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# Do Rare Earths and Energy Commodities Drive Volatility Transmission in Sustainable Financial Markets? Evidence from China, Australia, and the US

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**Abstract:** The high volatility and energy usage of rare earths have raised sustainable and financial concerns for environmentalists and sustainable investors. Therefore, this paper aims to investigate time-varying volatility transmission among rare earths elements, energy commodities, and sustainable financial markets. The sample covers global and major financial markets, i.e., US, China, and Australia. Using daily log returns from 2018 to 2022, the paper considers the dynamic Time Varying Parameter-Vector Autoregression (TVP-VAR) connectedness approach to gauge the time-varying features of volatility spillovers. The findings of total spillovers index reveal weak connectedness among markets during the sampled period. US and China rare earth markets were net volatility transmitters, whereas the Dow Jones Australia Sustainability Index (ASI), China Sustainability Index (CSI), Dow Jones Sustainability World Index (SWI), and MVIS Global Rare Earth Index (MVISGREI) were net recipients. Moreover, energy commodities i.e., WTI Crude Oil, Gasoline, and Natural Gas were net volatility transmitters, while ASI, CSI, and SWI were major volatility recipients. The weak financial contagion effect and connectedness across financial markets uncovers possible diversification opportunities. However, the US sustainable financial market is persistently not affected by these volatility spillovers. Policymakers need to establish strict regulations to protect sustainable financial markets in China and Australia.

**Keywords:** rare earths; energy commodities; crude oil; sustainable financial markets; TVP-VAR model

**JEL Classification:** C32; G12; G15; Q02

## 1. Introduction

Environmental sustainability is one of the most critical global economic concerns. Massive energy demands are fulfilled by dominating energy commodities i.e., crude oil, natural gas, and gasoline. Meanwhile, rare earths elements are important elements for electric vehicles (Haq et al. 2022), information technology firms (Fishman et al. 2018), and magnet production (Reboredo and Ugolini 2020). However, the energy consumption of rare earths results in severe climate change, carbon footprints, and air pollution issues (Balaram 2019; Dudley 2018; Kihombo et al. 2022). Noticeably, the majority of REEs extraction methods from primary or secondary resources involve dirty and energy-intensive extraction processes which cause environmental issues. In the 2019 International Energy Agency, carbon dioxide ($CO_2$) was the most significant component of greenhouse gas emissions, which soared by 1.7 percent in 2018 (Newell and Raimi 2020), signifying a record level of 33.1 Gt. Due to escalating effects of energy consumption and rare earths exploration on climate change and global warming, it is crucial to study the connectedness between rare earths, energy, and sustainable financial markets. In this way, economies can support the 2015 Paris Agreement and Sustainable Development Goals of the United Nations to mitigate $CO_2$ climate change and global warming and reform their economies to promote climate resilient global economy (Gaustad et al. 2021; Schulze and Buchert 2016). Additionally, Gaustad et al. (2021) noted that it is important to consider both environmental or social and economic or financial perspectives for investors and practitioners.

Rare earths, energy consumption, and sustainability have become major drivers of sustainable and green economic growth in the current era (Haq et al. 2021b, 2022; Zhou et al. 2022), which motivates this research to answer following two questions. First, is there a time-varying volatility connectedness between rare earths, energy, and sustainable financial markets in a normal period? Second, is there a time-varying volatility transmission between rare earths, energy, and sustainable financial markets during a fragile period, i.e., COVID-19?

Since that time, it has become critical for the global economy to transform its traditional energy resources into low-carbon resilient economies while maintaining environmental sustainability (Murshed 2018). As a result, scholars and environmentalists have been increasingly concerned about global climate change and carbon footprints (Singh and Dhadse 2021). Several studies have found that primary REEs extraction activities have degraded environmental quality and posed human health risks due to increased inorganic pollutant concentrations (Usman et al. 2020). While other studies have concluded that it is essential to restrict unregulated rare earth elements mining and that its extraction process effect on human health and the ecosystem should be reduced (Liang et al. 2014; Packey and Kingsnorth 2016). Due to the severe environmental effects and high energy requirements of the processes used to extract REE, environmental sustainability has now emerged as a crucial economic criterion. Thus, this study largely focuses on exploring the financial and environmental perspective of rare earth markets and energy commodities.

Evidently, before China's mining boom, the US held the monopoly on the global REE elements market for several decades through Mountain Pass production in 1965 (Barakos and Mischo 2017). Unfortunately, mining activities halted in 1998, due to Chinese REE market competition and environmental issues in the mountain pass region (Mancheri et al. 2019). As a result, the US economy has shifted its attention to REE recycling and imports a considerable quantity from several other countries (Marques et al. 2021). Meanwhile, other countries are also focusing on recycling REE materials and restricting their mining activities through primary resources to lessen environmental effects and improve energy efficiency (Brahim et al. 2022). These circumstances placed academics and environmentalists under immense pressure to investigate other REE sources and enhance extraction technology.

In prior research, Beylot et al. (2019) argued that significant investments are called for in the coming decades to achieve the objective of resilient economies with low carbon emissions. Additionally, impeding challenges including peak oil prices (Akhtaruzzaman et al. 2021c), economic vulnerability, and geopolitical issues have already prompted the need to diversify energy portfolios to achieve a global sustainable system (Balali and Stegen 2021). Therefore, increasing magnet use, rising global economic growth, and technological advancement are key drivers boosting demand for REEs. Global Market Insights Inc.'s 2020 research predicts that the annual growth rate of REE would be increased by 10.8% from 2022 to 2026, providing fund managers and investors throughout the world with a wide range of investment possibilities. So far, worldwide governments should undertake significant REE production plans and technology advances in REE's mining and recycling process as expansion in REE's market has piqued the interests of market participants. Moreover, the worsening impact of REEs on environmental quality and escalating climate challenges have spurred a global consensus to integrate global growth plans with concurrent environmental protection.

Therefore, the primary aim of our study is to reveal the dynamic volatility transmission across markets. In addition to exploring portfolio diversification or hedging opportunities across rare earths, energy, and sustainable financial markets. Generally, most portfolio managers and investors prefer higher returns at a given level of risk in their portfolios, which allows them to diversify their portfolio risk by integrating negatively or weakly correlated securities in their portfolio to obtain optimal portfolio performance (Evans and Archer 1968). Understanding volatility transmissions allows investors to better understand dynamic risk patterns during normal and adverse market conditions.

A strand of literature has investigated the information transmission among financial markets (Haq et al. 2022; Pantos et al. 2019; Papathanasiou et al. 2022b; Samitas and Kampouris 2019; Samitas et al. 2022b, 2022c). Energy commodities and rare earths have varying impacts across different financial markets (Haq et al. 2021b, 2022; Hau et al. 2022; Zhou et al. 2022). Hence, rare earths and energy commodities inherit varying hedging or diversification properties across time and frequency and may differ across multiple financial markets and energy commodities. In overview, our research is grounded on the theoretical standing of Markowitz's portfolio theory (Sharpe 1964). The idea of portfolio theory suggests that investors can design a portfolio of assets considering the negative correlation patterns or moderate positively correlated assets. In addition, an investor can earn and minimize the expected volatility at a given level of risk.

This study has a potential contribution to the existing literature (Bouri et al. 2021a; Chen et al. 2021; Haq et al. 2021b, 2022; Hau et al. 2022; Reboredo and Ugolini 2020; Shin et al. 2019; Song et al. 2021; Zheng et al. 2021, 2022; Zhou et al. 2022) in several ways. First, this study adds to the spillover and hedging literature (Haq et al. 2022; Pantos et al. 2019; Papathanasiou et al. 2022b; Reboredo and Ugolini 2020; Samitas and Kampouris 2019; Samitas et al. 2022b, 2022c) that rare earth elements and energy commodities, i.e., Gas, Natural Gas, and Crude Oil show heterogeneous volatility transmission toward financial markets in normal and fragile periods. Second, this research contributes to the recent body of literature (Haq et al. 2022; Samitas et al. 2022b, 2022d; Zhang et al. 2021), as no recent considered the dynamic volatility spillovers among these financial markets. Due to this, the sample set covers the impact of several financially and economically fragile periods, i.e., the COVID-19 episode (Haq and Awan 2020; Huynh et al. 2021). Finally, we uncover the dynamic volatility spillover in major economies, i.e., China, the USA, and Australia, which are largest consumers of energy commodities, i.e., crude oil, and possess 80% the world's REE reserves as reported in Table 1. Our empirical findings show heterogeneous volatility spillovers over time and that connectedness follows a random course over time. The volatility spillover has experienced a surge during the intense economic period, i.e., COVID-19. Total volatility spillovers present a spike around the COVID-19 outbreak, suggesting higher volatility transmission among financial markets during turbulent and crisis periods. Rare earth markets (the US and China) are net volatility transmitters and the Dow Jones Australia Sustainability Index (ASI), China Sustainability Index (CSI), Dow Jones Sustainability World Index (SWI), and MVIS Global Rare Earth Index (MVISGREI) are net recipients. Further analysis revealed that energy commodities (Crude Oil, Gasoline, and Natural Gas) are net volatility transmitters whereas ASI, CSI, and SWI are the main volatility recipients. Notably, rare earths or energy commodities failed to transmit volatility to the US sustainable financial market.

