et al. 2021). Therefore, investors are looking to diversify REEs' related volatility. Markowitz's (1952) portfolio theory supports the current research scenario. It describes that investors can form a portfolio of financial assets or commodities to minimize the expected risk and optimize expected returns (Bouri et al. 2021). In other words, investors can maximize the expected return on a given level of risk. Investors should add negatively correlated assets or securities in a basket to diversify the portfolio risk and moderate positively correlated assets can diversify the systematic risk (Bouri et al. 2020) because it offers more expected returns and less risk than those which are perfectly positively correlated (Baur and Lucey 2010). This study investigates the co-movement between REEs and the Solactive EVFM Index.

Rare earth resources are spread around different geographical locations in the world, however, China has monopolistic control over REEs. The volatility in the REEs market has been persistent over time and exhibits a long memory (Proelss et al. 2020). A recent study by Bouri et al. (2021) has investigated the return and volatility connectedness between rare earth elements and allied stocks. Results suggest that a strong dependence exists between rare earth and allied stock returns and volatility at lower and upper tails. Additionally, they argued that the outbreak of COVID-19 has strengthened this connectedness. The relationship between green bonds and rare earth elements showed a positive association over time (Haq et al. 2021b). Additionally, Haq et al. (2021b) documented that green bonds are diversifiers for the MVIS Global Rare Earth/Strategic Metal Index, and REEs are hedges and safe havens for economic policy uncertainty (EPU). Moreover, there is a strong linkage between rare earth stocks and the base metal market (Reboredo and Ugolini 2020). In addition, Reboredo and Ugolini (2020) found that financial markets, gold and clean energy stocks have a spillover effect on REEs (Reboredo and Ugolini 2020).

In a similar domain, Y. Chen et al. (2020) studied the dynamic linkage between crude oil, clean energy and rare earth metals from the Chinese perspective. They found a strong positive dynamic conditional correlation, indicating the usage of REEs in clean energy applications. Finally, they conclude that REEs can be a potential source to reduce risk in financial markets. Uddin et al. (2019) have investigated the dependence between renewable energy, gold, oil price and exchange rates. The relationship between these time series was asymmetric across quintiles. However, gold and exchange rates have a positive influence on renewable energy only during turmoil periods or extreme market conditions. Likewise, Baldi et al. (2014) analyzed the impact of rare earth materials (dysprosium and neodymium) on six clean energy stocks. They found a negative impact of both dysprosium (DY) and neodymium (NE) on clean energy indices during high prices.

Zhou et al. (2022) studied the return and volatility spillover relationship between political risk and REE stocks over the time and frequency domain. They documented 35.66% average spillovers which were even more pronounced during the short-term (71.21%). Overall, REEs are net receivers of political risks where Germany, India, France and Japan are receivers of political risk spillover, and Estonia, Japan, Myanmar and the Netherlands are

net spillover emitters. In a similar line, [Zheng et al. \(2021\)](#) explored the spillover between renewable energy and REE in China using wavelet coherence and network connectedness. Findings showed a moderate risk transfer between these financial markets over the time and frequency domain. They imply that the future volatility of REEs is reliant on several factors (including political and market). Another study investigated the spillover of trade control policies in terms of downstream and upstream sectors ([Z. Chen et al. 2021](#)). They concluded that China's export restrictions over REEs significantly increased the prices in other countries. Recently, [Song et al. \(2021\)](#) analyzed the connectedness between rare earth and financial markets during COVID-19, using the TVP-VAR model. They concluded that return connectedness is weaker than volatility connectedness, but varies over time. Return and volatility spillover were even stronger during the COVID-19 time. However, gold is a sole hedging instrument for the REEs market.

The emergence of REEs has been discussed in earlier studies in many research lines. In particular, the research of REEs focused on risk spillover ([Z. Chen et al. 2021](#); [Proelss et al. 2020](#); [Reboredo and Ugolini 2020](#); [Song et al. 2021](#); [Zheng et al. 2021](#); [Zhou et al. 2022](#)), supply/demand dynamics for technology firms ([Li et al. 2019](#); [Pan et al. 2021](#)) and risk management ([Song et al. 2021](#)). Particularly, previous research focused on the USA and Chinese future mobility and forecasted market trends ([Z. Chen et al. 2021](#); [Li et al. 2019](#); [Pan et al. 2021](#)). Overall, the literature on electric vehicles and spillover is growing. However, earlier research ignored the hedging and risk management perspective. Hence, our study proposes two hypotheses on the basis of the previous literature gap.

**Hypothesis 1 (H1).** *There is a significant co-movement between returns of REEs and the Solactive EVFM Index across multiple investment horizons.*

**Hypothesis 2 (H2).** *Returns of REEs lead the Solactive EVFM Index across multiple investment horizons.*

### 3. Material and Methods

#### 3.1. Data

This study considered daily prices for Dysprosium, Yttrium, Cerium, Europium, Lanthanum, Praseodymium and Terbium and MVIS Global Rare Earth/Strategic Metals Index and electric vehicles and future mobility index. The prices were denominated in US dollars (USD) for each time series. All prices were transformed into returns by taking logarithm (log) and first difference. The five-day (trading days) week was considered and covers the period from 1 June 2012 to 4 June 2021. These data cover several notable economic and financial turbulence periods (Rare earth crisis 2010–2012, 2015–2016 Chinese stock market turbulence, December 2020 to June 2021 stock markets crash due to COVID-19). Our analysis considered 2249 daily observations for each index. The data for individual REEs and MVIS Global Rare Earth/Strategic Metal Index were sourced from DataStream database and <https://www.mvis-indices.com> (accessed on 4 June 2021), respectively. In addition, the data for Solactive Electric Vehicles and Future Mobility Index were sourced from <https://www.solactive.com> (accessed on 4 June 2021). The index is available in daily prices, denominated in US Dollars.<sup>2</sup> Solactive EVFM Index tracks the performance of around 70 stocks of firms actively engaged in future mobility, electric vehicles, electric infrastructure, lithium, lead acid batteries and autonomous driving.

#### 3.2. TVP-VAR Approach

We employed TVP-VAR model of [Antonakakis and Gabauer \(2017\)](#) to measure the return interconnectedness between REEs and Solactive EVFM Index. We refer to [Antonakakis and Gabauer \(2017\)](#), and [Mishra and Ghate \(2022\)](#) for TVP-VAR model. However, this methodology is based on [Diebold and Yilmaz \(2012\)](#), and [Diebold and Yilmaz \(2014\)](#) works. The motivation of TVP-VAR follows several advantages. Firstly, the return connectedness follows time-variant feature, suggesting better understanding of connectedness for policy

makers and investors (Haq 2022). Second, there is no necessity to choose window size (Diebold and Yilmaz 2014). Finally, it produces accurate output even with small sample size (Mishra and Ghate 2022). The econometric explanation of TVP-VAR connectedness approach can be expressed as follows.

The equation below describes the TVP-VAR model,

$$X_t = B_t X_{t-1} + u_t u_t \sim N(0, S_t) \tag{1}$$

$$vec(B_t) = vec(B_{t-1}) + v_t v_t \sim N(0, R_t) \tag{2}$$

where  $X_t$ ,  $X_{t-1}$  and  $u_t$  (error term) are vectors of  $k \times 1$  and  $B_t$  and  $S_t$  are also vectors describing  $n \times n$  dimensions.  $vec(B_t)$  is the vectorized version of  $B_t$ , where  $B_t$  is the dimension of  $k^2 \times 1$ . Here, all information until  $t - 1$  is given by  $p_t - 1$ .  $\Omega_t$  represents the other error term where it has dimension  $k^2 \times 1$  and  $k^2 \times k^2$  for  $R_t$ . Overall,  $S_t$  and  $R_t$  is variance–covariance matrix with time-variant feature.

