

Dynamic tail risk connectedness in different types of rare earth metals markets during major geopolitical events

Sheena Rehman

IMS Unison University

Hayfa Kazouz

University of Sousse

Mohammad Subhan

subhan8860@gmail.com

Woxsen School of Business

Research Article

Keywords: Rare earth metals, Risk transmission, Geopolitical risk, Energy transition, Critical minerals, Supply chain risk

Posted Date: July 31st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10445687/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Dynamic tail risk connectedness in different types of rare earth metals markets during major geopolitical events

Abstract

Rare earth elements (REEs) are essential for renewable energy, electric vehicles, advanced electronics, and defense industries, making them strategically important for global supply chains. This study examines the connectedness dynamics among Heavy Rare Earth Metals (HREMs), Light Rare Earth Metals (LREMs), and Rare Earth Processing Materials (REPMs) within China's rare earth value chain. Using a Quantile on Quantile Connectedness framework, it analyzes asymmetric and nonlinear spillovers across bearish, normal, and bullish market conditions during the China export restriction crisis, the clean energy and electric vehicle boom, and the Russia–Ukraine war. Results reveal substantial heterogeneity in connectedness across market states and crisis periods. Total connectedness rises steadily toward upper quantiles, indicating near complete market integration under bullish conditions. LREMs consistently act as dominant shock transmitters, whereas REPMs remain net receivers. The findings provide valuable insights for portfolio risk management, critical mineral resilience, supply chain security, and strategic policy formulation.

JEL Code: Q32, Q42, G15, F51, C58, D81

Keywords: Rare earth metals, Risk transmission, Geopolitical risk, Energy transition, Critical minerals, Supply chain risk

1. Introduction

Since the 1980s, Rare earth metals (REMs, more precisely, rare earth elements - REEs) primarily used in colour televisions, glassmaking, and oil refining¹. Their ascent to geopolitical prominence tracks directly with the rise of modern technology and are now seen as “industrial vitamins” (Li et al., 2025). REEs are not only essential for high-tech industries, renewable energy, and defense, but became indispensable for clean technologies as well, such as wind turbines, EVs, batteries and semiconductors (Depraeter et al., 2025). Given this, the demand for REEs is expected to grow 400–600% over the next few decades² and the global value of REEs market is projected to reach USD 15.8 billion by 2032, at a CAGR of 12.45%³. Despite the rapid growth, REMs are not immune to disturbance; it is during crises that the inherent structural vulnerabilities of this growth narrative become most evident (Zada et al. 2025; Li et al., 2026). These interruptions are not just peripheral oddities to be disregarded in the overarching development story; instead, they signify critical structural characteristics of REMs market dynamics that expose the underlying fragility amid exponential rise. China export restriction crisis (2010-11), clean energy and EV boom (2017-18) and Russia-Ukraine conflict of 2022 have illustrated that the rising demand for REEs is not paralleled by a corresponding enhancement in supply resilience, resulting in a market where each subsequent crisis inflicts progressively significant disruptions on an increasingly essential commodity system. Consequently, examining the dynamics of REMs during periods of crisis offers both a retrospective analysis of growth disruptions and a prospective empirical basis for comprehending how an increasingly expansive and integrated rare earth market will respond to the crises that the geopolitical landscape is likely to precipitate in the forthcoming years.

REEs are a group of 17 metals (Peter Biedermann, 2014), with evident similar chemical properties conventionally divided into three groups: the light (lanthanum, cerium, praseodymium, neodymium), middle (samarium, europium, gadolinium, terbium) and heavy (dysprosium to lutetium) REEs (Fontana & Pietrelli, 2009). REMs differ in supply risk, pricing power, and global trade dependence, requiring separate criticality assessment frameworks. Xia et al. (2023) highlight that rare earth systems operate as interconnected networks with upstream, midstream, and downstream dependencies, where supply constraints, particularly in heavy rare earths, and bottlenecks in processing stages play a critical role in shaping market

¹ <https://worldfinancialreview.com/rare-earth-critical-minerals-geopolitics-supply-chains-and-emerging-tensions/>

² <https://news.climate.columbia.edu/2023/04/05/the-energy-transition-will-need-more-rare-earth-elements-can-we-secure-them-sustainably/>

³ <https://www.marketbusinessinsights.com/rare-earth-metals-market-size>

dynamics and price transmission. Moreover, connectedness analyses demonstrate that spillover effects in rare earth markets are time-varying and intensify during crisis periods (Zada et al., 2023; Li et al., 2025; Li et al., 2026). The 2010 crisis hit HREMs hardest, China's export embargo caused dysprosium and terbium prices to spike by several hundred percent⁴. Further, China's monopoly in the processing of key heavy rare earths like dysprosium and terbium, as well as light rare earths like neodymium and praseodymium, became a central flashpoint during the rapid acceleration of EV adoption in 2017-18⁵. In addition, Russia-Ukraine conflict accelerated demand for LREMs through a paradoxical mechanism, the energy crisis it created drove faster adoption of EVs and renewable energy in Europe, simultaneously increasing demand for neodymium and praseodymium. Therefore, disaggregating REMs into HREMs, LREMs and REPMs enables a more precise identification of shock origins, transmission channels, and amplification mechanisms within the rare earth supply chain.

Existing literature have explored the connectedness across energy metals (Arfaoui et al., 2025), however, the dynamic risk spillover among REMs during crises period is not yet explored. To address this gap, this study explores the quantile-on quantile risk transmission mechanism across HREMs, LREMs, and REPMs during recent and consecutive periods of market crises including the China export restriction crisis (2010-11), clean energy and EV boom (2017-18) and Russia-Ukraine War (2022 - present). Interestingly, this study raises several research questions regarding their relationship between HREMs, LREMs and REPMs, specifically focusing on the asymmetries and spillover effects among these metals at different quantiles. It explores how the return of these metals interacts and the impact of global events on these interactions across different market states. Understanding these dynamics can guide policymakers and regulators in developing effective strategies and provide investors with insights into the benefits of focusing on REEs for resource stabilization.

China is selected as the focal market for several compelling reasons. First, China's dominates over 44% reserves of global REMs, controlling roughly 70% of mining and over 90% of refining capacity¹. Chinese leader Deng Xiaoping correctly observed in the 1990s that “*There is oil in the Middle East; there is rare earth in China*” (Peter Biedermann, 2014). Second, considering China's commanding position across REEs, risk dynamics originating within its

⁴ <https://www.mining.com/featured-article/charts-rare-earth-export-restrictions-price-spikes-and-the-risks-of-demand-destruction/>

⁵ <https://www.theindustryoutlook.com/manufacturing/panorama/what-the-rare-earth-crisis-means-for-the-ev-and-electronics-industry-nwid-13410.html>

domestic sub-markets propagate globally through trade, pricing benchmarks, and supply chain dependencies. Understanding the internal connectedness structure of China's rare earth sub-markets is therefore not merely a domestic concern but a prerequisite for global rare earth supply chain risk management. Third, China is the only market where disaggregated sub-market price indices for HREMs, LREMs, and REPMs exist as distinct tradeable series. Fourth, China's rare earth sector has been the epicentre of multiple geopolitical and economic crises examined in this study, with the Chinese government actively deploying rare earth policy instruments during each episode. Finally, China's dual role as both a source and recipient of crisis-driven shocks, combined with its active policy interventions in rare earth markets during each examined crisis period, makes it the most informationally rich environment for studying dynamic risk transmission mechanisms.

This study contributes to the literature in several ways. First, unlike existing studies that examine rare earth markets at an aggregate index level (Zada et al. 2025; Li et al. 2026), this study pioneers the disaggregation of China's rare earth market into HREMs, LREMs, and REPMs, thereby capturing heterogeneous risk dynamics that aggregate-level analyses systematically obscure. Second, while prior studies predominantly employ TVP-VAR, DY spillover index, or GARCH-based frameworks, which capture mean-level connectedness under normal market conditions, this study applies the quantile-on-quantile (QQ) risk transmission mechanism. The QQ framework captures how risk transmission from one sub-market to other changes when both markets are simultaneously in bearish, normal, or bullish states, a dimension entirely missed by single-quantile approaches. Third, by analysing the evolution of the time-frequency spillover network for different crisis period with different magnitude, it is possible to help investors and policymakers understand the changes in the market structure during crisis, and to accurately identify and quantify how heavy, light and processing REMs are interconnected, which in turn reveals the transmission mechanism and the time-continuity effects of market risks. Consequently, it equips investors with a quantitative basis for assessing market risks and optimizing their portfolios in rare earth sectors, fostering sustainable industrial development.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology and data and presents preliminary statistical analysis. Section 4 interprets the results and discussion. Section 5 provides the implications and Section 6 concludes with directions for future research.

2. Literature Review

REMs sit at the intersection of the green energy transition, great-power competition, and environmental justice. Consequently, the research on REEs has been rising consistently and spans several interconnected themes, collectively reflecting the growing strategic, economic, and environmental significance of these materials in the modern global economy.

2.1 Rare Earth Elements Supply and Market Dynamics

Extant literature pointed out the heavy concentration of REE production in China, which dominates global supply and creates significant dependency for the rest of the world (Oka, 2025; Liu et al. 2025; Mariev and Blueschke, 2025; Zhou et al., 2026; Wang et al., 2026). Given this, Ding & Ge (2025) assessed China's future supply potential for critical REMs and determined that dysprosium, neodymium, and praseodymium face likely supply shortfalls, with terbium also at risk under high-demand scenarios. The authors proposed a multicyclic Generalized Weng model incorporating parameter optimization algorithms and an F-test to determine the optimal number of production cycles, allowing it to capture fluctuations in historical production patterns. Baldi et al. (2014) investigated how rising REM's prices affect the stock market performance of clean energy companies and demonstrated the negative relationship between REM price changes and the stock performance of several clean energy indices, including the European clean energy index during price rise. Jyothi et al. (2020) explored the recycling and recovery of REEs from secondary waste sources, discussing hydrometallurgical recycling routes, primarily chemical and bioleaching followed by solvent extraction and precipitation as sustainable and environmentally viable approaches for REE recovery.

2.2 Rare Earth Elements Trading Risk Spillovers and Market Connectedness

A significant strand of literature has focused on understanding how risks transmit across REE markets (Kamal and Bouri, 2023; Qiao et al. 2024; Zhu et al. 2025). Ye et al., (2023) examined the risk spillover effect of China's rare earth trading market by employing TVP-VAR with stochastic volatility. Findings revealed that overall linkage of the risk contagion in China's rare earth trading market is strong. Mabuh and Azimli (2025) analysed the connectedness dynamics between REMs and the financial markets in China by employing Wavelet Quantile Regression and Wavelet Geometric Quantile Correlation. Findings reveal unstable and nonlinear association between China's financial system and the rare earth market, highlighting the significance of market extremes. Hanif et al. (2023) examined the co-movements and spillovers

in returns and volatility between rare earth assets and major renewable energy stocks, with particular focus on how these dynamics changed during the COVID-19 pandemic. Using wavelet analysis and spillover index methodology, it found that COVID-19 significantly intensified co-movements and volatility spillovers across these markets.

2.3 Rare Earth Elements Market Vulnerability During Crisis and Geopolitical Shocks

A notable thread in the literature specifically examines how REE markets behave during periods of systemic stress (Seiler, 2024; Gao et al. 2024; Rasheed et al., 2025; Lin & Zhang, 2025; Sinclair & Coe, 2026). In this regard, Fan et al. (2023) examined the role of geopolitics in markets for rare earth metals and demonstrated that geopolitical risk positively (negatively) impacts the import price (value) of Japan. Geopolitical risks emanating from China have the strongest effect. Further, Huang et al. (2024) examined the spillover effects between geopolitical risk (GPR) and Chinese 5G, semiconductors, and REMs by combining a sparrow search algorithm-optimized variational mode decomposition with fuzzy c-means clustering, and then applied a TVP-VAR model to analyze time-varying connectedness across different cycles. The study found that risk spillovers exist between geopolitical risk and all three industries, with these spillovers intensifying during actual geopolitical events. Zada et al. (2025) examined the connectedness in returns and volatility between industrial and rare earth metals during the COVID-19 pandemic and the Russia–Ukraine conflict by using TVP-VAR approach. The findings reveal strong returns connectedness between industrial and rare earth metals in the COVID-19 pandemic and the Russia–Ukraine conflict, compared with the pre-COVID-19 pandemic.

2.4 Rare Earth Elements Price Volatility and Clean Energy Nexus

A growing body of research connects REE markets directly to the clean energy transition (Bouri et al. 2021; Nasir et al., 2024; Müller et al., 2025; Barut et al., 2026). Li et al. (2025) analyzed the relationship between rare earths, green bonds, and clean energy stocks of China by using QVAR model and observed the existence of significant risk contagion between rare earths, green bonds, and clean energy stocks. Results reveal that rare earth and green bond markets act as risk receivers, while clean energy stocks transmit risk. Assaf et al. (2025) examined the connectedness between renewable energy and rare earth markets by employing the TVP-VAR and the Quantile-VAR models. Rare earth index and the geothermal energy index appear to be a net receiver of return spillovers, while fuel cell and wind become net transmitters at the upper and lower tails. Results revealed that return connectedness intensifies during extreme events,

suggesting that asymmetric spillovers exist among these markets when considering the lower and upper tails. Akgul et al. (2026) investigated the relationship between maritime energy transportation markets and strategic metal and clean energy financial markets, utilising Generalized R^2 Connectedness framework. The results revealed that tanker freight indices serve as financial signals of structural shifts in the energy system.

3. Research Gaps

Despite the growing body of literature on REMs connectedness and risk transmission, several critical gaps remain unaddressed. First, existing studies examine China's rare earth market at an aggregate index level, obscuring the heterogeneous dynamics of its three structurally distinct sub-markets, including HREMs, LREMs, and RPEMs (Bouri et al., 2021; Gao & Liu, 2024). Second, the QQ risk transmission mechanism, which uniquely captures how transmission changes when both the source and recipient markets are simultaneously in extreme states has not been applied to rare earth sub-market analysis, leaving the asymmetric and non-linear dimensions of sub-market transmission entirely unmapped (Panazan & Gheorghe, 2025; Li et al., 2025). Third, existing studies either examine single crisis periods or pool multiple crises into full-sample analyses, failing to identify the structurally distinct transmission patterns that different crises activate across rare earth sub-markets (Nasir et al., 2024; Li et al., 2026). Fourth, the processing rare earth sub-market, the segment over which China exercises its most strategically consequential monopoly has not been studied as a standalone analytical unit in a quantile-based connectedness framework (Ye et al. 2023). Fifth, no existing study simultaneously addresses all three of these dimensions, sub-market disaggregation, QQ methodology, and crisis-period specificity, within a single unified empirical framework. The present study addresses all five gaps by applying the QQ risk transmission mechanism to China's HREM, LREM, and RPEM sub-markets across the Russia-Ukraine war and China's export control crisis periods, and during EVs and clean energy boom, generating the first sub-market-level, crisis-calibrated, tail-risk-specific empirical mapping of risk transmission within China's rare earth industry.