**Table 1.** World reserves of REE by principal countries.

| Country | Reserves in Tones (in Terms of REO) | % Share |
|---|---|---|
| Australia | 3,400,000 | 2.56 |
| Brazil | 22,000,000 | 16.67 |
| Canada | 830,000 | 0.63 |
| China | 44,000,000 | 33.33 |
| Greenland | 1,500,000 | 1.14 |
| India | 6,900,000 | 5.23 |
| Malaysia | 30,000 | 0.02 |
| Malawi | 140,000 | 0.11 |
| Russia | 18,000,000 | 13.64 |
| South Africa | 860,000 | 0.65 |
| Vietnam | 22,000,000 | 16.67 |
| USA | 1,400,000 | 1.06 |

Note: This table reports the country-wide reserves of REEs. Source: U.S. Geological Survey, 2020.

The remaining research structure of our paper is as follows: Section 2 discusses previous literature in the current strand. Section 3 describes the data and methodology used to analyze time-varying connectedness. Section 4 reports results and interpretation. Finally, Section 5 concludes our paper with policy implications.

## 2. Related Studies

Earlier research has studied the theoretical perspective of rare earth elements which demonstrates that previous economic literature on the financial contagion effect of REEs is scarce. The role of financial contagion effect and volatility transmission has been well-developed in finance literature, i.e., in financial markets, (Haq et al. 2022; Pantos et al. 2019; Papathanasiou et al. 2022b; Samitas and Kampouris 2019; Samitas et al. 2022b, 2022c), cryptocurrency market (Samitas et al. 2020; Ul Haq et al. 2022) and energy and metal markets (Haq et al. 2021b; Mensi et al. 2020). However, rare studies have investigated the financial contagion effects of rare earth and the energy market toward major green financial markets. This research attempts to fill this literature gap by examining the time-varying volatility spillovers using the TVP-VAR model.

The economic importance of rare earth elements (REEs) has thrived in the last decade. For instance, REEs have been identified as a crucial element in various environmentally sustainable technologies due to their exceptional conductive and magnetic properties (Zhou et al. 2017). The global trend of low-carbon resilient economies has been irresistible in recent years. In addition, it has arisen in conjunction with emerging sustainable technology in which rare earth elements play a vital role and have no other substitute in the global market (Zhao et al. 2017). Moreover, environmentally friendly technology manufacturing is largely based on REEs as these elements are essential components for manufacturing (De Koning et al. 2018). Inherited volatility and rising demand for sustainable technologies are damaging environmental and sustainable concerns around the globe (Haq et al. 2022; Reboredo and Ugolini 2020) due to unsustainable extraction and mining processes of REEs (Khorasanipour and Jafari 2018). Likewise, Balaram (2019); Mancheri et al. (2019) documented the influence of REEs occurrence, exploration, and recycling on environmental sustainability and revealed that policymakers should prioritize recycling of REE waste since it has a less severe environmental impact. Therefore, to overcome such economic and sustainable challenges, the rare earth elements industry should focus on long-run socially sustainable goals by promoting the United Nations sustainable development goals (SDGs) (Dushyantha et al. 2020).

On the other hand, $CO_2$ emissions have grown due to increased energy consumption, they have also emerged as the biggest threat to sustainable development (Nathaniel and Iheonu 2019) due to energy commodities. Unfortunately, human activities always remain the major driver of these global emissions (Du et al. 2019). So far, an extensive set of countries have worked together under the United Nations Climate Change Conference in

Paris 2015 to make their economies carbon resilient by promoting sustainable consumption (Cai et al. 2020; Sadiq et al. 2022). Furthermore, the Sustainable Development Goals (SDGs) emphasize that countries should reduce carbon emissions, increase energy efficiency, transition to a sustainable energy system, and ensure the supply of sustainable energy. The SDGs also emphasize the protection of biodiversity, maintenance of the ecosystem, and mitigation of environmental degradation to promote equitable human and economic growth.

The relationship between rare earths and financial markets has not yet been developed in the same way as other financial concepts. Some recent studies have examined the volatility connectedness between rare earths and financial markets. For example, Reboredo and Ugolini (2020) revealed that price fluctuations in the REE's market and supply interruptions had a detrimental impact on sustainable industries, especially when REE prices increase. Further, Song et al. (2021) examined the connectedness of REE with financial markets by using the TVP-VAR model to uncover dynamic connectedness during the COVID-19 pandemic. The findings of the study showed that the volatile REEs market has a strong interdependence with crude oil and the clean energy market. However, Bouri et al. (2021a) extended this framework by using a quantile based connectedness technique to explore both tail-based and average connectedness where they revealed that interdependence of these markets varies considerably at upper and lower quantiles. Moreover, they concluded that US–China trade has little effect on return and volatility dynamics. In a similar domain, Haq et al. (2021b) explored the dynamic association between global rare earths and sustainable markets by employing the DCC-MGARCH model to assess the time-varying comovements. The findings of this study showed that global rare earths exhibited safe-haven properties against economic policy uncertainty (EPU). More specifically, focusing on the impact of the 2015 Paris Agreement on sustainability, Zhou et al. (2022) noticed the extreme spillover effects between sustainable energy and metal markets by employing a spillover index and quantile approach. Further, the study indicated an asymmetric spillover effect among markets due to certain differences, especially in extremely negative and positive situations. Precedingly, Zheng et al. (2022) investigated time–frequency movements among REEs and energy markets by using the wavelet and BEKK–GARCH model. They found that REEs have a significant impact on advanced technology and sustainable energy markets and highlight potential portfolio and risk management strategies (Haq et al. 2022). In overview, the above discussion of the literature revealed rare earths markets are a strong source of financial contagion effect toward conventional and sustainable financial markets as economies are becoming more deliberate in regard to environmental protection and carbon resilience.

The association between energy commodities and financial markets has developed in finance literature. Previous research is segregated into two parts. In the first part, researchers examined the causal effects of technological, social, and economic activities on energy consumption (Danish and Ahmad 2018; Shahbaz et al. 2017). The findings of these studies demonstrated that the casual association between technological, social, and economic activities and $CO_2$ emissions caused by drastic energy consumption varies across counties due to differences in their institutional, economic, geographical, technological, and political conditions (Rahman and Kashem 2017). In the second part, scholars extended their analysis by adding the indicators of environmental deterioration which fostered the vulnerability of environmental sustainability, such as $CO_2$ emissions (Cetin et al. 2018; Ehigiamusoe and Lean 2019; Pablo-Romero and Jesús 2016). The findings showed that pollution caused by $CO_2$ emissions has a detrimental effect on human health and contributes to mortality (Khan et al. 2019). To combat this threat, previous literature urges various countries to turn their attention to sustainable energy sources since they are clean, have low carbon emissions, and encourage environmental sustainability (Shezan et al. 2017).

A strand of the literature concluded that energy commodities harm the environment due to their excessive consumption patterns, i.e., crude oil, natural gas, and gasoline throughout the world. Initially, Managi and Okimoto (2013) documented that increases in crude oil prices have a positive impact on other potential sustainable energy firms because escalating energy crises have driven the global economy to seek alternative energy sources. Nathaniel et al. (2019) explored energy consumption by applying the ARDL estimation approach and their findings reveal that economic growth and financial development have a devastating impact on the environment in the short run. Similarly (Maghyereh et al. 2019), documented that in the last decade, the main reason for fluctuations in oil prices was environmental sustainability, as crude oil is not only a primary energy resource but also has a wide range of environmental impacts due to carbon emissions during the combustion process, which results in increased global warming. Thus, fluctuations in crude oil prices have always been a major concern for portfolio managers, global investors, and policymakers during various energy crises. As dynamic fluctuations in crude oil have a substantial impact on investor's decisions regarding production plans, assets allocation, and implementation of regulations, it has an overall influential impact on the global economy (Aslam et al. 2022; Inshakov et al. 2019; Sorknæs et al. 2020).

More specifically, a range of studies have explored volatility spillovers using the TVP-VAR approach among financial markets during the pandemic period. For instance, Samitas et al. (2022a) recently found instant financial contagion due to the COVID-19 financial market using network analysis. Likewise, identical spillover patterns from the fine wine market to global financial markets were uncovered (Samitas et al. 2022d). Focusing on the COVID-19 period, Zhang et al. (2021) highlighted that COVID-19 has a significant impact on the financial contagion effect and that volatility connectedness heightened during the stress period. Similarly, using the TVP-VAR model, Haq (2022) revealed escalating volatility spillover of cryptocurrency environmental attention toward sustainable financial markets during the COVID-19 pandemic period. However, no study to date has examined the volatility spillovers of rare earths markets and energy commodities to sustainable financial markets considering pandemic episodes.