The next step is to estimate the generalized forecast error variance decomposition (GFEVD) following Koop et al. (1996), and Pesaran and Shin (1998) with H-step ahead forecast. Further, to determine GFEVD, the TVP-VAR then transformed to its corresponding vector moving average depiction or TVP-VMA consistent with Diebold and Yilmaz (2014). Considering this, the Wold theorem transformation can be described as below,

$$X_t = \sum_{i=1}^p B_{it} X_{t-1} + u_t + \sum_{j=0}^{\infty} A_{jt} u_{t-1} \tag{3}$$

$\zeta_{ij,t}^g(H)$  represents the unscaled GFEVD where it is normalized on each scale to ensure the the sum of each row is unity. Moving further, it indicates that the pairwise directional connectedness from variable  $j$  to variable  $i$ , where the impact of variable  $j$  on variable  $i$  is measured through error forecast variance. In order to estimate the above terms, the following equation can be done,

$$\zeta_{ij,t}^g(H) = \frac{S_{ii,t}^{-1} \sum_{t=1}^{H-1} (l_i' A_t S_t l_j)^2}{\sum_{j=1}^k \sum_{t=1}^{H-1} (l_i' A_t S_t l_j)^2} \tag{4}$$

$$\tilde{\zeta}_{ij,t}^g(H) = \frac{\zeta_{ij,t}^g(H)}{\sum_{j=1}^k \zeta_{ij,t}^g(H)} \tag{5}$$

where the selection vector is given by  $l_i$ , such that for the each variable  $i$ , the value must follow 1 and 0 elsewhere. These connectedness measures are exclusively driven from the work of Antonakakis and Gabauer (2017), Diebold and Yilmaz (2012) and Diebold and Yilmaz (2014).

$$TO_{jt} = \sum_{i=1, i \neq j}^k \tilde{\zeta}_{ij,t}^g(H) \tag{6}$$

$$FROM_{jt} = \sum_{i=1, i \neq j}^k \tilde{\zeta}_{ji,t}^g(H) \tag{7}$$

$$NET_{jt} = TO_{jt} - FROM_{jt} \tag{8}$$

$$TCI_t = k^{-1} \sum_{j=1}^k TO_{jt} \equiv k^{-1} \sum_{j=1}^k FROM_{jt} \tag{9}$$

The above equations explain four important elements of the TVP-VAR model. For instance, Equation (6) measures the total directional connectedness from variable  $j$  to variable “TO” all other variables in the system. Following Equation (6), Equation (7) measures the total directional connectedness of variable  $j$  “FROM” all other variables or markets in the

system or network. Equations (6) and (7) are also named as measures of total directional connectedness of variable  $j$  “TO” and “FROM” others. Equation (8) can be measured through taking the difference between Equations (6) and (7), where Equation (9) aims to measure the “NET” connectedness or net total directional connectedness. In other words,  $NET_{jt} > 0$ ,  $i$  indicating that that  $j$  is driver of network or volatility transmitter. Finally, the last equation (Equation (9)) refers to the aggregate measure of the total connectedness amongst all the variables or market in the system and acts as a proxy to the overall connectedness and risk associated with the market. Generally, a higher TCI describes that a shock in a variable or market substantially affects the overall system or network, whereas a lower TCI indicates vice-versa, i.e., a shock in a variable has no substantial affect on associated variable in the system or network, suggesting lower market risk.

### 3.3. Bivariate Wavelet Coherence Method

To investigate the time–frequency co-movement between REEs and Solactive EVFM Index, we employed bivariate wavelet coherence approach. It combines both time and frequency irrespective of the sample period (Karim and Naeem 2022). Put simply, the wavelet coherence has two categories, for instance cross-wavelet power (CWP) and cross-wavelet transform (CWT) where CWT can be segregated by dual time-sequence under the smoothing technique as  $i(t)$  and  $j(t)$ , where CWT for them is  $W_i(p, q)$  and  $W_j(p, q)$ . Hence the CWT can be expressed as follows:

$$W_{i,j}(p, q) = W_i(p, q) W_j^*(p, q) \quad (10)$$

where ‘ $p$ ’ and ‘ $q$ ’ are location index and scale (measure), respectively, and (\*) symbol on series ‘ $j$ ’ demonstrates composite index or complex conjugate. Collectively, wavelet transform measures the relationship (co-movement) between two variables ‘ $i$ ’ and ‘ $j$ ’.

Further, the CWT is used to measure wavelet power using the vector as  $W_i(p, q)$ . The spectra of CWP reveals notable concentration considering co-variance between two variables or time series in the time–frequency domain. In addition, the wavelet coherence approach captures economic turbulent or uncertain events through considering co-movements among markets or time-series. Following the extension of Torrence and Webster (1999), the coefficient of squared wavelet coherence is expressed as follows:

$$R^2(p, q) = \frac{|S[s^{-1}W_{i,j}(p, q)]|^2}{S[s^{-1}|W_i(p, q)|^2]S[s^{-1}|W_j(p, q)|^2]} \quad (11)$$

$S$  reveals smoothing operator over time–frequency where squared correlation coefficient follows  $0 \leq R^2(u, s) \leq 1$ . Squared correlation coefficient close to zero (unity) indicates no correlation (high correlation). However, wavelet coherence fails to differentiate positive and negative correlation direction, and hence ranges from 0 to 1. Following Torrence and Compo (1998), we followed “phase difference” mechanism to determine direction of the correlation between time-series or variables.

The phase difference can be expressed as follows:

$${}_{a,b}(u, s) \tan^{-1} \left( \frac{\text{Im} \left\{ S \left( s^{-1} W^{a,b}(u, s) \right) \right\}}{\text{Re} \left\{ S \left( s^{-1} W^{a,b}(u, s) \right) \right\}} \right) \quad (12)$$

where  $\text{Im}$  denotes the imaginary smoothed mechanism and  $\text{Re}$  reveals the real part of smoothed cross-wavelet transformation.

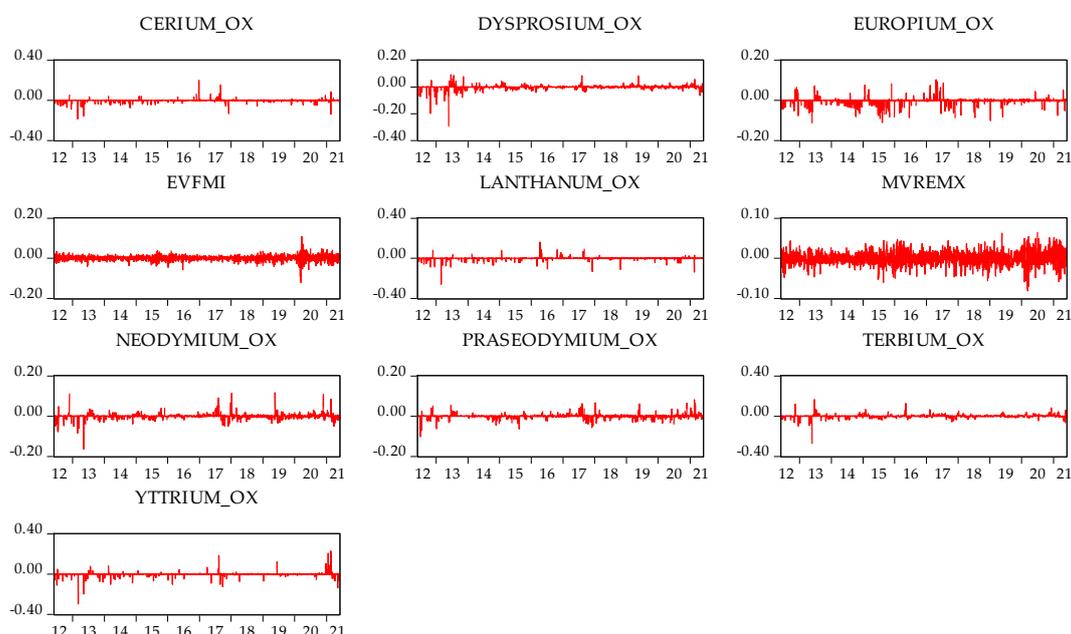
## 4. Preliminary Analysis and Results

### 4.1. Summary of Basic Statistics

The descriptive statistics are illustrated in Table 1 where the descriptive statistics are based on the daily first difference log series for all rare earth elements and the electric vehicle and future mobility index. They represent that the mean is positive for all level series. Standard deviation coefficients represent that the high daily price time series have higher standard deviations. The output of the Jarque Bera test confirmed that all series are non-normally distributed and significant at a 0.01 (1%) level.

