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Extreme Connectedness among Energy Transition Metals and Commodity Markets

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Abstract:

The global energy transition is reshaping commodity demand, yet its implications for commodity risk transmission remain unclear. We analyze connectedness among Energy Transition Metals (ETMs) – a subset of metals that are key inputs in clean energy technologies – energy commodities, and industrial metals using a Quantile Factor VAR framework. We document strong state dependence: spillovers are substantially larger in the tails of the return distribution than at the median. While crude oil remains influential, its dominance weakens post-Covid as ETMs, particularly base ETMs, gain centrality. A complementary event-study shows ETM-related policy announcements amplify spillovers in extreme regimes, indicating structural reconfiguration and systemic implications.

JEL: C32; C58; Q02; Q41; Q43; Q48

Keywords: Raw materials; Energy transition; Quantile Connectedness; Spillover effects; Commodity Markets

1 Introduction

The global transition toward a low-carbon economy is not only an environmental imperative but also a profound structural transformation of commodity markets. Achieving the 1.5°C target set by the Paris Agreement requires a rapid shift away from fossil fuels toward renewable energy systems and clean technologies. Clean energy investments have increased by 40% since 2020, and renewables are projected to account for 80% of new power capacity additions by 2030 (see e.g., Bouckaert et al., 2021; Gielen et al., 2019; IEA, 2023b). Supporting the deployment of clean energy technologies at the scale implied by this ambitious target entails a sharp increase in demand for a subset of metals that we refer to as Energy Transition Metals (ETMs), with projected growth potentially exceeding current production capacity.

While much attention has focused on the technological dimension of this transition, far less is known about how it reshapes the structure, direction, and state-dependence of risk transmission across global commodity markets. From a network perspective, structural shifts in demand and supply may alter the centrality of specific commodities, thereby changing how shocks are amplified and propagated throughout the system. As emphasized in network models of shock propagation, changes in node centrality can significantly modify the aggregate impact of idiosyncratic disturbances (Acemoglu et al., 2012, 2015). In this paper, we provide econometric evidence that the energy transition is not only changing commodity demand patterns but is also reconfiguring the network of spillovers that links traditional energy commodities, industrial metals, and transition-related resources.

The rapid deployment of clean energy technologies has prompted many countries to adopt official lists of Critical Raw Materials (CRMs) in order to monitor the supply of metals and materials that are strategically important for their economies and key policy objectives (Nakano, 2021).[1] Within this broader category, we focus on ETMs, a subset of metals that are essential inputs for wind turbines, electric vehicle batteries, electricity grids, and storage technologies.[2] In the Net Zero Emissions by 2050 (NZE) Scenario, demand for these minerals is projected to increase by between 1.5 and 7 times by 2030. Demand for minerals used in electric vehicles and battery storage alone is expected to grow at least 30-fold by 2040 (Bibra et al., 2022; Kim et al., 2021). Metals that were once considered peripheral industrial inputs are therefore becoming macroeconomically relevant assets with increasing financial and geopolitical importance.

Much like fossil fuels, the supply of ETMs is highly rigid. Developing new mining capac-

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[1] See e.g. the "European Critical Raw Materials Act of 2022". `https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661`.

[2] The IMF regualarly compiles a price index with 16 ETMs. These are the same we analyse and include seven base metals (aluminum, cobalt, copper, lead, molybdenum, nickel, zinc), three precious metals (palladium, platinum, silver), and six minor metals (chromium, lithium, manganese, rare earth elements, silicon, vanadium). See `https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661`.

ity is a lengthy process, often exceeding a decade from exploration to production. At the same time, production and refining are geographically concentrated in a limited number of countries, creating significant exposure to supply disruptions and geopolitical tensions.[3] These structural characteristics imply that shocks originating in ETMs markets may propagate across broader commodity systems, particularly during periods of stress. When commodities become more central within a production and financial network, disturbances affecting them may generate disproportionate aggregate effects through amplification mechanisms. As the energy transition accelerates, quantifying these evolving interdependencies becomes essential for assessing systemic risk, energy security, and the stability of the clean energy supply chain.

In our analysis, we examine how the topology of global commodity markets evolves in the context of the energy transition. In particular, we ask whether energy transition metals are merely passive recipients of shocks from traditional energy markets, or whether they are increasingly emerging as independent sources of systemic spillovers. If ETMs are gaining network centrality, shocks to these markets may no longer remain localized but instead cascade across energy and industrial commodity systems. To address this question, we construct eight commodity price indices (base ETMs, precious ETMs, minor ETMs, gold, industrial metals, coal, natural gas, and crude oil) and estimate a quantile factor vector autoregressive model that captures connectedness across the entire conditional return distribution. The quantile-based framework (see Ando et al., 2022) allows spillover parameters to vary across market states, thereby identifying heterogeneous transmission mechanisms that remain hidden in mean-based specifications. By explicitly modeling tail dynamics, we assess whether amplification effects become stronger under extreme market conditions, when diversification benefits may weaken and contagion risks become more pronounced.

We complement the static analysis with a time-varying connectedness framework that compares pre- and post-Covid-19 spillover structures, thereby capturing potential structural shifts in commodity market interconnectedness. In addition, using the bootstrap-after-bootstrap methodology proposed by Greenwood-Nimmo et al. (2024), we identify policy-related events that trigger statistically significant changes in connectedness. This event-based perspective enables us to distinguish between spillovers driven by broad macroeconomic forces and those associated with CRMs policies and regulatory interventions, while formally assessing their statistical relevance.

Our findings reveal three main results. First, connectedness is strongly state-dependent. Spillovers are substantially larger in the tails of the return distribution than at the median, indicating that commodity markets become significantly more interconnected during

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[3] According to IEA (2023a), the Democratic Republic of the Congo supplies 70% of the world's cobalt, China provides 60% of rare earth elements (REEs), and Indonesia supplies 40% of the world's nickel. Australia accounts for 55% of lithium mining, 25%. Moreover, China is expected to account for 80% of the announced additional copper production capacity by 2030 and to dominate refining capacity for key metals used in batteries, with 95% for cobalt and around 60% for lithium and nickel.

episodes of stress or exuberance. While crude oil remains an important shock transmitter under extreme conditions, energy transition metals—particularly base ETMs—have gained prominence as spillover sources, especially in the post-Covid-19 period.

Second, we document a structural shift in the configuration of commodity market linkages. Compared to the pre-Covid-19 period, the post-pandemic era is characterized by higher overall connectedness and a greater role for ETMs and gold in transmitting shocks to energy commodities and industrial metals. This evidence suggests a reordering of commodity market centrality consistent with the increasing macro-financial relevance of transition-related resources.

Third, the event study uncovers a pronounced asymmetry across market states. Policy announcements related to CRMs significantly affect connectedness primarily in the tails of the distribution, while their impact is limited under normal conditions. This evidence indicates that policy interventions and regulatory changes activate transmission mechanisms predominantly during extreme market episodes, reinforcing the importance of state-dependent econometric analysis.

Taken together, our results suggest that the energy transition is not only transforming patterns of commodity demand but is also altering the econometric structure and amplification dynamics of risk transmission across global commodity markets.

The rest of this paper is organized as follows: Section 2 presents the literature review on connectedness detection, Section 3 describes the data and methodology, Section 4 presents and discusses the empirical results, and Section 5 concludes. Finally, three Appendices report additional details, which can be found as Online Supplement.

2 Literature review

The study of financial and production networks shows that disruptions to specific nodes can propagate across the entire economy. This effect is particularly pronounced when certain nodes or sectors occupy disproportionately central positions within the network (Acemoglu et al., 2012; Carvalho, 2014). Moreover, as highlighted by Acemoglu et al. (2015), the magnitude of shocks plays a critical role in determining their propagation: once shocks exceed certain thresholds, network interactions amplify these disturbances, leading to heightened systemic fragility. In the context of commodity markets, structural shifts in demand and supply—such as those induced by the energy transition—may alter the centrality of specific commodities and thereby modify the transmission of shocks across the system.

A growing body of research further supports the use of network-based approaches for analyzing systemic risk and spillovers. For instance, Battiston et al. (2012); Battiston and Caldarelli (2013) emphasize how network structure can amplify financial shocks, while Bardoscia et al. (2017) investigate the mechanisms that lead to systemic instability. These insights suggest that changes in network topology, rather than solely the size of shocks, can materially influence aggregate outcomes.

Unlike trade networks, financial and commodity market networks are not directly observable, and the strength of connections across units must be estimated. Diebold and Yilmaz (2009) propose an h-step-ahead forecast error variance decomposition (FEVD) from a vector autoregression (VAR) model to quantify connectedness and spillover effects, capturing how much of the variability of one variable is explained by shocks to other variables. Later, Diebold and Yilmaz (2012); Diebold and Yılmaz (2014) extend this approach by proposing the usage of the *generalized* FEVD (GFEVD), which is invariant to the variables ordering and highlights both the strength and direction of spillovers (see also Koop et al., 1996; Pesaran and Shin, 1998, for more information on the generalized FEVD).[4]

Spillover effects based on GFEVD from VAR models have been widely studied in applications concerning financial markets (Casoli and Pedini, 2026; Diebold and Yilmaz, 2009; Greenwood-Nimmo et al., 2024) and commodity prices (Bastianin et al., 2023; Diebold et al., 2017). Other works include studies on petroleum markets (Baruník et al., 2015), non-ferrous metals and clean energy stocks (Wang et al., 2023; Chen et al., 2022a,b), as well as the interconnections between oil, non-energy commodities, and financial markets (Marobhe and Kansheba, 2023; Baruník and Kocenda, 2019). While these studies document substantial spillovers within and across commodity groups, they typically focus on mean-based transmission mechanisms and do not explicitly account for state-dependent amplification or structural changes in commodity centrality.

The standard VAR-based GFEVD method captures connectedness at the mean level but may overlook the heterogeneous propagation of large shocks relative to smaller ones, as well as tail-specific transmission mechanisms that emerge under extreme market conditions. Quantile VAR (QVAR) models address this limitation by allowing connectedness to vary across the conditional distribution of returns, thereby capturing spillover effects that are particularly relevant in the tails (Koenker, 2005; Cecchetti and Li, 2008). From a network perspective, tail-dependent connectedness is especially important, as amplification mechanisms are more likely to materialize when shocks are sufficiently large.

Examples using dynamic quantile connectedness include Chatziantoniou and Gabauer (2021), examining interest rate swaps, and Chatziantoniou et al. (2022), extending the approach to include green equity markets. However, applications to broad commodity systems remain limited, particularly in settings where structural shifts may alter the relative importance of individual assets within the network.

In a QVAR, a relevant assumption is that residuals are cross-sectionally uncorrelated. However, in practice, residuals are often correlated, and standard equation-by-equation quantile regression methods fail to account for cross-sectional interdependence, leading to inefficient or biased parameter estimates and unreliable predictions. To resolve this issue, Ando

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[4] Alternative approaches for evaluating connectedness are based on Granger-causality and Network VAR models (see e.g. Barigozzi and Brownlees, 2019; Barigozzi et al., 2022; Billio et al., 2012).

and Bai (2020); Ando et al. (2022) introduce the quantile factor VAR (QFVAR) model, which attributes residual correlation to common factors, isolates idiosyncratic shocks, and reduces potential estimation bias.

Against this background, our article contributes to the empirical literature on connectedness by applying the quantile factor vector autoregressive (QFVAR) framework proposed by Ando et al. (2022) to a broad system of metals and energy-related commodity markets. We jointly analyze energy transition metals, traditional energy resources, and other key commodities to assess whether the ongoing energy transition is associated with changes in spillover intensity and direction, particularly in the tails of the return distribution. By examining tail-specific connectedness while accounting for latent common factors, our analysis provides evidence on how structural shifts in commodity demand may reconfigure risk transmission across global commodity markets.

3 Data and methods

3.1 Data

According to the IMF Primary Commodity Price Index Technical Documentation, 16 minerals are classified as ETMs. Our dataset consists of the prices of seven commodities categorized as base ETMs (copper, aluminum, nickel, zinc, molybdenum, lead, and cobalt), three commodities categorized as precious ETMs (silver, platinum, and palladium), and six commodities categorized as other ETMs (silicon, manganese, chromium, rare earth elements, lithium, and vanadium). It also includes the prices of gold, industrial metals (iron and tin), and energy resources such as Newcastle coal, natural gas (Dutch TTF for the EU and Henry Hub for the US), and crude oil (WTI, Brent, and Dubai). The dataset includes commodity prices from June 2012 to November 2023, totaling 2,994 daily observations per commodity. Daily prices are converted to U.S. dollars and averaged weekly, resulting in 599 weekly observations per series. To account for inflation, the weekly averages are deflated using the interpolated U.S. Consumer Price Index (CPI), reflecting real prices. Subsequently, the real prices are normalized to their average prices in 2016, following the guidelines provided in the IMF Primary Commodity Price Index Technical Documentation.

Using these normalized weekly real prices, we construct eight indices (see Table 1 and Appendix A): ETM-B (base ETMs), ETM-P (precious ETMs), ETM-M (minor and other ETMs), Gold, INDMET (iron and tin), Coal, Nat Gas (natural gas for the EU and US), and Crude Oil (WTI, Brent, and Dubai).[5]

Figure 1 shows the weekly prices for eight indices. While most indices show slight increases, there is a notable surge in the prices of INDMET, Coal, and Nat Gas beginning

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[5] Each index is weighted by the share of individual commodities in global imports, ensuring that the combined weights for each index sum to 100%. The weighting scheme is sourced from the IMF Primary Commodity Price Index Technical Documentation. See `4https://www.imf.org/en/Research/commodity-prices`.

in 2020, driven by the effects of Covid-19.

Table 1: Commodity Weights by Index Type

Index	**Commodity**	**Weight (%)**	**Currency**
ETM-B	Copper	47.17	USD
	Aluminum	21.87	USD
	Nickel	9.22	USD
	Zinc	8.39	USD
	Molybdenum	7.29	USD
	Lead	5.23	USD
	Cobalt	0.83	USD
ETM-P	Silver	48.28	USD
	Platinum	30.34	USD
	Palladium	21.38	USD
ETM-M	Silicon	39.22	USD
	Manganese	28.46	USD
	Chromium	24.62	CNY
	Rare Earth (REE)	3.85	CNY
	Lithium	2.31	CNY
	Vanadium	1.54	USD
Gold	Gold	100.00	USD
INDMET	Iron Ore	94.00	USD
	Tin	6.00	USD
Coal	Newcastle Coal	100.00	USD
Nat Gas	Dutch TTF	50.00	EUR
	Henry Hub	50.00	USD
Crude Oil	Dubai Fateh	33.00	USD
	WTI	34.00	USD
	Brent Forties	33.00	EUR

The spillover index in this paper is constructed using the GFEVD matrix obtained from a quantile factor VAR estimated on weekly percentage log-returns. In quantile factor models, factor estimation can be distorted when extreme observations cause factors to capture idiosyncratic variation rather than common movements across variables, potentially biasing the identification of systemic spillovers. To mitigate this issue, we adjust for outliers and standardize weekly returns to ensure comparability across series.[6] Descriptive statistics are reported in Appendix A.

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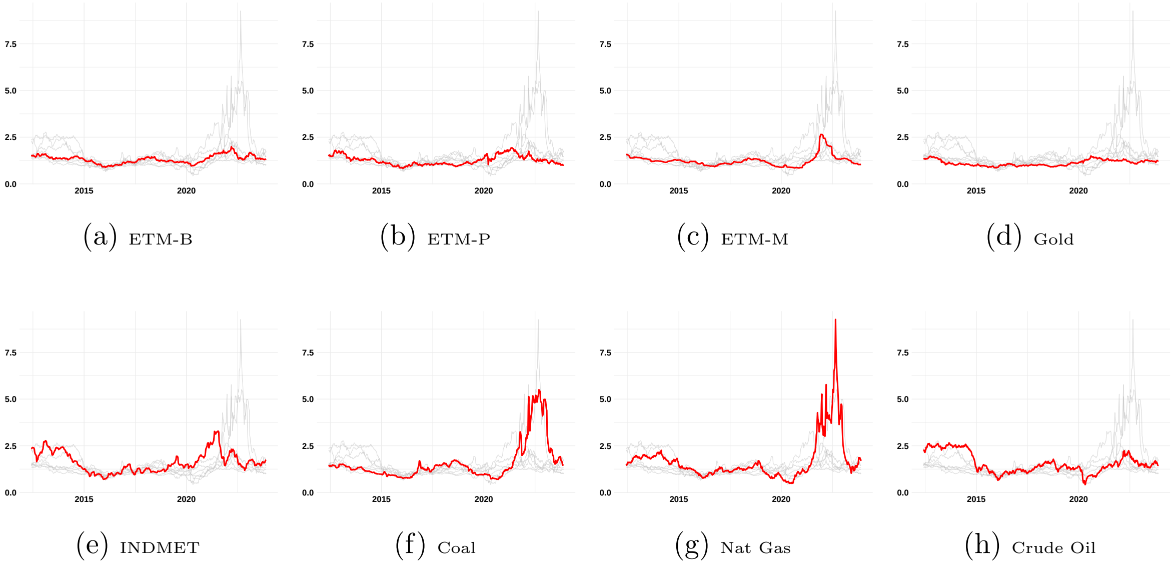
[6] We remove some extreme observations following the approach of McCracken and Ng (2016). Outliers are defined as values beyond median ± 10 × IQR, where the IQR is the range between the 25th and 75th percentiles. These outliers are replaced with zero: ETM-B (0), ETM-P (1), ETM-M (7), Gold (0), INDMET (0), Coal (4), Nat Gas (0), and Crude Oil (0). After this adjustment, each series is standardized by subtracting its mean and dividing by its standard deviation.

