Rare Earths, AI, and Digital Finance: Supply-Chain Risk and Managerial Implications

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Abstract: Rare earth elements (REEs) are an underexamined asset class at the intersection of digital finance, artificial intelligence (AI) and strategic resource management. AI infrastructure sustains demand for neodymium, dysprosium and terbium, whose supply chains remain highly concentrated in China. This paper analyses how REE supply-chain risk propagates into the equity markets of AI-intensive firms. Using open-source data from the International Energy Agency, the VanEck Rare Earth and Strategic Metals ETF (REMX) and the USGS Mineral Commodity Summaries, we characterise REE-sensitive instruments over 2020-2026 and propose a Shapley-value decomposition of REMX return predictions into concentration, geopolitical, technology-demand and macro-financial channels. The evidence suggests that REE concentration risk is a financially material and insufficiently priced systemic factor. We derive recommendations for portfolio construction, corporate disclosure and the regulation of digital finance infrastructure.

Key-words: Rare earth elements; artificial intelligence; digital finance; supply-chain risk; geopolitical risk; critical minerals; portfolio management; explainable AI.

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1 Introduction

The ascent of artificial intelligence as a transformative technology platform has redrawn the map of factor scarcity in modern economies. While attention has rightly focused on computational resources, data infrastructure, and algorithmic talent, a less visible but equally fundamental constraint has begun to bind: the physical materials from which AI hardware is constructed. Rare earth elements (REEs), a group of seventeen chemically similar metals whose properties underpin high-performance magnets, semiconductors, and optical devices, lie at the heart of this constraint, [1].

Supply chains for REEs are extraordinarily concentrated: for the magnet rare earths (neodymium, praseodymium, dysprosium and terbium), China accounted for around 60% of global mining output and about 91% of separation and refining in 2024, [2]. During 2025, China extended export controls first to seven heavy rare earth elements (April) and then to five more (October), bringing the total to twelve, and introduced licensing requirements for parts, components and assemblies containing Chinese-sourced rare earth materials. The IEA identifies energy, defence, semiconductors and AI data centres among the most exposed sectors, [2]. Each restriction reverberated through financial markets, yet the systemic nature of the exposure has received limited analytical treatment in the business and economics literature.

This paper offers three contributions. It situates REE supply-chain risk within digital finance, arguing that critical minerals constitute a new and underpriced systemic factor. It provides a descriptive empirical characterisation of REE-linked financial instruments together with a formal Shapley-value decomposition of their risk channels. And it derives actionable managerial and governance recommendations grounded in both empirical evidence and the extant literature on supply-chain risk and explainable AI.

2 Literature Review

The economic and financial study of critical minerals has a relatively short but rapidly expanding lineage. A foundational study, [3], documented the growing materials complexity of modern technologies and showed that, for a dozen metals, the potential substitutes in their major uses are inadequate or nonexistent, laying the groundwork for multidimensional assessments of criticality. Related evidence, [4], shows that many technologically essential met-

als are recovered mainly as by-products of major carrier metals, which makes their supply structurally problematic and weakly responsive to demand.

Regarding REEs and financial markets, an economic theory of risk specific to critical mineral supply chains has been developed in [5], which introduces the "back-ended risk premium" and argues that investment in AI-based methods can reduce this premium. That study, published in *Nature Communications*, provides one of the most rigorous treatments of AI as an instrument for managing critical mineral risk, a dual role that is central to the framework adopted here.

The geopolitical dimension is analysed in [6], which documents nonlinear, regime-dependent interdependencies between REE markets and critical sectors including AI and semiconductors, combining quantile-on-quantile regression and wavelet coherence on daily data from 2018 to 2025. The evidence that REE indices lead AI-sector equities at low frequencies directly informs our hypothesis.

From the digital finance perspective, rising REE prices have been shown to suppress fintech productivity during long-term growth regimes, while geopolitical turmoil disproportionately harms fintech outputs during market downturns, [7]. On the supply side, the IEA projects that demand for magnet rare earths grows by 50-60% by 2040 even under the Stated Policies Scenario, [8], and that China still accounts for 77% of refined rare earth output in 2030, [1].

The explainability dimension builds on the Shapley additive explanation (SHAP) framework introduced in [9] and on its application to machine-learning asset pricing in [10], where SHAP values and local surrogate models were used to interpret Random Forest and XGBoost price forecasts and to rank the contribution of each market variable.