4. Data and Methodology

4.1 Data and primary analysis

This paper explores the QQ risk transmission mechanism between HREMs, LREMs and RPEMs in major periods of market turbulence and structural transformation of the global rare earth industry. The analysis particularly focuses on three major events that significantly

impacted the dynamics of rare earth markets. The first event is the crisis involving China's export restrictions from 2010-01-04 to 2011-12-26. The second event is the clean energy and EV boom from 2017-01-02 to 2018-12-31. The third event is the Russia–Ukraine war period starting from 2022-02-28 and continuing thereafter. These periods reflect different sources of market stress, such as supply chain disruptions, demand-led industrial expansions, and geopolitical uncertainty that impact strategic mineral supply chains. The study uses daily price data for a wide range of rare earth assets, divided into the three main segments of the rare earth value chain, covering the period from 2010 to 2025, in order to capture these dynamics. Table 1 presents HREMs, LREMs, and REPM-related assets in the dataset, enabling a detailed study on heterogeneous spillover dynamics across extraction activities, rare earth oxides, metals, and processing materials. All variables are in Chinese yuan (CNY) per kilogram and are obtained from Refinitiv, which provides coherent and high-frequency market data for China's rare earth industry.

Table 1: Variable Descriptions and Sources

Group	Market	<i>Symbol</i>	<i>Description</i>	<i>Source</i>
Heavy Rare Earth Metals	Dyspraseodymium Oxidesium	DRM	Dyspraseodymium Oxidesium total return in CYN per kg	Refinitiv
	Dysprosium oxide	DXO	Dysprosium oxide total return in CYN per kg	Refinitiv
	Terbium oxide	TXO	Terbium oxide total return in CYN per kg	Refinitiv
	Gadolinium oxide	GXO	Gadolinium oxide total return in CYN per kg	Refinitiv
	Yttrium metal	YMT	Yttrium metal total return in CYN per kg	Refinitiv
	Praseodymium Neodymium Oxide	DIO	Praseodymium Neodymium Oxide total return in CYN per kg	Refinitiv
Light Rare Earth Metals	Neodymium oxide	NXO	Neodymium oxide total r eturn in CYN per kg	Refinitiv

	Neodymium metal	NDM	Neodymium metal total return in CYN per kg	Refinitiv
	Praseodymium	PRT	Praseodymium total return in CYN per kg	Refinitiv
	Praseodymium-Neodymium (PrNd) metal	PNA	Praseodymium-Neodymium (PrNd) metal total return in CYN per kg	Refinitiv
	Erbium Oxide	EXO	Erbium Oxide total return in CYN per kg	Refinitiv
Rare Earth Processing Materials	Terbium Metal	TRM	Terbium Metal total return in CYN per kg	Refinitiv
	Praseodymium oxide	PXO	Praseodymium oxide	Refinitiv
	Cerium	CRM	Cerium total return in CYN per kg	Refinitiv

The descriptive statistics of rare earth returns are provided in Table 2. From Table 2, there are several important characteristics of the returns. First, the average values differ widely across assets, reflecting differences in price levels and performance across market segments. Some light rare earth metals, like PRT and NXO, and HREMs like DRM and DIO display relatively high mean values, indicating stronger valuation from their strategic role in advanced technologies. Moreover, the high variances for most series, especially DRM, DXO, and NXO, reveal considerable volatility, which is a feature of the volatile nature of rare earth markets that are often driven by geopolitical and industrial factors. In addition, the skewness coefficients are positive and significant for all variables, revealing right-skewed distributions and indicating that extreme positive shocks occur more frequently than negative ones. Moreover, the high excess kurtosis values confirm leptokurtic distributions characterized by fat tails, suggesting a higher probability of extreme events. Consistently, the Jarque-Bera statistics are all significant, leading to the rejection of the normality hypothesis for all series, while the ERS test indicates that most variables are stationary. Finally, the Q(10) and Q²(10) statistics are highly significant, providing strong evidence of autocorrelation and ARCH effects in the series, thereby justifying the use of dynamic econometric models capable of capturing volatility clustering and time-varying dependencies.

Table 2: Descriptive Summary of the Variables

Group	Symbol	Mean	Variance	Skewness	Ex. Kurtosis	JB	ERS	Q(10)	Q2(10)
HREM	DRM	289.849	98960.394	3.449***	12.943***	7610.080***	-2.437**	4267.227***	4002.901***
	DXO	274.807	87117.99	3.970***	18.491***	14325.351***	- 2.899***	4099.426***	3593.978***
	TXO	193.539	38089.875	1.694***	2.791***	681.650***	-1.990**	4222.790***	3668.734***
	GXO	-16.58	2039.262	1.906***	5.091***	1430.809***	-2.562**	4247.262***	3117.257***
	YMT	10.102	1251.474	2.901***	9.030***	4075.559***	- 3.007***	3949.214***	3109.584***
	DIO	521.818	101488.263	1.599***	2.882***	655.622***	-1.061	4104.338***	3785.360***
LREM	NXO	499.986	112107.805	1.783***	3.705***	935.635***	-1.391	4145.470***	3800.400***
	NDM	432.884	85549.378	1.764***	3.489***	870.874***	-1.201	4158.263***	3827.702***
	PRT	534.263	62233.822	0.760***	1.163***	129.650***	-0.64	4182.182***	4070.364***
	PNA	450.147	76380.845	1.749***	3.826***	950.747***	-1.353	4081.494***	3737.811***
	EXO	-12.428	27187.495	3.785***	17.487***	12845.334***	- 3.697***	4103.802***	2984.963***
REPM	TRM	204.595	38057.397	1.663***	2.535***	618.728***	-1.930*	4262.234***	3869.855***
	PXO	560.196	77954.796	1.025***	1.516***	230.147***	-0.788	4102.970***	3865.473***
	CRM	36.297	20793.32	2.761***	6.937***	2781.055***	-1.974**	4525.757***	4347.498***

Note: *, **, and *** indicate 10, 5, and 1% level of significance.

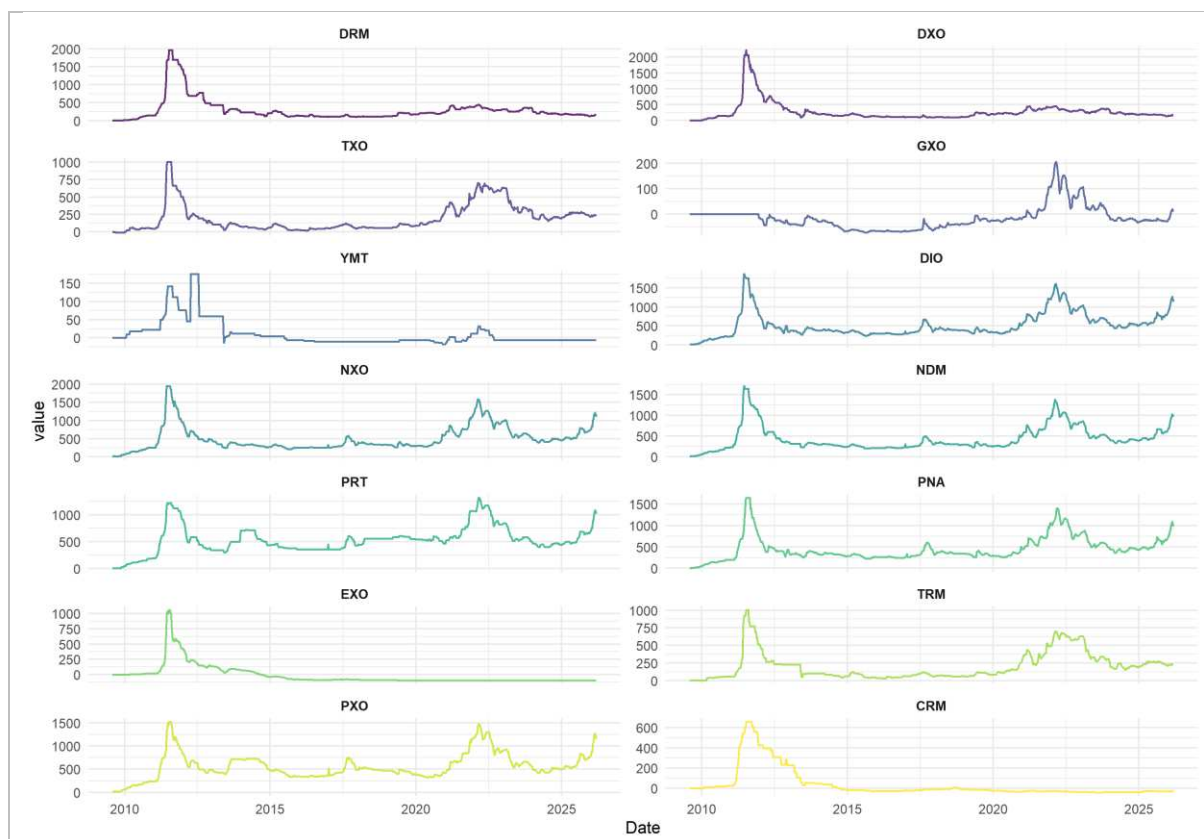


Fig 1. Trend graphs of the total return series. Notes: This figure represents the time evolution of returns series for the HREM, LREM and REPM.

Figure 1 illustrates the evolution of return series for HREMs, LREMs, and REPMs over the period 2010–2025. At first sight, most of the variables display roughly similar dynamics with an initial stable phase followed by large fluctuations. Specifically, some assets, notably DRM, DXO, and NXO, experience sharp spikes around 2010–2011, reflecting the impact of the China export restriction crisis.

The series then does not evolve uniformly. Some variables, such as TXO, NXO, and NDM, decline after the initial shock, followed by a relatively moderate period, then show renewed, pronounced peaks around 2021–2022. This suggests that rare earth markets are driven by cycles associated with major exogenous events. Specifically, the observed fluctuations are consistent with significant periods (e.g., China export restriction crisis 2010–2011, clean energy and EV boom 2017–2018, and Russia-Ukraine war 2022), suggesting an important role of geopolitical factors and energy transition in driving market dynamics.

4.2 Methodology

The empirical analysis follows a structured sequential framework designed to examine risk transmission dynamics across rare-earth sub-markets. The first step is to construct return series for each market, where the logarithmic first difference of price series is applied, which is a useful transformation to capture the time-varying characteristics of market fluctuations. The volatility of the market is then estimated directly from the distribution of returns. This gives a robust and consistent measure of uncertainty and clustering of risk. This methodological choice is well-rooted in the financial econometrics literature, since volatility measures based on returns are good proxies of the magnitude of the market shocks and of their persistence over time (Bollerslev, 1986; Byun & Cho, 2013; Mensi et al., 2024).

4.2.1 Volatility estimation

The return vector is defined as $ret_t = [ret_{1,t}, \dots, ret_{n,t}]$. The corresponding model is specified as:

$$ret_t = \mu_t + \delta ret_{t-1} + \varepsilon_t \quad (1)$$

Here, μ_t denotes the vector of returns captured through a constant term, while the error term is given by $\varepsilon_t = [\varepsilon_{1,t}, \dots, \varepsilon_{n,t}]$.

The conditional volatility for each series, denoted by $\sigma_{i,t}^2$, is estimated using:

$$\sigma_{i,t}^2 = c + \varepsilon_{i,t-1}^2 + \beta h_{i,t-1}^2 \quad (2)$$

In this framework, the parameters satisfy $c > 0$, $\alpha \geq 0$, and $\beta \geq 0$, with the additional restriction $\alpha + \beta < 1$. These conditions ensure non-negativity of the variance and stationarity of the process. The parameters c , α , and β capture the long-run variance, the effect of past shocks, and the persistence of volatility, respectively.

4.2.2 QQ Risk Transmission Framework

The primary analytical framework is based on the QQ risk transmission approach, first developed by Ando et al. (2022) and further developed by Arfaoui et al. (2025). The proposed framework improves traditional quantile-based methods by jointly modelling risk transmission among different levels of conditional distributions, rather than limiting inference to one quantile. One key strength of the QQ-VAR approach is its ability to capture nonlinear and asymmetric interdependencies across different segments of the conditional return distributions, which makes it particularly well suited for the analysis of tail risk spillovers, financial stress periods and extreme market conditions.

The Quantile Vector Autoregressive model of order p , denoted as QVAR(p), is defined as:

$$y_t = v(\Phi) + \sum_{j=1}^p D_j(\Phi) y_{t-j} + \theta_t(\Phi) \quad (3)$$

Where y_t and y_{t-j} are $K \times 1$ vectors of endogenous variables, Φ denotes the quantile vector defined over the interval $[0,1]$, p refers to the lag order of the QVAR model, $v(\Phi)$ is a $K \times 1$ vector of conditional means, $D_j(\Phi)$ is a $K \times K$ matrix containing the coefficients of the QVAR model and $\theta_t(\Phi)$ denotes a $K \times 1$ error vector associated $K \times K$ variance-covariance matrix. Building Wold's Decomposition Theorem, the QVAR model is subsequently reparametrized into a Quantile Vector Moving Average (QVMA) representation:

$$y_t = v(\Phi) + \sum_{j=1}^p D_j(\Phi) y_{t-j} + \theta_t(\Phi) = v(\Phi) + \sum_{j=1}^p D_j(\Phi) y_{t-j} + \sum_{i=0}^{\infty} B_i(\Phi) \theta_{t-i}(\Phi) \quad (4)$$

We use the Generalised Forecast Error Variance Decomposition (GFEVD) introduced by Koop et al. (1996) to measure the propagation of shocks across variables. Equation (5) formally captures the contribution of a shock originating in variable j to the forecast error variance of variable i over a horizon of Z steps:

$$\psi_{i \leftarrow j, \Phi}^g(Z) = \frac{\sum_{z=1}^{Z-1} (a_i' B_z(\Phi) H(\Phi) e_j)^2}{H_{ii}(\Phi) \sum_{z=1}^{Z-1} (a_i' B_z(\Phi) H(\Phi) B_z(\Phi)' e_i)} \quad (5)$$

Here, e_i is a $K \times 1$ selection vector with unity at the “ i ” position and zeros elsewhere. To ensure additivity, the row GFEVD is normalised by its row sum, as in Diebold and Yilmaz (2012). The scaled GFEVD $g_{i \leftarrow j}^{SOT}(Z)$, is then based on this and is used for all subsequent spillover computations.