Figure 1: Weekly Prices



(a) ETM-B (b) ETM-P (c) ETM-M (d) Gold

(e) INDMET (f) Coal (g) Nat Gas (h) Crude Oil

Note: The y-axis represents the price normalized by the average price in 2016.

3.2 The Quantile Factor VAR

We follow Ando et al. (2022) and rely on a QFVAR model to incorporate common factors that capture latent macroeconomic comovements in commodities. The factor structure of the model helps to mitigate the impact of cross-sectional correlation in the error terms, allowing for equation-by-equation quantile estimation. Consider a standard VAR model with p lags, denoted as VAR(p), where the vector of intercepts is omitted for simplicity of notation:

$$\mathbf{x_t} = \sum_{\mathbf{j=1}}^{\mathbf{p}} \mathbf{A_j x_{t-j}} + \mathbf{u_t}, \quad t = 1, \dots, T, \tag{1}$$

In this model, $\mathbf{x_t}$ is an $m \times 1$ vector of variables and $\mathbf{A_j}$ represents the j-th $m \times m$ autoregressive coefficients matrix. The residuals $\mathbf{u_t}$ form an $m \times 1$ zero-mean, serially uncorrelated vector with a positive-definite $m \times m$ covariance matrix $\mathbf{\Sigma}$, that is, $\mathbf{u_t} \sim (0, \mathbf{\Sigma})$. The residuals have a factor representation such that:

$$\mathbf{u_t} = \mathbf{\Lambda f_t} + \upsilon_{\mathbf{t}} \tag{2}$$

where $\mathbf{\Lambda}$ is a $m \times f$ matrix of factor loadings with $f < m$, $\mathbf{f_t}$ is a $f \times 1$ vector of common factors, and $\upsilon_{\mathbf{t}}$ is a $m \times 1$ vector idiosyncratic components. The idiosyncratic shocks, $\upsilon_{\mathbf{t}}$ are assumed to be cross-sectional uncorrelated and normal distrubuted as $\upsilon_{\mathbf{t}} \sim N(0, \Omega)$, where Ω is a diagonal $m \times m$ covariance matrix, defined as $\mathbf{\Omega} = diag(\omega_{11}, \omega_{22}, ...\omega_{mm})$.

By combining Equations (1) and (2), we derive the factor VAR model with f factors, denoted as FVAR(p, f), as follows:

$$\mathbf{x_t} = \sum_{\mathbf{j=1}}^{\mathbf{p}} \mathbf{A_j x_{t-j}} + \mathbf{\Lambda f_t} + \upsilon_{\mathbf{t}}, \quad t = 1, \dots, T. \tag{3}$$

To account for tail dependence, the QFVAR model evaluates the system at the τ-th conditional quantile, represented as QFVAR(p, τ, f), which modifies Equation (3) as follows:[7]

$$\mathbf{x_t} = \sum_{\mathbf{j=1}}^{\mathbf{p}} \mathbf{A_{j(\tau)} x_{t-j}} + \mathbf{\Lambda_{(\tau)} f_t} + \upsilon_{\mathbf{t}(\tau)}, \quad t = 1, \dots, T, \tag{4}$$

where $\tau \in (0, 1)$ denotes the quantile level.

In the QFVAR analysis, the number of factors can vary across quantiles. We select the optimal number of factors by minimizing the information criterion proposed by Ando and Bai (2020). For further details on the QFVAR estimation and the optimal number of factors, see Appendix B.

3.3 Generalized Forecast Error Variance Decomposition

For a given quantile, the GFEVD measures the proportion of the h-step-ahead forecast error variance of the j-th variable, x_{jt}, attributed to the i-th idiosyncratic shock, $\upsilon_{it(\tau)}$, for $i, j = 1, 2, \dots, m$. Assuming that $Q_\tau(\upsilon_{\mathbf{t}(\tau)} | \mathcal{F}_{t-1}) = 0$, where $\mathcal{F}_{t-1}$ denotes the information set available at time $t-1$, and Q_τ represents the conditional quantile operator at quantile τ, the Wold representation is:

$$\mathcal{Q}_\tau(\mathbf{x_t} | \mathcal{F}_{\mathbf{t-1}}) = \sum_{\mathbf{j=0}}^{\infty} \mathbf{B_{j(\tau)}} \upsilon_{\mathbf{t-j}(\tau)} + \sum_{\mathbf{j=0}}^{\infty} \mathbf{C_{j(\tau)} f_{t-j}},$$

where $\mathbf{B_{j(\tau)}} = \mathbf{A_{1(\tau)} B_{j-1(\tau)}} + \mathbf{A_{2(\tau)} B_{j-2(\tau)}} \cdots$ for $j = 1, 2 \cdots$, with $\mathbf{B_{0(\tau)}} = \mathbf{I_m}$, and $\mathbf{C_{j(\tau)}} = \mathbf{B_{j(\tau)} \Lambda_{(\tau)}}$. The vector of forecast errors associated with the prediction $\mathbf{x_{t+h}}$ conditional on the information at time $t-1$ and on the common factors is given by:

$$\mathbf{V_{t+h(\tau)}} = \sum_{\iota=\mathbf{0}}^{\mathbf{h}} \mathbf{B}_{\iota(\tau)} \upsilon_{\mathbf{t+h}-\iota(\tau)}.$$

Given that the GFEVD is invariant to the ordering of the innovations, the contribution of the i-th idiosyncratic shock $\upsilon_{it(\tau)}$ to the h-step ahead GFEVD of the j-th variable in $\mathbf{x_t}$ at quantile τ is given by:

$$GFEVD(x_{jt}; V_{it(\tau),h}) = \frac{\omega_{ii}^{-1} \sum_{\iota=0}^{h} \left(\mathbf{e_j'} \mathbf{B}_{\iota(\tau)} \mathbf{\Omega e_i}\right)^2}{\sum_{\iota=0}^{h} \mathbf{e_j'} \mathbf{B}_{\iota(\tau)} \mathbf{\Omega B'}_{\iota(\tau)} \mathbf{e_j}}$$

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[7] When exposing the empirical results, the QVAR model with p lags at the τ-th conditional quantile is denoted as QVAR(p, τ).

where $\upsilon_{\mathbf{t}(\tau)} \sim i.i.d(\mathbf{0}, \mathbf{\Omega})$ with $\mathbf{\Omega} = diag(\omega_{11}, \omega_{22}, \cdots \omega_{mm})$, $\iota = 0, 1, \cdots h$ and $i, j = 1, \cdots m$, $\mathbf{e_i}$ is an $m \times 1$ selection vector with a 1 in the i-th position and zeros elsewhere.

3.4 Connectedness measurement

Building on the GFEVD framework, we now introduce measures to quantify connectedness within the system, focusing on how idiosyncratic shocks propagate at different quantiles. For the baseline approach, we refer the reader to Diebold and Yilmaz (2012); Diebold and Yılmaz (2014).

The metric $\breve{\vartheta}^{(H)}_{j\leftarrow i,(\tau)} = GFEVD(x_{jt}; V_{it(\tau),h})$ captures the spillover of idiosyncratic shocks from variable i to variable j at the τ-th quantile over the h-step horizon. These spillovers are organized into the h-step $m \times m$ spillover matrix for $(\mathbf{x_t})$, evaluated at the τ-th conditional quantile:

$$\mathcal{A}^{(H)}_{(\tau)} = \begin{bmatrix} \breve{\vartheta}^{(H)}_{1\leftarrow 1,(\tau)} & \breve{\vartheta}^{(H)}_{1\leftarrow 2,(\tau)} & \cdots & \breve{\vartheta}^{(H)}_{1\leftarrow m,(\tau)} \\ \breve{\vartheta}^{(H)}_{2\leftarrow 1,(\tau)} & \breve{\vartheta}^{(H)}_{2\leftarrow 2,(\tau)} & \cdots & \breve{\vartheta}^{(H)}_{2\leftarrow m,(\tau)} \\ \vdots & \vdots & \ddots & \vdots \\ \breve{\vartheta}^{(H)}_{m\leftarrow 1,(\tau)} & \breve{\vartheta}^{(H)}_{m\leftarrow 2,(\tau)} & \cdots & \breve{\vartheta}^{(H)}_{m\leftarrow m,(\tau)} \end{bmatrix}$$

The standard VAR-based GFEVD contains on cross-sectionally correlated disturbances, which can lead to the row sums of the GFEVD table exceeding 100% and is generally solved by imposing a row-sum normalization. However, in the GFEVD derived from QFVAR framework, the assumption of a diagonal covariance matrix $\mathbf{\Omega}$ ensures that the row sums of the GFEVD table remains bounded between 0 and 1, satisfying:

$$\sum_{j=1}^{m} \breve{\vartheta}^{(H)}_{i\leftarrow j,(\tau)} = 1$$

and for the entire system:

$$\sum_{i=1,j=1}^{m} \breve{\vartheta}^{(H)}_{i\leftarrow j,(\tau)} = m.$$

The total spillover from the system to variable i, denoted as "FROM", measures how much variable i is affected by shocks from other variables:

$$FROM^{(H)}_{i\leftarrow\bullet,(\tau)} = \sum_{j=1,j\neq i}^{m} \breve{\vartheta}^{(H)}_{i\leftarrow j,(\tau)}.$$

Similarly, the total spillover from variable i to the system, denoted as "TO", quantifies the impact of shocks from i on other variables:

$$TO^{(H)}_{\bullet\leftarrow i,(\tau)} = \sum_{j=1,j\neq i}^{m} \breve{\vartheta}^{(H)}_{j\leftarrow i,(\tau)}.$$

Note that $TO^{(H)}_{\bullet\leftarrow i,(\tau)}$ can be greater than or less than one. The net directional connectedness for variable i, denoted as "NET", captures whether variable i is primarily a shock receiver or contributor:

$$NET^{(H)}_{i\leftarrow i,(\tau)} = TO^{(H)}_{\bullet\leftarrow i,(\tau)} - FROM^{(H)}_{i\leftarrow\bullet,(\tau)}.$$

Finally, the total connectedness index (TCI) at the τ-th conditional quantile provides an aggregate measure of spillovers across the system (see e.g. Chatziantoniou et al., 2021; Gabauer, 2021). It ranges between 0 and 1 and is defined as:

$$TCI^{(H)}_{(\tau)} = \frac{\sum_{i=1}^{m} FROM^{(h)}_{i\leftarrow\bullet,(\tau)}}{m-1}$$

The spillover index quantifies system interconnectedness as the percentage of off-diagonal elements in the GFEVD matrix, capturing cross-variable spillovers relative to self-driven shocks.

4 Empirical results

4.1 Model selection and factor analysis

We select the optimal lag order of the VAR by minimizing the Schwarz Information Criterion (SIC), resulting in a $p = 1$ order, which is uniformly applied to all our models.

Table 2 reports the results of the information criterion proposed by Ando and Bai (2020) for choosing the number of factors, for both QFVAR(p, τ, f) and FVAR(p, f) models across different τ levels and factor selections. In the QFVAR models, the optimal number of factors increases to 3 at the tail quantiles ($\tau = 0.1$ and $\tau = 0.9$), while a single factor is sufficient for intermediate quantiles.

The increase in the optimal number of factors at the tail quantiles suggests that extreme market conditions are characterized by a richer latent dependence structure. While a single common factor is sufficient to capture co-movements under normal conditions, stress episodes appear to activate additional common drivers. This pattern is consistent with the notion of state-dependent amplification in commodity networks, where extreme shocks trigger broader synchronization across asset classes. The higher-dimensional factor structure in the tails, therefore, indicates that common shocks become more pervasive when markets depart from their median regime.

Incorporating factors significantly reduces residual correlations, with the sum of absolute residual correlations decreasing from 4.06 in the QVAR model to 3.08 in the QFVAR model. These results highlight the effectiveness of factor inclusion in capturing common latent movements and mitigating cross-sectional residual correlations. For a visual screening of the absolute residual correlations between the QVAR and the QFVAR model, we refer

Table 2: Ando and Bai (2020) Information Criterion

	QFVAR(1,τ,f)									FVAR(1,f)
f	$\tau = 0.1$	$\tau = 0.2$	$\tau = 0.3$	$\tau = 0.4$	$\tau = 0.5$	$\tau = 0.6$	$\tau = 0.7$	$\tau = 0.8$	$\tau = 0.9$	
1	-1.85	**−1.38**	**−1.22**	**−1.13**	**−1.11**	**−1.13**	**−1.22**	**−1.41**	-1.88	**−0.17**
2	-1.90	-1.36	-1.11	-1.02	-0.99	-1.02	-1.13	-1.39	-1.94	-0.16
3	**−1.98**	-1.29	-1.01	-0.89	-0.87	-0.89	-1.04	-1.32	**−1.98**	-0.15

Notes: Bold values indicate the optimal number of factors according to the Ando and Bai (2020) information criterion. A maximum of three factors is considered.

the reader to Appendix C.

From an economic perspective, the reduction in residual correlations is not merely a statistical refinement. By isolating common latent components, the QFVAR framework allows the spillover measures to reflect predominantly idiosyncratic transmission rather than mechanical co-movement driven by shared global shocks. This distinction is particularly important in commodity systems, where broad macroeconomic forces—such as global demand cycles or inflationary pressures—can induce spurious connectedness if not properly accounted for. The factor adjustment, therefore, enhances the interpretability of the estimated spillovers as genuine network effects.

Factor analysis. Table 3 displays the R^2 values from regressions of each of the eight individual commodity returns on the first three factors at the $\tau = 0.1$, $\tau = 0.5$ and $\tau = 0.9$ quantiles. The first factor primarily loads on ETM-B, ETM-P, and Gold, suggesting the presence of a transition-sensitive common component that links ETMs with traditional safe-haven assets. This factor appears to capture broad macro-financial forces affecting transition-related resources. The second factor is associated with ETM-P and Gold in the tails but shifts toward Coal and Natural Gas at the median, indicating that the composition of common shocks changes across market states. Under extreme conditions, precious metals co-move more strongly with transition metals, whereas in normal periods, fossil-related commodities regain relevance within the latent structure. The third factor predominantly loads on ETM-M, particularly at the median, pointing to a more segmented component related to minor transition metals that may reflect supply-specific dynamics.

Overall, the factor structure reveals that energy transition metals are not isolated assets but share common latent components with both traditional energy commodities and precious metals. Importantly, the configuration of these common components varies across quantiles, reinforcing the relevance of a state-dependent modeling framework for assessing commodity market connectedness during the energy transition.

Table 3: Pairwise Regression of Variables on Factors

R^2	Factor	ETM-B	ETM-P	ETM-M	Gold	INDMET	Coal	Nat Gas	Crude Oil
$\tau = 0.1$	Factor 1	0.312	0.318	0.011	0.221	0.138	0.127	0.065	0.173
	Factor 2	0.090	0.139	0.007	0.229	0.008	0.125	0.071	0.056
	Factor 3	0.004	0.029	0.218	0.005	0.216	0.043	0.064	0.061
$\tau = 0.5$	Factor 1	0.388	0.676	0.002	0.506	0.059	0.067	0.043	0.109
	Factor 2	0.000	0.061	0.025	0.128	0.000	0.205	0.320	0.126
	Factor 3	0.036	0.011	0.672	0.005	0.023	0.068	0.000	0.004
$\tau = 0.9$	Factor 1	0.270	0.333	0.023	0.249	0.167	0.082	0.060	0.146
	Factor 2	0.095	0.211	0.006	0.264	0.015	0.089	0.087	0.029
	Factor 3	0.034	0.021	0.126	0.001	0.098	0.000	0.100	0.146

Notes: The factors are extracted from QFVAR(1,τ,3) models at quantile levels $\tau \in \{0.1, 0.5, 0.9\}$. Each variable is regressed separately on each extracted factor using OLS, and the table reports the corresponding R^2 values.

4.2 Full sample static analysis

In the static analysis, the connectedness indices are estimated using the full sample, covering the period from June 2012 to November 2023. Table 4 presents the Connectedness Table for the QFVAR(1, 0.5, 1) model. The total connectedness among all indices remains relatively low at 13.38. Gold, as a safe-haven asset, acts as both a major transmitter (34.76) and a receiver of shocks (27.17). ETM-B, ETM-P, and Crude Oil exhibit high levels of both shock transmission and reception, indicating that they occupy relatively central positions within the commodity network. However, ETM-B and ETM-P emerge as the largest net shock receivers, with net measures of -2.75 and -4.97, respectively. This suggests that, in the median regime, transition metals are still predominantly influenced by broader commodity dynamics rather than acting as primary sources of systemic disturbances.