All level series are represented in Figure 1. Out of ten time series, six level series (Cerium, Dysprosium, Europium, Lanthanum, Yttrium and MVREMX) are positively skewed and three (Neodymium, Terbium and the Solactive EVFM Index) are negatively skewed. The negatively skewed level series shows a mountainous growth over the period, the considered period and vice-versa. Noticeably, returns have experienced a rise for rare earth metals (Dysprosium, Neodymium, Praseodymium, Terbium and Yttrium) since COVID-19. A similar upward trend in price is evidenced in the MVIS Global Rare Earth/Strategic Metal Index (MVREMX). The share price of electric vehicles and the future mobility index has plunged since the COVID-19 outbreak. Thus, Figure 1 shows that there has been an upward trend in price since the outbreak of COVID-19 (Haq and Awan 2020).

We estimated an unconditional correlation for any  $i$ -th series on  $(t - 0)$ . The outcomes of the unconditional correlation are reported in Table 2. They show that the correlation between rare earth metals and electric vehicles and future mobility is predominantly negative, except for Neodymium and Terbium where the correlation remains moderately positive (0.447 and 0.541, respectively). The finding of the unconditional correlation suggests that potential hedging and diversification avenues exist between rare earth elements and electric vehicles and future mobility. The low/moderate positive correlation between markets offers better diversification gains than perfectly positively correlated markets, hence they can be termed as diversifiers following Baur and Lucey (2010) and Haq et al. (2021a).



**Figure 1.** Plots of differenced log returns. Note: This figure presents the logarithm first difference (log-returns) from 1 June 2012 to 4 June 2021.

**Table 1.** Descriptive statistics.

Variables	Mean	Median	Std. Dev.	Skewness	Kurtosis	Jarque–Bera	Observations
CE	−0.0004	0.0000	0.0052	−1.6527	106.2403	5400.60 ***	2249
DY	−0.0002	0.0000	0.0062	−6.4457	122.3671	3275.55 ***	2249
EU	−0.0007	0.0000	0.0058	−2.0082	26.1718	613.54 ***	2249
LA	−0.0004	0.0000	0.0054	−5.3868	128.3859	5873.60 ***	2249
MVREMX	−0.0001	−0.0002	0.0068	−0.1485	4.8488	301.31 ***	2249
NE	0.0000	0.0000	0.0049	0.5362	50.6489	2321.39 ***	2249
PR	0.0000	0.0000	0.0039	0.1466	30.8785	251.63 ***	2249
EVFMI	0.0003	0.0005	0.0055	−0.7966	14.4822	1556.20 ***	2249
TE	0.0000	0.0000	0.0057	−2.7720	110.2917	5350.18 ***	2249
YT	−0.0003	0.0000	0.0070	−1.3691	112.7002	2548.34 ***	2249

Note: This table explains the descriptive statistics for all level series. Jarque–Bera test determines that all series are non-normally distributed. (\*\*\*) displays the statistical significance of results at a 1% or  $p \leq 0.001$  level. Abbreviations: CERIUM = CE, DYSPROSIUM = DY, EUROPIUM = EU, LANTHANUM = LA, NEODYMIUM = NE, PRASEODYMIUM = PR, TERBIUM = TE and YTTRIUM = YT.

**Table 2.** Unconditional correlation.

Pairs	Correlation	t-Statistic	Probability	Observations
Solactive EVFM Index and Cerium	−0.520	−28.886	0.000	2249
Solactive EVFM Index and Dysprosium	−0.090	−4.301	0.000	2249
Solactive EVFM Index and Europium	−0.637	−39.179	0.000	2249
Solactive EVFM Index and Lanthanum	−0.535	−30.018	0.000	2249
Solactive EVFM Index and Neodymium	0.447	23.665	0.000	2249
Solactive EVFM Index and Praseodymium	−0.133	−6.371	0.000	2249
Solactive EVFM Index and Terbium	0.541	30.482	0.000	2249
Solactive EVFM Index and Yttrium	−0.530	−29.623	0.000	2249
Solactive EVFM Index and MVREMX Index	−0.384	−19.729	0.000	2249

Note: This demonstrates the unconditional correlation between rare earth elements and electric vehicles and the future mobility index.

Table 3 reported the Pearson correlation coefficients (PPCs) where coefficients are statistically significant at a 1% level. In addition, the red color shows correlation values near to 1 or perfectly positively correlated. The green color demonstrates diversification avenues among rare earth elements where the correlation is positive, but not perfectly positive. Moreover, bold values in light grey demonstrate PCCs between individual rare earth elements and electric vehicles and future mobility, which are predominantly negative, as also reported in Table 2. Diagonal values highlighted white are to demonstrate the correlation of any time series with itself.

**Table 3.** Correlation matrix.

Variables	CE	DY	EU	LA	MVREMX	NE	PR	EVFMI	TE	YT
CE	<b>1.000</b>	0.775	0.890	0.998	0.854	0.393	0.306	−0.520	0.297	0.970
DY	0.775	<b>1.000</b>	0.685	0.768	0.675	0.668	0.313	−0.090	0.734	0.813
EU	0.890	0.685	<b>1.000</b>	0.885	0.901	0.301	0.528	−0.637	0.211	0.944
LA	0.998	0.768	0.885	<b>1.000</b>	0.844	0.371	0.283	−0.535	0.282	0.969
MVREMX	0.854	0.675	0.901	0.844	<b>1.000</b>	0.538	0.614	−0.384	0.378	0.889
NE	0.393	0.668	0.301	0.371	0.538	<b>1.000</b>	0.494	0.447	0.896	0.424
PR	0.306	0.313	0.528	0.283	0.614	0.494	<b>1.000</b>	−0.133	0.255	0.374
EVFMI	−0.520	−0.090	−0.637	−0.535	−0.384	0.447	−0.133	<b>1.000</b>	0.541	−0.530
TE	0.297	0.734	0.211	0.282	0.378	0.896	0.255	0.541	<b>1.000</b>	0.354
YT	0.970	0.813	0.944	0.969	0.889	0.424	0.374	−0.530	0.354	<b>1.000</b>

Note: This table illustrates the Pearson correlation coefficient (PCC) among all level rare earth elements indices and electric vehicle and future mobility. Coefficients in green show potential avenues for diversification as the correlation is not perfectly positive. Values in red demonstrate that no diversification properties exist as coefficients are near to 1 or perfect positive correlation. Correlation coefficients in light-grey demonstrate Pearson correlation between rare earth elements and electric vehicles and future mobility index. All coefficients are statistically significant at a 1% or  $p \leq 0.001$  level.

### 4.2. TVP-VAR Analysis

First, we employed a TVP-VAR-based time-varying connectedness approach to examine the dynamic connectedness between REEs and the Solactive EVFM Index. Table 4 demonstrates the connectedness between REEs and the Solactive EVFM Index from 1 June 2012 to 4 June 2021. Generally, we see the total connectedness index is 68.18%, indicating that REEs returns and the Solactive EVFM Index have strong interconnectedness over time, where NEODYMIUM (11.85%) is a leading return contributor and DYSPROSIUM (−11.37%) is a leading return receiver following the Solactive EVFM Index (−10.41%). The analysis of individual REEs shows that CERIUM, EUROPIUM, LANTHANUM, NEODYMIUM and TERBIUM are NET return transmitters and the Solactive EVFM Index, DYSPROSIUM, PRASEODYMIUM and MVREMX are NET return recipients from others, i.e., their returns tend to be influenced by shocks in returns of other REEs or markets in the overall system.