The total directional risk passed to other markets from series “ i ” is defined as:

$$S_{i \rightarrow \blacksquare, \Phi}^{gen, to} = \sum_{k=1, i \neq j}^K gSOT_{k \leftarrow i, \Phi} \quad (6)$$

Conversely, the total directional risk received from all other markets by series “ i ” is expressed as:

$$S_{i \leftarrow \blacksquare, \Phi}^{gen, from} = \sum_{k=1, i \neq j}^K gSOT_{i \leftarrow k, \Phi} \quad (7)$$

The net directional risk transmission for series “ i ” is then obtained as the difference between the outgoing and incoming risk flows of the series:

$$S_{i, \Phi}^{gen, Net} = S_{i \rightarrow \blacksquare, \Phi}^{gen, to} - S_{i \leftarrow \blacksquare, \Phi}^{gen, from} \quad (8)$$

A strictly positive value of $S_{i, \Phi}^{gen, Net}$ classifies series “ i ” as a net transmitter of risk, i.e. that exerts a greater influence on the system than it absorbs. A negative value, on the other hand, indicates that series “ i ” is a net receiver of risk, suggesting that it is more sensitive to external market shocks than it is influential on others.

Finally, the total Connectedness Index (TCI) is obtained, which represents the overall level of market integration and systematic risk in the network as:

$$TCI_{\phi}(Z) = \frac{K}{K-1} \sum_{k=1}^K S_{i \leftarrow \bullet, \phi}^{gen, from} = \sum_{k=1}^K S_{i \rightarrow \bullet, \phi}^{gen, to} \quad (9)$$

A higher TCI value suggests greater exposure to systemic risk and higher interdependence between the markets. Further information is obtained from the estimated QQ risk transmission measures to construct dynamic pairwise spillover networks and detect the time-varying net directional risk transmission among the sampled rare-earth sub-markets. To facilitate the comparison, this framework follows Diebold and Yilmaz (2014) and uses the generalised VAR(p) approach, assuming covariance stationarity and modelling the system as $y_t = \sum_{i=1}^p \Phi y_{t-i} + \omega_t$, where $\omega_t \sim (0, \mu)$ is an i.i.d. disturbance term. It thereby allows for the calculation of total, directional and net spillover measures over time.

5. Empirical Results

5.1 Connectedness Structure

Figure 2 shows the connectedness network of the markets under consideration for the whole sample period. To be clear, the thicker and darker the arrow, the stronger the transmission effect, the higher the level of interdependence across markets.

There is a significant interconnectedness between HREM and LREM at the median quantiles, which reflect normal market conditions. In particular there is a strong bidirectional relationship between DIO and NXO, which indicates that there are significant spillover effects from one segment to the other. Furthermore, REPM, especially TRM and PXO, are in close association with heavy rare earth metals. TRM seems to play the role of an active transmitter of shocks, especially through its interaction with TXO, while PXO acts more as a net receiver, suggesting a higher sensitivity to external disturbances.

These results are in line with the structural interdependence of rare earth markets, which stems from the complementarity of industrial uses, integrated supply chains, and common exposure to global macroeconomic conditions. Such linkages are particularly strong given the critical role of rare earth elements in clean technologies and electric mobility. The transition towards EVs will result in a substantial increase in demand for key rare earth elements such as neodymium (Nd) and dysprosium (Dy), increasing pressure on supply and strengthening global

interdependencies (Habib et al., 2020). Similarly, Zada et al. (2025) and Li et al. (2025) find that the markets for rare earths are embedded in highly interconnected systems, where prices are heavily affected by cross-market interactions and industrial demand.

The connections are stronger and more focused at the lower quantiles, showing that negative shocks from HREM affect LREM more intensely. Some variables become more central, and the risk can be diversified over the network. This pattern points to a higher contagion in times of market stress, which lowers diversification benefits and enhances interdependence among segments. This is consistent with Arfaoui et al. (2025), who find that market linkages tend to increase during crises due to increased risk aversion and synchronised investor behaviour.

Conversely, at higher quantiles, the network is very dense and fully integrated across HREM, LREM and REPM. Positive shocks are more evenly transmitted across markets without distinct segmentations. The pattern can be explained by a simultaneous expansion in demand, especially triggered by the growth of clean energy technologies and EVs that jointly depend on these materials. In this line of thinking, Wisetsri (2022) demonstrates that rare earth markets are highly correlated with future mobility dynamics, and prices and markets show increasing co-movements and market synchronisation. Moreover, expectation-driven dynamics and speculative behaviour reinforce this synchronisation, while processed materials' intermediary role accelerates the transmission of shocks along the value chain. So, in summary, bullish market conditions are marked by widespread market dynamics, which means a greater degree of integration along the rare earth value chain.

5.2 Sub-sample analysis of connectedness

A) Median (50%-50%) Quantiles	B) Lower (5%-5%) Quantiles
-------------------------------	----------------------------

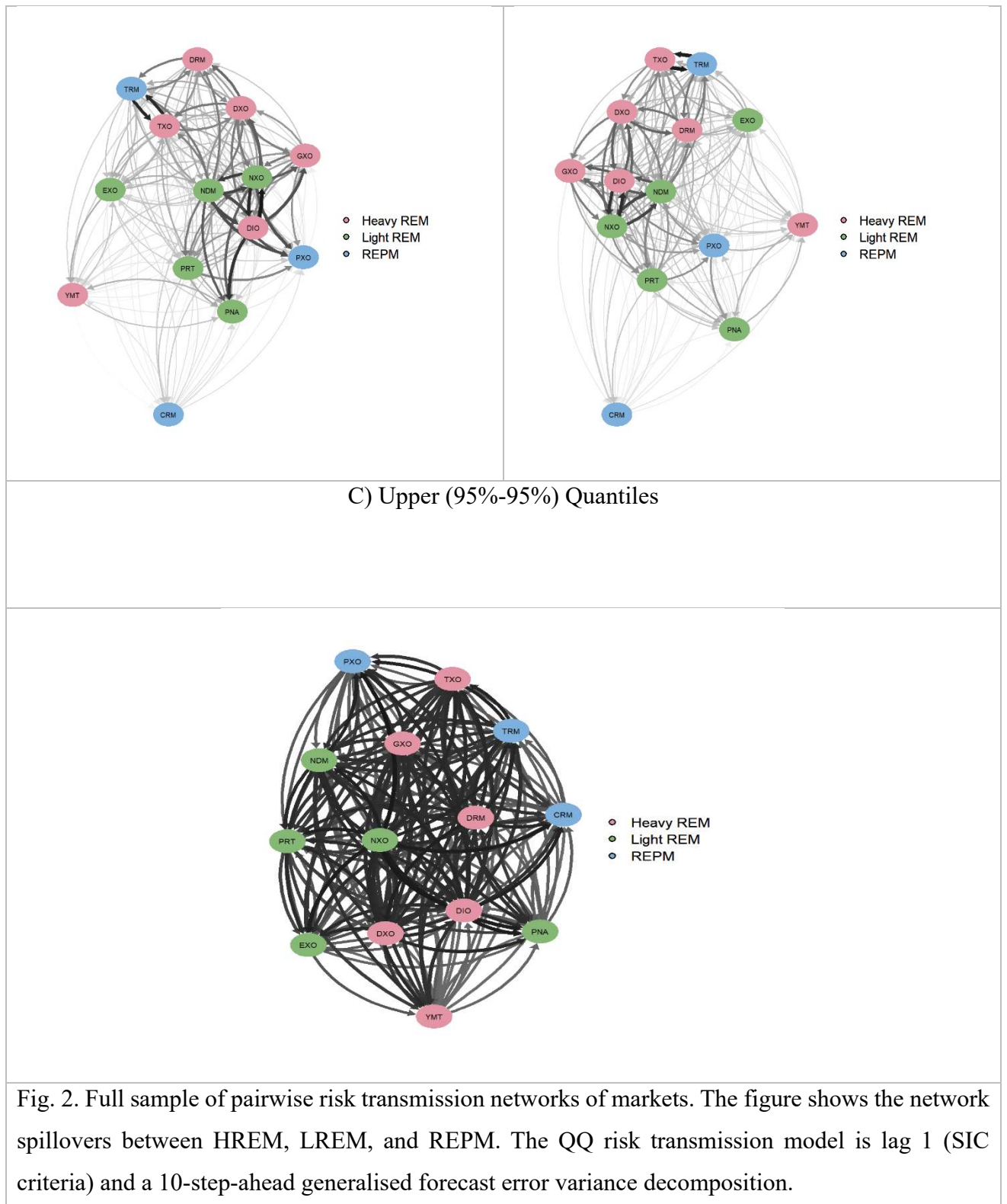


Figure 3A highlights the pairwise connectedness across the examined markets during the crisis of China's export restrictions, the clean energy and EV boom, and the Russia–Ukraine war at the median quantiles. In normal market conditions, the whole network seems to be more interconnected in the period of the Russia–Ukraine war, which indicates a higher degree of

integration across the rare earth market. This result is consistent with the findings of Li et al. (2026). Specifically, the strongest linkages are found among core metals such as DIO and NXO and between NDM and PNA, showing significant spillover effects in the Light REM component. Moreover, there are also strong linkages between HREMs, in particular TXO and DXO, and between TXO and TRM, suggesting that processing materials are instrumental in cross-segment transmission.

The China export restriction crisis also exhibits relatively high interconnectedness, but the network remains partly segmented, consistent with the localised nature of supply-driven shocks targeting specific metals such as dysprosium (DRM, DXO) and TXO, as noted by Xia et al. (2023). On the other hand, the period of the Russia–Ukraine war shows a more pervasive and system-wide connectedness, where both HREM and LREM, such as DIO, NXO, and PNA, are strongly interconnected with REPM indices such as TRM and PXO. This indicates a fully integrated market structure driven by global demand pressures, escalating geopolitical uncertainty, and pervasive supply chain disruptions.

During the clean energy and EV-boom period (Figure 3Aii), the LREM primarily concentrates the spillover effects. More specifically, metals like DIO, NXO, NDM and PNA form a tightly connected core which mirrors their central position in EV production and green technologies, particularly in permanent magnets and advanced electronic components, reflecting their key role in clean energy technologies, which enhances the interdependency of these metals as their demand evolves in tandem (Depraeter et al., 2025). Large linkages also exist across segments between LREMs and REPM, especially through PRT–PXO and NDM–CRM relationships, highlighting the role of midstream processing activities in transmitting shocks downstream in the value chain. This result is in line with Xia et al. (2023), who highlight the role of processing segments as strategic bottlenecks that increase price transmission because of the high concentration of refining capacities. In contrast, some assets, such as YMT and EXO, are more in a peripheral position, being less sensitive to demand dynamics related to the energy transition. This can be explained by their relatively limited involvement in fast-growing clean energy applications, as their uses are less directly tied to electric mobility and renewable technologies (Gielen & Lyons, 2022).

The results of extreme lower quantiles (5%, 5%) depicted in Fig.3 (B) indicate that the market behavior exhibits consistent patterns with slight variations across the three crisis periods compared to the median quantile results, reflecting the heightened sensitivity of rare earth

markets under bear market conditions. As established in the quantile connectedness literature, extreme market states systematically amplify shock transmission beyond what median-based estimators predict due to distinct tail dependencies (Ando et al., 2022). Specifically, during the crisis of China's export restrictions (Fig. 3B-i), the connectedness across the examined rare earth markets intensifies considerably relative to the median quantile, suggesting that extreme downside market pressure amplifies the transmission of supply-driven shocks. The network is still very dense and centralised, with HREMs (pink nodes) and REPMs (green nodes) being the center of the spillover activity. In particular, the connectedness between Heavy REM assets such as DXO, TXO, and DRM is significantly increased in the lower quantile, indicating the concentrated vulnerability of these metals to China's export restriction policies that disproportionately impact the supply of critical heavy rare earths (Xia et al., 2023). Light REMs such as NXO and DIO exhibit stronger linkages with REPM nodes, suggesting that under bearish conditions the partial segmentation at the median disappears and the network becomes more integrated, driven by co-movements across segments. This finding is consistent with Kyriazis et al. (2024), who document stronger and more integrated connectedness under extreme market conditions.

During the clean energy and EV boom (Fig. 3B-ii), we note that the connectedness across the markets considered is reduced compared to the China export restriction crisis. But the network has a very well-connected core, consisting mainly of major LREMs like PRT, NDM and NXO, HREMs like DIO, DXO and GXO, and REPM assets like PXO and CRM. This centrality is due to their key role in clean energy technologies, especially in the production of permanent magnets used in EVs and wind turbines. The concurrent increase in the demand for these technologies will induce a co-movement in the prices of these metals, thereby strengthening their interdependence (Depraeter et al., 2025; Gao et al., 2024).

Furthermore, the strong links between PRT–CRM and NDM–PXO suggest that processing activities are important for transmitting shocks from upstream extraction to downstream industrial applications and for facilitating the diffusion of market dynamics along the rare earth value chain (Ye et al., 2023). In the HREM segment, assets such as DXO, TXO, DRM and TRM are also relatively tightly clustered, with the strongest link between TXO and TRM. This is driven by the fact that they are used together in high-tech applications, in particular high-performance permanent magnets, and thus their price dynamics are sensitive to similar demand drivers. This implies that the shocks initially propagate inside the HREM segment and then extend to other segments through processing materials (Nasir et al., 2024).

In contrast, assets such as YMT and EXO are more peripheral in the network and have weak and limited connections. Their relatively smaller role in the energy transition is explained by their applications being more concentrated in traditional and less dynamic industries. Similarly, PNA appears rather isolated, even if it is part of the LREM group, indicating a lower synchronisation of price dynamics with the market core, likely due to a lower direct exposure to the dominant demand linked to EV technologies (IEA, 2024 — Global Critical Minerals Outlook).

In the Russia-Ukraine war period (Fig. 3B-iii), the lower-quantile results exhibit a particularly dense and centralised connectedness structure, reflecting a substantial intensification of risk transmission across rare earth markets. Both Heavy and LREMs, especially DIO, NXO, NDM, DXO, GXO, TXO and DRM with strongly reinforced spillover relationships are mainly located in the core of the network. In particular, processed materials, especially TRM, are also closely related to the center of the system, indicating their important role in the transmission of shocks along the rare earth value chain. In contrast, PXO has less robust linkages to the network core, suggesting only partial integration into the crisis dynamics. Under extreme bearish market conditions, the integration of rare earth markets intensified the Russia–Ukraine conflict as a result of global supply chain disruptions, increased geopolitical tensions, and uncertainty surrounding strategic raw materials (Li et al., 2026). However, some assets, such as PNA and CRM, are still relatively peripheral, suggesting that the intensity of spillover transmission is uneven across market segments. YMT, despite its network connectivity, also exhibits relatively limited linkages, confirming its lower sensitivity to geopolitical shocks. The results presented in the paper indicate that periods of geopolitical instability significantly increase risk spillovers and reduce diversification benefits across rare earth markets, supporting the findings of Antonakakis et al. (2017).