From the above discussion, we infer two observations. First, the dynamic connectedness between financial markets has been extensively developed; with heterogenous transmission patterns revealed over time. However, earlier research is inclusive and ignores empirical evidence on the volatility spillovers of rare earths, energy, and sustainable financial markets. Second, several recent studies investigated whether the dynamic connectedness and financial contagion effect of rare earths, energy commodities, and sustainable financial markets is underdeveloped, considering the COVID-19 health crisis. However, the earlier research neglected to study the dynamic connectedness between these financial markets considering the COVID-19 episode.

## 3. Material and Methods

### 3.1. Data

We considered daily first-differenced returns[1] encompassing from 1 January 2018 to 20 June 2022. Since the country-wide rare earth data is not available for more years, the data set data was used according to the rare earth indices. Our dataset covers eleven series, which include rare earth markets, sustainable markets, and energy commodities. First, it composes four sustainable financial market indices, namely Dow Jones Australia Sustainability Index (ASI), China Sustainability Index (CSI), US Sustainability Index (USSI), and Dow Jones Sustainability World Index (SWI) as proxies for the global sustainable financial market and country-wide sustainable financial markets for Australia, China, and the USA. Second, it combines four rare earth market indices, namely, the China Rare Earth Element Index (CHNREE), Lynas Rare Earth Australia Index (LYC), US Rare Earth Index (USREE), and MVIS Global Rare Earth Index (MVISGREI) as proxies for global rare earth market and country-wide rare earth markets for Australia, China, and the USA. In the end, it comprises three energy commodities, namely WTI Crude oil price index (WTI), NYSE Gasoline Funds (GAS), and Natural Gas NYMEX, (NGAS) as proxies for energy commodity markets. The data were sourced from Bloomberg. This data sample reveals the financial contagion during the COVID-19 pandemic in Australia China and USA.

### *3.2. TVP-VAR Approach*

A multivariate time series time-varying parameter—vector autoregression model (TVP-VAR) model was initially established by (Primiceri 2005). We employed one of the widely accepted and effective connectedness models, Antonakakis and Gabauer (2017) Dynamic TVP-VAR connectedness approach. The dynamic connectedness approach is considered in recent studies (Bouri et al. 2021b; Hadi et al. 2022; Karim and Naeem 2022; Liu 2020) to explore time-varying connectedness and volatility spillovers. This approach has several key benefits. The model has the distinct feature of incorporating nonlinear time-varying relationships between economic variables by allowing time variations for both coefficients and variance–covariance matrix (He et al. 2019; Nakajima 2011; Samitas et al. 2021; Samitas et al. 2022d). In other words, it can adjust immediately to the events, hence incorporating the scholastic volatility element (Antonakakis and Gabauer 2017). TVP-VAR model has a strong ability to capture structural breaks (Hadi et al. 2022). Therefore, it provides important reasons to understand the connectedness among rare earth elements, energy commodities, and sustainability indices. In sum, the TVP-VAR dynamic connectedness approach identifies whether the large fluctuations have come from small fluctuations or the impact of financial contagion or volatility spillover. Overall, the TVP-VAR model uncovers direct output in terms of net recipient or transmitter, TO-Others, and FROM-others which enable to identify of volatility spillover and financial contagion effect (Balcilar et al. 2021; Bouri et al. 2021c; Haq 2022; Haq et al. 2022).

According to Antonakakis et al. (2020); Antonakakis and Gabauer (2017); Haq (2022); Nakajima (2011) standard TVP-VAR model can be described as follows:

$$y_t = \alpha_t + B_{1,t}y_{t-1} + B_{2,t}y_{t-2} + \cdots \ldots\ldots + B_{n,t}y_{t-n} + A_t^{-1}\sum_t \varepsilon_t \tag{1}$$

In the above-mentioned equation $y_t$ is indicating $k \times 1$ vector of observed variables; where $B_{1,t}, B_{2,t}, \ldots, B_{n,t}$ representing $k \times k$ coefficient matrices, $\varepsilon_t$ captured disturbance term, whereas $A_t$ is a lower triangular matrix as expressed in Equation (2)

$$A_t = \begin{pmatrix} 1 & 0 & \vdots & 0 \\ a_{21,t} & \ddots & \cdots & \ddots \\ \ddots & \vdots & \ddots & 0 \\ a_{k1,t} & \cdots & a_{kk-1,t} & 1 \end{pmatrix} \tag{2}$$

$\sum t$ stands for diagonal matrix in Equation (3)

$$\sum t = \begin{bmatrix} \sigma_{1,t} & 0 & \vdots & 0 \\ 0 & \vdots & \cdots & \cdots \\ \cdots & \cdots & \vdots & 0 \\ 0 & \vdots & 0 & \sigma_{n,t} \end{bmatrix} \tag{3}$$

In Equation (3) $\sigma_{i,t}$ is the standard deviation of structural variations and $I$ = 1,2, … , $n$. Following, (Degiannakis et al. 2018; Jebabli et al. 2014; Toparlı et al. 2019), this model can be extended in such a way:

$$y_t = X_t\beta_t + A_t^{-1}\sum_t \varepsilon_t \qquad t = s+1, \ldots\ldots, n \tag{4}$$

Here, $\beta_t$, $A_t$, and $\sum t$ all are time-varying parameters, we consider $\alpha_t$ as a stacked vector of lower triangular elements in $A_t$, $h_t = (h_{1t},\ h_{2t},\ \ldots\ldots,\ h_{nt})$, where $h_{kt} = \log \sigma_{kt}^2$

and $k$ = 1,2, . . . , $n$ and $t = s + 1, \ldots, n$. Therefore, we suppose that parameters in Equation (4) are determined by the random walk process described in $y$ following equations.

$$\beta_{t+1} = \beta_t + \varphi_{\beta t} \tag{5}$$

$$\alpha_{t+1} = \alpha_t + \varphi_{\alpha t} \tag{6}$$

$$h_{t+1} = h_t + \varphi_{ht} \tag{7}$$

$$\beta_{s+1} \sim N\left(\varphi_{\beta_o}, \sum \beta o\right) \tag{8}$$

$$\alpha_{s+1} \sim N\left(\varphi_{\alpha_o}, \sum \alpha_o\right) \tag{9}$$

$$h_{s+1} \sim N\left(\varphi_{h_o}, \sum h_o\right) \tag{10}$$

The random walk process assumption enables both permanent and temporary variations in the coefficients (Zhou et al. 2020). In this way, we can capture both the factors of structural breaks and gradual changes. The model innovation in the variance-covariance matrix is a block diagonal as represented in the below-mentioned equation:

$$\begin{pmatrix} \varepsilon_t \\ \varphi_{\beta t} \\ \varphi_{\alpha t} \\ \varphi_{ht} \end{pmatrix} \sim N\left(0, \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \sum \beta & 0 & 0 \\ 0 & 0 & \sum \alpha & 0 \\ 0 & 0 & 0 & \sum h \end{pmatrix}\right) \tag{11}$$

Using stochastic volatility, each parameter must be set following maximum likelihood estimation. In this way, sampling was simulated by using Markov chain Monte Carlo estimation based on Bayesian inference (Chen et al. 2022; Huang et al. 2022; Liu et al. 2020).

## 4. Empirical Results

The paper investigates the dynamic connectedness of rare earth elements and energy commodities with major sustainability indices, i.e., Dow Jones World Sustainability Index (SWI), USA Sustainability Index (USSI), China Sustainability Index (CSI), and Dow Jones Australia Sustainability Index (ASI). The study considered TVP-VAR time-varying approach from 2018 to 2022.

### *4.1. Preliminary Statistics*

The preliminary statistics reported in Table 2, involve the estimation of mean, standard deviation, skewness, kurtosis, Jerque–Bera Test, and stationarity test of Augmented Dicky–Fuller. The mean values for all return series are positive and near zero, indicating positive access returns. The China-REE showed the highest standard deviation (0.082) and SWI and ASI demonstrated the lowest standard deviation (0.010) for each. Indicating that rare earth assets are more volatile however sustainable or green finances are stable with less exposure. Returns showed a mixed distribution trend across different asset classes where Chin-REE, NGAS, and WTI are positively skewed and negatively skewed for the rest of the assets, and leptokurtic with fat tails indicates stationarity among time series over time. The fat tails, non-normal distribution, and stationarity among all return series can be observed in Figure 1. Interestingly, noticeable large fluctuations can be observed near the end of 2019 and the beginning of 2020, which indicated the spillover effect of the global uncertainty event of the COVID-19 outbreak. These findings also corroborate earlier research where studies have supported the idea that COVID-19 has fostered financial and economic uncertainty across the globe (Haq 2022; Haq et al. 2021b; Mensi et al. 2022; Tiwari et al. 2022).