Figure 2 indicates the total connectedness index for the overall system from 1 June 2012 to 4 June 2021. The figure shows that the connectedness among REEs and the Solactive EVFM Index remains higher throughout the sample period, particularly from 2012 to 2016, after which it decreases by 50% in 2018. Notably, the figure shows a noticeable spike around the rare earth crisis from 2010 to 2012 and the COVID-19 pandemic period, indicating a higher interconnectedness during economic turbulent periods, consistent with earlier findings (Reboredo and Ugolini 2020; Song et al. 2021). The higher connectedness indicates substantial risks associated with REEs and the Solactive EVFM Index.



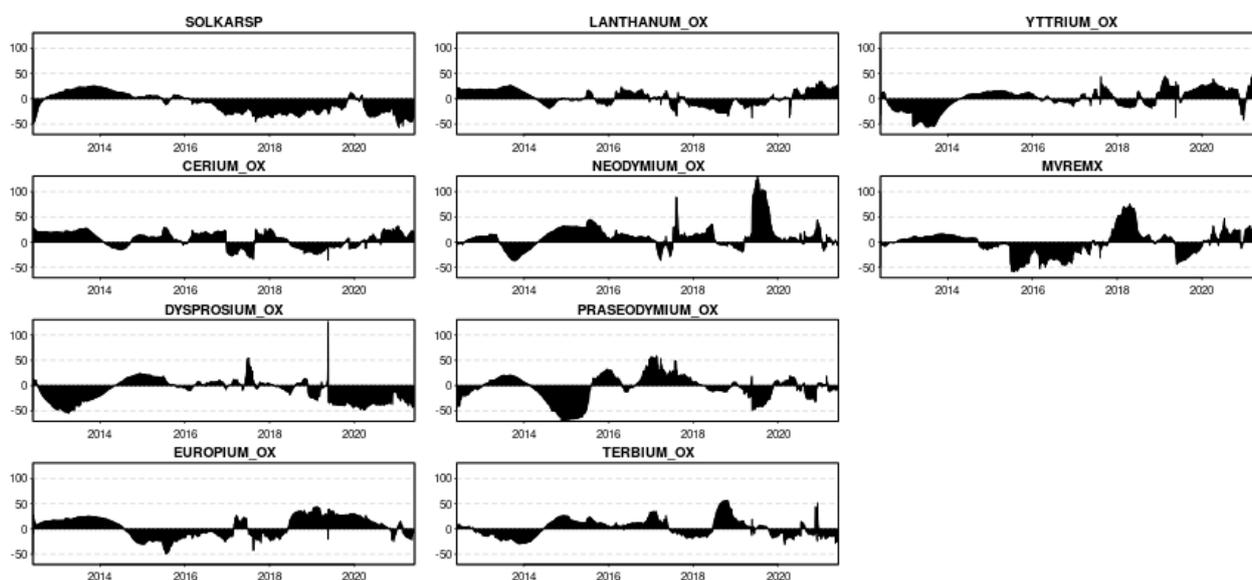
**Figure 2.** Time-varying total connectedness. Note: this figure demonstrates time-varying total return connectedness between REEs and Solactive EVFM Index using TVP-VAR model from 1 June 2012 to 4 June 2021.

**Table 4.** Total connectedness table.

	EVFMI	CE	DY	EU	LA	NE	PR	TE	YT	MVREMX	FROM
EVFMI	33.27	5.48	5.78	12.78	5.21	6.88	5.64	5.61	8.30	11.05	66.73
CE	4.32	28.15	4.02	7.73	19.44	10.29	7.17	8.05	6.40	4.42	71.85
DY	6.72	4.91	32.23	9.43	4.34	8.71	3.84	10.00	12.81	7.01	67.77
EU	8.88	11.16	4.01	27.01	11.25	7.27	6.78	6.38	9.51	7.74	72.99
LA	4.35	20.56	3.55	8.40	29.20	8.68	7.40	6.92	6.31	4.63	70.80
NE	6.07	8.17	8.24	5.01	7.56	28.76	10.96	11.22	8.85	5.15	71.24
PR	5.61	6.72	8.42	6.33	5.93	12.80	36.07	5.37	8.27	4.49	63.93
TE	5.20	6.03	9.52	5.69	6.13	12.01	6.81	35.07	8.09	5.45	64.93
YT	7.78	7.60	8.06	14.55	7.23	8.93	6.05	6.23	26.35	7.23	73.65
MVREMX	7.40	6.83	4.81	7.07	6.47	7.51	4.76	6.45	6.66	42.04	57.96
TO	56.32	77.45	56.43	76.99	73.56	83.08	59.42	66.24	75.20	57.16	681.84
NET	−10.41	5.60	−11.35	4.00	2.76	11.85	−4.51	1.31	1.55	−0.80	TCI = 68.18%

Note: this table reports output of total return connectedness between REEs and Solactive EVFM Index using TVP-VAR model from 1 June 2012 to 4 June 2021.

Figures A1 and A2 in Appendix A present the total return and directional return connectedness “TO” other and “FROM” others for each of the REE and the Solactive EVFM Index, respectively. However, Figure 3 shows the individual net directional connectedness of each REE and the Solactive EVFM Index in the overall system. These findings are consistent in Table 4, where “NET” “TO” and “FROM” other transmitters and recipients were reported. This analysis is helpful in understanding individual NET receivers and transmitters of shocks that might affect the returns in the overall system. The figure recalls that CERMIUM, EUROPIUM, LANTHANUM, NEODYMIUM and TERBIUM are NET return transmitters and the Solactive EVFM Index, DYSPROSIUM, PRASEODYMIUM and MVREMX are NET return recipients from others, i.e., their returns tend to be influenced by shocks in the returns of other metals or markets in the overall system. Notably, NET connectedness follows heterogenous patterns and time-varying where the Solactive EVFM Index shows positive and negative NET connectedness, indicating returns with mixed transmitter/recipient roles.



**Figure 3.** Time-varying NET connectedness. Note: this figure represents the time-varying NET connectedness between REEs and Solactive EVFM Index using TVP-VAR model from 1 June 2012 to 4 June 2021.

#### 4.3. Wavelet Coherence Analysis

We examined bivariate wavelet coherence between eight individual rare earth elements and the Solactive EVFM Index. We also investigated the co-movement between the MVIS Global Rare Earth/Strategic Metal Index and electric vehicles and the Solactive EVFM Index across both the time and frequency domains. The output of the bivariate wavelet coherence analysis is presented in Figure 4. Figure 4a presents the wavelet coherence between the Cerium returns and the Solactive EVFM Index. Generally, arrows are directed left which indicates a negative correlation (out of the phase relationship) between the Cerium returns and the Solactive EVFM Index. More specifically, left-direction arrows are more visible at the right and left sides of the figure during the first 700 days (from 1 June 2012 to 24 March 2015) and the last 700 days (from 15 August 2018 to 4 June 2021). Notably, the coherence remains stronger in the medium-term and long-term than the short-term scales, suggesting a limited hedging ability of Cerium for the Solactive EVFM Index in the medium-term and long-term investment horizons. However, the predominant blue area shows a weak connectedness between Cerium and the Solactive EVFM Index between 2014 and 2019 across multiple frequency scales, signifying the diversification and weak hedging abilities of Cerium. Cerium returns are lagging from the Solactive EVFM Index in the medium-term and long-term investment horizons, suggesting rare earths are recipients of the returns

spillover from financial markets (Bouri et al. 2021; Song et al. 2021; Zheng et al. 2021). This finding justifies that the rising electric vehicles and future mobility industry might influence the returns of Cerium due to its important use in electric vehicles (Elwert et al. 2017; Fernandez 2017; Li et al. 2019). Overall, these results confirm that Cerium is a hedge against the Solactive EVFM Index in medium-term and long-term investment horizons during normal and turbulent periods, i.e., COVID-19.