The relatively low level of total connectedness (TCI = 13.38) suggests that, on average, commodity markets retain a substantial degree of idiosyncratic behavior. In contrast to periods of systemic stress documented in the broader connectedness literature, the median regime is characterized by limited cross-market amplification. This finding implies that structural interdependencies among commodities are present but not dominant under normal conditions, consistent with a network configuration in which common shocks remain partially contained.

The rising demand for energy transition metals (ETMs) does not mechanically displace fossil fuels or traditional industrial metals. Instead, the energy transition generates a complex combination of substitution and complementarity effects. While transition metals gain prominence in renewable technologies, fossil fuels and industrial metals remain critical inputs in infrastructure, transportation, and manufacturing. Oil and industrial metals continue to play central roles in both real economic activity and financial portfolios, whereas gold maintains its distinct role as a safe-haven asset. As a result, commodity demand structures are

Table 4: Connectedness Table: QFVAR(1, 0.5, 1), $h = 4$

	ETM-B	**ETM-P**	**ETM-M**	**Gold**	**INDMET**	**Coal**	**Nat Gas**	**Crude Oil**	**FROM**
ETM-B	83.13	4.96	1.89	8.35	0.85	0.27	0.04	0.51	16.87
ETM-P	4.31	74.07	0.75	13.34	2.68	0.69	0.55	3.60	25.93
ETM-M	0.37	0.79	97.14	0.01	0.25	0.02	0.50	0.93	2.86
Gold	7.31	9.18	0.08	72.83	2.29	1.71	0.76	5.83	27.17
INDMET	0.65	3.12	0.15	3.05	92.53	0.26	0.15	0.10	7.47
Coal	0.35	0.52	0.03	2.12	0.18	92.47	4.07	0.26	7.53
Nat Gas	0.51	1.02	0.51	0.92	0.13	3.74	91.72	1.45	8.28
Crude Oil	0.61	1.38	0.79	6.97	0.10	0.04	1.01	89.10	10.90
TO	14.12	20.96	4.19	34.76	6.49	6.73	7.08	12.68	107.01
NET	-2.75	-4.97	1.33	7.59	-0.98	-0.80	-1.20	1.78	**TCI = 13.38**

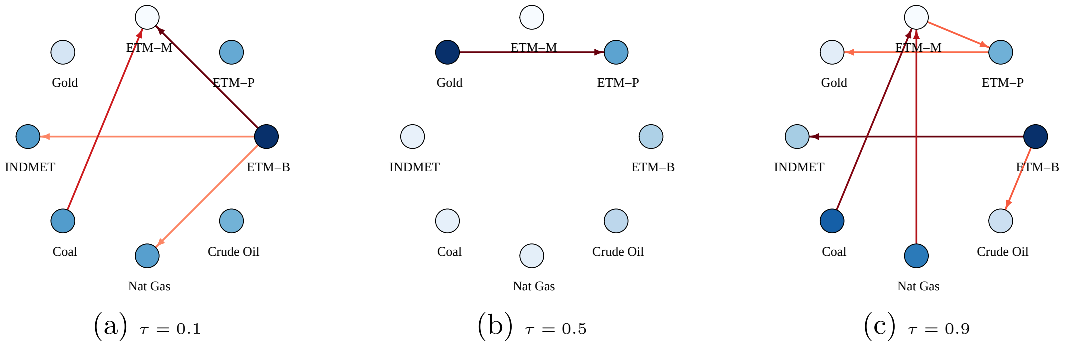
jointly shaped by technological change, industrial production, and financial portfolio allocation. These overlapping channels generate spillover patterns that can shift depending on whether complementarity or substitution effects dominate, thereby altering the direction and intensity of risk transmission across markets.

Our results at $\tau = 0.5$ align with the existing literature on commodity spillover effects. Specifically, natural gas is identified as a net recipient of connectedness from other commodities (Diebold et al., 2017), while non-ferrous metals (ETM-B and ETM-P) are net receivers compared to crude oil (Umar et al., 2022; Wang et al., 2023). Additionally, our findings are consistent with quantile-based studies indicating that crude oil serves as a larger driver of spillovers than gold, particularly in the tails rather than across all quantiles (see Chen et al., 2022a, and Appendix C). While our median-quantile findings are broadly consistent with prior evidence, the QFVAR framework allows us to disentangle common global factors from idiosyncratic spillovers. This distinction suggests that the observed net receiver status of ETMs at the median quantile reflects genuine network positioning rather than shared exposure to global demand or macroeconomic shocks.

Figure 2 presents the network visualization of spillover effects for the QFVAR(1, $\tau = 0.5$, f) model. Compared to the extreme quantiles ($\tau = 0.1$ and $\tau = 0.9$), spillovers are weaker at the median quantile ($\tau = 0.5$). At the tails, spillover effects occur both within the ETMs (ETM-P, ETM-B, and ETM-M) and between the ETMs and other commodities. Specifically, ETM-M receives shocks from energy commodities (Coal, Nat Gas), while ETM-B acts as a major transmitter to other commodities. Notably, the role of gold reverses across quantiles. While it acts as a net shock transmitter at the median quantile, it becomes a net receiver in the upper tail ($\tau = 0.9$). This reversal reflects the classical safe-haven behavior of gold: during extreme positive or negative commodity shocks, gold absorbs disturbances originating in other markets rather than initiating them. The quantile-specific reversal underscores the importance of state-dependent modeling in accurately capturing commodity network dynamics.

The emergence of stronger bidirectional spillovers at the tails indicates that extreme market conditions activate additional transmission channels within the commodity network. In these regimes, ETMs are no longer purely reactive assets but become more deeply embedded in cross-commodity feedback loops. This pattern is consistent with network amplification mechanisms, where large shocks increase synchronization across nodes and elevate the systemic relevance of assets that are otherwise peripheral in normal times.

Figure 2: Network Visualization of spillover

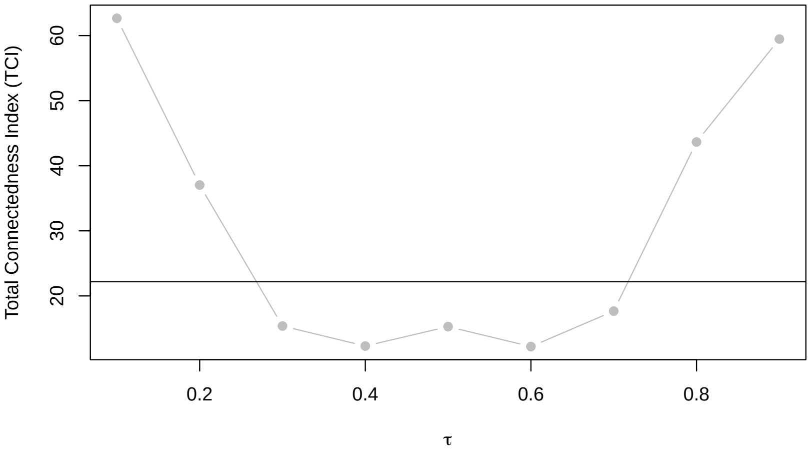


(a) $\tau = 0.1$ (b) $\tau = 0.5$ (c) $\tau = 0.9$

Notes: This figure highlights the main pairwise spillovers between commodities. The arrow direction represents the net spillover direction. Node color reflects the total magnitude of shocks transmitted by each commodity (darker nodes indicate larger shocks). Edge color indicates the strength of the spillover between nodes (darker edges indicate stronger spillovers, lighter edges weaker).

Figure 3 displays the evolution of the TCI across different quantiles, highlighting pronounced state dependence in commodity spillovers. At the extremes ($\tau = 0.1$ and $\tau = 0.9$), the TCI rises markedly, indicating that extreme returns are associated with substantially stronger cross-market transmission. In these regimes, shocks are less likely to remain localized and instead propagate across multiple commodity groups. By contrast, at the median quantile ($\tau = 0.5$), connectedness declines, suggesting that normal (or optimistic) market conditions are characterized by relatively segmented dynamics. This nonlinear pattern provides direct evidence of tail-specific amplification, consistent with network models in which systemic fragility increases once shocks exceed certain thresholds.

Figure 3: Total Connectedness Index across Quantiles



Note: The curve represents the total connectedness index (TCI) evaluated at the τ-th conditional quantile for the QFVAR(1,τ,f) model with a forecast horizon of 4. The number of factors for each quantile is optimally selected based on the information criterion in Ando and Bai (2020). For comparison, the solid line represents the VAR(1) model with a forecast horizon of 4.

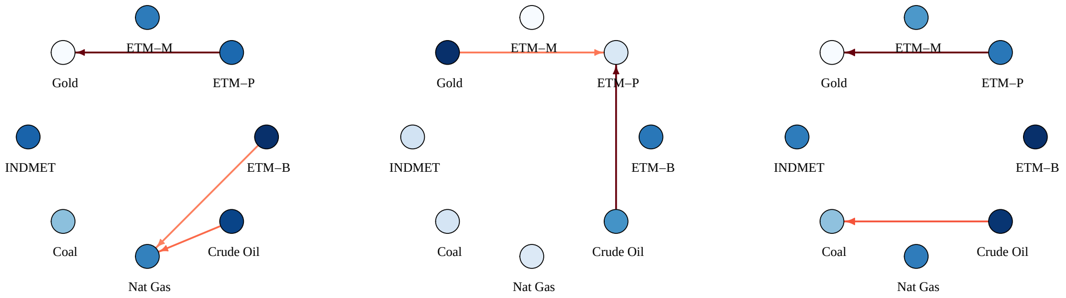
4.3 Pre- and post-Covid-19 analysis

We now examine spillover dynamics during the pre- and post-Covid-19 periods. The pre-Covid-19 period spans from June 8, 2012, to February 28, 2020, while the post-Covid-19 sample extends from March 6, 2020, to November 22, 2023.

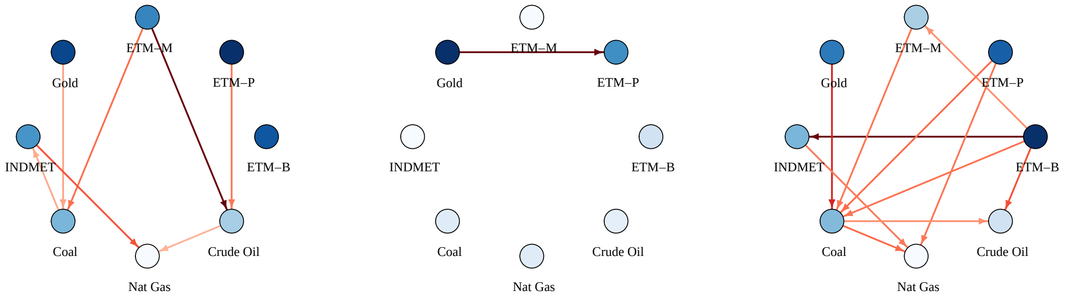
The Covid-19 pandemic introduced a significant exogenous shock to the global economy and commodity markets. Government-imposed lockdowns, travel restrictions, and industrial shutdowns caused major disruptions on both the supply and demand sides. Firms experienced material shortages, while demand for many goods declined sharply. These effects were fundamentally different from those of typical economic downturns, as they originated from public health interventions rather than internal market dynamics. In comparison to the pre-Covid-19 period, the post-Covid-19 era can be seen as a broader phase of economic restructuring. This phase encompasses both the immediate response to the crisis and the gradual recovery, shaped by evolving supply chains, shifting industrial priorities, and a growing emphasis. on green investment. These structural changes are particularly relevant for ETMs, whose strategic importance in supporting low-carbon technologies has gained increased recognition.

Figure 4 depicts the network visualization of spillover effects for the QFVAR(1, $\tau = 0.5$, f) models. During the Pre-Covid period, Crude Oil functioned as a primary shock transmitter to other commodities, while ETM-P channeled shocks to Gold, particularly in the tails. In the Post-Covid period, the ETMs emerged as dominant spillover sources, amplifying their impact on other commodities at the tails, despite relatively weak intra-group

Figure 4: Network Visualization of spillover



(a) Pre-Covid $\tau = 0.1$ (b) Pre-Covid $\tau = 0.5$ (c) Pre-Covid $\tau = 0.9$



(d) Post-Covid $\tau = 0.1$ (e) Post-Covid $\tau = 0.5$ (f) Post-Covid $\tau = 0.9$

Notes: This figure highlights the main pairwise spillovers between commodities. The arrow direction represents the net spillover direction. Node color reflects the total magnitude of shocks transmitted by each commodity (darker nodes indicate larger shocks). Edge color indicates the strength of the spillover between nodes (darker edges indicate stronger spillovers, lighter edges weaker).

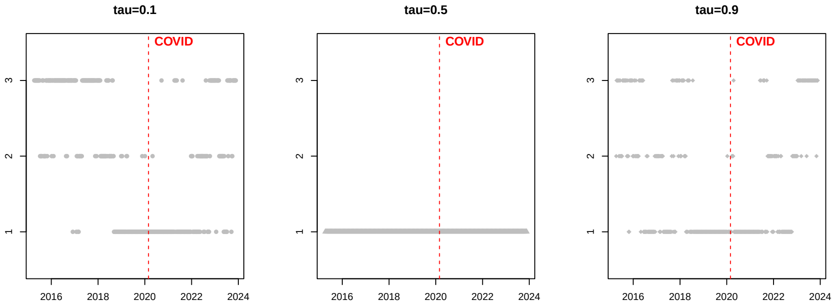
spillovers. Specifically, energy commodities (Coal, Nat Gas, and Crude Oil) and INDMET have increasingly become recipients of shocks from the ETMs and Gold. Note that the post-Covid period includes both the ongoing effects of the pandemic and phases of economic recovery. This makes it a transitional phase with changing market conditions. Because of this, and since it is difficult to clearly separate the shock-impact period from the recovery period, the results for this timeframe should be interpreted with caution. They mainly provide a general view of how the economy and connectedness patterns have changed before and after the onset of Covid-19.

4.4 Dynamic analysis

To analyze the temporal dynamics of the spillover effect, this section estimates connectedness using a 150-period rolling window approach. The number of factors is dynamically determined for each period based on the Information Criterion proposed by Ando and Bai (2020).

Figure 5 illustrates the optimal number of factors across time and quantiles. The grey horizontal dots indicate the optimal number of factors, while the red vertical line marks the onset of Covid-19. A single factor is consistently identified as optimal at the median quantile ($\tau = 0.5$), whereas the tails require additional factors to account for latent common movements.

Figure 5: Optimal Number of Factors

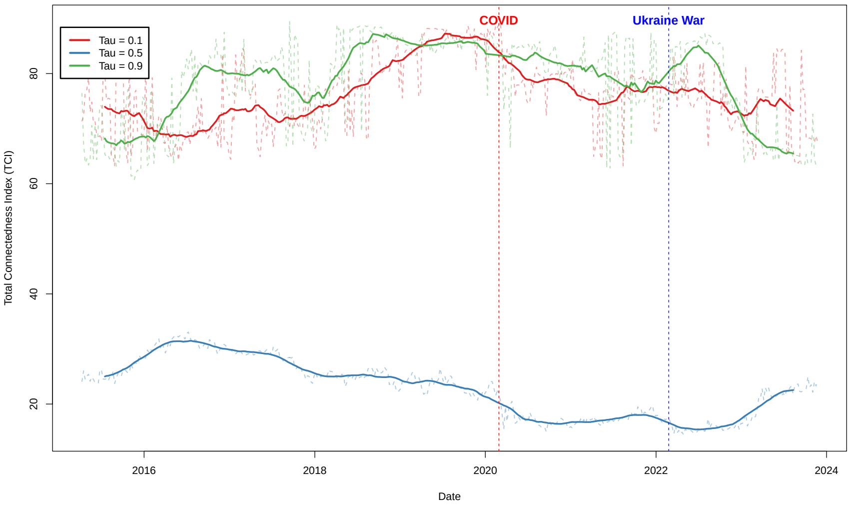


Notes: This figure shows the evolution of the optimal number of factors over time. The y-axis indicates the optimal number of factors (ranging from 1 to 3). The vertical red line marks the onset of Covid-19. As the number of factors increases, the model may capture idiosyncratic features rather than comovements across variables, potentially leading to a singularity problem. In such cases, we assume that a single factor is sufficient to capture the comovements. For the 451 rolling windows, these adjustments were applied to two rolling windows for $\tau = 0.1$ and 22 rolling windows for $\tau = 0.9$.

Notably, at the lower tail ($\tau = 0.1$), the post-Covid period exhibits a higher prevalence of a single optimal factor. This pattern suggests that extreme downside movements became increasingly driven by a dominant common component, consistent with heightened market synchronization during systemic stress. In such regimes, idiosyncratic commodity-specific shocks appear to be overshadowed by global risk factors, reflecting a compression of the network structure and stronger co-movement across markets.

Figure 6 presents the TCI over time for QFVAR$(1, \tau, f)$ models, with the period following the onset of Covid-19 marked by a vertical red line and the start of the Ukraine war indicated by a vertical blue line. Connectedness is notably higher at the tails of the return distribution. The time-varying evolution of the TCI reveals that commodity interconnectedness is not constant but evolves in response to major macroeconomic and geopolitical shocks. In particular, the widening gap between tail and median connectedness during crisis episodes indicates that systemic risk materializes primarily through extreme return realizations. This nonlinear behavior underscores the importance of modeling state-dependent spillovers in the context of the energy transition.