The results shown in Fig. 3(C) are focused on the bull market and show a significant and remarkable increase in the connectedness across the markets under consideration during the different crisis period compared to the bear and normal market situations. Notably, the degree of interconnectedness progressively intensifies across the three periods, from the China export restriction crisis to the clean energy and EV boom, and reaches its peak during the Russia–Ukraine war period. The increasing trend shows the magnification of market co-movement under the positive expectation on strategic minerals and clean energy demand. This finding suggests that bullish conditions amplify the market integration along the rare earth value chain, as investors and industrial demand simultaneously respond to expectations of future scarcity,

energy transition policies, and increasing geopolitical competition over critical minerals, in line with the findings of Nasir et al. (2024) and Gao et al. (2024) who document that bullish market regimes significantly strengthen spillover effects and higher-order connectedness across rare earth

The network shows a moderate but significant interconnectedness with spillover effects among HREMs, LREMs, and REPMs for the China export restriction crisis (Fig. 3C-i). However, the network structure in this episode is still much less dense than in the following episodes, and at least one peripheral node is clearly isolated from the main cluster, indicating that some segments of the market are still partially decoupled from the dominant transmission channels in this phase. Specifically, metals such as DIO, DXO, NXO, NDM and TXO occupy relatively central positions in the network, while processing materials such as TRM, CRM and PXO act as transmission channels linking the different segments. This structure reflects the high sensitivity of global rare earth markets to Chinese export policies and refining capacities. Supply-side disruptions travel through a large part of the industrial chain, but not yet uniformly across all nodes. Moreover, the centrality of processing materials, as emphasised by Xia et al. (2023) as key transmission mechanisms in the rare earths supply chain, underscores the strategic relevance of China's midstream industry in channelling shocks in the market. This finding also fits with Seiler (2024) who finds that shocks from the Chinese domestic rare earth market are transmitted strongly to international rare earth prices in periods of geopolitical and trade tensions.

During the clean energy and EV boom (Fig. 3C-ii), the network is much denser and more integrated than the previous episode, with peripheral positions almost completely disappearing. The LREM block including DIO, NXO, NDM and PRT exhibits strong bidirectional spillovers with REPM indices such as CRM and PXO. Such a configuration reflects the increasing industrial reliance on rare earth inputs for EVs, renewable energy technologies, batteries and advanced electronic components. The common increase in demand for these strategic materials further intensifies the price co-movements and reinforces the market interdependence along the rare earth value chain. This finding is consistent with Habib et al. (2020) who show that the rapid growth of electric mobility greatly increases the demand pressures for critical REEs such as neodymium and dysprosium. Depraeter et al. (2025) make a similar argument that the increased use of EVs and wind turbines increases the strategic interdependence of rare earth metals as they are both used in the development of permanent magnet technologies. Moreover, the important role of REPMs gives additional evidence that refinement and transformation are

key transmission mechanisms linking upstream extraction and downstream industrial applications, consistent with Ye et al. (2023).

Finally, in the period of the Russia–Ukraine war (Fig. 3C-iii), the network exhibits the highest degree of systemic integration among all periods, with extremely dense and widespread spillover relations across almost all nodes. HREMs, LREMs and REPMs are found to be simultaneously interconnected suggesting that geopolitical uncertainty, energy security concerns and global supply chain disruptions increase synchronised movements across the whole rare earth market. In particular, DIO, NXO, DXO, TXO, PRT, PXO and CRM turn out as key interconnected nodes within the system, while peripheral positions almost completely disappear, a structural feature that makes this episode clearly differ from the China export restriction crisis period, when partial decoupling was still observable. This finding suggests that geopolitical crises not only increase downside risk transmission, but can also induce strong upward co-movements through expectations of future scarcity, strategic stockpiling and increasing demand for critical minerals related to energy transition policies. This interpretation is supported by Zheng et al. (2025), who show that geopolitical tensions significantly increase long- and short-term spillovers between rare earth and strategic energy-transition metals. Similarly, Panazan and Gheorghe (2025) demonstrate that extreme bullish regimes substantially intensify co-volatility and interdependence between rare earths, clean energy technologies, semiconductors, and defense-related industries. Overall, the upper-quantile results confirm that bullish market conditions considerably reinforce the integration of rare earth markets, with interconnectedness escalating progressively across crisis periods and thereby reducing diversification opportunities as spillover effects become increasingly widespread across the entire rare earth value chain.

5.3 Averaged total connectedness

Fig. 4 illustrates the averaged total connectedness across the considered rare earth sub-markets over the QQ spectrum. The results reveal a clear and asymmetric intensification of connectedness as market conditions shift from bearish to extreme bullish states. Under lower and median quantile combinations, the TCI remains moderate, ranging between 68.1% at ($\tau_1=0.0$; $\tau_2=0.0$) and approximately 77.1% at ($\tau_1=0.0$; $\tau_2=0.9$), suggesting that rare earth sub-markets preserve a certain degree of segmentation during stable market conditions. This relative independence allows investors to exploit diversification opportunities across HREMs,

LREMs, and REPMs in view of the heterogeneous industrial structures and transmission mechanisms of each segment, as in Xia et al. (2023).

We find a gradual increase in connectedness as the market approaches the upper quantiles and a substantial increase under extreme bullish states. In particular, the TCI sharply increases in the upper right of the quantile spectrum and finally reaches its highest level at the upper quantile combination ($\tau_1=0.9$; $\tau_2=0.9$), where the connectedness equals 99.7%. This very high level of integration implies that rare earth markets are almost completely synchronised in extreme bullish periods, which implies an increased spillover transmission across the entire rare earth value chain.

A particularly interesting pattern arises when the role of the receiving quantile is considered. The connectedness can still be 77.1% when the sending quantile is low ($\tau_1=0.0$), and the receiving quantile is high ($\tau_2=0.9$). Similarly, the values in the rightmost column are high for all sender quantile levels, ranging from 93.4% to 99.7%. This implies that the presence of bullish conditions in receiving markets is enough per se to boost integration, no matter the market condition of the transmitting segment. This suggests that the direction and intensity of connectedness are largely determined by the condition of the receiving market, rather than a symmetric alignment of sender and receiver. This brings significant nuance to the conventional understanding of spillover dynamics in rare earth markets.

This relative independence allows investors to exploit diversification opportunities across HREMs, LREMs, and REPMs in view of the heterogeneous industrial structures and transmission mechanisms of each segment, as in Xia et al. (2023).

We find a gradual increase in connectedness as the market approaches the upper quantiles and a substantial increase under extreme bullish states. In particular, the TCI sharply increases in the upper-right of the quantile spectrum and finally reaches its highest level at the upper quantile combination ($\tau_1=0.9$; $\tau_2=0.9$), where the connectedness equals to 99.7%. This very high level of integration implies that rare earth markets are almost completely synchronised in extreme bullish periods, which implies an increased spillover transmission across the entire rare earth value chain.

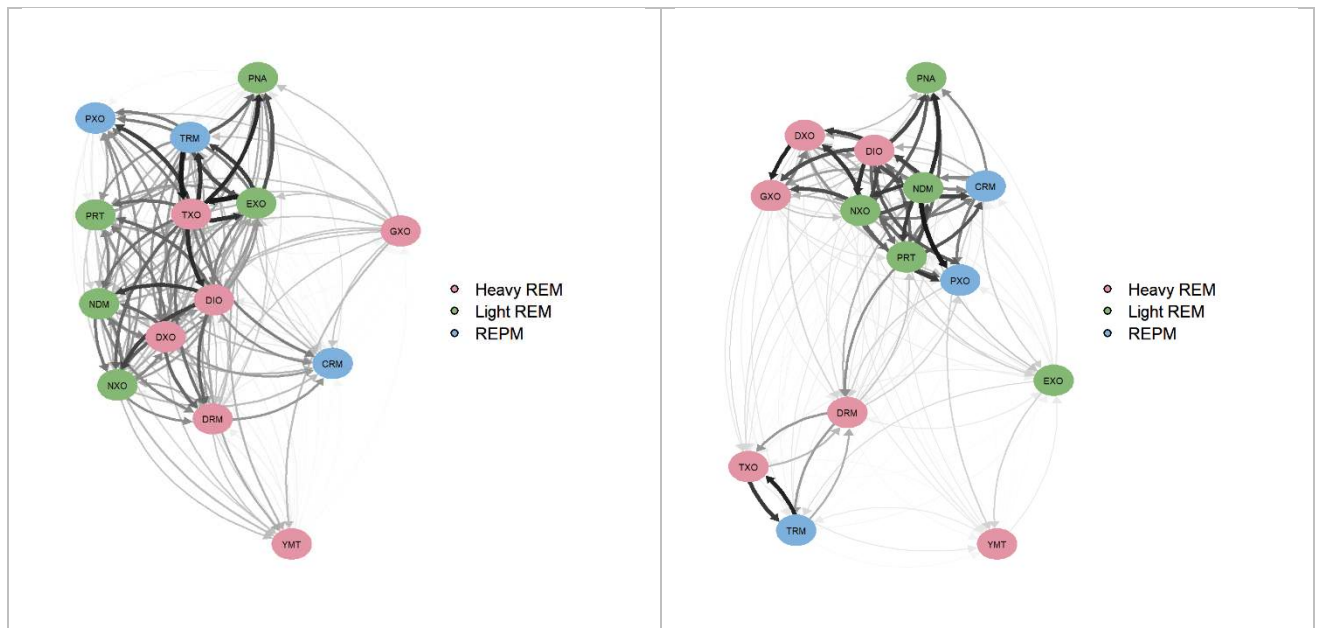
A particularly interesting pattern arises when the role of the receiving quantile is considered. The connectedness can still be 77.1% when the sending quantile is low ($\tau_1=0.0$), and the receiving quantile is high ($\tau_2=0.9$). Similarly, the values in the rightmost column are high for all sender quantile levels, ranging from 93.4% to 99.7%. This implies that the presence of

bullish conditions in receiving markets is enough per se to boost integration, no matter the market condition of the transmitting segment. This suggests that the direction and intensity of connectedness is largely determined by the condition of the receiving market, rather than a symmetric alignment of sender and receiver. This brings significant nuance to the conventional understanding of spillover dynamics in rare earth markets.

Such behaviour implies that optimistic expectations about clean energy technologies, EV, strategic stockpiling and future scarcity simultaneously drive HREMs, LREMs and REPMS, reinforcing co-movements among the different sub-markets. The increasing interconnection under upper quantiles also captures the increasing strategic importance of rare earth elements in EV motors, wind turbines, semiconductors and advanced manufacturing systems where positive demand shocks rapidly propagate over highly integrated supply chains. This interpretation is supported by Habib et al. (2020), who emphasise that the increasing penetration of clean energy technologies significantly increases the joint demand and interdependence of critical rare earth elements. The increasing interconnection under upper quantiles also captures the increasing strategic importance of rare earth elements in EV motors, wind turbines, semiconductors and advanced manufacturing systems where positive demand shocks rapidly propagate over highly integrated supply chains. This interpretation is supported by Habib et al. (2020) who emphasise that the increasing penetration of clean energy technologies significantly increases the joint demand and interdependence of critical rare earth elements.

Consequently, diversification opportunities become considerably weaker under bullish market conditions, as spillover effects spread broadly across HREMs, LREMs, and RPMS. This finding is in line with Nasir et al. (2024), who document that bullish market regimes significantly intensify spillover effects and market interconnectedness across rare earth and strategic commodity markets.

A) Median (50%-50%) Quantiles	
i) China export restriction crisis	ii) Clean energy and EV boom



iii) Russia-Ukraine War

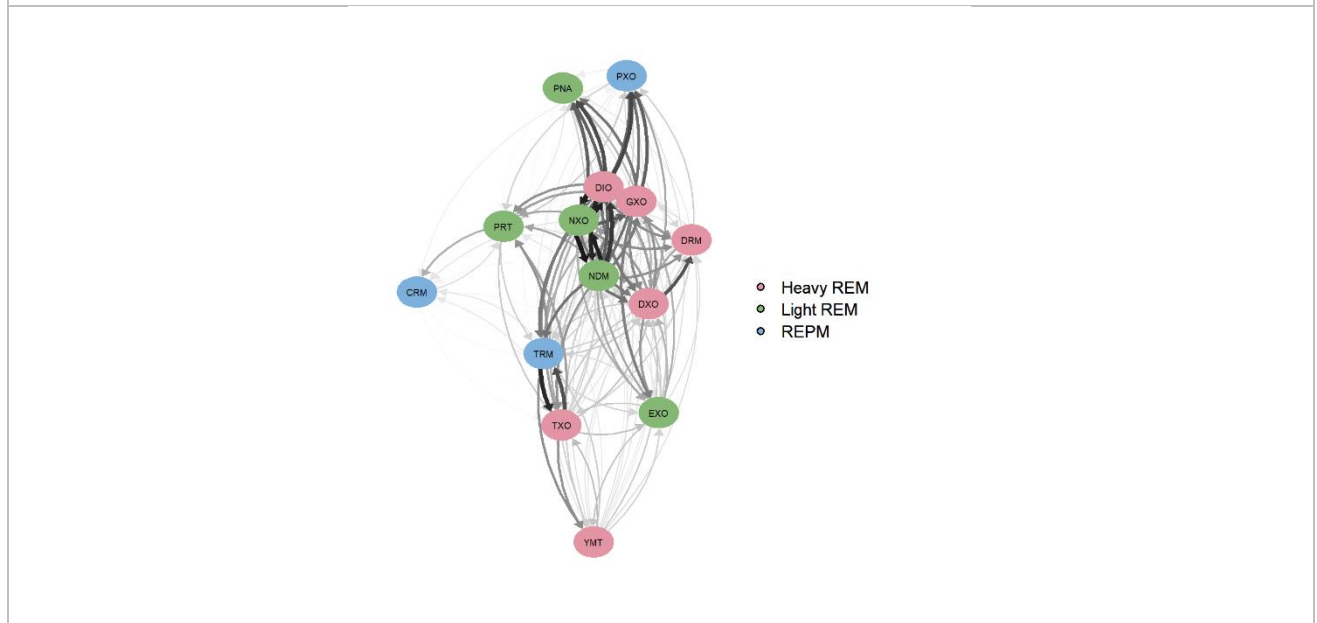
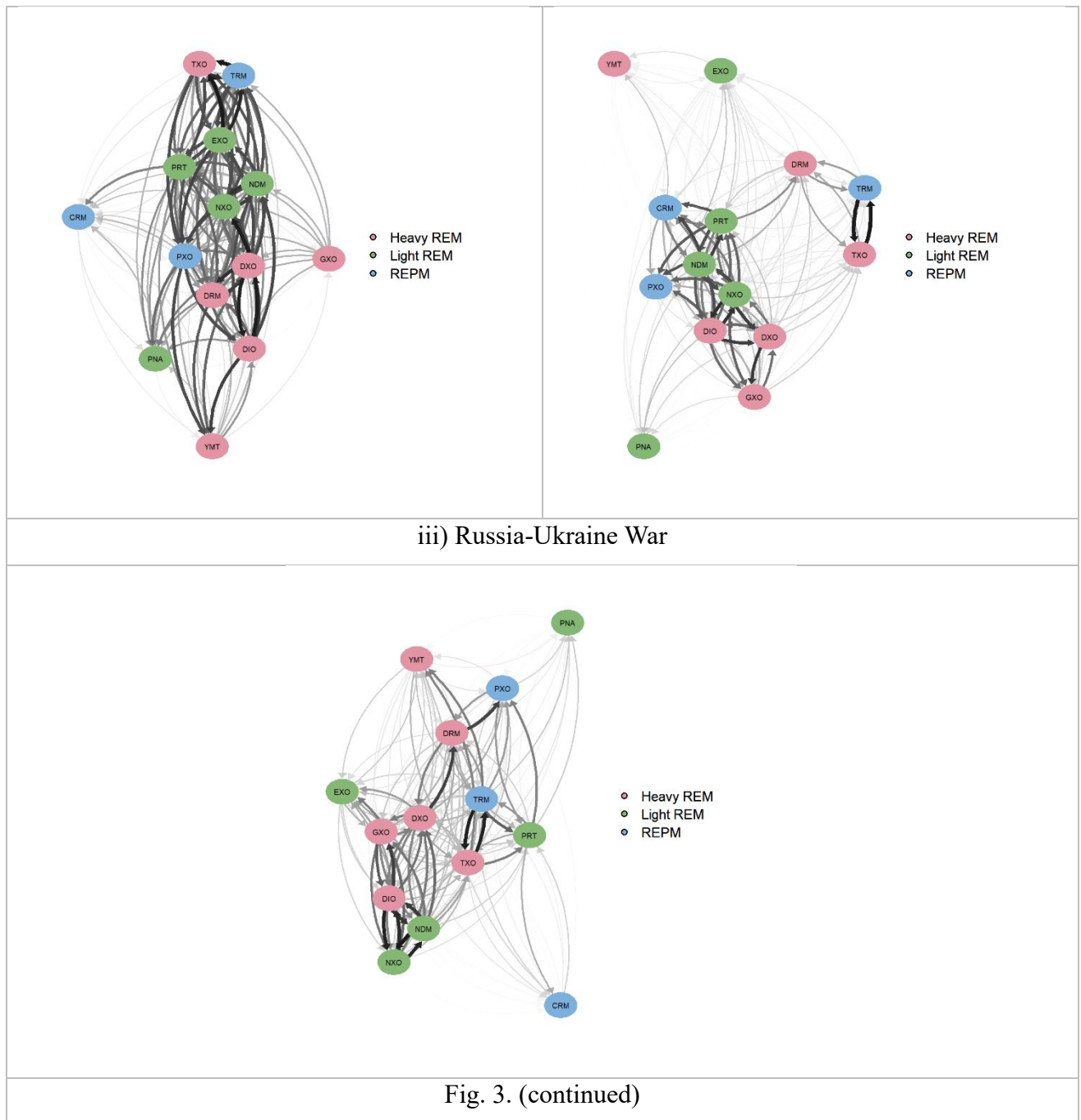