Figure 4b shows the wavelet coherence between Dysprosium returns and the Solactive EVFM Index. Black right-directed downward arrows are visible at the right side of the bottom, indicating an in-phase (positive correlation) association between Dysprosium returns and the Solactive EVFM Index in the 128–256 days and 256–512 days scales during the last 800 days from 1 June 2012 to 23 March 2017. Therefore, Dysprosium's failure to act as a hedging commodity or instrument for the Solactive EVFM Index during the COVID-19 period and strong connectedness during turbulent periods corroborates with Ajmi et al. (2021), Haq (2022), and Karim and Naeem (2022). Additionally, the rest of the blue area and a few yellow spots on the graph show the weak and moderate positive co-movement across multiple scales. These findings are consistent with Haq et al. (2021b) and Song et al. (2021) and indicate weak hedging and diversification opportunities in the short-term and medium-term investment horizons. Dysprosium returns are leading the Solactive EVFM Index. The current results corroborate with Li et al. (2019) who found that not only can the electric vehicles industry influence the rare earths, but the rare earth returns, i.e., Dysprosium, may predict electric vehicles and future mobility returns due to a strong dependence of electric vehicles on rare earths. Overall, these findings demonstrate that Dysprosium has positive co-movement with the Solactive EVFM Index, restricted to a long-term investment horizon, and Dysprosium returns lead the Solactive EVFM Index.

Figure 4c demonstrates the wavelet coherence between Europium returns and the Solactive EVFM Index. At Figure 4c, the backward left-directed arrows at both the right and left sides of the figure exhibit a negative correlation (out of the phase) between the Europium returns and the Solactive EVFM Index in the 32–64 days, 64–128 days and 256–512 days scales during the first 400 days (from 1 June 2012 to 8 January 2014), and in the 64–128 days, 128–256 days and 256–512 days scales during last 700 days (from 6 June 2018 to 4 June 2021). Meanwhile, the blue area and several yellow contours indicate weak and moderate positive correlations from 2013 to 2018 across multiple wavelet components. In addition, wavelet coherence shows a consistent weak connectedness in short-term investment horizons. These findings are consistent with Figure 4a and (Fernandez 2017; Haq et al. 2021b) and show that Europium is a strong hedge or safe haven for the Solactive EVFM Index in medium-term and long-term investment horizons for a limited timeframe, and a weak hedge and diversifier in the short-term investment horizon. Europium returns are lagging for the Solactive EVFM Index in the medium-term and long-term and particularly during COVID-19 crisis period. Overall, the findings indicate that Europium acts as a suitable hedge against the Solactive EVFM Index in medium-term and long-term investment horizons. Moreover, investors need to understand the correlation and lead/lag relationship while designing portfolios and taking short or long positions.

Figure 4d plots the outcomes of the wavelet coherence between Lanthanum returns and the Solactive EVFM Index. Generally, arrows are left-directed in the wavelet coherence plot. Left-directed downward and upward arrows imply an out-of-the-phase (negative correlation) association between Lanthanum returns and the Solactive EVFM Index during the first 750 days (from 1 June 2012 to 5 June 2015) and last 750 days (from 6 June 2018 to 4 June 2021) in the 32–64 days, 64–128 days, 128–256 days and 256–512 days wavelet scales. The graph shows a predominant blue area with several yellow spots in the middle, showing weak and moderate positive co-movement between Lanthanum returns and the Solactive EVFM Index from 2014 to 2019, aligned with previous research which documented low (Fernandez 2017) and moderate positive (Haq et al. 2021b) correlations between rare earths and financial markets. Similar to Cerium and Europium, Lanthanum can act as a hedge for the Solactive EVFM Index during medium-term and long-term investment horizons,

however, it is a weak hedge or diversifier during a short-term investment horizon. Where Lanthanum is lagging in the Solactive EVFM Index is in the medium-term and long-term investment horizons during a limited timeframe. Overall, the wavelet coherence output signifies that Lanthanum is a suitable hedge for the Solactive EVFM Index in normal and turbulent periods across medium-term and long-term investment horizons.

Further, Figure 4e demonstrates the outcomes of the wavelet coherence plot for Neodymium returns and the Solactive EVFM Index. The right-directed downward arrows denote in the phase (positive correlation) association between the Neodymium returns and the Solactive EVFM Index during the last 1200 days (from 1 June 2012 to 23 March 2017) in the 128–256 days and 256–512 days scales. The remaining graph area encompasses the blue area and yellow spots, suggesting weak and moderate positive co-movement at 2–4 days, 4–8 days, 8–16 days, 16–32 days, 32–64 days and 64–128 days scale. These findings show that Neodymium failed to act as a hedge in the long-term investment horizon, whereas it served as a weak hedge or diversifier in short-term and medium-term investment horizons, consistent with (Haq et al. 2021b). Generally, Neodymium returns are leading the Solactive EVFM Index in the long-term investment horizon only. Overall, these findings show a strong dependence of the Solactive EVFM Index on Neodymium returns in a long-term investment horizon and that Neodymium acts as a weak hedge or diversifier in the Solactive EVFM Index in short-term and medium-term horizons.