Figure 6: TCI Over Time for QFVAR(1, τ, f) Models



Notes: The plot depicts the Total Connectedness Index (TCI) over time for QFVAR(1, τ,f) models with quantiles $\tau = 0.1$, $\tau = 0.5$, and $\tau = 0.9$. The forecast horizon is set to 4, and the number of factors is dynamically selected based on the optimal factor model shown in Figure 5. Dashed curves represent dynamic connectedness at quantiles 0.1, 0.5, and 0.9, while solid curves show the corresponding 30-period moving averages. The vertical red line marks the onset of Covid-19, while the vertical blue line indicates the start of the Russia–Ukraine war.

The sharp contraction of economic activity in early 2020, both in the United States and the European Union, coincided with an abrupt increase in cross-commodity spillovers. The sudden halt in industrial production, disruptions in global supply chains, and unprecedented fiscal and monetary interventions created a common macroeconomic shock that propagated across energy and metal markets. The prolonged recovery phase further sustained elevated interconnectedness, reflecting persistent uncertainty and synchronized adjustments across commodity sectors.

The TCI at the upper tail ($\tau = 0.9$) remained persistently elevated from 2020 through early 2022, indicating that extreme positive return episodes were accompanied by intensified cross-market transmission. This pattern suggests that recovery-driven price increases and supply-side constraints generated upward spillover cascades across commodities. Around 2022, the sharp surge in upper-tail connectedness coincides with the Russia–Ukraine war, which amplified energy price volatility and reinforced the systemic linkage between fossil fuels and energy transition metals. The dominance of upper-tail connectedness during this period indicates that the commodity network became particularly sensitive to positive price shocks, consistent with a regime characterized by greenflation pressures and geopolitical supply risk.

In contrast, the TCI at the lower tail ($\tau = 0.1$) remained comparatively subdued during the same period. This asymmetry suggests that the dominant transmission channel in the post-pandemic environment operated through price increases rather than collapses. While downside spillovers were present during the initial pandemic shock, subsequent dynamics were primarily characterized by upward pressure driven by supply bottlenecks, energy market disruptions, and heightened demand for transition-related inputs.

Finally, the confidence intervals of the TCI associated with Figure 6, derived with bootstrap techniques, are presented in Figure 7. At the median quantile ($\tau = 0.5$), spillovers of shocks leading to both positive and negative returns are estimated at an average level. In this case, spillovers remain low, and confidence intervals are wider, reflecting greater uncertainty. In contrast, at the extremes ($\tau = 0.1$ and $\tau = 0.9$), spillover effects associated with extreme negative or positive returns are estimated with greater sensitivity to tail dynamics, resulting in narrower confidence intervals. The comparatively narrower confidence intervals at the tails indicate that extreme-state connectedness is estimated with greater precision during periods of heightened spillovers. This reinforces the interpretation that tail dynamics are not statistical artifacts but reflect economically meaningful transmission regimes.

Overall, the dynamic analysis reveals a structural shift in the commodity network following Covid-19. Spillovers not only intensified but became increasingly concentrated in the upper tail of the return distribution, highlighting the growing systemic relevance of energy and transition-related commodities. These findings suggest that the energy transition unfolds within a highly state-dependent network, where extreme events activate stronger cross-market amplification mechanisms and alter the hierarchy of commodity centrality.

Figure 7: TCI Over Time for Different Quantiles

Notes: The plot depicts the confidence intervals derived using a bootstrap-based approach, as described in Greenwood-Nimmo et al. (2024). The mean TCI and 95% confidence intervals are computed from bootstrap-estimated TCI samples, while the original TCI is calculated directly from the observed dataset. The number of factors is consistently set to 1 across all rolling windows and quantiles.

4.5 Event study

We follow the approach developed by Greenwood-Nimmo et al. (2024) to identify events that drive increases in spillovers. An event is considered significant when the probability that spillovers rise shortly after the announcement exceeds 90%.[8] The event-based framework allows us to assess whether policy interventions act as catalysts that activate latent transmission channels within the commodity network. In the context of the energy transition, policy announcements may alter expectations regarding future supply conditions, demand prospects, or regulatory constraints, thereby affecting the perceived centrality of ETMs within the broader commodity system.

The QFVAR model estimated in the previous sections emphasizes spillovers driven by idiosyncratic shocks while filtering out common macroeconomic fluctuations. For this reason, we abstract from broad global macroeconomic events and instead focus on policy announcements directly related to critical raw materials and ETMs. This approach allows us to evaluate whether transition-related regulatory and strategic interventions generate measurable changes in spillover intensity beyond those driven by general business cycle fluctuations.

Policy announcements are obtained from the IEA Policies database, which reports the announcement dates of policy measures related to the energy transition, energy efficiency, and associated technologies and resources.[9] These policies include funding programs, regulatory measures, government strategies, and international cooperation agreements implemented between 2012 and 2023. Since policy processes often unfold over multiple stages (e.g., proposal, approval, implementation), we use the date of the initial announcement. The event study should therefore be interpreted as capturing the impact of policy news rather than the effects of policies once fully implemented.

Because connectedness is estimated using a rolling window of 150 weekly observations, the events included in the analysis begin in April 2015. The rolling-window structure implies that detected effects should be interpreted as changes in the local spillover regime rather than instantaneous responses. Consequently, the event study captures whether policy announcements modify the short-term trajectory of connectedness rather than inducing isolated one-period jumps.[10] We evaluate the probability that spillovers increase within three horizons after the announcement: one week, two weeks, and four weeks.

Table 5a summarizes statistically significant events across quantiles and time horizons, revealing strong asymmetry. A total of 77 spillover events are detected in the tails: 44 (57.1%) in the lower tail ($\tau = 0.1$) and 32 (41.6%) in the upper tail ($\tau = 0.9$), while only one occurs at the median ($\tau = 0.5$). This indicates that policy announcements rarely affect

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[8] For a detailed discussion of the methodology, see Appendix A.3 and A.4.

[9] The complete list of policies can be accessed at `https://www.iea.org/policies`.

[10] For consistency, all event dates are aligned to the nearest Friday of the corresponding week. If an event occurs during a weekend, it is assigned to the following Friday. The full list of policy announcementsis provided in Appendix D.

connectedness under normal conditions but become relevant in extreme market regimes.

The timing suggests gradual spillover propagation. In the lower tail, 7 events (16%) occur within one week, while most materialize after two to four weeks (17 events, 39%; 20 events, 45%). A similar pattern emerges in the upper tail, with 9 events (28%) within one week, 14 (44%) within two weeks, and 9 (28%) within four weeks. Markets therefore appear to incorporate policy information with a delay as expectations adjust.

Table 5b classifies events by policy type. Resource governance and mining policies dominate. In the lower tail, they account for 18 events ($\approx$ 40%), followed by supply chain and circular economy measures (10; 23%), trade and investment coordination (9; 20%), and industrial or financial policies (7; 16%). The upper tail shows a similar structure: resource governance leads (15; 47%), followed by trade and investment (9; 28%), supply chain regulation (5; 16%), and industrial policies (3; 9%).

Overall, policies directly affecting mineral supply—such as mining regulation, strategic designations, and licensing—are the main drivers of increased connectedness. The concentration of effects in the tails further indicates that policy announcements activate transmission mechanisms primarily during periods of stress or rapid price increases.

Spillover dynamics also differ across regimes. In the lower tail, increases are mainly linked to regulatory tightening, permitting constraints, export restrictions, and strategic designations, which heighten supply risk and uncertainty, amplifying downside spillovers. In contrast, in the upper tail, spillovers are more often associated with clean energy initiatives, circular economy strategies, recovery plans, and international cooperation, which signal stronger future demand and induce synchronized price movements.

Overall, CRMs policies act as state-dependent transmission triggers: supply-side restrictions amplify downside spillovers, while demand-expanding policies strengthen upside comovements. This asymmetry implies that the systemic effects of the energy transition depend not only on structural demand shifts but also on the timing and nature of policy interventions.

5 Conclusions

This paper investigates spillover effects among eight commodity indices related to energy transition metals (ETMs) and traditional energy commodities using a Quantile Factor VAR framework. By estimating connectedness across the conditional return distribution and isolating idiosyncratic shocks from latent common factors, we provide evidence on how the structure of commodity risk transmission varies across market states. Our results indicate that the energy transition is associated not only with shifting demand for key inputs but also with a reconfiguration of spillover linkages between ETMs, fossil fuels, and industrial metals.

Spillovers are strongly state-dependent. Connectedness is substantially higher in the

Table 5: Summary of Significant Policy Events

Panel A: Events by Time Horizon

Quantile (τ)	1 week	2 weeks	4 weeks
0.1	7	17	20
0.5	0	0	1
0.9	9	14	9
Total significant events: 77			

Panel B: Events by Policy Category

Policy type	$\tau = 0.1$	$\tau = 0.9$	Total
Trade & Investment Coordination	9	9	18
Resource Governance & Mining Policy	18	15	33
Supply Chain & Circular Economy	10	5	15
Industrial Policy & Financial Support	7	3	10
Total	44	32	76

Notes: The table reports the number of statistically significant events detected using the bootstrap-based method of Greenwood-Nimmo et al. (2024). Only events with probability greater than 0.94 are included (** and *** levels in Appendix D). Panel A reports the number of events associated with increases in the spillover index at different horizons following the announcement. Each event–quantile–horizon combination is treated as a separate observation, so an event that is significant at multiple quantiles or horizons is counted more than once. Panel B classifies significant events according to the type of policy intervention. In both Panel A and Panel B, numbers represent the counts obtained after excluding events that belong to more than one policy category.

tails than at the median, indicating that commodity markets become more interconnected during extreme shocks, when network amplification mechanisms are most likely to operate. In the post-Covid-19 period, elevated upper-tail connectedness is consistent with supply bottlenecks, capacity constraints, and recovery-driven price pressures that propagated across energy and metal markets.

At the median, natural gas and ETMs primarily act as net shock receivers, while crude oil remains an important transmitter, in line with earlier evidence. However, the quantile perspective reveals important asymmetries: oil dominates transmission mainly in the tails and can itself become a net receiver in extreme scenarios, highlighting the bidirectional nature of stress-driven spillovers. We also document a post-Covid shift in centrality, with ETMs and gold gaining prominence as transmitters relative to crude oil, suggesting a gradual move away from a purely fossil-centric network configuration.

Substantial heterogeneity exists within ETMs. Minor ETMs predominantly receive shocks, whereas base ETMs increasingly act as net transmitters, reflecting their growing market depth and macro-financial relevance. Precious ETMs exhibit strong linkages with gold, consistent with their dual industrial and investment roles.

The event study provides complementary evidence that policy announcements related to CRMs significantly increase connectedness, primarily in the tails of the return distribution. This asymmetry suggests that regulatory interventions and strategic mineral policies activate transmission mechanisms mainly during stress or exuberance, amplifying systemic risk when markets are already in extreme regimes.

Overall, our findings suggest that the energy transition is reshaping commodity markets not only through changing demand patterns but through a structural transformation of risk transmission itself. As ETMs become more systemically relevant, transition-related shocks and policy actions can propagate across the broader commodity network in a state-dependent manner. This evolving configuration implies that supply security concerns, geopolitical fragmentation, and transition policies may carry wider macro-financial consequences, particularly when markets operate in extreme regimes.

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A Appendix A: Additional details on data

Table A.1: Commodities and Shares by Index

Commodity	**Shares**	**Source**
ETM-B		
Copper, grade A cathode, LME spot price, CIF European ports	47.17%	Refinitiv
Aluminum, 99.5% minimum purity, LME spot price	21.87%	Refinitiv
Nickel, melting grade, LME spot price	9.22%	Refinitiv
Zinc, minimum special high-grade zinc of 99.995% purity	8.39%	Refinitiv
Molybdenum MO3, Insurance and Freight North West Europe	7.29%	Refinitiv
Lead, 99.97% pure, LME spot price	5.23%	Refinitiv
Cobalt, minimum 99.80% purity, LME spot price	0.83%	Refinitiv
ETM-P		
Silver, London Bullion Market Association	48.28%	Refinitiv
Platinum, LME spot price	30.34%	Refinitiv
Palladium, LME spot price	21.38%	Refinitiv
ETM-M		
Silicon lumps, CIF North West Europe	39.22%	Refinitiv
Manganese Electro CIF North West Europe	28.46%	Refinitiv
Chromium, #1 Chromium = 99.2%, 99A, Coarse Particle	24.62%	Refinitiv
Rare earth carbonate REO 42-45% purity	3.85%	Refinitiv
Lithium, 99% pure, industrial grade, battery grade	2.31%	Refinitiv
Vanadium pentoxide, CIF North West Europe	1.54%	Refinitiv
Gold		
Gold, London Bullion Market Association	100%	Refinitiv
INDMET		
Iron ore fines 62% Fe CFR Futures	94%	Investing
Tin, standard grade, LME spot price	6%	Refinitiv
Coal		
Newcastle Coal Futures	100%	Investing
Nat Gas		
ICE Dutch TTF Natural Gas Futures	50%	Investing
Henry Hub Natural Gas	50%	Investing
Crude Oil		
Crude Oil (petroleum), Dubai Fateh Fateh 32 API	33%	Refinitiv
Crude Oil (petroleum), West Texas Intermediate Midland Texas, fob	34%	Refinitiv
Crude Oil (petroleum), Brent Forties Oseberg month 1 Europe, fob	33%	Refinitiv

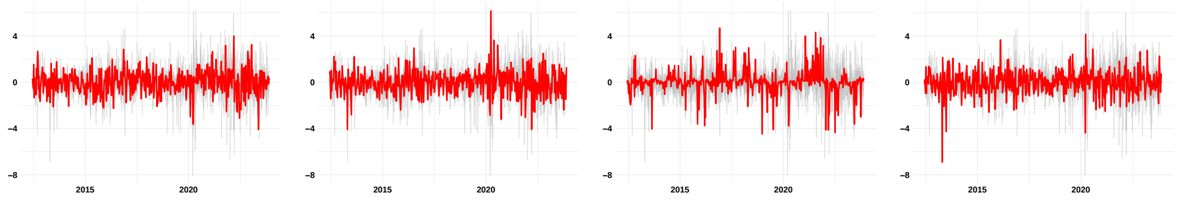
Notes: The sources from Investing can be accessed at `https://it.investing.com/`.

Table A.2: Descriptive Statistics of Weekly Returns

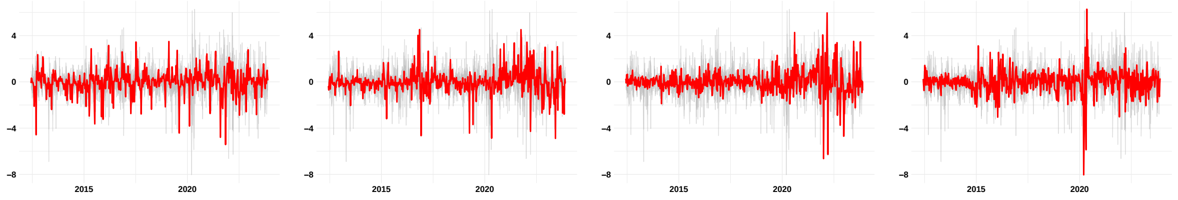
Index	**Mean**	**SD**	**Skewness**	**Kurtosis**	**JB Statistic**	**JB p-value**	**Coeff. Variation**
ETM-B	-0.020	1.873	-0.074	4.194	36.159	1.41e-08	-93.018
ETM-P	-0.061	2.970	-1.609	21.800	9079.548	0.000	-49.055
ETM-M	-0.069	2.027	1.770	51.045	57925.692	0.000	-29.518
Gold	-0.014	1.691	-0.578	7.930	639.960	0.000	-123.563
INDMET	-0.051	3.763	-0.929	7.897	684.765	0.000	-74.275
Coal	-0.000	4.688	-0.912	30.034	18323.892	0.000	-131510.46
Nat Gas	0.025	5.920	-0.152	12.890	2443.657	0.000	234.051
Crude Oil	-0.071	4.524	-1.003	15.193	3810.835	0.000	-63.470

Note: The Jarque-Bera test results reject normality, indicating significant skewness and excess kurtosis across all series. In traditional Vector Autoregression (VAR) models, normality is assumed for FEVD, as introduced by Koop et al. (1996), and later extended by Pesaran and Shin (1998) to Generalized FEVD (GFEVD), which removes dependence on variable ordering. However, Quantile VAR (QVAR) models the entire conditional distribution of returns at different quantiles rather than just the mean, explicitly accounting for heterogeneous tail behaviors, making the normality assumption unnecessary.

Figure A.1: Standardized Weekly Returns



(a) ETM-B (b) ETM-P (c) ETM-M (d) Gold



(e) INDMET (f) Coal (g) Nat Gas (h) Crude Oil

B Appendix B: Additional details on methods

B.1 Estimation of QFVAR

The estimation of QFVAR is based on Ando and Bai (2020), such that the unobservable common factors are allowed to vary between quantiles.