Fig. 3. Pairwise risk transmission networks of markets– Sub-sample. Note: This figure showcases the risk transmission networks of HREM, LREM and REPM for crisis periods, using a QQ risk transmission model with lag 1 (SIC criteria) and a 10-step-ahead generalized forecast error variance decomposition.

B) Lower (5%-5%) Quantiles

i) China export restriction crisis

ii) Clean energy and EV boom



C) Upper (95%-95%) Quantiles

i) China export restriction crisis

ii) Clean energy and EV boom





Fig. 4. Averaged TOTAL QQ risk transmission of markets. Notes: Results are based on a QQ risk transmission model with lag 1 (SIC criteria) and a 10-step-ahead generalized forecast error variance decomposition.

5.4 Averaged NET connectedness

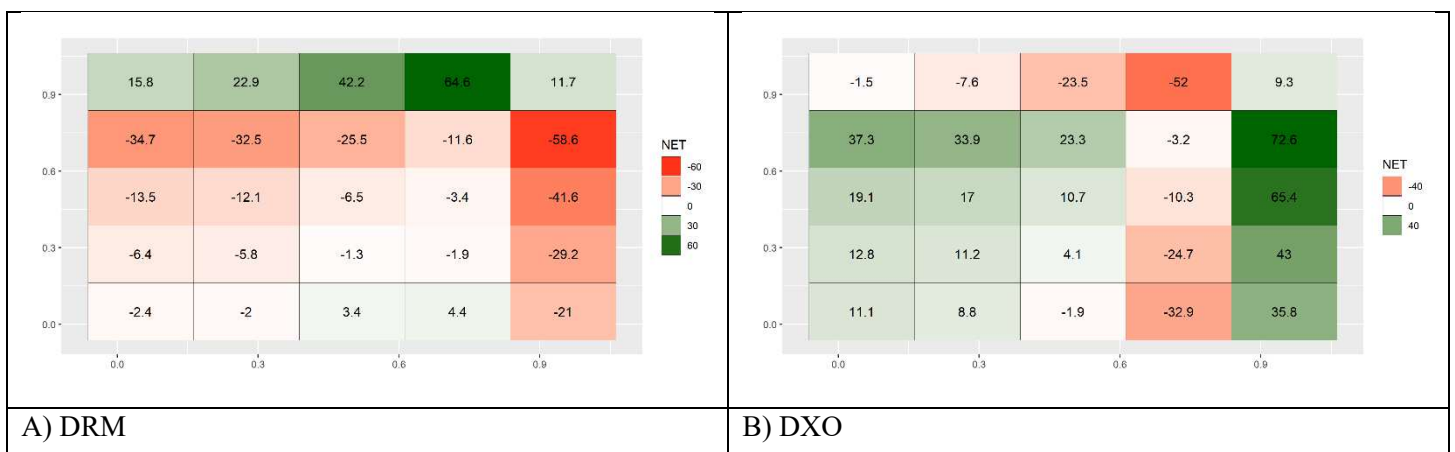
Fig. 5 presents the averaged QQ NET connectedness across the fourteen rare earth sub-markets. The results reveal that NET connectedness profiles vary substantially across market segments and market states, both in terms of intensity and direction of risk transmission. In other words, some markets mainly act as transmitters of shocks, while others predominantly absorb risks originating from the rest of the system.

In most quantile combinations, LREMs become the main net risk transmitters. Among these, NXO and NDM have the highest positive NET value, especially in upper quantiles. The maximum level for NXO is at the quantile combination ($\tau_1 = 0.9$; $\tau_2 = 0.9$), with values greater than 88.0. This indicates that neodymium oxide systematically sends more risk than it receives during bullish market periods. The same trend is also observed for the NDM, reinforcing the strategic importance of neodymium for EV and renewable energy applications, particularly in the production of permanent magnets. YMT also has the unique feature of positive NET values in almost all market regimes, indicating that yttrium is a structural source of systemic risk in the rare earth market. DIO shows a more regime-dependent behaviour. It is a net risk transmitter under upper quantiles and a net risk receiver under bearish and normal

market conditions. This means that the effect on the rare earth system is mainly magnified during periods of industrial optimism and robust demand growth.

On the contrary, the processing materials and REPM-related markets are characterised by mostly negative NET connectedness values. PXO, PNA, CRM and PRT therefore become structural net risk takers. PXO shows the largest negative values with -69.3 under upper quantiles, which means praseodymium oxide is very sensitive to the spillovers from upstream segments. PNA shows a similar pattern with large negative NET values in the central and upper quantiles. Receiver profiles are also visible in PRT and CRM during bullish periods. The higher quantiles show more negative NET values, which indicates that these markets are more vulnerable to shocks from LREMs as market optimism increases.

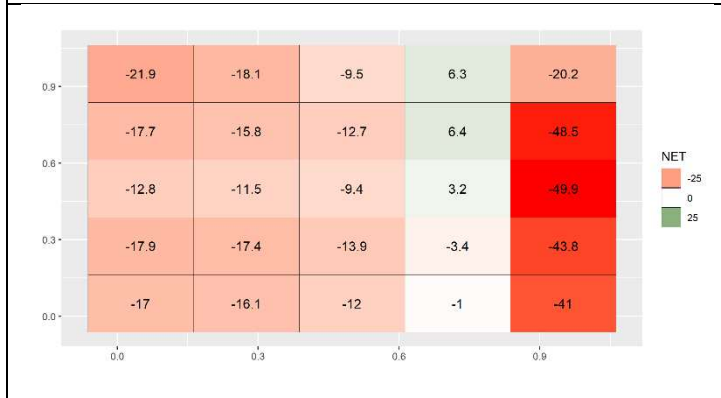
HREMs have a more heterogeneous structure. Overall, DRM and TXO are primarily characterised by negative NET values, consistent with their position as net risk receivers for most quantile combinations. The values for the upper quantiles of the DRM are about -47.6. GXO shows more asymmetric behaviour by acting as a net transmitter for some quantile configurations and then switching to a net receiver position when both markets enter strongly bullish states simultaneously. This finding suggests that gadolinium dynamics differ from those of other HREMs and remain highly dependent on prevailing market conditions. DXO also alternates between transmitter and receiver roles across quantile regimes, reflecting a more unstable sensitivity to market conditions.





C) TXO

D) GXO



E) YMT

F) DIO



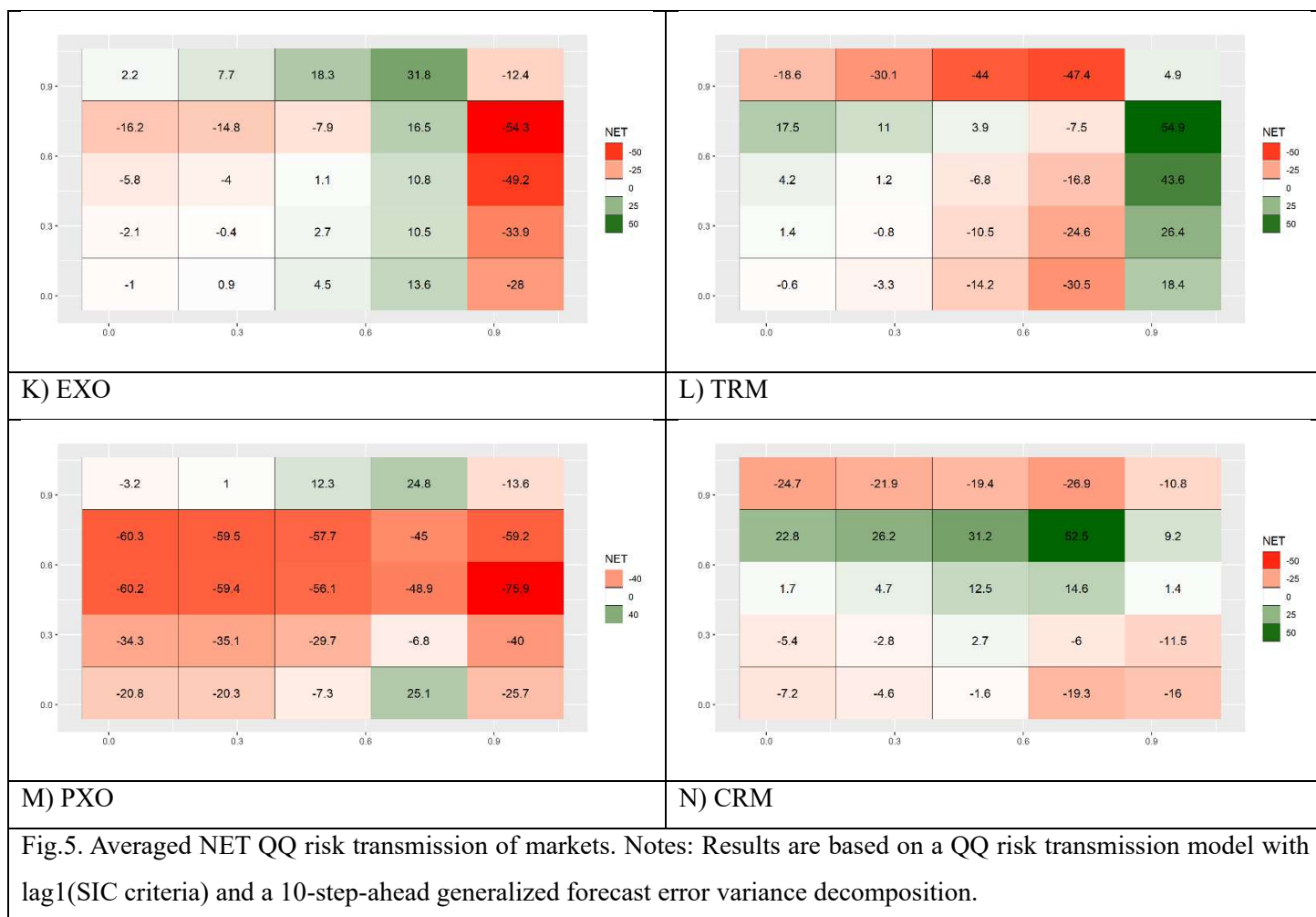
G) NXO

H) NDM



I) PRT

J) PNA



5.5 Dynamic connectedness

Fig. 6 presents the dynamic evolution of total connectedness across rare earth sub-markets over the entire sample period. The connectedness measures are estimated at three distinct quantile levels corresponding to the lower tail (5th–5th), the median quantile (50th–50th), and the upper tail (95th–95th).

At first glance, the results reveal a pronounced asymmetry between the connectedness observed at the median and upper quantiles and that associated with the lower quantile regime. Specifically, both the upper-tail connectedness, represented by the red dashed line, and the median connectedness, represented by the black solid line, remain persistently elevated and close to 100% throughout the entire sample period, exhibiting only limited and temporary fluctuations. Strong stability indicates that rare earth submarkets, including HREMs, LREMs, and RPEMs, develop in a highly synchronised environment not only during extreme bullish periods but also during normal market periods. This behaviour is consistent with

interdependence between rare earth segments being a built-in and persistent structural feature of these markets. This can mostly be explained by their joint sensitivity to global demand fundamentals, namely, the rapid growth of clean energy technologies and the increasing adoption of EVs (Gao et al., 2024; Yang et al., 2024).

The blue dashed line, representing lower-tail connectedness, appears to be significantly lower and much more time-varying over the sample period. Its level oscillates widely between 50% and 80%, indicating a much less pronounced degree of integration under bearish and stressed market conditions. This divergence suggests that rare earth sub-markets maintain a significant level of segmentation during down-market periods, thus retaining some diversification benefits across segments. Therefore, the results imply an asymmetric structure of risk transmission, with high market integration in the median and bullish regimes, whereas the bearish regimes are less integrated. This pattern is consistent with the asymmetric risk transmission mechanisms found in the commodity market connectedness literature (Diebold & Yilmaz, 2014; Nasir et al., 2024).

Closer analysis of major moments of crisis offers a deeper understanding of these dynamics. First, the China export restriction crisis in 2010-2011 (purple) is associated with a sharp decline of lower-tail connectedness to around 55%. The explanation of this evolution is the supply-side shock of China's unilateral cut of export quotas. Such restrictions created different scarcity conditions in the rare earth segments and temporarily broke the co-movement of their prices in a bear market condition. However, the median and the upper tail connectedness stay near 100% during this episode, indicating that the crisis mainly affects the adverse regimes of the market without changing the fundamental tightness of the synchronisation under normal and bullish regimes (Mancheri et al., 2019; Depraiter et al., 2025).