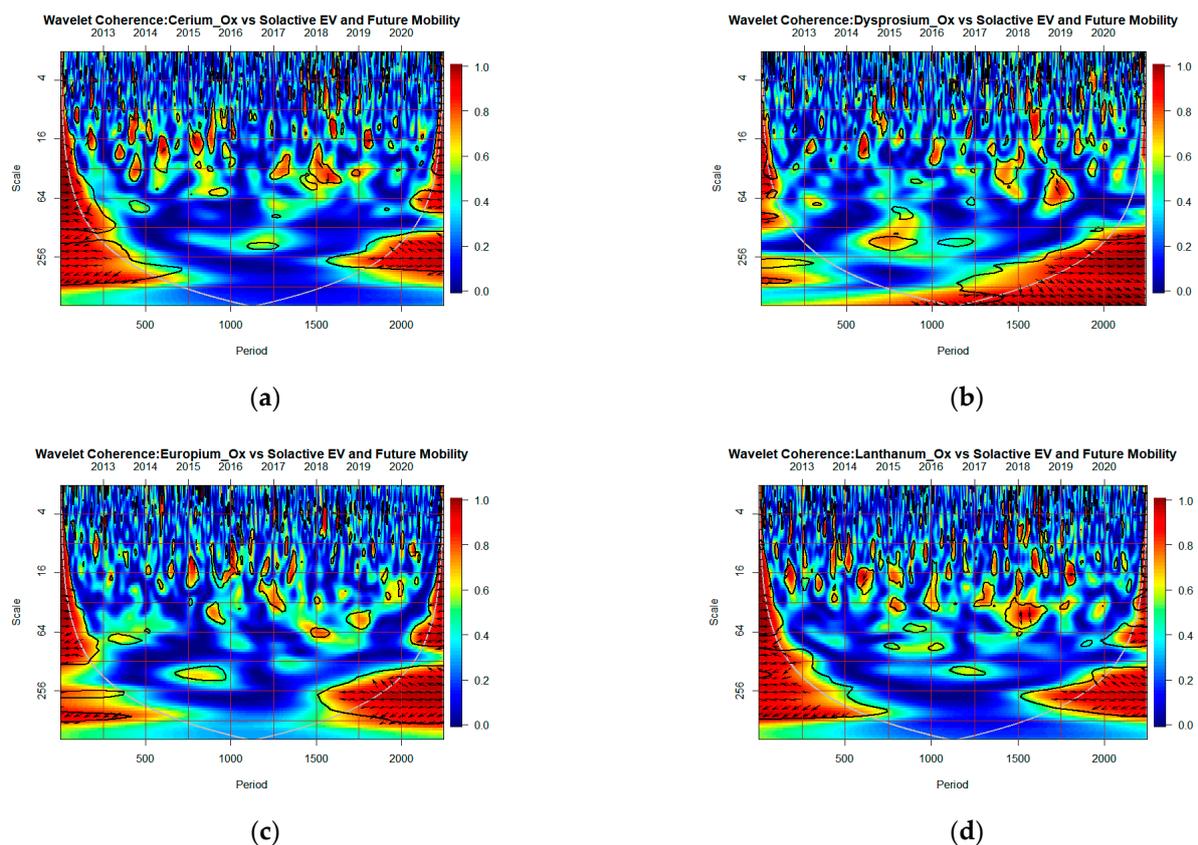
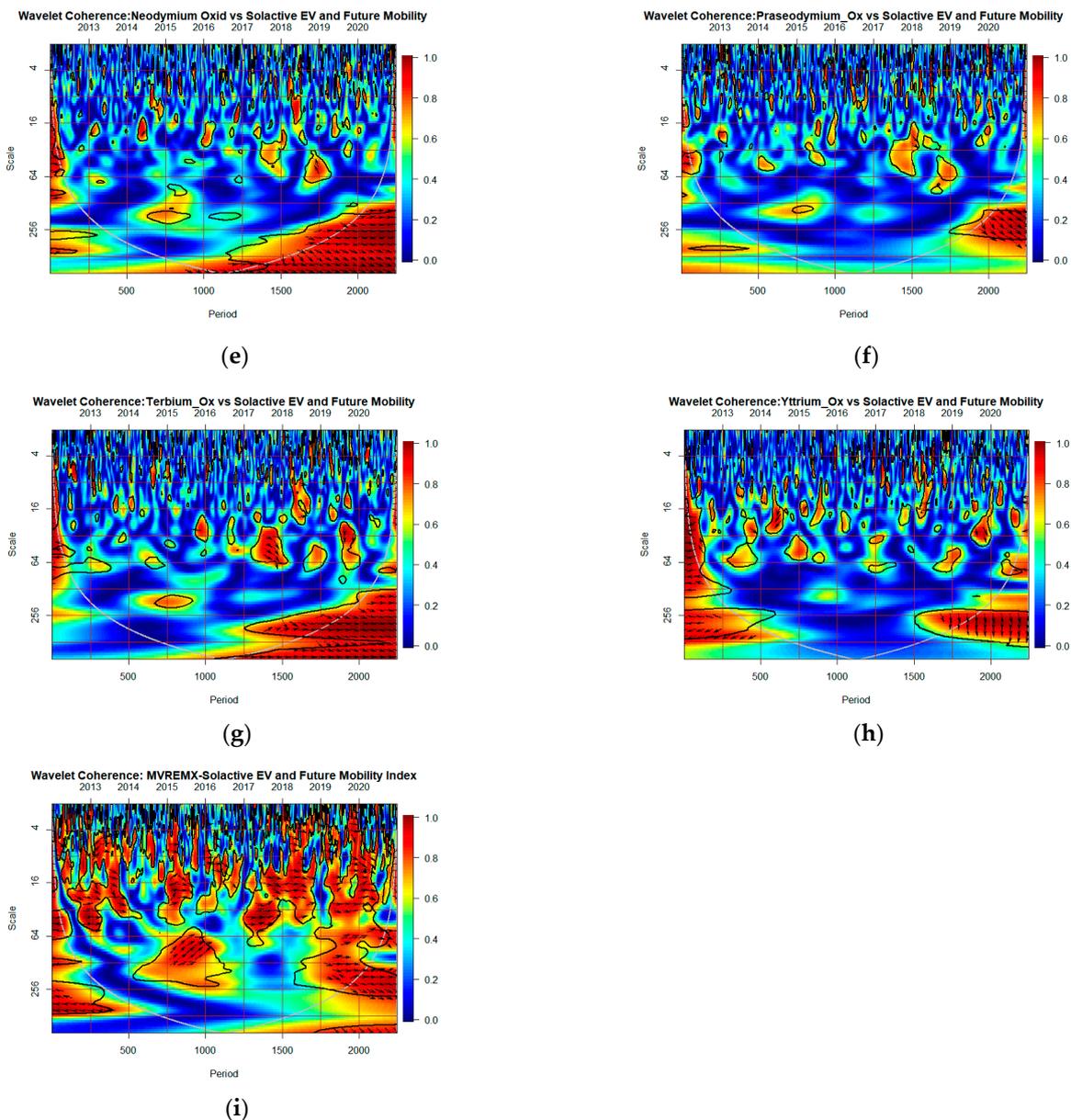


Figure 4. Cont.



**Figure 4.** Wavelet Coherence between REEs and Solactive EVFM Index. Note: Figure 4 indicates the wavelet coherency among rare earth elements and electric vehicle and future mobility index, where the horizontal axis presents the time in days (daily values within four points 500 = 4 June 2014, 1000 = 7 June 2016, 1500 = 6 June 2018, 2000 = 8 June 2020, and years on the top from 6 June 2012 to 6 June 2021). Vertical axis depicts the period (frequency) classified in 2–4, 4–8, 8–16, 16–32, 32–64, 64–128, 128–256 and 256–512 days). In general, cross-wavelet coherence estimation analysis yields a wavelet coherence plot. It comprises five essential chunks of findings: warm and cold colors, arrows with eight multiple routes, black contours, and a two-axis ( $x$ -axis/ $y$ -axis) with a cone of influence. First, colors reveal the magnitude of the correlation between two variables ranging from red to blue, indicating a high to low correlation of co-movement. Second, the  $\leftarrow$  ( $\rightarrow$ ) arrows denote a negative (positive) correlation direction or an out-of-phase (in-phase) link between two variables or time series. Furthermore,  $\nearrow$ ,  $\searrow$  ( $\nwarrow$ ,  $\swarrow$ ) arrows show that the first (second) time series of variable returns are leading the second (first) time series of variable returns. A zero-phase difference indicates that both variables are moving in the same direction. Third, the black contours reveal that correlation or co-movement is statistically significant at the 0.05 level. Fourth, the  $x$ -axis and  $y$ -axis show the time and frequency scale, respectively. In the end, a u-shaped white solid line signifies the cone of influence.

Figure 4f shows wavelet coherence between Praseodymium returns and the Solactive EVFM Index. Generally, the coherence remains weak across multiple time and multiple frequency scales. The right-directed arrows at the right side of the figure show an in-the-phase (positive) correlation during the last 500 days (from 7 June 2019 to 4 June 2021) or the COVID-19 episode, suggesting a higher connectedness during turbulent periods (Song et al. 2021). Positive co-movement is more visible in the long-term investment horizon. However, the remaining plot area encompasses the blue color and yellow spots, indicating a weak and moderate positive correlation across time and multiple wavelet components. These findings indicate that Praseodymium can act as a weak hedge and diversifier with the Solactive EVFM Index in short-term and medium-term investment horizons where it fails to do so in the long-term investment horizon. These findings are in line with Fernandez (2017), Song et al. (2021) and Zheng et al. (2021) where weak connectedness between rare earths and the financial market offers potential opportunities for portfolio diversification. Further, the leading role of Praseodymium is marginal, which was limited during the COVID-19 period in the long-term investment horizon. Overall, the findings suggest that Praseodymium returns predict the Solactive EVFM Index in a long-term investment horizon and are potential weak hedge and diversifier opportunities in short-term and medium-term investment horizons.