Specifically, for the i-th equation in the system for the τ-th conditional quantile function of the response y_{it}, we have:

$$\mathcal{Q}_{yit}(\tau|\mathbf{x_{it}}, \mathbf{f}_{\mathbf{t},\tau}, \lambda_{\mathbf{i},\tau}) = \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} + \mathbf{f}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau} \quad i = 1, \cdots, N, t = 1, \cdots, T. \tag{1}$$

Here, $\mathbf{x_{it}} = (x_{1t}, x_{2t}...x_{pt})'$ represents a $p+1$-dimensional vector of regressors, and $\mathbf{b}_{\mathbf{i},\tau} = (b_{i,0,\tau}, b_{i,1,\tau}...b_{i,p,\tau})'$ is the corresponding $p+1$-dimensional vector of regression coefficients. $\mathbf{f}_{\mathbf{t},\tau}$ is an $r_\tau \times 1$ vector of unobservable factors. $\lambda_{\mathbf{i},\tau}$ represents the factor loadings.

The objective is to minimize the following loss function:

$$\mathcal{L}_\tau(Y|X, B_\tau, F_\tau, \Lambda_\tau) = \sum_{i=1}^{N}\sum_{t=1}^{T} \rho_\tau(y_{it} - \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} - \mathbf{f}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau}) \tag{2}$$

where $Y \equiv \{y_{it}|i = 1, \cdots, N, t = 1, \cdots, T\}$, $X \equiv \{\mathbf{x_{it}}|i = 1, \cdots, N, t = 1, \cdots, T\}$ $B_\tau = \{\mathbf{b}_{\mathbf{1},\tau}, \cdot, \mathbf{b}_{\mathbf{N},\tau}\}$, $F_\tau = \{\mathbf{f}_{\mathbf{1},\tau}, \cdot, \mathbf{f}_{\mathbf{T},\tau}\}$, and $\Lambda_\tau = \{\lambda_{\mathbf{1},\tau}, \cdot, \lambda_{\mathbf{N},\tau}\}$. The check loss function $\rho_\tau(\cdot)$ is defined by

$$\rho_\tau(y_{it} - \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} + \mathbf{f}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau}) = (\tau - 1_{[y_{it} - \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} - \mathbf{f}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau} \leq 0]})(y_{it} - \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} - \mathbf{f}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau})$$

The estimation algorithm proceeds as follows:

1. **Initialize**: Set initial values for $\hat{B}_\tau, \hat{F}_\tau, \hat{\Lambda}_\tau$

2. **Update $\hat{\mathbf{b}}_{\mathbf{i},\tau}$ and $\hat{\lambda}_{\mathbf{i},\tau}$**: Given $\hat{F}_\tau$, update $\hat{\mathbf{b}}_{\mathbf{i},\tau}$ and $\hat{\lambda}_{\mathbf{i},\tau}$ by minimizing:

$$\sum_{t=1}^{T} \rho_\tau(y_{it} - \mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau} - \hat{\mathbf{f}}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau}) \quad i = 1, ..., N$$

3. **Update $\mathbf{f}_{\mathbf{t},\tau}$**: Given $\hat{\mathbf{b}}_{\mathbf{i},\tau}$ and $\hat{\lambda}_{\mathbf{i},\tau}(i = 1, ..., N)$, update $\mathbf{f}_{\mathbf{t},\tau}$ minimizing:

$$\sum_{i=1}^{N} \rho_\tau(y_{it} - \mathbf{x}'_{\mathbf{it}}\hat{\mathbf{b}}_{\mathbf{i},\tau} - \mathbf{f}_{\mathbf{t},\tau}\hat{\lambda}_{\mathbf{i},\tau}) \quad t = 1, ..., T$$

4. **Iterate until convergence**: Repeat steps 2 and 3 until the following convergence

condition is met:

$$N^{-1}\sum_{i=1}^{N}\|\hat{\mathbf{b}}^{\mathbf{new}}_{\mathbf{i},\tau}-\hat{\mathbf{b}}^{\mathbf{old}}_{\mathbf{i},\tau}\|^2+(NT)^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\{(\hat{\mathbf{f}}'_{\mathbf{t},\tau}\hat{\lambda}_{\mathbf{i},\tau})^{\mathbf{new}}-(\hat{\mathbf{f}}'_{\mathbf{t},\tau}\hat{\lambda}_{\mathbf{i},\tau})^{\mathbf{old}}\}^2<\delta^2$$

where δ^2 is a small threshold value.

More specifically, step 1 starts with minimizing:

$$\mathcal{L}_\tau(Y|X,B_\tau)=\sum_{i=1}^{N}\sum_{t=1}^{T}\rho_\tau(y_{it}-\mathbf{x}'_{\mathbf{it}}\mathbf{b}_{\mathbf{i},\tau})$$

This step yields the initial estimates $\mathbf{b}_{\mathbf{i},\tau}$ for $i=1,\cdots,N$. Given these initial estimates $\hat{\mathbf{b}_{\mathbf{i},\tau}}(i=1,\cdots,N)$, define $Z_\tau=\{\mathbf{z}_{\mathbf{1},\tau},...,\mathbf{z}_{\mathbf{N},\tau}\}$, where $\mathbf{z}_{\mathbf{i},\tau}=\mathbf{y}_\mathbf{i}-X_i\hat{\mathbf{b}_{\mathbf{i},\tau}}$. Using Z_τ, we can then compute the estimate of the principal components $\hat{F}_\tau=\{\hat{\mathbf{f}_{\mathbf{1},\tau}},\cdot,\hat{\mathbf{f}_{\mathbf{T},\tau}}\}$.

Then, obtain $\hat{\lambda_{\mathbf{i},\tau}}$ by minimizing

$$\sum_{t=1}^{T}\rho_\tau(y_{it}-\mathbf{x}'_{\mathbf{it}}\hat{\mathbf{b}_{\mathbf{i},\tau}}-\hat{\mathbf{f}}'_{\mathbf{t},\tau}\lambda_{\mathbf{i},\tau})\quad i=1,...,N$$

B.2 Optimal Number of Factors

For the quantile models, given the numbers of common factors r, the estimated parameters $\hat{\mathbf{b}}_{i,\tau}(r)$, $\hat{\lambda}_{i,\tau}(r)$, and the estimated common factors $\hat{\mathbf{f}}_{t,\tau}(r)$, the information criterion $IC_\tau(r)$ is expressed as:

$$IC_\tau(r)=\log\left[\frac{1}{NT}\sum_{t=1}^{T}\sum_{i=1}^{N}\rho_\tau\left(y_{it}-\mathbf{x}'_{it}\hat{\mathbf{b}}_{i,\tau}(r)-\hat{\mathbf{f}}_{t,\tau}(r)'\hat{\lambda}_{i,\tau}(r)\right)\right]+r\times q(N,T) \tag{3}$$

and

$$q(N,T)=\log\left(\frac{NT}{N+T}\right)\left(\frac{N+T}{NT}\right) \tag{4}$$

where $\rho_\tau(z)$ is the check loss function defined as

$$\rho_\tau(z)=z(\tau-1_{[z\leq 0]})$$

Similarly, the information criterion for conditional mean model, $IC(r)$ can be seen as:

$$IC(r)=\log\left(\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\left(y_{it}-\mathbf{x}'_{it}\hat{\mathbf{b}}_i(r)-\hat{\mathbf{f}}_t(r)'\hat{\lambda}_i(r)\right)^2\right)+r\times q(N,T) \tag{5}$$

B.3 Bootstrap Confidence Intervals

We follow a bootstrap-based procedure introduced by Greenwood-Nimmo et al. (2024) to compute the distribution of the bias-corrected Total Connectedness Index (TCI) for a quantile factor vector autoregressive model (QFVAR). The procedure consists of the following steps:

1. For the first rolling sample, we use the original data set $x_{\tau,t}$ to estimate the QFVAR model at a specified quantile and compute the corresponding spillover index $\hat{S}_{\tau}$.
2. Resample the residuals from the initial QFVAR model with replacement to generate B sets of bootstrapped residuals. For each bootstrap sample, we construct new data sets $x_{\tau,t}^{(b)}$ by adding bootstrapped residuals to the predicted values of the initial QFVAR model.
3. Re-estimate the QFVAR model for each of the B bootstrapped datasets $x_{\tau,t}^{(b)}$, and compute the spillover indices $\hat{S}_{\tau,\text{first}}^{(b)}$, for $b = 1, \ldots, B$.
4. Calculate the bias $\hat{\gamma}$ as the difference between the mean spillover index across the bootstrapped datasets and the spillover index from the original data:
$$\hat{\gamma} = \frac{1}{B}\sum_{b=1}^{B} \hat{S}_{\tau,\text{first}}^{(b)} - \hat{S}_{\tau}.$$
5. Discard the results from the previous bootstrapping, keeping only the computed bias $\hat{\gamma}$. Perform a second round of bootstrapping to generate B new spillover indices $\hat{S}_{\tau,\text{second}}^{(b)}$. For each iteration, subtract the bias from the bootstrapped spillover index to obtain bias-corrected spillover indices:
$$\tilde{S}_{\tau}^{(b)} = \hat{S}_{\tau,\text{second}}^{(b)} - \hat{\gamma}.$$
Finally, construct the bias-corrected empirical distribution of the spillover index.
6. Repeate it for all of the remaining rolling samples.

B.4 Probabilistic Analysis

The probabilistic analysis relies on the basis of the empirical distributions. Let $\bar{S}_{r_e-1,\tau}$ represent the bias-corrected mean spillover index at quantile τ from bootstrap samples in rolling window $r_e - 1$. It is computed as:

$$\bar{S}_{r_e-1,\tau} = \frac{1}{B}\sum_{b=1}^{B} \tilde{S}_{r_e-1,\tau}^{(b)}$$

where $\tilde{S}_{r_e-1,\tau}^{(b)}$ denotes the bias-corrected spillover index from the b-th bootstrap iteration at quantile τ in rolling sample $r_e - 1$.

The probability that the spillover index in rolling sample r_e+j exceeds the bias-corrected mean spillover index at quantile τ of the previous sample $r_e - 1$ is given by:

$$\Pr\left(S_{r_e+j,\tau} > \bar{S}_{r_e-1,\tau}\right) = \frac{1}{B}\sum_{b=1}^{B}\mathbb{I}\left(\tilde{S}^{(b)}_{r_e+j,\tau} - \bar{S}_{r_e-1,\tau} > 0\right)$$

Here, $S_{r_e+j,\tau}$ is the spillover index at quantile τ in rolling sample $r_e + j$. $\tilde{S}^{(b)}_{r_e+j,\tau}$ is the bias-corrected spillover index from the b-th bootstrap sample at quantile τ in rolling sample $r_e + j$. $\mathbb{I}(\cdot)$ is the indicator function that takes the value 1 if the condition in parentheses is true, and 0 otherwise.

Greenwood-Nimmo et al. (2024) replicate global stock market data from 19 countries based on the work of Diebold and Yilmaz (2009), and measure the intensity of volatility spillovers prior to an event using a volatility spillover index from the rolling sample just before the event. They then assess the probability of the spillover index increasing over four time windows: 0 days (contemporaneously), 1 day, 5 days (1 week), and 22 days (1 month) after the event. Their analysis shows that for 15 out of 19 events, there is a 90% probability that the spillover index increases in at least one of these time windows.

Endogenous detection of unknown events

Additionally, their methodology can be adapted to detect unknown events by testing for significant changes in spillover intensity in new rolling samples compared to previous ones.

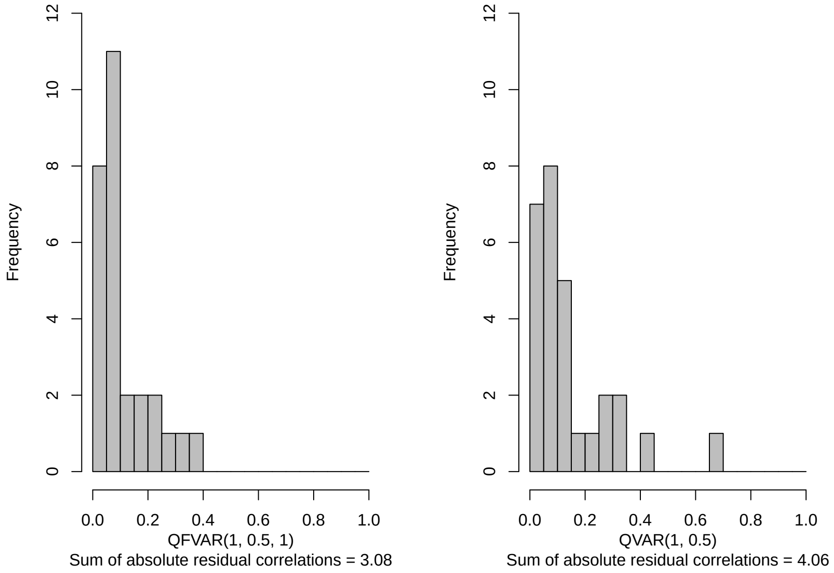
$$\Pr\left(100 \times \left[\frac{\tilde{S}^{(b)}_{t+i,\tau} - \bar{S}_{t-j,\tau}}{\bar{S}_{t-j,\tau}}\right] > \alpha\right) = \frac{1}{B}\sum_{b=1}^{B}\mathbb{I}\left(100 \times \left[\frac{\tilde{S}^{(b)}_{t+i,\tau} - \bar{S}_{t-j,\tau}}{\bar{S}_{t-j,\tau}}\right] > \alpha\right)$$

where α denotes the magnitude of the spillover change, with $i \in \{0, 1, \ldots\}$ and $j \in \{1, 2, \ldots\}$.

C Appendix C: Additional results

Figure C.1 shows histograms of the absolute residual correlations for the QFVAR(1,0.5,1) and QVAR(1,0.5) models. Incorporating factors significantly reduces residual correlations, with the sum of absolute residual correlations decreasing from 4.06 in the QVAR model to 3.08 in the QFVAR model. These results highlight the effectiveness of factor inclusion in capturing common latent movements and mitigating cross-sectional residual correlations.

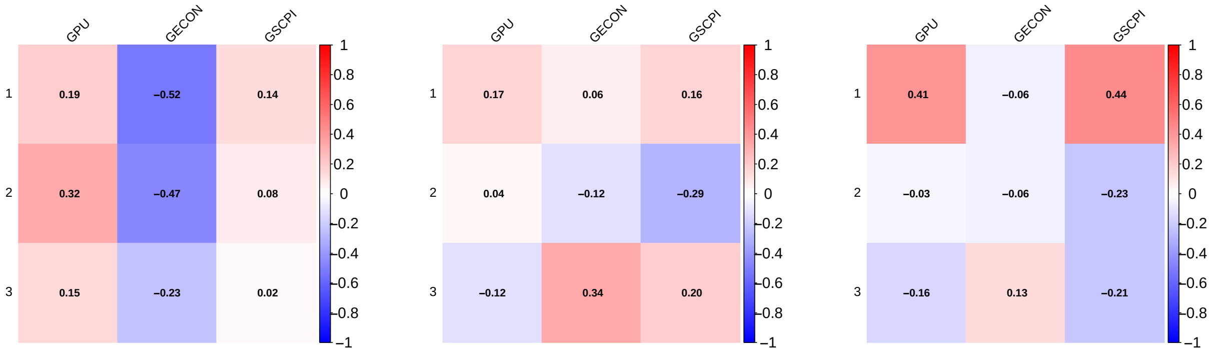
Figure C.1: Comparison of Absolute Residual Correlations



Note: The sum of absolute residual correlations is computed as: $\sum_{(i,j)\in\mathcal{L}} |\rho_{ij}|$. where ρ_{ij} denotes the correlation coefficient between the residuals of variables i and j. $\mathcal{L}$ represents the lower triangular part of the correlation matrix.

Figure C.2 shows the correlations between the first three factors extracted from the QFVAR model and three macroeconomic indicators: the Global Supply Chain Pressure Index, the Global Economic Policy Uncertainty Index, and the Global Economic Conditions Indicator[1]

Figure C.2: Correlations between Factors and Macroeconomic Variables



(a) QFVAR(1, 0.1,3) (b) QFVAR(1, 0.5,3) (c) QFVAR(1, 0.9,3)

Notes: This figure presents the correlation matrices between the extracted factors and macroeconomic variables for different quantiles ($\tau = 0.1, 0.5, 0.9$).

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[1] Global Supply Chain Pressure Index: `https://www.newyorkfed.org`.
Global Economic Policy Uncertainty Index: `https://www.policyuncertainty.com/`.
Global Economic Conditions Indicator: `https://sites.google.com/site/cjsbaumeister/datasets`.