Then, during the clean energy and EV expansion phase between 2017 and 2018, emphasised in pink, the lower-tail connectedness shows a steady recovery, reaching levels of about 65%-70% before falling again towards about 60% during 2018-2019. The improvement reflects the slow convergence of demand expectations between the rare earth segments as the global energy transition gathered pace. The simultaneous strengthening of demand for both light and heavy rare earths has led to increasing price co-movements across market segments (IEA, 2024⁶).

⁶ <https://www.iea.org/reports/global-critical-minerals-outlook-2024>

Meanwhile, median and upper-tail connectedness are still firmly anchored close to 100%, further confirming their structural stability regardless of market cycles.

Finally, the Russia–Ukraine War in 2022, shown in dark green, is associated with a renewed and sustained increase in lower-tail connectedness rising from almost 60% to around 75% and 80% in the post-conflict period. This rise can be explained by the general disruptions in the world supply chain, Western sanctions and the uncertainty of strategic commodity markets (Li et al., 2026; Banerjee et al., 2024; Antonakakis et al., 2017). Against this backdrop, serious concerns about the security and reliability of critical mineral supply chains prompted investors to reassess their exposure across the entire spectrum of rare earths at the same time, even in the face of dire market conditions. The degree of segmentation observed before at lower quantiles thus gradually diminished. Importantly, we find that the lower tail connectedness seems to gradually converge to the median level from 2022, indicating that extreme negative market states have become more integrated over time.

Fig. 7 shows the time-varying NET QQ risk transmission of the fourteen rare earth sub-markets under three different market regimes with median quantiles (50%–50%), lower quantiles (5%–5%), and upper quantiles (95%–95%) during the period 2011–2026. This dynamic framework extends the average results shown in Fig. 5 by showing the evolution of the directional balance between transmitted and received risks over time. It also allows us to determine whether the roles of transmitter and receiver that we have identified on average correspond to durable structural characteristics or to phenomena more closely linked to periods of crisis. The spillover effects in rare earth markets are dynamic in nature and tend to be aggravated at times of economic and geopolitical stress, as highlighted by Zada et al. (2025). Our time-varying framework is specifically designed to capture this characteristic at the sub-market level.

The results shown in Fig. 7(A) illustrate a rather stable but heterogeneous structure in the different market segments under normal market conditions. YMT, NXO and NDM appear to have mostly positive NET values through most of the sample period, suggesting the role of these countries as net risk transmitters is not an extreme event phenomenon but also a structural characteristic of the rare earth system under median market conditions. The intensity of their positive connectedness remains relatively moderate before 2019 before they strengthen progressively from 2020 onwards, a period marked by the acceleration of clean energy policies and the global expansion of EV adoption, both of which significantly increased industrial demand for neodymium and yttrium. This temporal intensification is in line with the findings

of Li et al. (2026) that shocks in clean energy markets significantly increase the short-term spillovers in China's rare earth industrial chain, while the Russia–Ukraine war further exacerbated these dynamics by accelerating energy transition policies.

On the other hand, PXO, PNA and PRT have mostly negative NET values across the sample period based on median quantiles, with their receiver role becoming particularly prominent around 2018-2019 during the clean energy and EV boom and again from 2022 onwards. Such persistent absorption behaviour is in line with the results of Ye et al. (2023) who show that in general the oxide markets in China's rare earth system are net risk receivers and their price dynamics are primarily driven by signals emanating from upstream segments rather than autonomous supply-side fundamentals. DIO also appears as one of the most active markets in this panel, switching from positive to negative NET values of moderate size during the whole sample period, with a slow switch to a net transmitter role, starting in 2021, consistent with the increasing strategic importance of didymium in the production of magnet alloys in the post-COVID industrial recovery.

The most volatile NET profiles under median quantiles are GXO and EXO, which often switch between being a transmitter and a receiver, with no clear role emerging over time. This instability is probably due to the more specialised and less liquid nature of the gadolinium and europium markets, where the directional risk exposure is very sensitive to idiosyncratic industrial shocks rather than to broader macroeconomic trends. This finding is consistent with Xia et al. (2023) who highlight the highly differentiated risk profiles and transmission mechanisms of rare earth sub-markets according to their position in the upstream–midstream–downstream value chain.

When the analysis is focused on the very bearish market states, the results as shown in Fig. 7(B) point to some important changes in the directional structure of risk transmission. The first striking observation is about PNA and PXO, which are net recipients during almost the entire sample period. Their negative NET values seem to be even more clustered than median conditions, especially in 2015-2016 and again in 2022-2023. This result indicates that praseodymium-related segments carry an outsized share of the risk from upstream markets during market downturns. This pattern is in line with the findings of Nasir et al. (2024), who show the importance of geopolitical risk and upstream rare earth markets as major transmitters under lower quantile conditions, and hence put more pressure on downstream processing-intensive sub-markets with less autonomous price formation mechanisms.

One of the most striking findings in this panel is the pronounced and persistent peaks of strongly positive NET values for DIO, especially around 2018–2019 and then again from 2024 onwards. This confirms the paradoxical behaviour of didymium markets as net risk emitters during bear periods. This pattern seems to illustrate the high sensitivity of DIO to supply restriction shocks that are associated with export control policies by China, which create upward price pressures despite depressed market conditions. This interpretation is in line with Seiler (2024), who finds that risk shocks from China's domestic rare earth market are transmitted to international prices during periods of geopolitical and trade tensions. NXO and NDM also have moderately positive NET profiles under lower quantiles for most of the sample period, although the intensity seems weaker than under median conditions. This finding indicates that the systemic role of neodymium as a risk transmitter is weakened during bearish periods, but not fully reversed. TXO and DRM, on the other hand, have mostly negative or relatively weak NET profiles at lower quantiles, suggesting that they tend to act more as net receivers in periods of stress. CRM also exhibits an interesting temporal pattern, moving from moderately negative values before 2020, to values closer to a weak receiver profile after 2021. This partially supports the findings of Zheng et al. (2025) according to which cerium generally acts as a net risk receiver within the broader rare earth and new energy metals system. The results obtained in extremely bullish market conditions exhibit the most dynamic structure of the three regimes studied. An important observation is that the roles of several sub-markets evolve substantially across crisis periods confirming that bullish market conditions activate different transmission architectures depending on the nature and origin of the underlying shocks. This finding is consistent with Bouri et al. (2021) who find that interdependence among rare earth markets can be very different at upper quantiles with extremely bullish scenarios having a particularly strong impact on return connectedness.

YMT, NXO and NDM are under upper quantiles with positive NET values during the whole sample period and their transmitter role has significantly increased since 2020. The period of (post-)COVID recovery and Russia–Ukraine war (circa 2021–2023) is a period of high NET connectedness for these markets. This dynamic is reflective of the simultaneously increasing demand for clean energy, strategic stockpiling behaviour and supply chain restructuring, all resulting in the concentration of systemic risk in the neodymium and yttrium complex. This increase during the Russia-Ukraine war is consistent with the findings of Nasir et al. (2024) who observe the considerable variations in the connectedness index after the conflict escalated and Gao et al. (2024) who demonstrate that spillovers of higher-order moments become

significantly more intense as the Russia-Ukraine war ensues between the markets of rare earth and clean energy. The most pronounced negative NET values for PXO and PNA occur in the upper quantiles during the 2021–2023 period, confirming that the increasing transmitter role of upstream segments is accompanied by an increasing receiver role of processed materials. The size of the negative NET values shown for PXO in 2022–2023 is one of the largest in the entire figure. This means that the praseodymium oxide markets had taken in very high incoming risk levels in the course of the Russia-Ukraine war, during strongly bullish times. This result confirms the network evidence in Fig. 3(C-iii) and is consistent with the conclusion in Li et al. (2026), which shows that the Russia–Ukraine conflict significantly increased short-term spillovers in China’s rare earth industrial chain. DXO also exhibits one of the most interesting temporal dynamics under upper quantiles, with a clear transition from a net receiver status before 2020 to a net transmitter role starting from 2021. Intermittently, strongly positive NET values can still be seen through 2024–2025, suggesting that DXO markets, traditionally thought of as absorbers of risk from upstream supply constraints, became active risk emitters in the post-pandemic bullish phase. The switch appears to be largely driven by the rapidly growing demand for heavy rare earths in high-performance EV motors and defence applications, consistent with Zheng et al. (2025), who highlight terbium- and dysprosium-related markets as major risk emitters in times of increased geopolitical tensions and fast-tracked energy transition dynamics. In addition, GXO and EXO are characterised by mixed behaviour during the whole sample period under the upper quantiles, changing from transmitter to receiver status and vice versa and no dominant role emerges over time. This instability is likely due to the more idiosyncratic demand structures of gadolinium and europium, which have industrial uses from medical imaging and defence electronics to emerging quantum technologies.

Fig. 8 depicts the dynamic evolution of directly related connectedness (Direct TCI), reversely related connectedness (Reverse TCI), and their difference (Δ TCI) over the full sample period. Overall, both the Reverse TCI and Direct TCI exhibit relatively similar dynamics throughout the sample, fluctuating mainly between 70% and 90%, which indicates a persistently high level of interconnectedness within the rare earth market system. In most periods, the Reverse TCI slightly exceeds the Direct TCI, as reflected by the predominantly negative values of Δ TCI, suggesting that reversely related spillovers generally dominate directly related spillovers across the network structure.

More precisely, a few episodes of temporary divergence can be identified. The first major rise in both connectedness measures is around 2014–2015, consistent with the post-China export restriction adjustment period and the reorganisation of global rare earth supply chains after the WTO dispute over China's export quotas. Another steep rise is observed in 2017–2018, when both indices show a temporary spike, likely due to the fast growth of clean energy technologies and EV markets, resulting in a substantial increase in the demand interdependence among rare earth segments. Another important result reported in Fig. 8 is the fact that the distance between Reverse TCI and Direct TCI increases significantly from early 2020 to about 2022, when the Reverse TCI constantly outperforms the Direct TCI. This time is also marked by the combined impact of the COVID-19 pandemic and the Russia-Ukraine war, which both severely disrupted global supply chains and heightened uncertainty in critical mineral markets. The shocks seem to have boosted the indirect and feedback transmission channels across rare earth sub-markets. Therefore, it adds to the importance of reversely related connectedness in periods of high geopolitical and economic stress.

Finally, both connectedness measures show a visible upward movement from 2024 onwards, with occasional spikes, especially in the Direct TCI series. This pattern may indicate a return to strategic competition over critical minerals, intensified industrial policies around the energy transition, and increasing worries about the security of rare earth supply chains in the post-pandemic geopolitical environment.

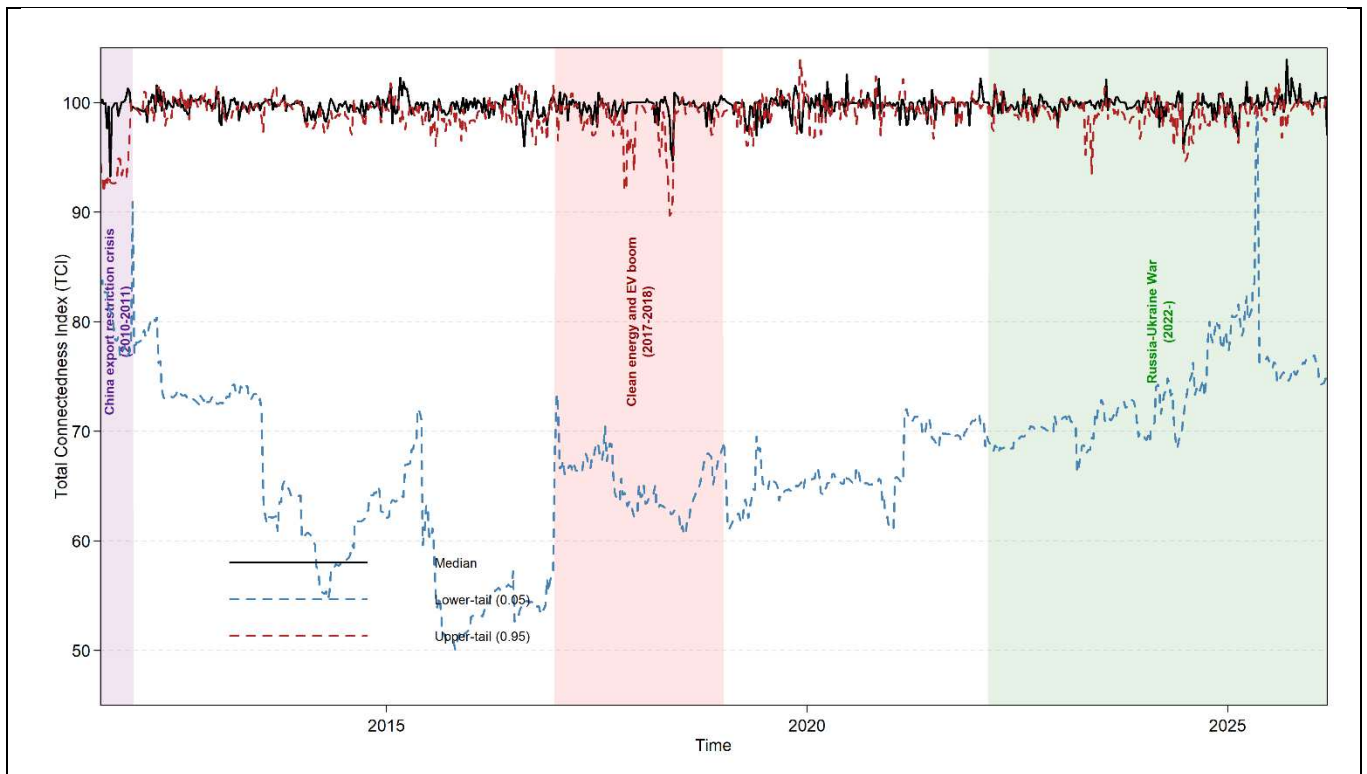
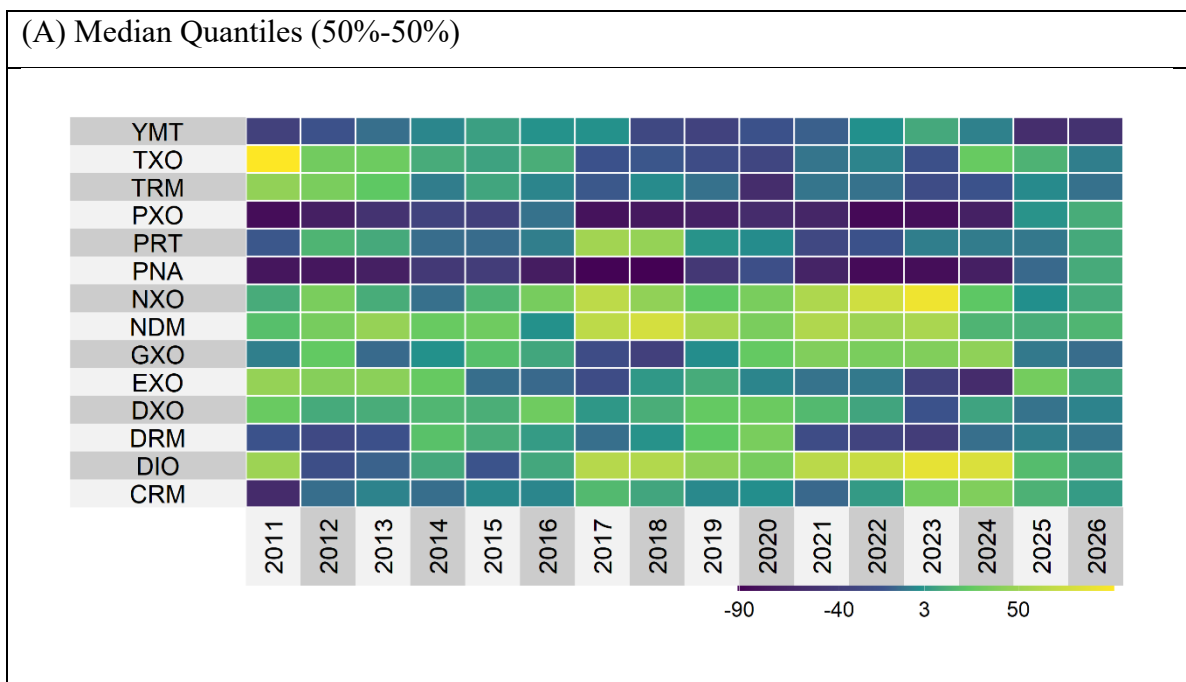
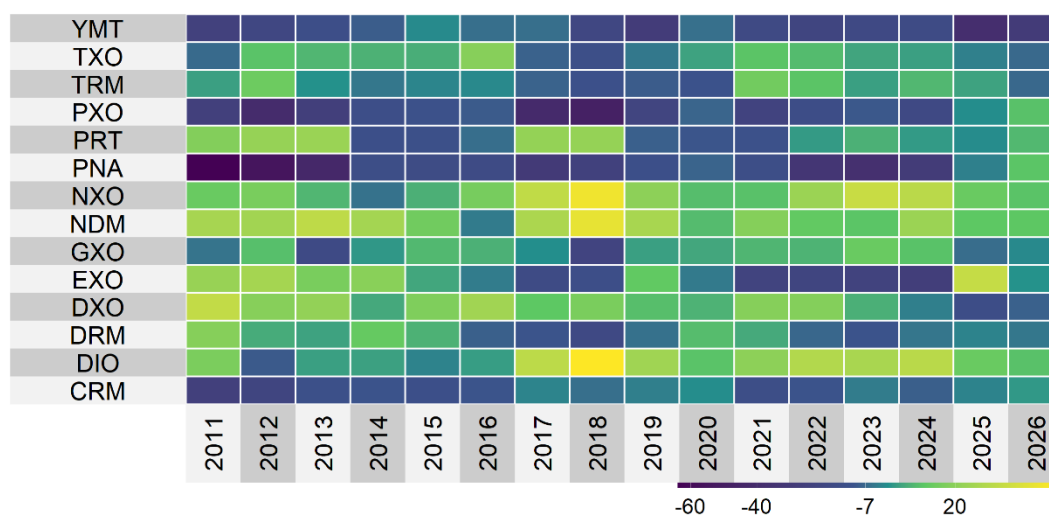