**Table 2.** Descriptive statistics of return series.

|  | M | Max | Min | SD | Skew | Kurt | JB | ADF | Obs. |
|---|---|---|---|---|---|---|---|---|---|
| ASI | 0.000 | 0.062 | −0.064 | 0.010 | −0.634 | 8.335 | 1415.900 * | −36.226 | 1130 |
| CHNREE | 0.001 | 2.183 | −0.318 | 0.082 | 17.293 | 442.130 | 9,135,629.000 * | −34.645 | 1130 |
| CSI | 0.000 | 0.084 | −0.078 | 0.014 | −0.142 | 6.297 | 515.500 * | −33.259 | 1130 |
| GAS | 0.001 | 0.180 | −0.253 | 0.028 | −1.394 | 20.064 | 14,075.300 * | −32.343 | 1130 |
| LYC | 0.000 | 0.300 | −1.390 | 0.055 | −14.168 | 362.027 | 6,106,863.000 * | −33.742 | 1130 |
| MVISGREI | 0.000 | 0.063 | −0.081 | 0.018 | −0.120 | 4.232 | 74.100 * | −28.814 | 1130 |
| NGAS | 0.001 | 0.198 | −0.181 | 0.035 | 0.174 | 7.033 | 771.600 * | −34.610 | 1130 |
| SWI | 0.000 | 0.077 | −0.106 | 0.010 | −1.464 | 23.769 | 20,712.600 * | −35.249 | 1130 |
| USREE | 0.000 | 0.137 | −0.216 | 0.026 | −0.877 | 10.835 | 3035.400 * | −34.816 | 1130 |
| USSI | 0.001 | 0.095 | −0.129 | 0.014 | −0.894 | 18.793 | 11,893.700 * | −40.983 | 1130 |
| WTI | 0.002 | 0.320 | −0.282 | 0.037 | 1.211 | 31.844 | 39,449.600 * | −28.605 | 1130 |

Note: This table reports summary of descriptive statistics and stationarity of return series. M = Mean, Max = Maximum, Min = Minimum, SD = Standard Deviation, Skew = Skewness, Kurt = Kurtosis, JB = Jerque-Bera, ADF = Augmented Dicky-Fuller, Obs. = Observations. The first column shows the variables in an alphabetic manner where, ASI = Dow Jones Australia Sustainability Index, CHNREE = China Rare Earth Element Index, CSI = China Sustainability Index, GAS = GAS, LYC = Lynas Rare Earth Australia Index, MVISGREI = MVIS Global Rare Earth Index, NGAS = Natural GAS, SWI Dow Jones Sustainability World Index, USREE = US Rare Earth Index, USSI = US Sustainability Index, WTI = Crude oil price index. "*" indicates results are statistically significant at a 1% or 0.001 significance level.

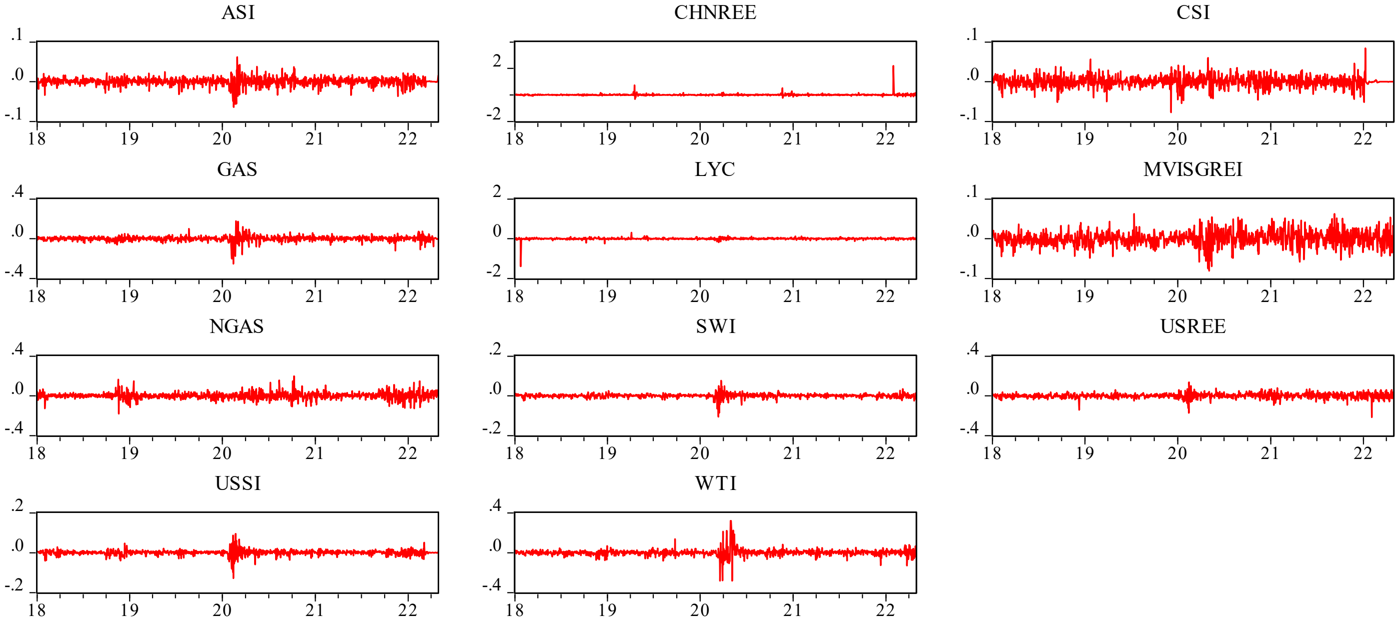


**Figure 1.** Daily Return plots.

The output of the Jerque–Bera test satisfied the condition of non-normality, where the null hypothesis of the normal distribution is rejected, hence all return series are non-normally distributed. In addition, to confirm the stationarity among returns series, the paper considered the Augmented Dicky–Fuller (ADF) test of stationarity. It is among the commonly used statistical measure to estimate stationarity. The output of ADF tests confirmed that all returns series are stationary over time, hence the null hypothesis of non-stationarity was rejected with a 0.001% significance level.

Table 3 reports the unconditional correlation for all returns series. Generally, the correlation between sustainability indices and energy commodities is moderate/weak positive and negative. On the other hand, the magnitude of the correlation between rare earth elements and substantiality indices was slightly higher than positive, and rare negative signs were found. These findings validate strong diversification and hedging opportunities across these financial assets. In comparison, energy commodities showed more negative signs, indicating the hedging ability of energy commodities for sustainability indices.

**Table 3.** Correlation Matrix.

| | ASI | CHNREE | CSI | GAS | LYC | MVISGREI | NGAS | SWI | USREE | USSI | WTI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ASI | 1.000 | −0.009 | −0.009 | 0.080 | 0.015 | −0.017 | 0.005 | 0.056 | 0.036 | −0.001 | −0.072 |
| CHNREE | −0.009 | 1.000 | 0.005 | −0.014 | −0.028 | −0.007 | −0.025 | 0.015 | −0.049 | 0.004 | 0.008 |
| CSI | −0.009 | 0.005 | 1.000 | −0.037 | 0.039 | 0.031 | −0.009 | −0.010 | 0.012 | 0.005 | 0.025 |
| GAS | 0.080 | −0.014 | −0.037 | 1.000 | −0.020 | 0.054 | 0.022 | −0.015 | 0.248 | 0.326 | 0.055 |
| LYC | 0.015 | −0.028 | 0.039 | −0.020 | 1.000 | −0.015 | −0.034 | −0.001 | −0.017 | −0.026 | −0.035 |
| MVISGREI | −0.017 | −0.007 | 0.031 | 0.054 | −0.015 | 1.000 | −0.020 | 0.034 | 0.007 | 0.040 | −0.017 |
| NGAS | 0.005 | −0.025 | −0.009 | 0.022 | −0.034 | −0.020 | 1.000 | 0.007 | 0.065 | 0.042 | −0.041 |
| SWI | 0.056 | 0.015 | −0.010 | −0.015 | −0.001 | 0.034 | 0.007 | 1.000 | −0.029 | −0.091 | 0.004 |
| USREE | 0.036 | −0.049 | 0.012 | 0.248 | −0.017 | 0.007 | 0.065 | −0.029 | 1.000 | 0.551 | 0.034 |
| USSI | −0.001 | 0.004 | 0.005 | 0.326 | −0.026 | 0.040 | 0.042 | −0.091 | 0.551 | 1.000 | 0.041 |
| WTI | −0.072 | 0.008 | 0.025 | 0.055 | −0.035 | −0.017 | −0.041 | 0.004 | 0.034 | 0.041 | 1.000 |

Note: This table reports unconditional correlation matrix where off-diagonal values indicate correlation coefficients. The first column shows the variables in an alphabetic manner where, ASI = Dow Jones Australia Sustainability Index, CHNREE = China Rare Earth Element Index, CSI = China Sustainability Index, GAS = GAS, LYC = Lynas Rare Earth Australia Index, MVISGREI = MVIS Global Rare Earth Index, NGAS = Natural GAS, SWI Dow Jones Sustainability World Index, USREE = US Rare Earth Index, USSI = US Sustainability Index, WTI = Crude oil price index. All results are statistically significant at 1% or 0.001 significance level.