Table C.1: Connectedness Table: QFVAR(1, 0.1, 3), Forecast Horizon = 4

	ETM-B	ETM-P	ETM-M	Gold	INDMET	Coal	Nat Gas	Crude Oil	FROM
ETM-B	36.61	5.96	6.25	1.76	12.15	10.55	11.40	15.32	63.39
ETM-P	5.58	42.01	2.11	20.13	8.19	5.12	5.82	11.04	57.99
ETM-M	13.78	1.43	56.43	2.10	2.55	15.58	6.07	2.06	43.57
Gold	2.84	20.44	2.15	53.87	5.26	5.00	4.89	5.54	46.13
INDMET	15.30	7.98	1.00	3.11	41.21	10.03	11.72	9.66	58.79
Coal	12.46	4.40	9.99	3.65	10.34	46.48	10.22	2.46	53.52
Nat Gas	14.54	5.85	3.41	3.50	10.93	9.37	43.91	8.49	56.09
Crude Oil	17.10	10.51	4.35	4.07	10.44	4.01	8.68	40.84	59.16
TO	81.60	56.55	29.26	38.33	59.86	59.66	58.80	54.57	438.64
NET	18.21	-1.44	-14.31	-7.80	1.07	6.14	2.71	-4.58	TCI 54.83

Table C.2: Connectedness Table: QFVAR(1,0.9,3), Forecast Horizon = 4

	ETM-B	ETM-P	ETM-M	Gold	INDMET	Coal	Nat Gas	Crude Oil	FROM
ETM-B	43.23	4.23	7.78	1.96	11.00	11.79	9.79	10.22	56.77
ETM-P	5.57	45.61	4.82	16.22	7.24	6.09	5.17	9.27	54.39
ETM-M	10.46	1.55	52.79	2.79	1.57	14.41	15.06	1.37	47.21
Gold	2.68	19.30	3.60	52.26	5.13	5.15	4.99	6.89	47.74
INDMET	17.17	7.29	1.81	4.37	44.74	6.87	6.83	10.92	55.26
Coal	9.48	5.59	8.58	4.24	6.21	47.83	14.85	3.23	52.17
Nat Gas	9.03	4.45	9.92	5.03	7.59	14.38	46.75	2.85	53.25
Crude Oil	13.62	10.48	1.74	6.82	9.93	3.97	2.91	50.53	49.47
TO	68.02	52.89	38.25	41.42	48.66	62.67	59.60	44.74	416.26
NET	11.25	-1.50	-8.95	-6.32	-6.60	10.50	6.35	-4.73	TCI 52.03

Table C.3: NET Connectedness

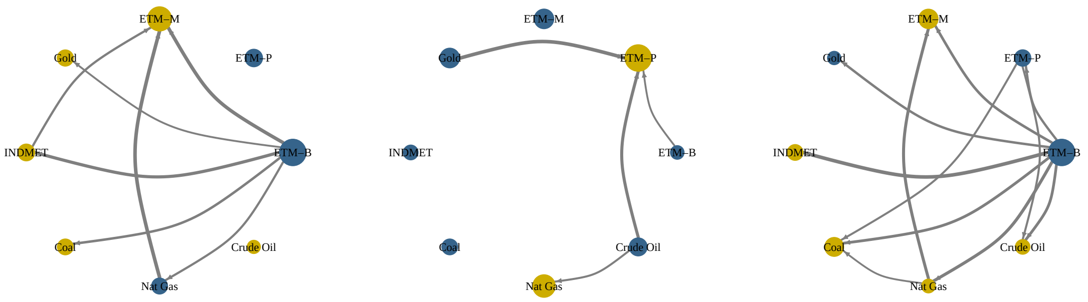
	ETM-B	ETM-P	ETM-M	Gold	INDMET	Coal	Nat Gas	Crude Oil
Lower Tail ($\tau = 0.1$)								
All	18.21	-1.44	-14.31	-7.80	1.07	6.14	2.71	-4.58
Pre-COVID	13.34	4.11	-1.95	-14.15	0.33	-6.89	-0.24	5.45
Post-COVID	1.37	16.51	8.82	12.61	-0.71	-8.51	-18.44	-11.66
Median Quantile ($\tau = 0.5$)								
All	-2.75	-4.97	1.33	7.59	-0.98	-0.80	-1.20	1.78
Pre-COVID	2.36	-16.26	1.09	3.11	1.82	3.37	-2.45	6.95
Post-COVID	-4.66	-3.64	2.06	6.33	1.71	-1.28	0.92	-1.44
Upper Tail ($\tau = 0.9$)								
All	11.25	-1.50	-8.95	-6.32	-6.60	10.50	6.35	-4.73
Pre-COVID	12.06	3.44	-3.97	-14.31	-0.96	-10.89	3.12	11.51
Post-COVID	27.13	12.31	0.42	7.63	-8.69	-10.33	-19.41	-9.09

Table C.4: Factor Loadings for QFVAR(1,τ,3) Models

τ	Factor	ETM-B	ETM-P	ETM-M	Gold	INDMET	Coal	Nat Gas	Crude Oil
0.1	Factor 1	-1.471	-1.394	-0.808	-1.244	-1.009	-0.915	-0.929	-1.108
	Factor 2	0.091	0.476	-0.181	0.587	-0.136	-0.534	-0.590	-0.187
	Factor 3	0.023	-0.164	0.826	-0.023	0.285	0.016	-0.372	-0.361
0.5	Factor 1	0.696	0.829	0.003	0.721	0.173	0.221	0.193	0.401
	Factor 2	-0.044	0.225	0.189	0.404	-0.001	-0.577	-0.689	-0.379
	Factor 3	0.183	-0.171	0.774	-0.174	0.183	0.248	-0.142	-0.109
0.9	Factor 1	1.340	1.325	0.950	1.258	1.090	1.048	1.018	1.048
	Factor 2	0.172	0.490	-0.251	0.558	-0.060	-0.546	-0.598	-0.093
	Factor 3	-0.088	-0.075	0.837	0.082	0.164	-0.028	-0.270	-0.530

Figure C.3 presents the dynamic net pairwise connectedness network. Specifically, ETM-M acts as a shock giver at the median but becomes a receiver at the tails, whereas ETM-P exhibits the opposite pattern. ETM-B emerges as a strong shock transmitter to energy commodities (Coal, Nat Gas, and Crude Oil), as well as INDMET. Gold and INDMET serve as shock givers to other commodities but receive shocks from ETM-B at the tails. Meanwhile, Nat Gas and Crude Oil function as a receiver and a giver, respectively, at the median, with their roles reversing at the tails. We also conduct a pre-COVID and post-COVID analysis, which reveals that in the post-COVID period, Gold consistently transmits shocks across quantiles, while Nat Gas primarily acts as a shock giver at the median (see Figure C.4).

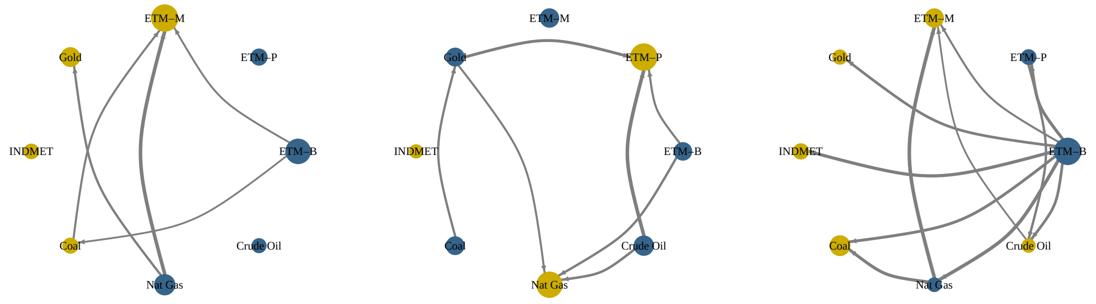
Figure C.3: Network of the dynamic net pairwise connectedness



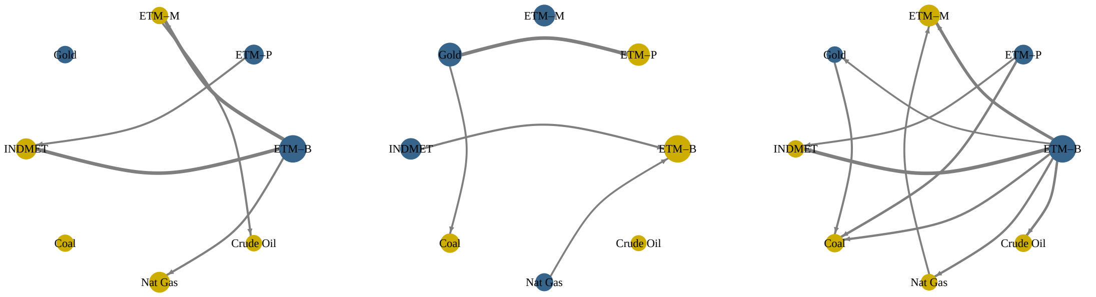
(a) $\tau = 0.1$ (b) $\tau = 0.5$ (c) $\tau = 0.9$

Notes: The graphs visualize dynamic net pairwise connectedness (NPDC), which is the average of the net pairwise connectedness across time. The size of a node represents the sum of the net pairwise connectedness of that node with other nodes, which includes both how much it influences other nodes and how much it is influenced by other nodes. Blue nodes represent net givers (influencers) in the network, while Gold nodes represent net receivers (influenced) in the network. The arrow points from the influencing node (where the influence originates) to the influenced node (where the influence is received). The thickness of the arrow reflects the magnitude of the influence, with thicker arrows representing stronger directional influence. To highlight the main propagations, a threshold of 0.5 was applied for the plotting the arrows.
The model used is QFVAR(1,τ,f), with the number of factors dynamically and optimally selected. The window size is 150, and the forecast horizon is 4.

Figure C.4: Network of the dynamic net pairwise connectedness



(a) Pre-COVID $\tau = 0.1$ (b) Pre-COVID $\tau = 0.5$ (c) Pre-COVID $\tau = 0.9$



(d) Post-COVID $\tau = 0.1$ (e) Post-COVID $\tau = 0.5$ (f) Post-COVID $\tau = 0.9$

Notes: The graphs visualize dynamic net pairwise connectedness (NPDC), which is the average of the net pairwise connectedness across time. The size of a node represents the sum of the net pairwise connectedness of that node with other nodes, which includes both how much it influences other nodes and how much it is influenced by other nodes. Blue nodes represent net givers (influencers) in the network, while Gold nodes represent net receivers (influenced) in the network. The arrow points from the influencing node (where the influence originates) to the influenced node (where the influence is received). The thickness of the arrow reflects the magnitude of the influence, with thicker arrows representing stronger directional influence. To highlight the main propagations, a threshold of 0.5 was applied for the plotting the arrows.
The model used is QFVAR(1,τ,f), with the number of factors dynamically and optimally selected. The window size is 150, and the forecast horizon is 4.

D Appendix D: Events Tables

Table D.1 lists 342 potential events. Among them, 51 events are statistically significant at $\tau = 0.1$, 4 at $\tau = 0.5$, and 40 at $\tau = 0.9$ for at least one time horizon, based on a significance probability greater than 0.9 (see Table D.2, Table D.3, and Table D.4).

Table D.1: Critical Mineral Events

Event	Date	Country
Resolution 180102 – 2012 by which some minerals are determined as a strategic interest for the country	2012-01-24	Colombia
Law No. 1-12 that establishes the National Development Strategy 2030	2012-01-25	Dominican Republic
Export Control Regulations 2012	2012-02-10	South Africa
Resource Security Action Plan	2012-03-16	United Kingdom
Ministerial Regulations No 002/2012/MINIRENA of 28/03/2012 on the regional certification mechanism for minerals	2012-03-28	Rwanda
Waste Electrical and Electronic Equipment Directive	2012-07-04	European Union
Executive Order No. 79, s. 2012	2012-07-06	Philippines
Clean Energy Finance Corporation Act	2012-07-22	Australia
National Minerals Strategy	2013-06-07	Sweden
EU Copper Scrap Criteria	2013-07-25	European Union
Korea Energy Master Plan: Outlook and Policies to 2035 (Second Energy Master Plan)	2014-01-14	Korea
Environmental Regulation of Mining Activities	2014-03-27	Ecuador
UK waste classification technical guidance	2014-04-01	United Kingdom
Mines Regulations 2014	2014-04-06	United Kingdom
Law No 535: Mining and Metallurgy Law	2014-05-28	Plurinational State of Bolivia
Mongolia Mineral Law 2014	2014-07-01	Mongolia
Decree No. 2014-928 of August 19, 2014 relating to waste electrical and electronic equipment and used electrical and electronic equipment	2014-08-19	Korea
D.S No 040-2014-EM: Regulation for the environmental protection and management applicable to mining exploitation, processing, general work, transportation, and storage activities	2014-11-05	Peru
Extractive Sector Transparency Measures Act	2014-12-16	Canada
Legislative Decree No. 49 of 2014	2015-03-14	Italy
Canadian Industry Program for Energy Conservation (CIPEC) Funding for TSM Protocol	2015-06-04	Canada
Launch of "One Belt One Road" Mining Industry Development Fund	2015-06-09	People's Republic of China
NETL Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal By-products	2015-08-21	United States
Electrical and Electronic Equipment Act	2015-10-20	Germany
Legislative Decree No 27 of 15 February 2016	2016-03-20	Italy
Resolution No 40391 by which the National Mining Policy is approved	2016-04-20	Colombia
Vision 2030	2016-04-25	Saudi Arabia
Northern Australia Infrastructure Facility Act and Investment Mandate	2016-05-04	Australia
Federal Law of Transparency and Public Information Access	2016-05-09	Mexico
Law 20920. Establishment of a framework for waste management, extended producer responsibility and recycling.	2016-06-01	Chile
Hazardous and Other Wastes Rules	2016-07-06	India
Critical Non-Fuel Mineral Resources for India's Manufacturing Sector	2016-07-26	India
Hazardous and Electronic Waste Control and Management Act, 2016 (Act 917)	2016-08-10	Ghana
Earth's Crust Act	2016-10-27	Estonia
National Plan for Mineral Resources (2016-2020)	2016-11-29	People's Republic of China
Pan-Canadian Framework on Clean Growth and Climate Change	2016-12-09	Canada
Environmental Permitting (England and Wales) Regulations 2016	2016-12-11	United Kingdom
Decree 1278 approving the Law on Solid Waste Management	2016-12-23	Peru
Plan for the Implementation of the Extended Producer Responsibility System	2016-12-25	People's Republic of China
French Corporate Duty of Vigilance Law	2017-03-27	France
Law No 928: Law of the National Strategic Public Company for Bolivian Lithium Deposits- YLB	2017-04-27	Plurinational State of Bolivia

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Table D.1: Critical Mineral Events (continued)

Event	Date	Country
New Online Mining Registry	2017-05-08	Chile
Australia Minerals National Mineral Exploration Strategy	2017-07-18	Australia
Implementation Plan for Prohibiting the Entry of Foreign Waste	2017-07-18	People's Republic of China
Proposal for a strategy for a sustainable management of mine waste	2017-09-14	Sweden
European Battery Alliance	2017-10-11	European Union
Executive Order 13817, A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals	2017-12-20	United States
Interim Provisions on the Traceability Management of Power Battery Recycling in New Energy Vehicles	2018-02-26	People's Republic of China
Mining Code of the Democratic Republic of Congo	2018-03-28	Democratic Republic of the Congo
Announcement on Adjustment to the Catalogue for the Administration of Import Solid Waste	2018-04-19	People's Republic of China
Resources for France Plan	2018-04-23	France
Colombian Standard for public reporting of the results of mineral exploration, resources and reserves (ECRR)	2018-05-24	Colombia
EU Strategic Action Plan on Batteries	2018-05-17	European Union
Guidelines for additional environmental measures for operating surface metallic mines (DENR Administrative Order 2018-19)	2018-08-17	Philippines
Germany's Untied Loan Guarantees (UFK)	2018-08-31	Germany
Bill H.R. 302 - The BUILD Act	2018-10-05	United States
Ministerial Decree #18/042 declaring cobalt, germanium and colombo-tantalite strategic mineral substances	2018-11-24	Democratic Republic of the Congo
Decree 430-18 by which the Province of "Pedernales" is declared as "Avila" Mining Fiscal Reserve, for the exploration and evaluation of possible "rare earth" deposits developed directly by the State or through contracts	2018-11-30	Dominican Republic
Modern Slavery Act	2018-12-10	Australia
Announcement on Adjustment of Import Waste Management Catalogue Announcement No. 36 of 2009	2018-12-25	People's Republic of China
Minerals for the Green Economy	2019-01-15	Norway
The Plan for the Development of Marine Energy and Mineral Resource	2019-02-15	Japan
The Canadian Minerals and Metals Plan	2019-03-31	Canada
Act on resource circulation of electrical and electronic equipment and vehicles (EEEV Act)	2019-04-27	Korea
National E-Waste Management Strategy 2019-2024	2019-04-30	Kenya
Ministry of Energy and Natural Resources, Strategic Plan 2019-2023	2019-05-01	Republic of Turkiye
Mining (Designated Minerals Certification) Regulations	2019-06-07	United Republic of Tanzania
Proposal to create the National Management System for State Mining Income	2019-06-10	Dominican Republic
Energy Resource Governance Initiative	2019-06-11	United States
Impact Assessment Act	2019-06-21	Canada
Strategic and Critical Materials Stock Piling Act	2019-06-27	United States
Eleventh Development Plan (2019-2023)	2019-07-18	Republic of Turkiye
UKRI Driving the Electric Revolution Challenge	2019-07-25	United Kingdom
Amendment of Mineral Resources Law	2019-08-08	Egypt
Joint Resolution 564 (National Mineral Agency) and 374 (Colombian Geological Survey) of September 2, 2019	2019-09-02	Colombia
Research Program on the Kinetics of Ultra-Concentrated Mineralisation of Strategic and Critical Metals	2019-09-30	People's Republic of China
Hardrock Leasing and Reclamation Act of 2019	2019-10-23	United States
Article 29 of the Energy and Climate Law	2019-11-08	France
National Waste Policy Action Plan	2019-11-08	Australia
Responsibility Delivering Value: A Minerals and Petroleum Resource Strategy for Aotearoa New Zealand	2019-11-06	New Zealand
Ministerial Decree #19/15 about the safeguarding of the activities related to artisanally exploited strategic minerals	2019-11-05	Democratic Republic of the Congo
Ministerial Resolution No 390-2019 to create the Committee for Gender Equality of the Ministry of Energy and Mines	2019-11-19	Peru
Energy Innovation (STI) inter ministerial committee	2019-12-12	Brazil
3.2 billion euros fund for research and innovation in battery technology	2019-12-09	European Union
Raw materials strategy of the Federal Government: Securing a sustainable supply of non-energy mineral raw materials for Germany	2019-12-30	Germany
Prohibition of the export of nickel ore	2020-01-01	Indonesia
2.9 billion euro fund for research and innovation in battery technology	2020-01-01	European Union
Canada-US Joint Action Plan on Critical Minerals Collaboration	2020-01-09	Multilateral
Global Trace Protocol Project	2020-02-09	United States