Fig. 6. Time-varying TOTAL risk transmission of markets.

Notes: Results are based on a 105-day Rolling Window QQ risk transmission model with lag 1 (SIC criteria) and a 10-step-ahead generalized forecast error variance decomposition. The black line represents risk transmission at 50–50 (Median) quantiles, while the blue (dashed) and the red (dashed) lines represent the results of the 5–5 (Lower) and 95–95 (Upper) quantiles, respectively. Purple, firebrick, and dark green shaded areas represent crisis periods.



(B) Lower Quantiles (5%-5%)



(C) Upper Quantiles (95%-95%)

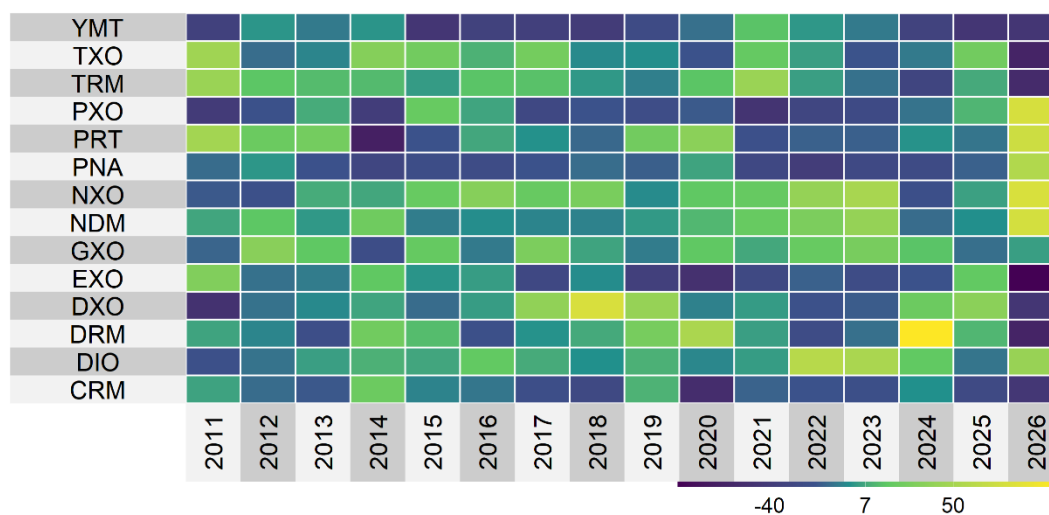
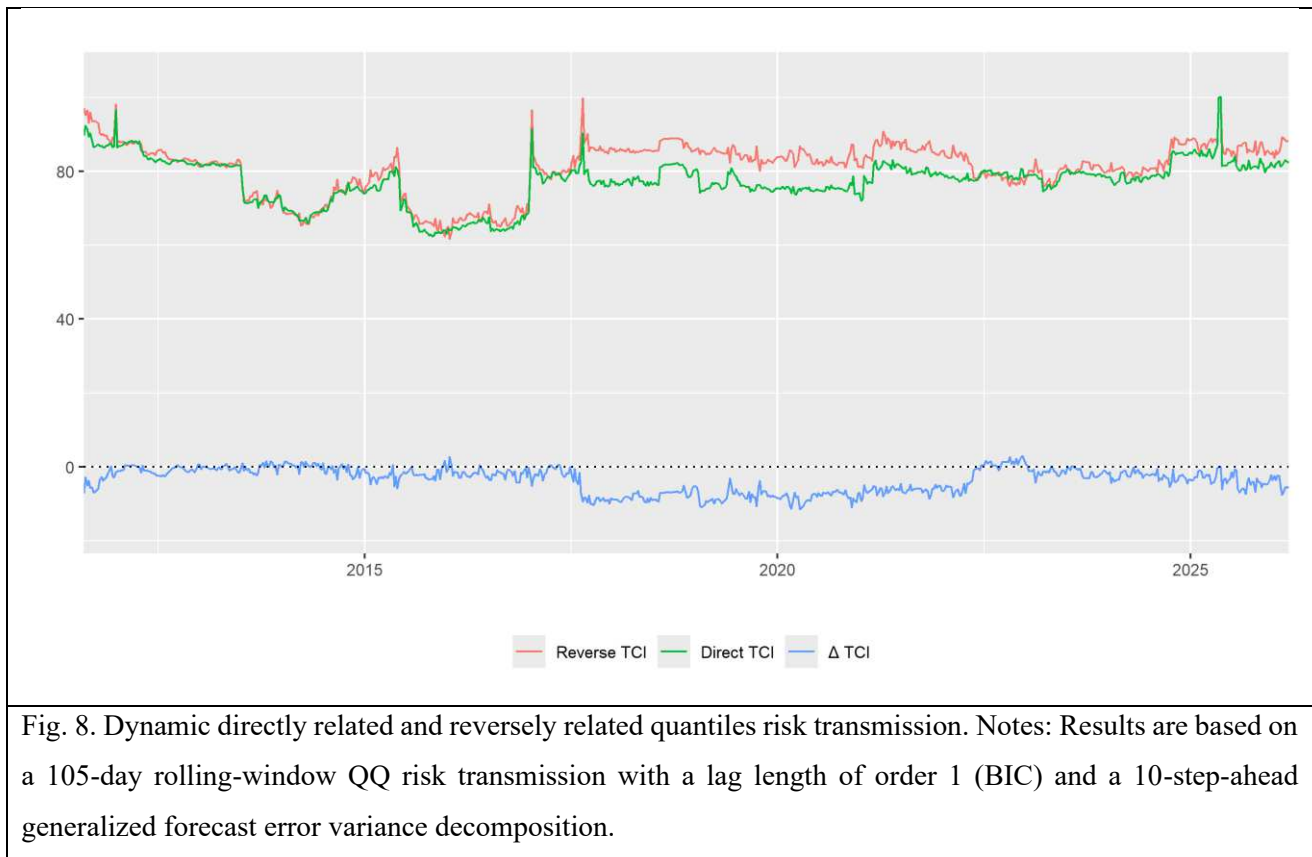


Fig. 7. Time-varying NET risk transmission of markets. Notes: Results are based on a 105-day rolling-window QQ risk transmission with a lag length of order 1 (BIC) and a 10-step-ahead generalized forecast error variance decomposition.



6. Implications of the Study

This study provides important implications for investors, portfolio managers, policymakers, and corporate stakeholders operating in rare earth and energy transition markets. For investors and portfolio managers, the results suggest that HREMs, LREMs and REPMs should not be treated as homogeneous assets within portfolio allocation frameworks. The findings reveal that REPMs, particularly TRM and PXO, frequently emerge as major transmission channels during crisis periods, while LREMs such as DIO, NXO, NDM, and PNA become highly interconnected during bullish market regimes associated with clean energy expansion. Consequently, portfolio diversification and hedging strategies should adopt dynamic and regime-dependent approaches rather than relying on static correlation structures. Investors should also closely monitor geopolitical events and energy transition policies, as these factors significantly amplify systemic risk transmission across rare earth markets.

The results also show that the Russia–Ukraine conflict led to the highest level of market integration and spillover intensity among rare earth segments, indicating the fragility of global critical mineral supply chains to geopolitical disruptions. This implies that policymakers in rare earth importing economies should focus on strategic stockpiling, supply chain diversification

and domestic processing capacity development to reduce excessive reliance on concentrated refining networks. In particular, the strong spillover role of processing materials confirms the strategic bottleneck of midstream refining activities in the global rare earth value chain. Governments should therefore promote investing in recycling technologies, processing infrastructure and alternative sourcing agreements to strengthen supply resilience in future crises.

The results show that risk transmission is much more aggressive in tail market conditions for corporate procurement managers and manufacturing industries that depend on the inputs of rare earths, including the EV, semiconductor, renewable energy, and defence industries. Firms should thus go beyond average volatility-based procurement models and adopt scenario-based supply chain risk management frameworks that take into account nonlinear and quantile-dependent spillovers. These results also emphasise the importance of supplier diversification and long-term strategic contracts to reduce exposure to crisis-driven price contagion across rare earth markets.

7. Conclusion

This study investigates the QQ risk transmission mechanisms among HREMs, LREMs, and REPMs during three major crisis periods, including the China export restriction crisis (2010–2011), the clean energy and EV boom (2017–2018), and the Russia–Ukraine war period (2022–present). The study employed a QQ connectedness framework that went beyond the traditional mean-based approaches and captured the asymmetric, nonlinear, and regime-dependent nature of spillover dynamics that characterise REMs under different market conditions. The empirical results show that the risk transmission across the rare earth sub-markets is highly heterogeneous and changes significantly across bearish, normal and bullish market states as well as crisis periods.

Our results indicate that the connectedness in rare earth markets is significantly stronger under upper quantile conditions, suggesting that bullish market regimes lead to substantially stronger synchronisation across HREMs, LREMs, and REPMs. The mean TCI is generally close to full market integration at higher quantiles and the maximum level of the mean TCI is achieved at the (0.9, 0.9) quantile setting. On the other hand, lower quantile conditions are characterised by relatively weaker integration, implying that rare earth sub-markets retain partial segmentation during unfavourable market conditions. These results suggest that the

opportunities for diversification are much weaker in optimistic market regimes, which are driven by strong clean energy demand, strategic stockpiling and geopolitical uncertainty.

Furthermore, the study also finds that LREMs especially NXO and NDM are predominantly net risk transmitters consistently across most of the quantile configurations, especially in the bullish states of the market associated with the growth of EV and renewable energy technologies. In contrast, the markets related to processing, such as, PXO, PNA and CRM, show a dominant pattern of being net receivers of spillovers. This is in line with their high dependence on upstream supply and demand shocks. DXO and GXO change their roles as transmitter and receiver depending on the prevailing market conditions and crisis intensity, which makes HREMs more heterogeneous in their behaviour. The results show that the rare earth value chain is conveyed through highly differentiated mechanisms, each segment of which has a distinct systemic role in the broader market network.

The crisis-specific analysis is also an important insight into the changing structure of rare earth market risks. The China export restriction crisis has mainly generated supply-driven spillovers concentrated in HREMs and processing materials, which indicates the strategic vulnerability of China's export controls and refining dominance. The rapid growth of clean energy and EVs created a demand-driven transmission mechanism, whereby the fast-growing industrial demand for neodymium and praseodymium substantially increased the connectedness among LREMs and processing activities. In the meantime, the systemic integration of the Russia-Ukraine war reached the highest across all rare earth segments, driven by the combined impacts of geopolitical uncertainty, energy security concerns, strategic stockpiling behaviour, and global supply chain disruptions. In this episode, spillover effects became extremely widespread and synchronised across almost all nodes of the rare earth network.

The dynamic connectedness results also confirm the evidence that REMs have become more and more integrated over time especially after 2020. In prior crises, the lower-tail connectedness was rather moderate, but it converged more and more with the median and upper-tail levels during the post-pandemic and the Russia-Ukraine war periods. This implies that even bearish market scenarios are becoming increasingly correlated as the role of rare earths in global decarbonisation technology and advanced manufacturing systems increases. The results thus suggest that geopolitical conflicts, clean energy transitions and industrial policy interventions serve to reinforce the systemic interconnectedness of critical mineral markets.

The findings of this research show that rare earth markets exhibit asymmetric, crisis-sensitive and highly dynamic spillover structures which are poorly described by the traditional linear connectedness models. The findings emphasise the importance of using quantile and sub-market-level approaches in the analysis of strategic mineral markets under geopolitical disruptions and energy transition pressures. The study also stresses that resilient and sustainable clean energy transitions require not only technological progress but also proactive management of supply chain vulnerabilities, processing bottlenecks and geopolitical risks encoded in global rare earth systems.