### *4.2. Evidence from Dynamic TVP-VAR Approach*

Table 4 reports the output of dynamic connectedness (TVP-VAR) for rare earth elements and sustainability indices from 2018 to 2022. There are three elements in total connectedness tables, i.e., "TO", "FROM", and "NET". The value of "TO" is the aggregate of each column indicating the contribution of each financial asset/market to the others. In contrast, the "FROM" value is the sum of each row suggesting the level of contribution of each financial asset/market to the overall system. In the last, "NET" is the difference between these two ("TO" and "FROM"). Generally, the "NET" value identifies the "transmitter" and "recipient" roles. More specifically, the positive "NET" value indicates the transmitter role, and the negative "NET" value shows the recipient role of system-wide volatility spillover. The total connectedness index (TCI) or total system-wide connectedness between rare earth elements and energy commodities is reported at 14.17%, where CHNREE is the leading transmitter of volatility spillover among other financial asset/markets followed by USREE and USSI. In contrast, MVISGREI and ASI are major recipients of volatility transmitters, having net connectedness values of 5.88%, and 2.57%, respectively. LYC, CSI, and SWI are least connected; however, they are transmitters in the system of various financial assets/markets. Overall, CHNREE and USREE are the major net contributors to volatility transmission, and MVISGREI, ASI, LYC, CSI, and SWI are net receivers or receipts of volatility spillovers. Generally, the connectedness and spillover from rare earth elements to sustainable financial markets are lower and weak, suggesting that rare earth elements are potential instruments for diversification in line with Haq et al. (2021b). In addition, these findings corroborate with Reboredo and Ugolini (2020) who documented that rare earth stocks are weakly connected with commodity and financial markets. Finally, current findings are concurrent with the idea of Zheng et al. (2021) who emphasized that the development of the rare earth market is beneficial in risk management against financial market uncertainty.

**Table 4.** Total Connectedness Index.

| | LYC | CHNREE | MVISGREI | USREE | CSI | ASI | USSI | SWI | FROM |
|---|---|---|---|---|---|---|---|---|---|
| LYC | 91.890 | 1.150 | 0.870 | 1.130 | 0.770 | 1.680 | 0.710 | 1.800 | 8.110 |
| CHNREE | 0.710 | 95.260 | 0.610 | 0.860 | 0.580 | 0.650 | 0.760 | 0.580 | 4.740 |
| MVISGREI | 0.950 | 2.210 | 89.070 | 1.720 | 1.730 | 0.740 | 0.890 | 2.690 | 10.930 |
| USREE | 0.730 | 1.290 | 0.860 | 70.320 | 0.830 | 1.490 | 23.650 | 0.830 | 29.680 |
| CSI | 0.660 | 1.670 | 0.990 | 1.110 | 92.640 | 0.910 | 0.760 | 1.260 | 7.360 |
| ASI | 2.190 | 1.560 | 0.840 | 1.780 | 0.830 | 88.380 | 2.950 | 1.460 | 11.620 |
| USSI | 0.520 | 1.680 | 0.810 | 23.350 | 0.910 | 1.910 | 69.490 | 1.340 | 30.510 |
| SWI | 1.690 | 1.060 | 1.390 | 1.970 | 1.200 | 1.670 | 1.450 | 89.570 | 10.430 |
| TO | 7.430 | 10.620 | 6.370 | 31.930 | 6.850 | 9.050 | 31.170 | 9.970 | 113.390 |
| NET | −0.680 | 5.880 | −4.560 | 2.250 | −0.510 | −2.570 | 0.660 | −0.460 | TCI = 14.17% |

Note: This table presents total volatility spillovers or total connectedness index of rare earths and sustainable financial markets between 1 January 2018 to 20 June 2022. The first column shows the variables where, ASI = Dow Jones Australia Sustainability Index, CHNREE = China Rare Earth Element Index, CSI = China Sustainability Index, LYC = Lynas Rare Earth Australia Index, MVISGREI = MVIS Global Rare Earth Index, SWI Dow Jones Sustainability World Index, USREE = US Rare Earth Index, USSI = US Sustainability Index.

Table 5 presents the findings of the TVP-VAR model for energy commodities and sustainability indices. The total connectedness index (TCI) is reported at 10.09% where GAS is the leading contributor of volatility spillover among other financial markets 2.97%, followed by WTI and NGAS. On the other hand, SWI is the leading receipt with 2.88% of volatility transmission from other financial assets/markets. In addition, ASI and CSI are also major volatility recipients after SWI. Therefore, GAS, WTI, and NGAS are volatility net transmitters whereas SWI, CSI, and ASI are net receivers or recipients of volatility spillovers. Generally, the total connectedness between energy commodities (GAS, WTI, and NGAS) and sustainability indices (SWI, CSI, ASI, and USSI) is weak. These results are consistent with earlier research where energy commodities presented the least volatility spillover effect to the green bond market (Tsagkanos et al. 2022). In addition, energy commodities are negatively correlated with clean energy stocks, suggesting the hedging potential of energy commodities (Tang and Aruga 2021).

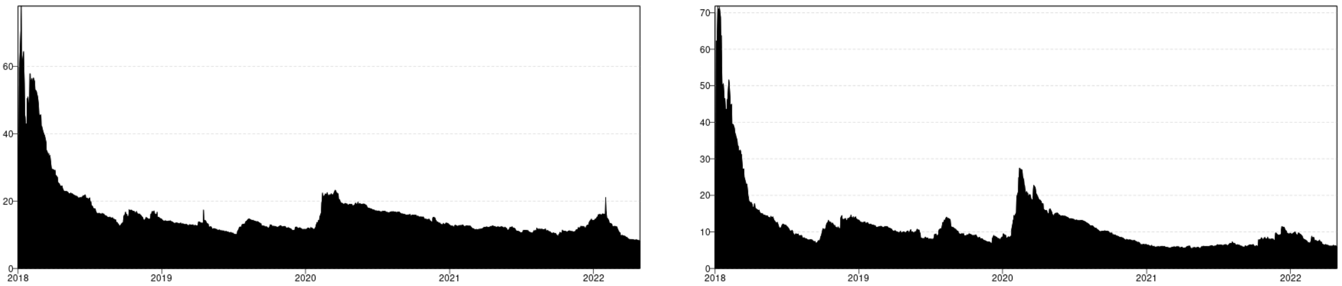
**Table 5.** Total Connectedness Index.

| | GAS | WTI | NGAS | CSI | ASI | USSI | SWI | FROM |
|---|---|---|---|---|---|---|---|---|
| GAS | 85.780 | 1.380 | 0.920 | 1.070 | 1.030 | 9.130 | 0.690 | 14.220 |
| WTI | 1.180 | 92.620 | 2.110 | 0.640 | 1.530 | 0.900 | 1.020 | 7.380 |
| NGAS | 1.180 | 1.830 | 92.980 | 1.040 | 0.670 | 1.750 | 0.560 | 7.020 |
| CSI | 2.560 | 1.250 | 1.070 | 92.550 | 0.750 | 0.810 | 1.000 | 7.450 |
| ASI | 1.690 | 2.280 | 0.940 | 0.870 | 90.020 | 3.010 | 1.190 | 9.980 |
| USSI | 9.070 | 1.330 | 1.100 | 0.890 | 1.940 | 84.230 | 1.440 | 15.770 |
| SWI | 1.510 | 1.570 | 1.850 | 1.100 | 1.270 | 1.490 | 91.220 | 8.780 |
| TO | 17.190 | 9.630 | 7.990 | 5.610 | 7.200 | 17.090 | 5.900 | 70.600 |
| NET | 2.970 | 2.250 | 0.970 | −1.840 | −2.790 | 1.310 | −2.880 | TCI = 10.09% |

Note: This table presents total volatility spillovers or total connectedness index of major energy commodities and sustainable financial markets from 1 January 2018 to 20 June 2022. The first column shows the variables where, ASI = Dow Jones Australia Sustainability Index, CSI = China Sustainability Index, SWI Dow Jones Sustainability World Index, USSI = US Sustainability Index, LYC = Lynas Rare Earth, NGAS = Natural GAS and WTI = Crude oil price index.