Continued on next page

Table D.1: Critical Mineral Events (continued)

Event	Date	Country
Anti-Waste Law 2020	2020-02-10	France
Greenland's Mineral Strategy 2020-2024	2020-02-15	Greenland
Green Deal: Circular Economy Action Plan	2020-03-11	European Union
JOGMEC & JBIC financial support for overseas minerals projects	2020-04-01	Japan
Multiannual Planning for Energy	2020-04-21	France
Mineral Raw Materials Due Diligence Act of April 29, 2020	2020-04-29	Germany
Geological Survey of Finland Strategy 2020-2023	2020-04-30	Finland
Gateway to Earth: British Geological Survey Science Strategy 2019-2023	2020-05-08	United Kingdom
(California) California Energy Commission grants for geothermal and lithium recovery projects	2020-05-13	United States
Mining Law No. 3/2020	2020-06-10	Indonesia
German Resource Efficiency Programme (ProgRess)	2020-06-17	Germany
Strategic Minerals List	2020-06-18	Nigeria
Circular economy - Strategy for the transformation of Sweden	2020-07-09	Sweden
Exploring for the Future Program	2020-07-23	Australia
International Resource Strategy - National stockpiling system	2020-07-31	Japan
Resolution No 47/2020 by which the Mining Strategic Plan is approved	2020-08-03	Argentina
Operating regulations of the multi-stakeholder group EITI-Ecuador	2020-08-04	Ecuador
European Action Plan on Critical Raw Materials	2020-09-03	European Union
European Raw Materials Alliance	2020-09-03	European Union
The 2020 EU Critical Raw Materials List	2020-09-03	European Union
Ordinance No. 354/2020. The Mining and Development Program	2020-09-28	Brazil
Executive Order 13953, Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries	2020-09-30	United States
Law 2056 to regulate the organisation and functioning of the general system of royalties	2020-09-30	Colombia
New Energy Vehicle Industry Development Plan (2021-2035)	2020-10-20	People's Republic of China
Extended Producer Responsibility Regulations 2020	2020-11-05	South Africa
Announcement on the Comprehensive Ban on the Import of Solid Waste	2020-11-25	People's Republic of China
Recycling and Waste Reduction Act 2020	2020-12-15	Australia
Energy Act of 2020 (Critical minerals provisions)	2020-12-27	United States
EU Regulation 2017/821 Supply chain due diligence for minerals from conflict-affected and high-risk areas	2021-01-01	European Union
Horizon Europe Strategic Plan (2021 – 2024)	2021-01-01	European Union
Interdisciplinary Circular Economy Centre for Technology Metals (Met4Tech)	2021-01-01	United Kingdom
Critical Minerals and Materials: US Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains	2021-01-20	United States
State support for investment projects with significant investments in Ukraine (Law No. 1116)	2021-02-13	Ukraine
CONPES 4023: Policy for Reactivation, Revitalisation, and Sustainable and Inclusive Growth	2021-02-11	Colombia
Executive Order 14017 of America's Supply Chains	2021-02-24	United States
State's Raw Materials Policy 2050 (PSP2050)	2021-03-01	Poland
Critical Minerals List 2021	2021-03-11	Canada
National Science and Technology Major Project on Strategic Mineral Resources Development and Utilization	2021-03-11	People's Republic of China
SEC Disclosure of Payments by Resource Extraction Issuers	2021-03-16	United States
Mandate for investigation into the sustainable extraction and recycling of metals and minerals from secondary resources	2021-03-26	Sweden
The National Programme for Resources Development	2021-03-31	Korea
Act on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal	2021-04-01	Korea
Canada's Clean Energy for Rural and Remote Communities	2021-04-16	Canada
EU Corporate Sustainability Reporting Directive	2021-04-21	European Union
National Mineral Industry Transformation Plan 2021-2030	2021-04-22	Malaysia
National Plan for Recovery and Resilience– Component 5.3: Circular Economy	2021-04-30	Belgium
National Recovery and Resilience Plan / M2C1 Sustainable agriculture and circular economy	2021-04-30	Italy
EU-UK Rules of Origin for EV batteries	2021-05-01	European Union
Critical Energy Minerals Roadmap	2021-05-19	Australia
Circular Economy Action Plan	2021-05-25	Spain
100-day reviews under EO 14017: Building resilient supply chains, revitalizing American manufacturing, and fostering broad-based growth	2021-06-08	United States

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Table D.1: Critical Mineral Events (continued)

Event	Date	Country
Supply Chain Act	2021-06-11	Germany
Implementing the United Nations Declaration on the Rights of Indigenous Peoples Act	2021-06-21	Canada
Resolution No 2 by which some minerals are determined as a strategic for the country	2021-06-22	Brazil
National Battery Strategy 2025	2021-06-26	Finland
14th Five Year Plan on circular economy	2021-07-07	People's Republic of China
Ukraine - EU Strategic Partnership on Raw Materials	2021-07-12	Multilateral
Blockchain Pilot Grants: Critical minerals	2021-07-12	Australia
Law 31.283 by which the exploration, exploitation and industrialisation of lithium and its derivates are determined as public necessity, national interest, and strategic resources for the country	2021-07-16	Peru
Canada-EU Strategic Partnership on Raw Materials	2021-07-19	Multilateral
National Planning Policy Framework	2021-07-20	United Kingdom
Modern Manufacturing Initiative - Recycling and Clean Energy projects funding	2021-07-26	Australia
The National Program for Metal (Nonferrous and Rare) Stockpiling	2021-08-05	Korea
Decree 151: Action Plan for the Ecuadorian mining sector	2021-08-05	Ecuador
Rare Metals Supply Plan 2.0	2021-08-05	Korea
DOE funding to secure domestic supply chain of critical elements and minerals	2021-09-02	United States
Philippine Mineral Reporting Code	2021-09-02	Philippines
Twelfth Malaysia Plan 2021-2025: A Prosperous, Inclusive, Sustainable Malaysia	2021-09-27	Malaysia
Critical Minerals Facility	2021-09-28	Australia
Resolution No 255/2021 to create the Federal Network of Argentinian Mining Women	2021-09-30	Argentina
Foreign investments for nuclear related projects and critical minerals	2021-10-05	Japan
Law implementing EU regulation 2017/821 relative to minerals from conflict-affected and high-risk areas	2021-10-09	France
Memorandum of Understanding Between US Departments of Interior, Agriculture, Defense, Energy, and the Environmental Protection Agency to Improve Public Land Renewable Energy Project Permit Coordination	2021-10-11	United States
Net Zero Strategy: Build Back Greener	2021-10-19	United Kingdom
The EU's "Equality platform for the energy sector"	2021-10-29	European Union
Cross-border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations	2021-10-31	Canada
Decree 10.657. Establishes the policy to support the environmental licensing of investment projects for strategic minerals production.	2021-11-11	Brazil
Infrastructure and Jobs Act: Critical Minerals permitting and information	2021-11-15	United States
Critical and Strategic Minerals Assessment and Mapping	2021-12-01	France
Ordinance on Due Diligence Obligations and Transparency Regarding Minerals and Metals from Conflict Areas and Child Labour	2021-12-03	Switzerland
Law No. 14,260/2021 - establishes incentives for the recycling industry	2021-12-08	Brazil
Administrative Measures for the Transformation, Upgrading and Decommissioning of Wind Farms	2021-12-13	People's Republic of China
Australia - Korea Comprehensive Strategic Partnership	2021-12-14	Multilateral
European Commission Recommendation on the use of Environmental Footprint methods	2021-12-16	European Union
Federal action plan for a circular economy (2021-2024)	2021-12-17	Belgium
14th FYP for Raw Material Industry Development	2021-12-21	People's Republic of China
DENR Administrative Order 2021-40	2021-12-23	Philippines
SASAC announcement on the establishment of China Rare Earth Group	2021-12-23	People's Republic of China
Uyghur Forced Labor Prevention Act	2021-12-23	United States
Special Administrative Measures for Foreign Investment Access (Negative List) (2021)	2021-12-27	People's Republic of China
Crude Nickel Cobalt Hydroxide standard	2021-12-30	People's Republic of China
Material and Digital Traceability for the Certification of Critical Raw Materials	2022-01-01	European Union
EUR 37.5 million granted to Midac for R&D in the field of batteries	2022-01-01	Italy
"France 2030 investment Plan"- Critical minerals investment	2022-01-10	France
Decree No. 08/2022/ND-CP	2022-01-10	Viet Nam
Varin report on critical minerals	2022-01-11	France
Companies and LLPs ESG Regulatory Requirement	2022-01-17	United Kingdom

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Table D.1: Critical Mineral Events (continued)

Event	Date	Country
Request for Information - Rare Earth Element Demonstration Facility	2022-02-14	United States
Directive on Corporate Sustainability Due Diligence (CSDD)	2022-02-23	European Union
Final List of Critical Minerals 2022	2022-02-24	United States
America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition	2022-02-24	United States
National Mining Policy	2022-03-02	Chile
Major Project Status conceded to AUD 560 million cobalt project in Broken Hill	2022-03-02	Australia
Resolution 40109 of 18 March 2022 of the Ministry of Mines and Energy	2022-03-18	Colombia
Decree-law 21 March 2022, N. 21, Art. 30	2022-03-21	Italy
Australia - India Critical Minerals Investment Partnership	2022-03-29	Multilateral
Interagency Working Group on Mining Reform Fundamental Principles	2022-03-31	United States
Memorandum on Presidential Determination Pursuant to Section 303 of the Defense Production Act of 1950, as amended	2022-03-31	United States
Defense Production Act	2022-03-31	United States
Law implementing the EU regulation 2017/821 relative to conflict minerals	2022-04-01	Belgium
Investments in rare earth refining	2022-04-04	Australia
Australia-India Strategic Research Fund	2022-04-06	Multilateral
Canada's Federal Budget 2022	2022-04-07	Canada
Critical Mineral Exploration Tax Credit (CMETC)	2022-04-07	Canada
Supporting Canada's Rural Communities	2022-04-07	Canada
Targeted Critical Minerals and Metals List	2022-04-14	South Africa
Reform of the Mining Code	2022-04-14	France
Exploration Strategy for the Mining Industry of South Africa	2022-04-14	South Africa
Energy Ministry Decree No.77k/MB.01/MEM.B/2022	2022-04-14	Indonesia
Mining Reforms 2022 - DECREE by which various provisions of the Mexican Mining Law are amended and added	2022-04-21	Mexico
Pakistan Import Policy Order 2022	2022-04-22	Pakistan
Rare earth elements content disclosure in consumer goods	2022-04-29	France
Canada Launches Call for Proposals for Critical Mineral Development	2022-05-11	Canada
Biden-Harris Permitting Action Plan	2022-05-11	United States
Joint Communication to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the regions. EU External energy engagement in a changing world	2022-05-18	European Union
Minerals Security Partnership	2022-06-01	Multilateral
Increased supply readiness for goods and services from industry	2022-06-07	Sweden
Supplementary directive to the Investigation on a sustainable supply of innovation-critical metals and minerals	2022-06-10	Sweden
Critical Minerals Strategy Discussion Paper	2022-06-14	Canada
DENR Administrative Order 2022-04: Enhancing Biodiversity Conservation and Protection in Mining Operations	2022-06-23	Philippines
National Environmental Management: Biodiversity Act, 2022 Amendment	2022-06-24	South Africa
National Hazardous Waste Management Policy, 2022	2022-06-28	Pakistan
Decree No. 11.108. Establishes the Brazilian Mineral Policy and the Mineral Policy National Council	2022-06-29	Brazil
2022 Critical Minerals Strategy	2022-07-06	Australia
Law 2250 of 2022	2022-07-11	Colombia
Australia - United States Net Zero Technology Acceleration Partnership	2022-07-12	Multilateral
Raw materials guarantee scheme	2022-07-14	Sweden
Critical Minerals List	2022-07-22	United Kingdom
Resilience for the future: The UK's critical minerals strategy	2022-07-22	United Kingdom
Automotive Transformation Fund	2022-07-22	United Kingdom
Proposed Minerals Act (2022)	2022-08-01	Norway
Regulatory Decree of the Environment and Sustainable Development Sector addresses WEEE, batteries and accumulators	2022-08-05	Colombia
USD 675 million for expansion of domestic critical minerals supply chains	2022-08-09	United States
Critical Minerals Research Program Request for Information	2022-08-09	United States
National Environmental (Electrical/Electronic Sector) Regulations, 2022	2022-08-16	Nigeria
Inflation Reduction Act 2022: Sec. 13401 Clean Vehicle Credit	2022-08-16	United States
Battery Waste Management Rules 2022	2022-08-22	India
Decree by which the decentralised public body Lithium for Mexico is created	2022-08-23	Mexico
Roadmap for the sustainable management of mineral raw materials	2022-08-30	Spain

Continued on next page

Table D.1: Critical Mineral Events (continued)

Event	Date	Country
(Sonora) Renewable Energy Plan	2022-08-30	Mexico
The government's proposal to parliament to amend the Mining Act (HE 126/2022)	2022-09-08	Finland
National Strategy for the Circular Economy	2022-09-19	Italy
Critical Minerals Supply Chain Cooperation MOUs	2022-09-22	Multilateral
Korea-Canada MOU on Cooperation in Critical Mineral Supply Chains, the Clean Energy Transition and Energy Security	2022-09-23	Multilateral
Critical Minerals Development Program	2022-10-21	Australia
Australia - Japan Critical Minerals Partnership	2022-10-22	Multilateral
Policy Regarding Foreign Investments from State-Owned Enterprises in Critical Minerals under the Investment Canada Act	2022-10-28	Canada
E-Waste Management Rules, 2022	2022-11-02	India
Clean Technology (CT) Investment Tax Credit (ITC)	2022-11-03	Canada
Kazakhstan-EU Strategic Partnership on Raw Materials	2022-11-07	Multilateral
Namibia-EU Strategic Partnership on Raw Materials	2022-11-08	Multilateral
Policy Statement on Mineral Exploration and Mining	2022-12-07	Ireland
Canada's Critical Minerals Strategy	2022-12-09	Canada
Decree on the Interministerial Delegation for the Supply of Strategic Minerals and Metals	2022-12-10	France
Sustainable Critical Minerals Alliance	2022-12-12	Multilateral
Energy Ministry Decree regarding National Planning on Mineral and Coal 2022-2027	2022-12-19	Indonesia
Geological Survey of Norway Award Letter	2022-12-21	Norway
Export Ban on Bauxite Ores	2022-12-21	Indonesia
Directorate of Mining Award Letter	2022-12-21	Norway
National Defense Authorization Act	2022-12-23	United States
Malawi Action Plan for the Open Government Partnership 2023-2025	2022-12-29	Malawi
Catalogue of Commodities subject to the Administration of Export Licences	2022-12-30	People's Republic of China
Catalogue for Encouraged Foreign Investment (2022)	2023-01-01	People's Republic of China
Policy paper of the Federal Ministry of Economics and Climate Action: Ways to a sustainable and resilient supply of raw materials	2023-01-03	Germany
Swedish center for strategic metals and minerals	2023-01-10	Sweden
Policy for Efforts to Ensure Stable Supply of Important Minerals	2023-01-19	Japan
Policy on initiatives for ensuring stable supply of critical minerals	2023-01-19	Japan
Circular Critical Materials Supply Chains (CLIMATES) Programme	2023-02-01	United Kingdom
Safe and sustainable access to innovation-critical raw materials	2023-02-02	Sweden
Statement on Seabed Mining	2023-02-09	Canada
Japan's Resource Diplomacy Guideline	2023-02-10	Japan
Belgium National Energy and Climate Plan (2021-2030)	2023-02-14	Belgium
Ukraine Critical Minerals List for Production Sharing Agreements	2023-02-14	Ukraine
DOE Awards for Small Businesses Developing Technologies to Cut Emissions and Study Climate	2023-02-22	United States
The strategy for securing reliable critical minerals supply	2023-02-27	Korea
Critical Mineral List in Korea	2023-02-27	Korea
EU Rules on End-of-Life Vehicles	2023-03-01	European Union
United Kingdom - Canada Joint Statement of Intent on Collaboration on Critical Minerals	2023-03-06	Multilateral
Critical Minerals Refresh	2023-03-13	United Kingdom
Critical Minerals Subsidy Program	2023-03-14	Japan
European Critical Raw Materials Act	2023-03-16	European Union
US - Japan Agreement on Strengthening Critical Minerals Supply Chains	2023-03-28	Multilateral
Joint Statement of Intent between Australia and the United Kingdom on collaboration on critical minerals	2023-04-04	Multilateral
Amendment to the Subsoil Use Law	2023-04-04	Ukraine
Joint declaration of intent between Australia and Germany on a critical minerals value chain feasibility study	2023-04-06	Multilateral
Critical Materials for Magnets (Innovate UK) - Circular Critical Materials Supply Chains Programme	2023-04-11	United Kingdom
France - Netherlands Joint Declaration 2023	2023-04-12	Multilateral
National Lithium Strategy	2023-04-24	Chile
Korea-U.S. High-Tech Industry & Clean Energy Partnership MOU	2023-04-26	Multilateral
Qinghai-Tibet Plateau Ecological Protection Law of the People's Republic of China	2023-04-26	People's Republic of China
2023-2024 Budget	2023-05-01	Australia
Government Regulation No.25/2023 regarding mining territory	2023-05-05	Indonesia