8. Limitations and Future Research Directions

There are a number of limitations to this study that provide opportunities for future research. The first is that the analysis is limited to the Chinese rare earth market because of the dominance of China in the global mining. Therefore, we expect future research to further extend the analysis to a multi-country or global rare earth network framework to examine whether the regional market structures generate heterogeneous spillover patterns and asymmetric transmission channels. Second, the study analyses three major crisis periods. Future research may explore if different types of geopolitical such as US–China trade conflict, financial and environmental crises trigger different tail-risk transmission mechanisms across rare earth sub-markets. Third, the empirical framework is mostly based on QQ connectedness measures derived from return-based volatility dynamics. It does not explicitly incorporate structural macroeconomic drivers; however, incorporating macro-financial and policy variables in a multivariate quantile connectedness framework could provide richer insights into the channels through which external shocks transmit across the rare earth supply chains. Future studies might integrate supply chain network analysis, input-output frameworks or inventory-based indicators to better reflect the interaction between physical and financial transmission mechanisms, given that rare earth markets are strongly impacted by industrial and geopolitical supply chain dependencies.

Artificial Intelligence Generated Content (AIGC) tools declaration:

The authors used Grammarly to improve the language, grammar, spelling, and readability of the manuscript. No content, analysis, interpretation, or conclusions were generated by artificial intelligence tools. All intellectual content and final revisions remain the sole responsibility of the authors.

References

- Akgul, E. F., Haralambides, H., & Akdamar, E. (2026). Strategic metals, rare earths, green transition, and tanker markets: Dynamic connectedness and strategic decision-making. *Research in Transportation Economics*, 117, 101783. [10.1016/j.retrec.2026.101783](https://doi.org/10.1016/j.retrec.2026.101783)
- Antonakakis, N., Chatziantoniou, I., & Filis, G. (2017). Oil shocks and stock markets: Dynamic connectedness under the prism of recent geopolitical and economic unrest. *International Review of Financial Analysis*, 50, 1-26.
- Ando, T., Greenwood-Nimmo, M., & Shin, Y. (2022). Quantile connectedness: Modeling tail behavior in the topology of financial networks. *Management Science*, 0(0). <https://doi.org/10.1287/MNSC.2021.3984>
- Arfaoui, N., Roubaud, D., & Naeem, M. A. (2025). Energy transition metals, clean and dirty energy markets: A quantile-on-quantile risk transmission analysis of market dynamics. *Energy Economics*, 143, 108250.
- Assaf, A., Al Daia, R., Charif, H., & Mokni, K. (2025). Extreme return connectedness among renewable energy and rare earth markets: The role of global factors. *Research in International Business and Finance*, 77, 102979. <https://doi.org/10.1016/j.ribaf.2025.102979>
- Baldi, L., Peri, M., & Vandone, D. (2014). Clean energy industries and rare earth materials: Economic and financial issues. *Energy Policy*, 66, 53-61. Ltd. <http://dx.doi.org/10.1016/j.enpol.2013.10.067>
- Banerjee, A. K., Sensoy, A., & Goodell, J. W. (2024). Volatility connectedness between geopolitical risk and financial markets: Insights from pandemic and military crisis periods. *International Review of Economics & Finance*, 96, 103740. [10.1016/j.iref.2024.103740](https://doi.org/10.1016/j.iref.2024.103740)
- Barut, A., Proskuryakova, L., Iakutkina, V., Erdem, A., Capitani, D. H., & Milshina, Y. (2026). The role of resource scarcity in shaping the green energy mix in the largest rare-earth metal trading nations. *Renewable Energy*, 125736. <https://doi.org/10.1016/j.renene.2026.125736>
- Bouri, E., Kanjilal, K., Ghosh, S., Roubaud, D., & Saeed, T. (2021). Rare earth and allied sectors in stock markets: extreme dependence of return and volatility. *Applied Economics*, 53(49), 5710-5730. <https://doi.org/10.1080/00036846.2021.1927971>

- Bollerslev, T. (1986). Generalized autoregressive conditional heteroskedasticity. *Journal of econometrics*, 31(3), 307-327.
- Byun, S. J., & Cho, H. (2013). Forecasting carbon futures volatility using GARCH models with energy volatilities. *Energy Economics*, 40, 207-221.
- Depraiter, L., Goutte, S., & Porcher, T. (2025). Geopolitical risk and the global supply of rare earth permanent magnets: Insights from China's export trends. *Energy Economics*, 146, 108496. <https://doi.org/10.1016/j.eneco.2025.108496>
- Diebold, F. X., & Yilmaz, K. (2012). Better to give than to receive: Predictive directional measurement of volatility spillovers. *International Journal of forecasting*, 28(1), 57-66.
- Diebold, F. X., & Yilmaz, K. (2014). On the network topology of variance decompositions: Measuring the connectedness of financial firms. *Journal of econometrics*, 182(1), 119-134. <https://doi.org/10.1016/j.jeconom.2014.04.012>
- Ding, H., & Ge, J. (2025). Towards clean energy technologies: Assessing the supply potential of critical rare earth elements in China. *The Extractive Industries and Society*, 22, 101603. <https://doi.org/10.1016/j.exis.2024.101603>
- Fan, J. H., Omura, A., & Roca, E. (2023). Geopolitics and rare earth metals. *European Journal of Political Economy*, 78, 102356. <https://doi.org/10.1016/j.ejpoleco.2022.102356>
- Fontana, D., & Pietrelli, L. (2009). Separation of middle rare earths by solvent extraction using 2-ethylhexylphosphonic acid mono-2-ethylhexyl ester as an extractant. *Journal of rare earths*, 27(5), 830-833. [https://doi.org/10.1016/S1002-0721\(08\)60344-0](https://doi.org/10.1016/S1002-0721(08)60344-0)
- Gao, W., Wei, J., Zhang, H., & Zhang, H. (2024). The higher-order moments connectedness between rare earth and clean energy markets and the role of geopolitical risk: New insights from a TVP-VAR framework. *Energy*, 305, 132280. <https://doi.org/10.1016/j.energy.2024.132280>
- Gao, Y., & Liu, X. (2024). Time and frequency spillovers and drivers between rare earth and energy, metals, green, and agricultural markets. *The North American Journal of Economics and Finance*, 72, 102128. <https://doi.org/10.1016/j.najef.2024.102128>
- Gielen, D., & Lyons, M. (2022). Critical materials for the energy transition: Rare earth elements. *International Renewable Energy Agency, Abu Dhabi*, 1-48.

- Hanif, W., Mensi, W., Gubareva, M., & Teplova, T. (2023). Impacts of COVID-19 on dynamic return and volatility spillovers between rare earth metals and renewable energy stock markets. *Resources Policy*, 80, 103196. [10.1016/j.resourpol.2022.103196](https://doi.org/10.1016/j.resourpol.2022.103196)
- Huang, Q., Wang, B., & Lin, J. (2024). The risk spillover between geopolitical risk and China's 5G, semiconductor and rare earth industries. *Heliyon*, 10(22). [10.1016/j.heliyon.2024.e40048](https://doi.org/10.1016/j.heliyon.2024.e40048)
- Jyothi, R. K., Thenepalli, T., Ahn, J. W., Parhi, P. K., Chung, K. W., & Lee, J. Y. (2020). Review of rare earth elements recovery from secondary resources for clean energy technologies: Grand opportunities to create wealth from waste. *Journal of Cleaner Production*, 267, 122048. <https://doi.org/10.1016/j.jclepro.2020.122048>
- Kamal, E., & Bouri, E. (2023). Dependence structure among rare earth and financial markets: a multiscale-vine copula approach. *Resources Policy*, 83, 103626. [10.1016/j.resourpol.2023.103626](https://doi.org/10.1016/j.resourpol.2023.103626)
- Kyriazis, N., Papadamou, S., Tzeremes, P., & Corbet, S. (2024). Quantifying spillovers and connectedness among commodities and cryptocurrencies: Evidence from a Quantile-VAR analysis. *Journal of Commodity Markets*, 33, 100385. [10.1016/j.jcomm.2024.100385](https://doi.org/10.1016/j.jcomm.2024.100385)
- Li, H., Li, Y., Luo, F., & Guo, L. (2025). Navigating extreme risk spillovers: Building a synergistic network of rare earths, green bonds, and clean energy markets in China. *Energy Economics*, 147, 108562. <https://doi.org/10.1016/j.eneco.2025.108562>
- Li, J., Zhao, Y., Dou, S., Zhu, Y., & Xu, D. (2026). The impact of China's clean energy market on the market connectivity of rare earth industrial chain. *Plos one*, 21(2), e0342223. <https://doi.org/10.1371/journal.pone.0342223>
- Liu, W., Guo, W., Chen, J., Peng, S., Ru, L., Chen, Y., ... & Xie, X. (2025). Tracking terbium metabolism in China with implications for its dominance in global rare earth supply. *Resources, Environment and Sustainability*, 100263. <https://doi.org/10.1016/j.resenv.2025.100263>
- Mabuh, M., & Azimli, A. Connectedness Dynamics Between Rare Earth Metals and the Financial Market in China. *Available at SSRN 5817181*.
- Mancheri, N. A., Sprecher, B., Bailey, G., Ge, J., & Tukker, A. (2019). Effect of Chinese policies on rare earth supply chain resilience. *Resources, Conservation and Recycling*, 142, 101-112. <https://doi.org/10.1016/j.resconrec.2018.11.017>

- Mariev, O., & Blueschke, D. (2025). Interplay of Chinese rare earth elements supply and European clean energy transition: A geopolitical context analysis. *Renewable Energy*, 238, 121986. <https://doi.org/10.1016/j.renene.2024.121986>
- Mensi, W., Kumar, A. S., Ko, H. U., & Kang, S. H. (2024). Intraday spillovers in high-order moments among main cryptocurrency markets: the role of uncertainty indexes. *Eurasian Economic Review*, 14(2), 507-538. <https://doi.org/10.1016/j.eurasc.2024.05.007>
- Müller, D., Groves, D. I., Santosh, M., & Yang, C. X. (2025). Critical metals: Their applications with emphasis on the clean energy transition. *Geosystems and Geoenvironment*, 4(1), 100310. <https://doi.org/10.1016/j.geogeo.2024.100310>
- Nasir, R. M., He, F., & Kim, N. H. (2024). Quantile and time-frequency spillover between rare earth and its interlinked markets: A geopolitical perspective. *Journal of Cleaner Production*, 476, 143745. <https://doi.org/10.1016/j.jclepro.2024.143745>
- Oka, A. (2025). Diversification of rare earth metals supply chain: Can the US rely on non-Chinese sources?. *Journal of Government and Economics*, 100156. <https://doi.org/10.1016/j.jge.2025.100156>
- Panazan, O., & Gheorghe, C. (2025). Strategic risk spillovers from rare Earth markets to critical industrial sectors. *International Journal of Financial Studies*, 13(3), 156. <https://doi.org/10.3390/ijfs13030156>
- Peter Biedermann, R. (2014). China's rare earth sector—between domestic consolidation and global hegemony. *International Journal of Emerging Markets*, 9(2), 276-293. <https://doi.org/10.1108/IJoEM-05-2013-0080>
- Qiao, S., Chang, Y., Mai, X. X., & Dang, Y. J. (2024). Climate policy uncertainty, clean energy and energy metals: A quantile time-frequency spillover study. *Energy economics*, 139, 107919. <https://doi.org/10.1016/j.eneco.2024.107919>
- Rasheed, M. Q., Yuhuan, Z., & Ahmed, Z. (2025). The interactions of rare earth minerals with renewable energy production alongside artificial intelligence and geopolitical risk. *Renewable Energy*, 124301. <https://doi.org/10.1016/j.renene.2025.124301>
- Seiler, V. (2024). The relationship between Chinese and FOB prices of rare earth elements—Evidence in the time and frequency domain. *The Quarterly Review of Economics and Finance*, 95, 160-179. <https://doi.org/10.1016/j.qref.2024.03.007>

- Sinclair, L., & Coe, N. M. (2026). Extreme derisking of Australian rare earth projects: The geopolitical imperatives reshaping global production networks. *Energy Research & Social Science*, 136, 104671. <https://doi.org/10.1016/j.erss.2026.104671>
- Wang, P., Liu, T., Cheng, G., Wu, Y., Wang, S., & Zhu, K. (2026). Securing low-carbon rare earth supply for the renewable energy sector: Demand, circularity, and carbon mitigation of neodymium and dysprosium. *Resources, Conservation and Recycling*, 228, 108784. <https://doi.org/10.1016/j.resconrec.2026.108784>
- Xia, Q., Du, D., Cao, W., & Li, X. (2023). Who is the core? Reveal the heterogeneity of global rare earth trade structure from the perspective of industrial chain. *Resources Policy*, 82, 103532. [10.1016/j.resourpol.2023.103532](https://doi.org/10.1016/j.resourpol.2023.103532)
- Yang, X., Islam, M. M., Mentel, G., Ahmad, A., & Vasa, L. (2024). Synergistic dynamics unveiled: Interplay between rare earth prices, clean energy innovations, and tech companies' market resilience amidst the Covid-19 pandemic and Russia-Ukraine conflict. *Resources Policy*, 89, 104615.
- Ye, R., Gong, J., & Xia, X. (2023). Trading Risk Spillover Mechanism of Rare Earth in China: New Perspective Based on Time-Varying Connectedness Approach. *Systems*, 11(4), 168. <https://doi.org/10.3390/systems11040168>
- Zada, H., Parahara, N., Nanayakkara, M., Usman Masood, S. M., & Wong, W. K. (2025). Connectedness between Industrial and Rare Earth Metals: Implications for Portfolio Diversification During the COVID-19 Pandemic and the Russia–Ukraine Conflict. *Annals of Financial Economics*, 2550021. <https://doi.org/10.1142/S2010495225500216>
- Zheng, R., Nong, H., Chen, Q., Shao, L., Zhang, H., & Zhang, Y. (2025). Study on risk contagion between rare earth and new energy-related metals markets from the perspective of co-production and co-consumption. *Frontiers in Physics*, 13, 1616099. <https://doi.org/10.3389/fphy.2025.1616099>
- Zhou, X., Liu, G., Li, H., Chang, W., Deng, Q., & Casazza, M. (2026). Biodiversity loss from rare earth production for green technologies in China: a global supply chain perspective. *Resources, Environment and Sustainability*, 100314. <https://doi.org/10.1016/j.resenv.2026.100314>

Zhu, Y., Gong, Y., Yang, L., & Xu, D. (2025). The rise of clean energy markets: Evidence from frequency-domain spillover effects between critical metals and energy markets. *Energy Economics*, 141, 108126. [10.1016/j.eneco.2024.108126](https://doi.org/10.1016/j.eneco.2024.108126)