### 4.3. Time-Varying Total Connectedness

Figure 2 represents the total connectedness with the time-variant feature of rare earth elements (CHREE, USREE, LYC, and MVISGREI) and energy commodities (GAS, WTI, NGAS) with sustainability indices (SWI, CSI, USSI, ASI) from 2018 to 2022. Plots for dynamic total connectedness uncover two key findings. Firstly, the connectedness in both panels (Panel A and Panel B) is heterogenous and dynamic over time, hence supporting the idea of scholastic volatility in financial assets/markets. This finding corroborates with earlier studies (Bouri et al. 2021a; Fernandez 2017; Hau et al. 2022; Reboredo and Ugolini 2020; Song et al. 2021; Zheng et al. 2021) where the connectedness between financial markets followed heterogenous pattern across time. Noticeably, it supports the idea that markets are not efficient, hence following a random course over time (Kang et al. 2022; Shahzad et al. 2020). In addition, dynamic REE markets require effective hedging strategies due inherently risky nature (Song et al. 2021), and no such option is available to act as a hedge or safe haven for REE volatility (Proelss et al. 2020). More specifically it relates to Haq et al. (2021b), who found a dynamic conditional correlation between rare earth elements, clean energy stocks, and green bonds using the DCC-GARCH model. Secondly, the connectedness or volatility transmission sparks during the crisis period or economically stressed period and several normalized circumstances of financial markets. It supports the notion that the volatility spillover fosters during the global uncertainty or COVID-19 period (Ajmi et al. 2021; Hazgui et al. 2021; Maghyereh and Abdoh 2022; Rubbaniy et al. 2022). More specifically, concurrent with recent studies, several studies (Dai and Zhu 2022; Hau et al. 2022; Song et al. 2021; Zhou et al. 2022) documented a similar volatility transmission hike during the COVID-19 pandemic episode, indicating the higher financial market integration in the turbulent COVID-19 days (Haq et al. 2021a). In overview, dynamic connectedness over time (Panel A and Panel B) indicates that global financial markets are sensitive to crisis periods, i.e., COVID-19 in our case and market volatility is driven by turbulent periods. In this way, the volatility connectedness and spillover become high during abnormal market conditions and the market becomes stable when markets return to the new normal.

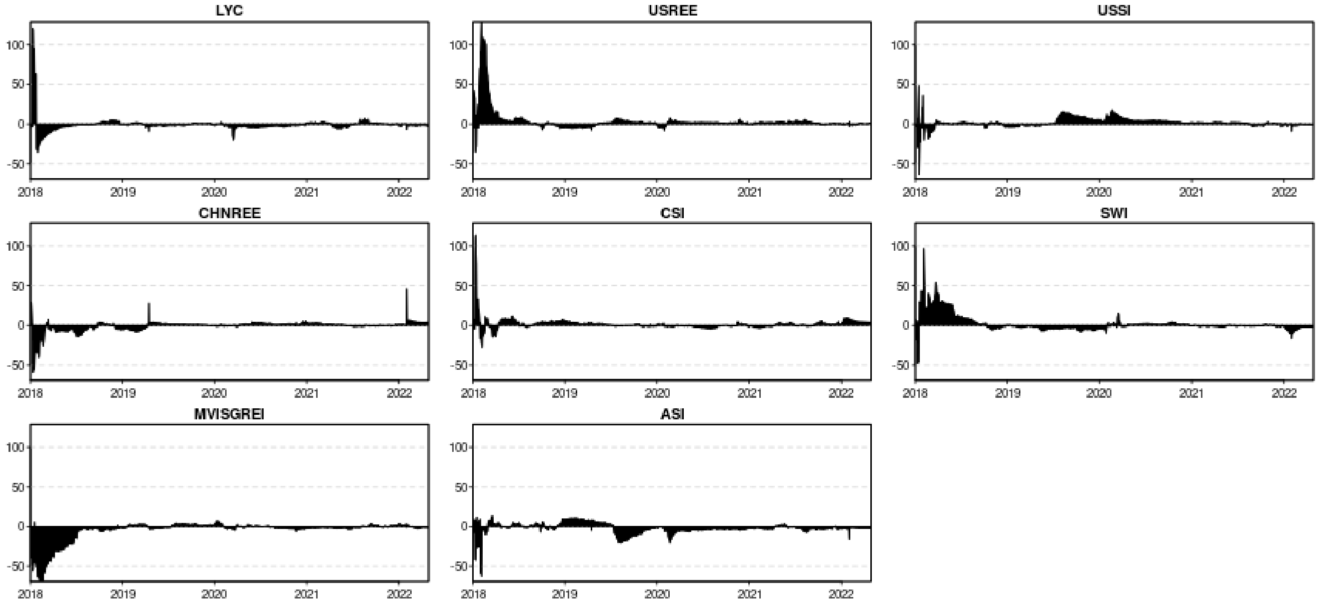


(Panel **A**) (Panel **B**)

**Figure 2.** Total dynamic connectedness. Note: (Panel **A**) represents the total volatility spillovers among rare earth elements and sustainability indices, and (Panel **B**) represents the total volatility spillovers among energy commodities and sustainability indices.

Figure 3 (Panel A) presents the dynamic net connectedness of rare earth elements and sustainability indices (Panel A) and energy commodities and sustainability indices (Panel B). Considering Panel A, where results recall the net contribution of CHREE and USREE during the sample period. The net transmitter role of CHREE corroborates with the findings of Reboredo and Ugolini (2020), who suggest China has the largest rare earth resources and monopolistic control over them. Therefore, China's rare earth index is a major contributor to volatility transmission to other markets. In addition, USREE is the second contributor of volatility transmission to sustainability indices. Because, the US is a major importer of rare earth metals or elements due to the huge consumption of information technology (Kennedy 2019) and clean energy applications (Song et al. 2021), i.e., hybrid vehicles. Additionally, the US is among one key producer of rare earth elements. This is a major reason, why USREE transmits system-wide volatility. Meanwhile, our findings are consistent with those (Reboredo and Ugolini 2020; Zhou et al. 2022).

Dynamic NET connectedness (Panel **A**)



Dynamic NET connectedness (Panel **B**)

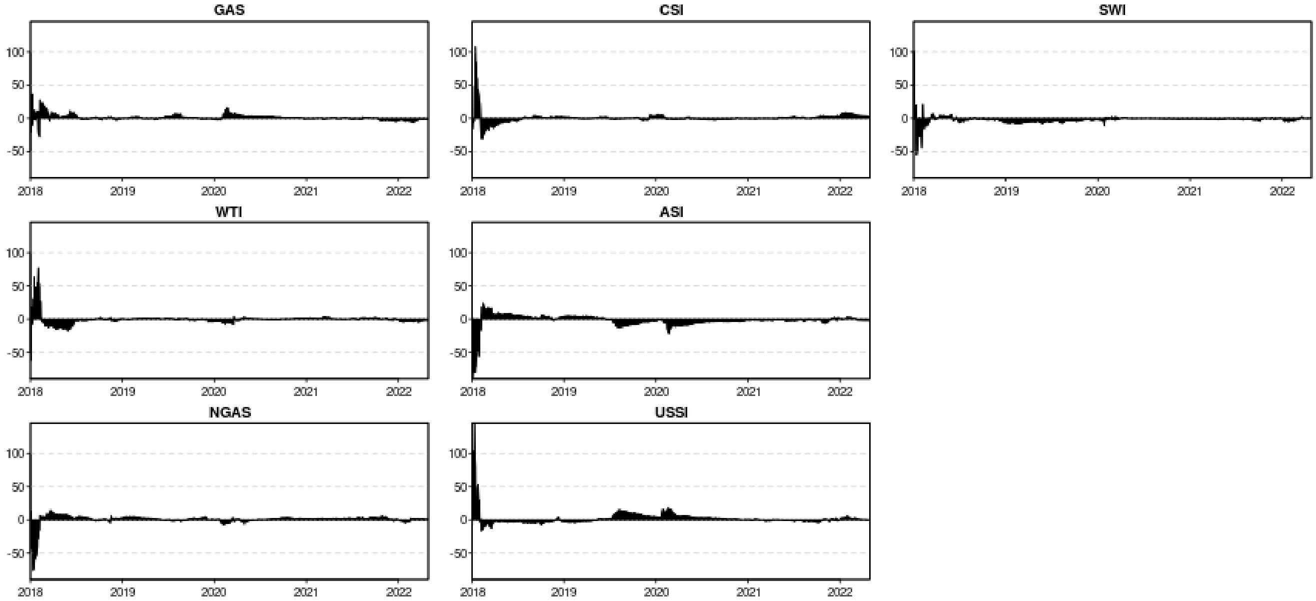


**Figure 3.** Dynamic NET connectedness. Note: (Panel **A**) represents the Dynamic NET connectedness among rare earth elements and sustainability indices, and (Panel **B**) represents the Dynamic NET connectedness among energy commodities and sustainability indices.

Alternatively, MVISGREI, LYC, ASI, CSI, and SWI show negative spillover in general, suggesting that these assets/markets are net receivers of volatility spillovers. MVISGREI, as a NET receiver of volatility spillovers, contradicts Özdurak and Ulusoy (2020) and Haq et al. (2021b) where MVISHREI showed positive connectedness with financial markets, i.e., green bond and clean energy markets. Generally, sustainability indices are volatility recipients because rare earth elements adversely affect sustainable features pinned with sustainable financial assets/markets concurrent with Klinger (2018) where rare earth production needs to be revised for better and sustainable output to promote sustainability and green concerns. In addition, current findings corroborate with Reboredo and Ugolini (2020), where rare earths are weakly connected with sustainable investment, i.e., clean energy.