Figure 4g shows wavelet coherence between Terbium returns and the Solactive EVFM Index. The right-directed arrows on the right side and middle of the figure indicate an in-phase (positive correlation) relationship between Terbium and the Solactive EVFM Index during the last 1000 days (from 6 June 2017 to 4 June 2021) in the 32–64 days, 64–128 days, 128–256 days and 256–512 days scales. However, the dominant blue area in the 2–4 days, 4–8 days and 8–16 days scales suggests a weak association between Terbium returns and the Solactive EVFM Index. These findings suggest that Terbium fails to behave in the same way as a hedge in medium-term and long-term investment horizons. Investors might earn financial gains considering a weak hedging instrument or diversifier with the Solactive EVFM Index in short-term investment horizons, which corroborates with (Fernandez 2017; Haq et al. 2021b). The lead/lag relationship implies that Terbium returns lead the Solactive EVFM Index predominantly in the medium-term and long-term, which is consistent with (Song et al. 2021; Zheng et al. 2021). Overall, these outcomes confirm that Terbium returns can predict the Solactive EVFM Index. Hence, Terbium returns have a positive impact on the Solactive EVFM Index.

Figure 4h exhibits wavelet coherence between Yttrium returns and the Solactive EVFM Index. Black left-directed and downward arrows are visible at the left and right sides of the bottom, indicating out-of-phase (negative correlation) connectedness between Yttrium and the Solactive EVFM index during the first 500 days (from 1 June 2012 to 24 November 2014) in the 16–32 days, 32–64 days, 64–128, 128–256 and 256–512 days frequency scales, and the last 750 days (6 June 2018 and 4 June 2021) in the 256–512 days frequency scale. However, several yellow spots and the wide range of the blue area from 2014 to 2018 present weak and moderate positive co-movement across all investment horizons. These findings show weak hedging and diversification properties of Yttrium which are limited in the short-term investment horizon, and also that Yttrium behaves as a strong hedge in medium-term and long-term investment horizons. These findings are consistent with Fernandez (2017) and Haq et al. (2021b) who presented that rare earths and financial markets are weakly connected and, hence, can be a potential source of diversification. Similar to other rare earths, Yttrium returns are lagging for the Solactive EVFM Index's short-term and medium-term investment horizons, suggesting the dependence of the Solactive EVFM Index on rare earth elements.

Finally, Figure 4i shows the wavelet coherence between MVREMX returns and the Solactive EVFM Index. In comparison to individual rare earths, it demonstrates a stronger positive co-movement between MVREMX returns and the Solactive EVFM Index across all wavelet scales. The left-directed arrows at the left bottom of the figure demonstrate the out-of-the-phase (negative correlation) relationship between MVREMX returns and

the Solactive EVFM Index during the first 700 days (1 June 2012 to 24 March 2015) in the 256–512 days scale. This finding suggests that MVREMX can act as a hedge during normal market conditions or normalized circumstances of financial markets in the long-term investment horizon. This finding corroborates with [Reboredo and Ugolini \(2020\)](#) who show the negative return and volatility connectedness of MVREMX with financial markets. Meanwhile, the right-directed arrows, which are predominantly visible in the large area of the wavelet coherence plot, indicate an in-phase (positive correlation) relationship throughout the considered period in the 2–4 days, 4–8 days, 8–16 days, 16–32 days, 32–64 days, 64–128 day, and 128–264 days scales. MVREMX presents the strongest and most significant positive co-movement with the Solactive EVFM Index, among others, across multiple wavelet components. This result indicates that MVREMX is unable to hedge the Solactive EVFM Index across normalized circumstances and the COVID-19 crisis period due to a higher integration and return spillover between rare earth and financial markets during COVID-19 ([Bouri et al. 2021](#); [Song et al. 2021](#)). These findings corroborate with earlier research ([Zhou et al. 2022](#)) which found that connectedness increased significantly during the COVID-19 and financial crisis periods. The lead/lag relationship indicates that MVREMX returns lead in the Solactive EVFM Index across short-term, medium-term and long-term investment horizons. These results are consistent with [Fernandez \(2017\)](#) and [Haq et al. \(2021b\)](#) who found a positive conditional correlation between MVREMX returns and financial markets. Overall, the hedging ability of MVREMX was limited for 400 days (from 1 June 2012 to 8 January 2014) in the long-term investment horizon, however, the rest of the connectedness remained positive within both the time and frequency domains.

## 5. Conclusions and Policy Implications

This study investigates co-movement between individual REEs (Cerium, Dysprosium, Europium, Lanthanum, Neodymium, Praseodymium, Terbium, Yttrium) and the Solactive EVFM Index using a TVP-VAR connectedness approach and bivariate wavelet coherence method from 1 June 2012 to 4 June 2021. We further studied global perspective considering the return connectedness between the MVIS Global Rare Earth/Strategic Metal Index and Solactive EVFM Index.

Using a TVP-VAR model, we found strong interconnectedness between REEs returns and the Solactive EVFM Index which is time-varying. The return connectedness shows noticeable spikes around economic turbulent periods, such as the rare earth crisis 2010–2012 and COVID-19. More specifically, Cerium, Europium, Lanthanum, Neodymium and Terbium are NET return transmitters to others, and the Solactive EVFM Index, Dysprosium, Praseodymium and MVREMX are NET return recipients of return shocks from others. The NET connectedness follows a positive/negative time-varying feature. In addition, our wavelet coherence results reveal heterogeneous co-movements across multiple wavelet investment horizons between individual rare earth returns and the Solactive EVFM Index. Generally, three of five light REEs (Cerium, Europium, Lanthanum) show dominant negative co-movements with the Solactive EVFM Index in medium-term and long-term investment horizons, whereas Neodymium and Praseodymium show positive co-movement in a long-term investment horizon. In addition, two of three heavy REEs (Terbium, Dysprosium) present positive co-movement in a long-term investment horizon, whereas Yttrium alone has negative co-movement during the last days of the sample period in the long-term investment horizon. The co-movement between indices remains weak in a short-term investment horizon. These findings indicate that Cerium, Europium, Lanthanum and Yttrium (lagging) are strong hedges for the (leading) Solactive EVFM Index in the medium-term and long-term, whereas Neodymium, Praseodymium, Terbium and Dysprosium (leading) show no hedging properties for the (lagging) Solactive EVFM Index across these horizons. Notably, REEs are weak hedges or diversifiers with the Solactive EVFM Index in the short-term. Considering the global perspective, MVREMX shows strong positive co-movement with the Solactive EVFM Index across all wavelet components except for early sample days. MVREMX is not a suitable hedge or diversifier for the Solactive EVFM

Index. MVREMX returns lead the Solactive EVFM Index across all wavelet components. The strong dependence of the Solactive EVFM Index upon MVREMX advocated that REEs are indispensable for the electric vehicles and future mobility industry (Fernandez 2017). Notably, the co-movement becomes stronger and more visible during the beginning and at the end of the sample period. Meanwhile, the COVID-19 pandemic has contributed to a larger connectedness toward the end of the sample period. Moreover, the rare earth market crisis between 2010 and 2012 vindicates higher connectedness in initial sample years. Those results corroborate the findings of earlier research (Bouri et al. 2021; Reboredo and Ugolini 2020; Song et al. 2021) that supported higher co-movement between the rare earth market and financial markets during a turbulent economic period or crisis periods. The positive co-movements suggest the rising electric vehicles industry and energy technologies which lead to an increase in REEs' prices. These findings are in line with Y. Chen et al. (2020) where the authors found a strong positive conditional correlation between energy technologies and rare earth elements. This might be due to high REE consumption in electric vehicles and the future forecasted demand by Habib and Wenzel (2014), and Filippas et al. (2021).