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Table D.1: Critical Mineral Events (continued)

Event	Date	Country
Mining Reforms 2023 - Decree by which by which various provisions of the Mexican Mining Law (and others) are amended, added and repealed	2023-05-08	Mexico
Base Minerals Export Control	2023-05-08	Zimbabwe
Supporting Australian Critical Minerals	2023-05-09	Australia
Critical minerals and metals equity fund	2023-05-11	France
Mining Royalty Bill	2023-05-17	Chile
Grants to invigorate Australian critical minerals projects	2023-05-18	Australia
Australia - US Climate, Critical Minerals and Clean Energy Transformation Compact	2023-05-20	Multilateral
Quad Statement of Principles on Clean Energy Supply Chains in the Indo-Pacific	2023-05-20	Multilateral
Resolution to adopt a New National Mining Policy	2023-06-06	Colombia
Argentina - EU Strategic Partnership on sustainable raw materials value chains	2023-06-13	Multilateral
National Security Strategy: Integrated Security for Germany	2023-06-14	Germany
Critical Minerals Strategy 2023-2030	2023-06-20	Australia
Regulation for small electrical products and solar photovoltaic systems	2023-06-20	Australia
Norwegian Mineral Strategy	2023-06-21	Norway
Strategy for Industrial New Growth through Invigoration of Circular Economy	2023-06-21	Korea
US - India Joint Statement on Critical Minerals	2023-06-22	Multilateral
France-Germany-Italy Joint Communique on Critical Raw Materials	2023-06-26	Multilateral
Saudi Arabia - Vale-Minerals Agreement	2023-07-01	Multilateral
Announcement on the Implementation of Export Control of Items Related to Gallium and Germanium	2023-07-03	People's Republic of China
EU Sustainable Batteries Regulation	2023-07-12	European Union
Chile - EU Strategic Partnership on sustainable raw materials value chains	2023-07-17	Multilateral
Chile - EU Strategic Partnership on sustainable raw materials value chains	2023-07-18	Multilateral
2023 Tax Revision Bill	2023-07-27	Korea
"Recycling, recyclability and material reincorporation" call for projects	2023-07-28	France
Amendment to Waste Management Act - includes standards to improve circularity of EV battery wastes	2023-08-03	Korea
US DOE Critical Materials List 2023	2023-08-04	United States
Mines and Minerals (Development & Regulation) Amendment Act, 2023	2023-08-09	India
New Growth Acceleration Program (Novo PAC)	2023-08-11	Brazil
Temporary import tax decrease	2023-08-16	Mexico
Energy Ministry Decree No.258.K/MB.01/MEM.B/2023	2023-08-18	Indonesia
Malaysia's Plan to Ban Rare Earth Exports	2023-09-11	Malaysia
Energy Ministry Regulation No.10/2023	2023-09-11	Indonesia
Energy Ministry Regulation No.10/2023 Regarding Procedures for Reporting the Implementation of Mineral and Coal Mining Business Activities	2023-09-11	Indonesia
Energy Ministry Decree Regarding Classification of the Critical Minerals Lists	2023-09-14	Indonesia
General Law for the Prevention and Integral Management of Wastes	2023-10-08	Mexico
Energy Ministry Decree N0.373.k/MB.01/MEM.B/2023	2023-10-20	Indonesia
Financing for Environmentally Friendly Business Activities from Bank Rakyat Indonesia (BRI)	2023-10-21	Indonesia
Indonesia Guidelines for Application, Evaluation, and Business and Special Business Permit for Mining Territory Expansion in the context of Mineral and Coal Conservation	2023-10-23	Indonesia
DRC - EU Strategic Partnership on sustainable raw materials value chains	2023-10-26	Multilateral
Zambia - EU Strategic Partnership on sustainable raw materials value chains	2023-10-26	Multilateral
Fighting Against Forced Labour and Child Labour in Supply Chains Act (S.C. 2023, c. 9)	2023-11-05	Canada
Canada-UK Critical Minerals: Sustainability and Circularity funding competition	2023-11-20	Multilateral
Resolution 1006 of 30 November 2023	2023-11-30	Colombia
Joint Statement on the Minerals Security Partnership Announce Support for Mining, Processing and Recycling Projects	2023-12-06	United States
Call for proposals for grants that support the Critical Minerals Traceability Project (CMTP)	2023-12-07	Canada
Zimbabwe's Strategic Minerals List	2023-12-14	Zimbabwe
Colombia's Mining Traceability and Transaction Control System	2023-12-22	Colombia

Continued on next page

Table D.1: Critical Mineral Events (continued)

Event	Date	Country
Made in Italy - Traceability	2023-12-27	Italy
Organic provisions for the valorisation, promotion and protection of Made in Italy	2023-12-27	Italy
Law No. 21649 Modifying Provisions of the Mining Code	2023-12-30	Chile
Critical Minerals Security Act of 2024	2024-01-18	United States

Table D.2: Critical Mineral Policies and Probabilities (τ: 0.1)

Date	Event	Country	Weeks		
			1	2	4
10/23/2015	Electrical and Electronic Equipment Act	Germany		**	**
06/03/2016	Law 20920. Establishment of a framework for waste management, extended producer responsibility and recycling.	Chile		*	
12/16/2016	Environmental Permitting (England and Wales) Regulations 2016	United Kingdom	***	***	***
03/31/2017	French Corporate Duty of Vigilance Law	France		*	**
07/21/2017	Australia Minerals National Mineral Exploration Strategy	Australia			**
07/21/2017	Implementation Plan for Prohibiting the Entry of Foreign Waste	People's Republic of China			**
12/22/2017	Executive Order 13817, A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals	United States			**
03/02/2018	Interim Provisions on the Traceability Management of Power Battery Recycling in New Energy Vehicles	People's Republic of China			*
11/30/2018	Decree 430-18 by which the Province of "Pedernales" is declared as "Avila" Mining Fiscal Reserve, for the exploration and evaluation of possible "rare earth" deposits developed directly by the State or through contracts	Dominican Republic		*	***
11/30/2018	Ministerial Decree #18/042 declaring cobalt, germanium and colombo-tantalite strategic mineral substances	Democratic Republic of the Congo		*	***
12/14/2018	Modern Slavery Act	Australia		*	
12/28/2018	Announcement on Adjustment of Import Waste Management Catalogue Announcement No. 36 of 2009	People's Republic of China	*		
10/04/2019	Research Program on the Kinetics of Ultra-Concentrated Mineralisation of Strategic and Critical Metals	People's Republic of China			**
01/10/2020	Canada-US Joint Action Plan on Critical Minerals Collaboration	Multilateral	*		
04/03/2020	JOGMEC & JBIC financial support for overseas minerals projects	Japan	***	***	
05/15/2020	(California) California Energy Commission grants for geothermal and lithium recovery projects	United States		*	
07/10/2020	Circular economy - Strategy for the transformation of Sweden	Sweden		***	***
07/24/2020	Exploring for the Future Program	Australia	*	***	***
06/11/2021	Supply Chain Act	Germany			*
06/11/2021	100-day reviews under EO 14017: Building resilient supply chains, revitalizing American manufacturing, and fostering broad-based growth	United States			*
06/25/2021	Resolution No 2 by which some minerals are determined as a strategic for the country	Brazil		**	***
06/25/2021	Implementing the United Nations Declaration on the Rights of Indigenous Peoples Act	Canada		**	***
07/02/2021	National Battery Strategy 2025	Finland	*	***	
07/09/2021	14th Five Year Plan on circular economy	People's Republic of China	***	***	
12/31/2021	Crude Nickel Cobalt Hydroxide standard	People's Republic of China	***		
12/31/2021	Special Administrative Measures for Foreign Investment Access (Negative List) (2021)	People's Republic of China	***		
02/18/2022	Request for Information - Rare Earth Element Demonstration Facility	United States			***
03/04/2022	Major Project Status conceded to AUD 560 million cobalt project in Broken Hill	Australia		***	***
03/04/2022	National Mining Policy	Chile		***	***
03/18/2022	Resolution 40109 of 18 March 2022 of the Ministry of Mines and Energy	Colombia		***	
04/22/2022	Pakistan Import Policy Order 2022	Pakistan			***
04/22/2022	Mining Reforms 2022 - DECREE by which various provisions of the Mexican Mining Law are amended and added	Mexico			***
04/29/2022	Rare earth elements content disclosure in consumer goods	France			***
05/13/2022	Biden-Harris Permitting Action Plan	United States	**	***	***
05/13/2022	Canada Launches Call for Proposals for Critical Mineral Development	Canada	**	***	***

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Table D.2: Critical Mineral Policies and Probabilities (continued)

Date	Event	Country	Weeks		
			1	2	4
05/20/2022	Joint Communication to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the regions. EU External energy engagement in a changing world	European Union	***	***	***
10/21/2022	Critical Minerals Development Program	Australia		**	**
10/28/2022	Policy Regarding Foreign Investments from State-Owned Enterprises in Critical Minerals under the Investment Canada Act	Canada	***	**	***
10/28/2022	Australia - Japan Critical Minerals Partnership	Multilateral	***	**	***
11/04/2022	Clean Technology (CT) Investment Tax Credit (ITC)	Canada	*	**	
11/04/2022	E-Waste Management Rules, 2022	India	*	**	
01/06/2023	Policy paper of the Federal Ministry of Economics and Climate Action: Ways to a sustainable and resilient supply of raw materials	Germany			**
01/06/2023	Catalogue for Encouraged Foreign Investment (2022)	People's Republic of China			**
01/20/2023	Policy for Efforts to Ensure Stable Supply of Important Minerals	Japan		***	*
01/20/2023	Policy on initiatives for ensuring stable supply of critical minerals	Japan		***	*
05/05/2023	Government Regulation No.25/2023 regarding mining territory	Indonesia			*
05/05/2023	2023-2024 Budget	Australia			*
09/15/2023	Energy Ministry Decree Regarding Classification of the Critical Minerals Lists	Indonesia		***	
09/15/2023	Energy Ministry Regulation No.10/2023	Indonesia		***	
09/15/2023	Energy Ministry Regulation No.10/2023 Regarding Procedures for Reporting the Implementation of Mineral and Coal Mining Business Activities	Indonesia		***	
09/15/2023	Malaysia's Plan to Ban Rare Earth Exports	Malaysia		***	

Notes: Over three time windows (1 week, 2 weeks, and 4 weeks after the event), 0.90–0.94 (*), 0.95–0.98 (**), and 0.99–1.00 (***) indicate the probability that the spillover index increases.

Table D.3: Critical Mineral Policies and Probabilities (τ: 0.5)

Date	Event	Country	1	2	4
01/03/2020	Raw materials strategy of the Federal Government: Securing a sustainable supply of non-energy mineral raw materials for Germany	Germany			*
01/03/2020	2.9 billion euro fund for research and innovation in battery technology	European Union			*
01/03/2020	Prohibition of the export of nickel ore	Indonesia			*
03/10/2023	United Kingdom - Canada Joint Statement of Intent on Collaboration on Critical Minerals	Multilateral			**

Notes: Over three time windows (1 week, 2 weeks, and 4 weeks after the event), 0.90–0.94 (*), 0.95–0.98 (**), and 0.99–1.00 (***) indicate the probability that the spillover index increases.

Table D.4: Critical Mineral Policies and Probabilities (τ: 0.9)

Date	Event	Country	Weeks		
			1	2	4
03/25/2016	Legislative Decree No 27 of 15 February 2016	Italy			**
04/22/2016	Resolution No 40391 by which the National Mining Policy is approved	Colombia			*
12/02/2016	National Plan for Mineral Resources (2016-2020)	People's Republic of China	**	***	**
06/07/2019	Mining (Designated Minerals Certification) Regulations	United Republic of Tanzania		**	
06/14/2019	Energy Resource Governance Initiative	United States	**		*
06/14/2019	Proposal to create the National Management System for State Mining Income	Dominican Republic	**		*
06/21/2019	Impact Assessment Act	Canada			*
10/02/2020	Executive Order 13953, Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries	United States		**	
10/02/2020	Law 2056 to regulate the organisation and functioning of the general system of royalties	Colombia		**	

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Table D.4: Critical Mineral Policies and Probabilities (continued)

			Weeks		
Date	Event	Country	1	2	4
10/02/2020	Ordinance No. 354/2020. The Mining and Development Program	Brazil		**	
12/18/2020	Recycling and Waste Reduction Act 2020	Australia			**
02/12/2021	CONPES 4023: Policy for Reactivation, Revitalisation, and Sustainable and Inclusive Growth	Colombia		***	
02/19/2021	State support for investment projects with significant investments in Ukraine (Law No. 1116)	Ukraine	***	**	
02/26/2021	Executive Order 14017 of America's Supply Chains	United States	**		
04/16/2021	Canada's Clean Energy for Rural and Remote Communities	Canada			***
04/23/2021	National Mineral Industry Transformation Plan 2021-2030	Malaysia			**
04/23/2021	EU Corporate Sustainability Reporting Directive	European Union			**
04/30/2021	National Plan for Recovery and Resilience– Component 5.3: Circular Economy	Belgium		***	***
04/30/2021	National Recovery and Resilience Plan / M2C1 Sustainable agriculture and circular economy	Italy		***	***
05/07/2021	EU-UK Rules of Origin for EV batteries	European Union	**	**	***
05/21/2021	Critical Energy Minerals Roadmap	Australia		**	***
05/28/2021	Circular Economy Action Plan	Spain	***	***	**
07/30/2021	Modern Manufacturing Initiative - Recycling and Clean Energy projects funding	Australia			***
10/22/2021	Net Zero Strategy: Build Back Greener	United Kingdom	*	*	**
01/21/2022	Companies and LLPs ESG Regulatory Requirement	United Kingdom		*	
02/18/2022	Request for Information - Rare Earth Element Demonstration Facility	United States	**		
06/03/2022	Minerals Security Partnership	Multilateral			*
06/17/2022	Critical Minerals Strategy Discussion Paper	Canada	**	*	
01/20/2023	Policy for Efforts to Ensure Stable Supply of Important Minerals	Japan		*	
01/20/2023	Policy on initiatives for ensuring stable supply of critical minerals	Japan		*	
02/17/2023	Ukraine Critical Minerals List for Production Sharing Agreements	Ukraine			*
02/17/2023	Belgium National Energy and Climate Plan (2021-2030)	Belgium			*
02/24/2023	DOE Awards for Small Businesses Developing Technologies to Cut Emissions and Study Climate	United States		*	***
03/03/2023	Critical Mineral List in Korea	Korea		**	
03/03/2023	The strategy for securing reliable critical minerals supply	Korea		**	
03/03/2023	EU Rules on End-of-Life Vehicles	European Union		**	
03/10/2023	United Kingdom - Canada Joint Statement of Intent on Collaboration on Critical Minerals	Multilateral	*		
06/09/2023	Resolution to adopt a New National Mining Policy	Colombia	**	**	
06/16/2023	National Security Strategy: Integrated Security for Germany	Germany	**	**	
06/16/2023	Argentina - EU Strategic Partnership on sustainable raw materials value chains	Multilateral	**	**	

Notes: Over three time windows (1 week, 2 weeks, and 4 weeks after the event), 0.90–0.94 (*), 0.95–0.98 (**), and 0.99–1.00 (***) indicate the probability that the spillover index increases.

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