Meanwhile, Figure 3 (Panel B) demonstrates time-varying NET connectedness among energy commodities and sustainability indices. Time-varying NET showed that all considered energy commodities such as GAS, NGAS, and WTI are a net contributor to volatility transmission to China, Australia's sustainable markets, and world sustainability. The net transmitter spillover effect of GAS, WTI, and NGAS, concurrent with earlier findings where marginal volatility spillover was found from energy commodities to financial markets (Aziz et al. 2020). Volatility transmission was more pronounced during the turmoil period among energy commodities (Zhang et al. 2020). Energy commodities and the energy sector were found to be a source of volatility spillover to subsectors (Ameur et al. 2021) and significant spillover exists from energy commodities to agriculture commodities (Ji et al. 2018). Likewise, energy commodities showed strong connectedness with Chinese stock markets during normal and financial turbulent periods (COVID-19) (Dai and Zhu 2022). On the other hand, the time-varying connectedness for sustainability indices i.e., CSI, SAI, and SWI indicate negative spillover, suggesting that they are net receivers of spillovers. Sustainability indices (China, Australia, world) are NET recipients of spillover from energy commodities, corroborates with energy commodities adversely affect sustainability and environment, so do the same for sustainable financial assets or markets. Likewise, these findings are consistent with Haq (2022) where SAI and SWI are consistent recipients of volatility from cryptocurrency-related environmental attention (Wang et al. 2022). Additionally, our results are consistent with Mensi et al. (2017). Figures A1 and A2 represent the total directional volatility connectedness "TO others" and "FROM" others, respectively, for each panel (Panel A and Panel B). These findings are consistent with total connectedness in Tables 4 and 5, where the value of "TO" is the aggregate of each column indicating the contribution of each financial asset/market to the others. In contrast, the "FROM" value is the sum of each row suggesting the level of contribution of each financial asset/market to the overall system. These findings are in line with total connectedness in Tables 4 and 5 (see the first row and last column of Tables 4 and 5, respectively).

Figure 4 present the bivariate network connectedness for Panel A and Panel B. In network plots, the blue node indicates the transmitter role of volatility spillover whereas the yellow nodes signify the receipt role of volatility spillover. The size of the node determines the strength or weakness of the spillover magnitude where the fatter the node the stronger the volatility transmission and wise versa. Additionally, yellow (blue) circles indicate the respective market is recipients (transmitter). Generally, these results of network connectedness are consistent with Tables 4 and 5 where results for the total connectedness index are reported. More specifically, CHREE and USREE are major contributors to volatility transmission and sustainability indices are volatility receivers. On the other hand, GAS, WTI, and NGAS are volatility transmitters, and a majority of sustainability indices are receivers. These results indicate that the inherent high volatility feature of rare earth markets (China, USA, and Australia) fosters volatility among green financial assets, i.e., USSI, CSI ASI, and SWI. In this way, REE's volatility might dampen the aim of sustainable or green investments in China, the USA, Australia, and global sustainability. These findings are concurrent with those (Klinger 2018) who emphasized that sustainability is a key issue in current rare earth production models. In addition, the increasing volatility in crude oil prices (Papathanasiou et al. 2022a, 2022c) might negatively impact major financial markets (Awan et al. 2021).

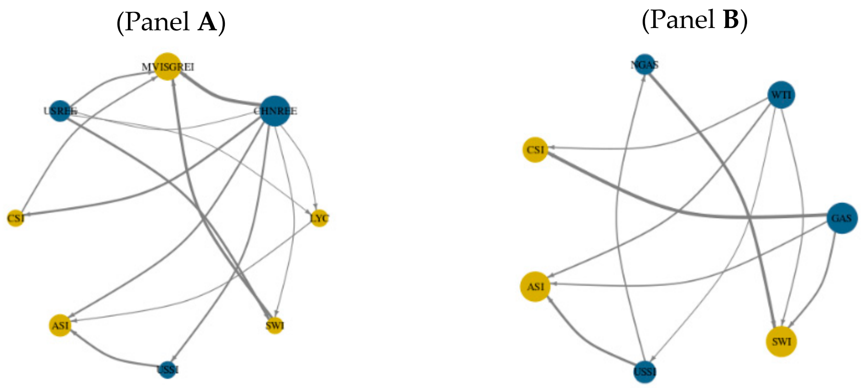


**Figure 4.** Pairwise network connectedness. Note: (Panel **A**) represents the pairwise network connectedness among rare earth elements and sustainability indices, and (Panel **B**) represents the pairwise network connectedness among energy commodities and sustainability indices.

## 5. Conclusions and Policy Implications

Our study provides evidence of the dynamic connectedness of rare earth elements (US, China, Australia), energy commodities (Gas, Crude oil, and Natural gas), and major sustainability indices (US, China, Australia) using the TVP-VAR connectedness approach from 2018 to 2022. We further investigated the role of global rare earth elements on world sustainability. Our findings uncover that CHREE and USREE are major transmitters of volatility spillovers whereas MVISGREI, ASI, CSI, SWI, and LYC are net recipients of spillovers. Besides, Gas, WTI, and NGAS (energy commodities) are net contributors to volatility transmission, and CSI, ASI, and SWI are net receivers of volatility spillovers. The time-varying connectedness presented a spillover spike around the outbreak of the COVID-19 pandemic. The NET connectedness reiterated that CHREE and USREE are NET volatility transmitters whereas the remaining markets are presented as NET recipients. In addition, GAS, WTI, and NGAS are NET volatility transmitters however, recent the markets are demonstrated as NET recipients. In addition, MVISGREI and DJSWI are receivers of volatility from other markets. The findings stipulate intriguing implications for investors, portfolio managers, financial market participants, and policymakers. The total connectedness index suggests weak connectedness in both cases, suggesting that sustainable investments are potential sources of hedging the inherent high volatility of rare earths (Song et al. 2021) among Australian and Chinese sustainable markets. In general, the majority of spillover of energy commodities and rare earth elements to the sustainable market is weak, suggesting the diversification opportunities of energy commodities and rare earth elements for Australia, China, and the global sustainable market. In this way, investors (institutional and individual) and portfolio managers can choose markets with greater diversification potential. The connectedness between energy commodities and sustainable markets is considerably weaker than between rare earths and sustainable financial markets. Due to this, there exist significant diversification and risk management opportunities for conventional and sustainable investors. However, energy commodities show stronger diversification potential than rare earth elements for sustainable financial assets. On the other hand, energy commodities and rare earths markets are sources of worsening sustainability and increasing volatility for the Australia sustainability index, China sustainability index, and Dow Jones sustainability world index. More specifically, global, Chinese, and Australian sustainable financial markets are most sensitive and vulnerable to carbon emissions, climate change, and circumventing environmental disasters. Hence, policymakers and regulators need to design policies and regulations to restrain the negative impact of rare earths and energy markets on the global sustainable economy and sustainable development goals. Moreover, enhancement of governance can substantially decrease the vulnerability of carbon risk (Tran et al. 2022). The current need is encouragement of green and sustainable investments to dampen the devasting role of rare earths and energy commodities.

Our findings are basically based on the time-varying method, i.e., TVP-VAR model which can only measure volatility connectedness across time. However, conventional and sustainable investors have a diverse range of investment objectives across investment horizons, i.e., short, medium, and long (Ul Haq et al. 2022). Therefore, future research should consider a wavelet coherence approach to examine the co-movement across both time and frequency settings. Our study explored the financial contagion effect of rare earths and energy commodities on major sustainable financial markets; however, future research could extend the sample and add clean energy stocks and green bonds (Haq et al. 2021b), considering the COVID-19 crisis (Akhtaruzzaman et al. 2021a). Studying the hedge or safe-haven role of gold (Akhtaruzzaman et al. 2021b) for rare earth markets could be another possible extension of the topic.