The above findings have enormous implications for investors, portfolio managers, electric vehicle and future mobility companies and policymakers. Our results may be of particular interest to portfolio managers and investors to understand the hedging and diversification opportunities associated with the REE market, and electric vehicles and future mobility companies. Additionally, returns are individual REEs that interact with the Solactive EVFM Index over time, and multiple investment horizons would be highly useful to earn potential financial gains and learning how to manage diversification in a portfolio across multiple investment horizons. The connectedness implies that the elevated prices of REEs are not due to the clean energy market and trade restrictions alone, but the impact of electric vehicles and future mobility sectors are making them more volatile. The dependence of electric vehicles and future mobility companies upon rare earth may be relevant to automobile companies. Over-dependence on REE may restrict the financial and market growth. Hence, companies need to introduce new technology alternatives to REEs to ensure cost-effective and energy-efficient electric vehicle and battery production. Policymakers need to take countermeasures to restrict the financial contagion effect associated with dynamic interconnectedness.

This research is not without limitations. Firstly, this research considered rare earth elements and electric vehicles and future mobility only, but ignores the consequence to the environment and energy consumption as a whole. Further, it only investigated the co-movement in a sample period of 2012 to 2021, which can uncover hedge and diversifier properties; however, the safe-haven role was ignored. We will test its safe-haven properties against VIX, EPU, Oil Price Volatility and the COVID-19 fear index in next study. Additionally, the author used level series for wavelet coherency analysis. Future research should explore the impact of electric vehicles and future mobility in sustainability and environmental performance. In addition, electric vehicles and future mobility should be studied in the context of energy and petroleum efficiency. Modern scholars should explore the safe-haven properties of rare earth elements considering the COVID-19 period separately. In the future, we can check if inclusion of rare earth metals improves the returns of investors in these companies with the increase in Sharpe ratios. The wavelet approach is not as useful to test whether the portfolio risk is actually reduced for EVs market investors as the Share ratio. More research is called to explore this linkage in the context of returns and volatility co-movements.

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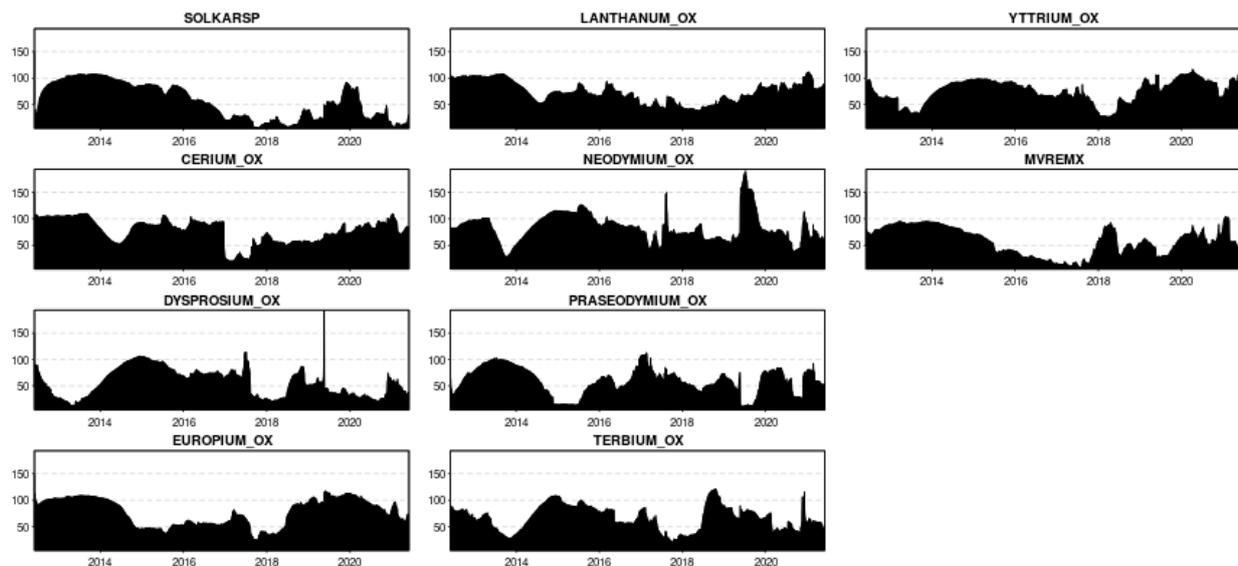
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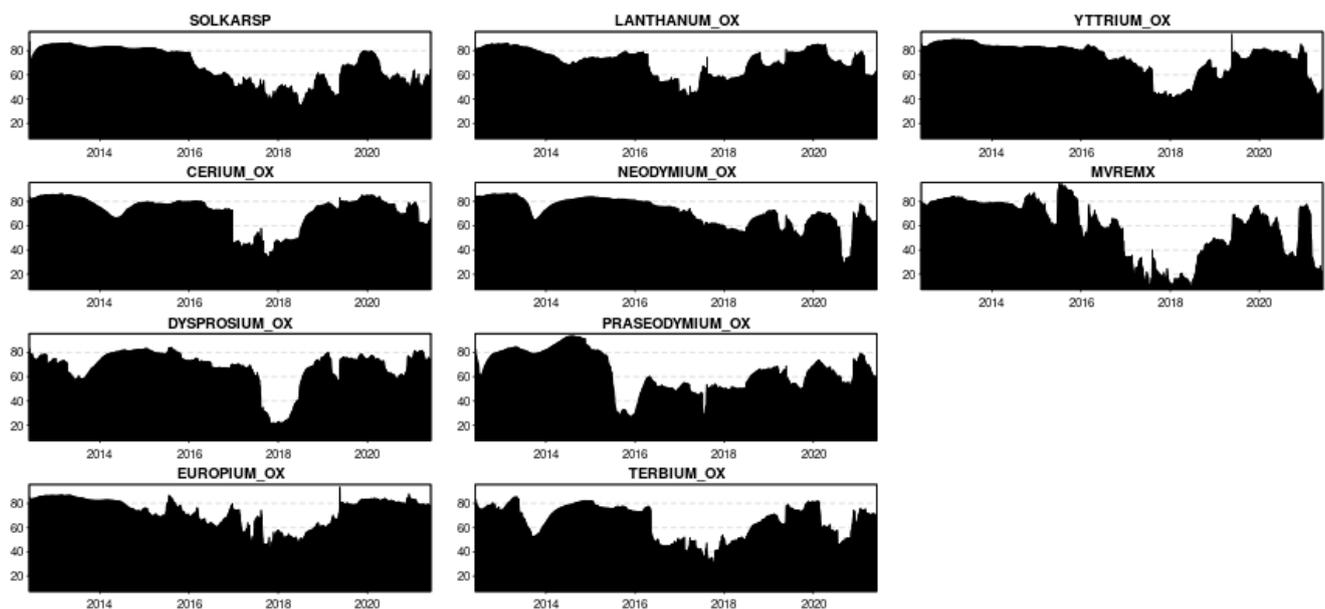
**Data Availability Statement:** Data are available upon request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A



**Figure A1.** Time-varying connectedness TO others. Note: this figure represents the time-varying TO other returns connectedness between REEs and Solactive EVFM Index using TVP-VAR model from 1 June 2012 to 4 June 2021.



**Figure A2.** Time-varying connectedness FROM others. Note: this figure represents the time-varying FROM other returns connectedness between REEs and Solactive EVFM Index using TVP-VAR model from 1 June 2012 to 4 June 2021.

## Notes

- <sup>1</sup> Fishman et al. (2018) investigated current demand and supply of rare earth in electric vehicles industry. In addition, they explored projected demand and supply of rare earth until 2050 in US. Similarly, while examining global demand and supply of rare earth resources, Dutta et al. (2016) revealed that REE demand is expected to grow by 5% in future.
- <sup>2</sup> See <https://www.solactive.com/Indices/?index=DE000SLA5B80> (accessed on 4 June 2021).

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