**Author Contributions:** Conceptualization, I.U.H., N.H. and H.N.; methodology, I.U.H. and A.M.; software, A.M. and S.S.; validation, T.K., W.W. and S.S.; formal analysis, I.U.H.; investigation, A.M. and T.K.; resources, W.W.; data curation, H.N. and N.H.; writing—original draft preparation, I.U.H. and H.N.; writing—review and editing, I.U.H. and N.H.; visualization, A.M.; supervision, I.U.H.; project administration, I.U.H.; funding acquisition, S.S., T.K. and W.W. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

(Panel **A**)

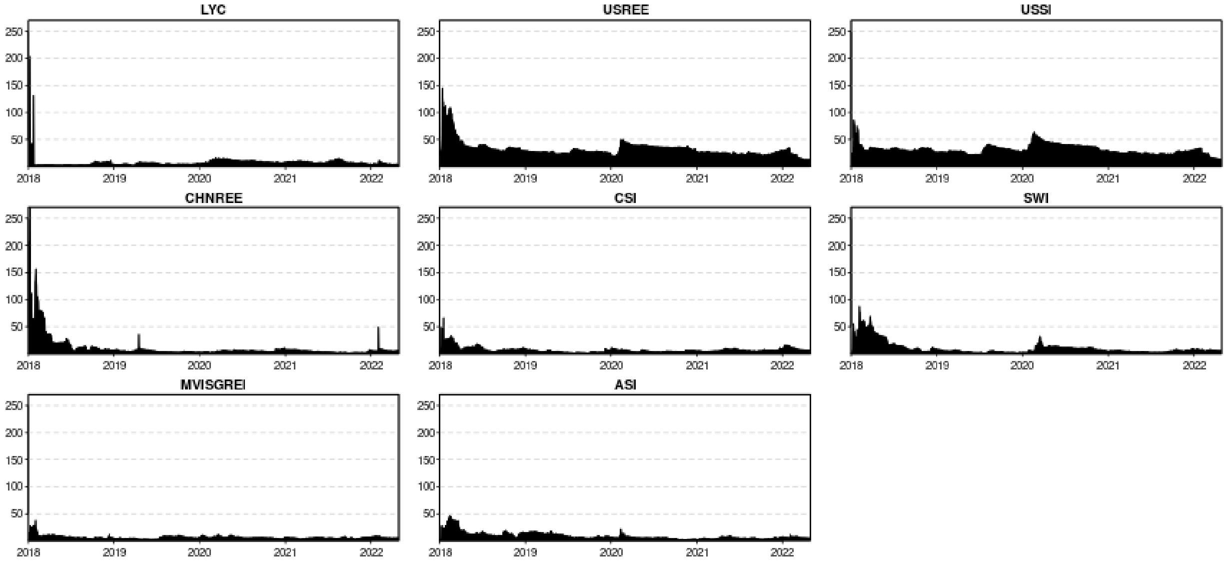

**Figure A1.** *Cont.*

(Panel **B**)

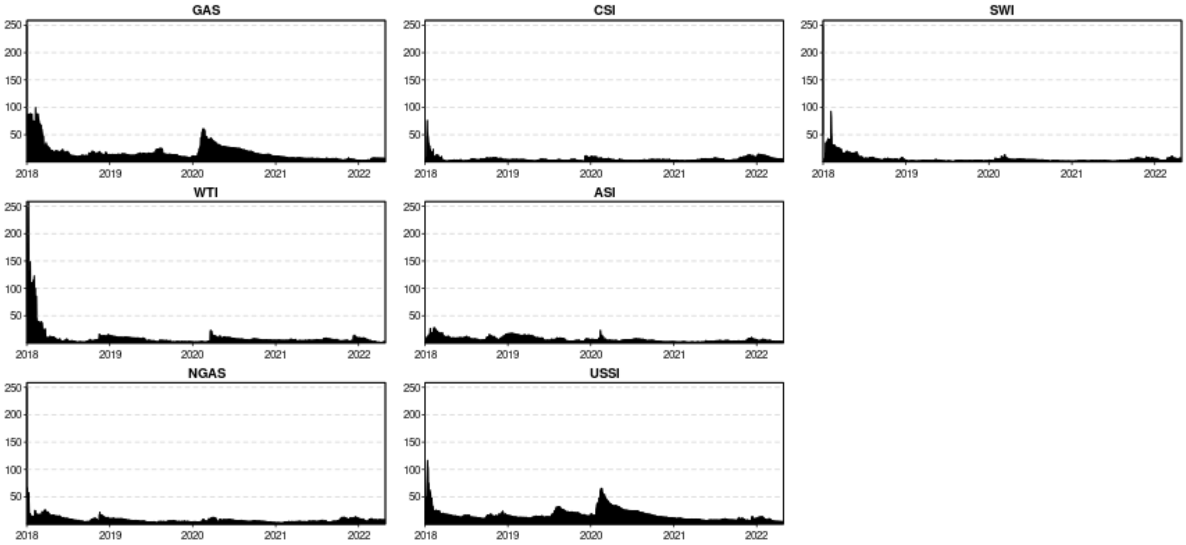

**Figure A1.** Total directional connectedness TO Others. Note: (Panel **A**) represents the Total directional connectedness TO Others among rare earth elements and sustainability indices, and (Panel **B**) represents the Total directional connectedness TO Others among energy commodities and sustainability indices.

(Panel **A**)

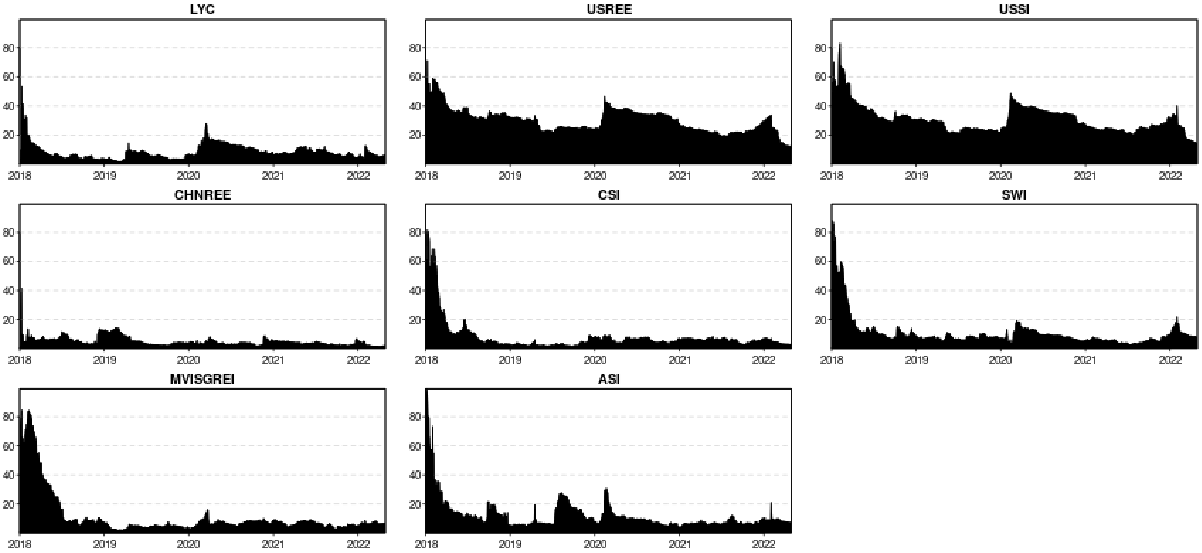

**Figure A2.** *Cont.*

(Panel **B**)

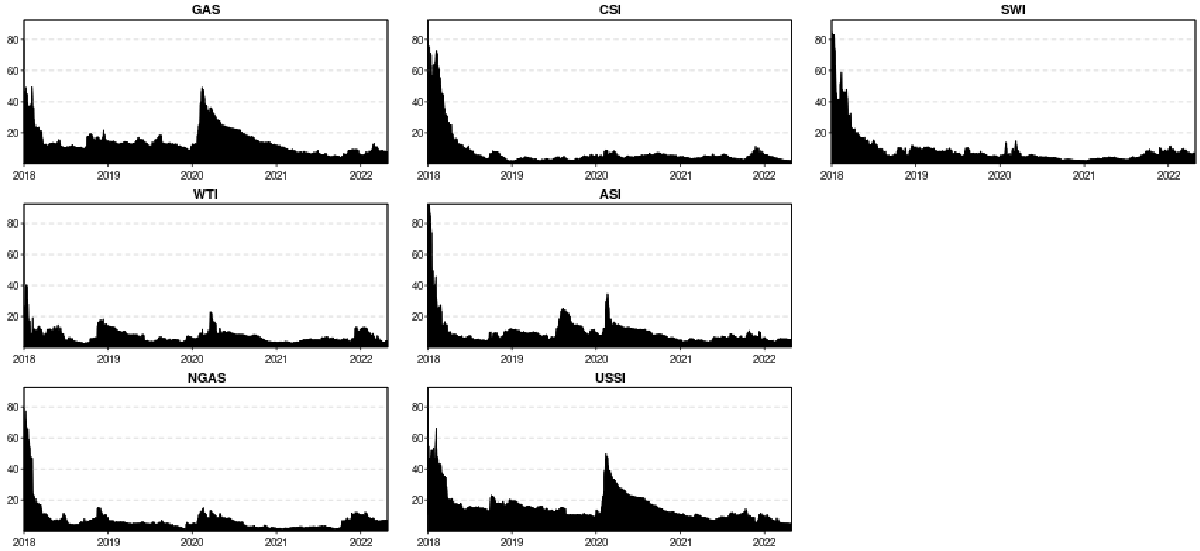

**Figure A2.** Total directional connectedness FROM Others (Panel B). Note: (Panel **A**) represents the Total directional connectedness FROM Others among rare earth elements and sustainability indices, and (Panel **B**) represents the Total directional connectedness FROM Others among energy commodities and sustainability indices.

## Note

[1] $R_{i,t} = (\ln(P_{i,t}) - \ln(P_{i,t-1}))$.

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