3 The Structure of REE Financial Markets

3.1 The REE Asset Class in Digital Finance

Rare earth elements do not trade as standardised contracts on major commodity exchanges. Unlike copper, oil, or gold, REEs are traded primarily through opaque over-the-counter markets and long-term bilateral contracts. This structure implies that price discovery is inefficient and that the informational content of available market signals is limited.

The most liquid instrument providing REE exposure is the VanEck Rare Earth and Strategic Metals ETF (NYSE Arca: REMX), which tracks the MVIS Global Rare Earth/Strategic Metals Index (MVREMXTR), [11]. As of early April 2026, the fund managed approximately USD 3.0 billion in assets, with top holdings in China Northern Rare Earth Group (7.9%), Albemarle Corporation (7.65%), and Lynas Rare Earths (7.26%), [12].

The digital finance ecosystem engages with REE markets through channels that conventional asset pricing frameworks do not model explicitly. AI hardware manufacturers hold concentrated exposures to REE input prices. Tokenised commodity instruments create novel transmission channels for price volatility into digital asset markets. And AI-driven portfolio management systems introduce a reflexive loop: the very systems dependent on REE-intensive hardware are used to manage REE market exposures.

3.2 China's Structural Dominance

China holds about 44 million tonnes of rare earth oxide reserves, nearly half of known world reserves, [13], yet its power lies above all in processing: about 91% of global refining of magnet rare earths and 94% of sintered permanent magnet manufacturing, [2], [14]. In 2024, China exported 58,000 tonnes of rare earth magnets, used across automotive motors, industrial motors, wind turbines, defence systems and data centres, [2]. The October 2025 expansion of export controls to include "parts, components and assemblies" directly threatened these sectors, [2].

4 Empirical Analysis

4.1 Data Sources

The empirical analysis draws on three open-source datasets. The *IEA Critical Minerals Data Explorer* provides harmonised annual demand and supply series for rare earth elements, [8]. The *REMX historical series* from Yahoo Finance covers daily observations from January 2020 to March 2026, [12]. The *USGS Mineral Commodity Summaries*, [13], supply annual production and trade data for individual REEs. No proprietary data were used.

4.2 Stylised Facts: REMX Dynamics, 2020-2026

Table 1 presents summary statistics for REMX over the sample period. The 52-week range spanning USD 32.36 to USD 103.68 reflects exceptional volatility: a price ratio exceeding three to one. The 5-year monthly beta of 1.55 confirms that the instrument amplifies systematic market movements.

Table 1. REMX summary statistics

Statistic	Value
52-week high (USD)	103.68
52-week low (USD)	32.36
Net assets (USD bn)	3.04
Expense ratio (%)	0.58
5-year beta (monthly)	1.55
YTD return (%, to Jan. 2026)	17.78
Top 3 holdings (% AUM)	
China Northern Rare Earth	7.90%
Albemarle Corp. (ALB)	7.65%
Lynas Rare Earths (LYC.AX)	7.26%

Source: Yahoo Finance, [12], data as of early April 2026.

The fund's compositional feature has a direct financial implication: Chinese export restrictions simultaneously constrain Chinese holdings (compliance costs) while improving the competitive positioning of Western holdings (negotiating leverage). The net effect on fund value is a priori ambiguous and depends on the relative magnitudes and timing of these opposing forces.

4.3 REE Demand Projections and the AI Channel

Table 2 synthesises IEA indicators for the magnet rare earth value chain. Demand for magnet rare earths is projected to grow by 50-60% by 2040 under the Stated Policies Scenario (STEPS), [8], while China's share of refined output is expected to remain at 77% in 2030, [1]. The AI demand channel compounds this pressure: AI chips and data centres draw on gallium, germanium, indium, palladium and tantalum, while rare earth magnets are used in data centre cooling fans, robotics and autonomous systems, [15].

Table 2. Magnet rare earth value-chain indicators

Indicator	Value
China: share of mining, 2024	about 60%
China: share of refining, 2024	about 91%
China: sintered magnets, 2005 / 2024	50% / 94%
China: refined output, 2030 base case	77%
Demand growth to 2040 (STEPS)	50-60%

Source: International Energy Agency, [1], [2], [8], licensed under CC BY 4.0.

4.4 Geopolitical Shocks and Market Responses

The wavelet coherence analysis in [6], covering 2018-2025, identifies strengthened low-frequency coherence between the MVREMXTR index tracked by REMX and the S&P Kensho Artificial Intelligence Enablers & Adopters index (NDXAI) during 2020-2023. Phase arrows indicate that REE price movements *lead* AI-sector equity adjustments, consistent with supply-chain risk priced with a lag. The IEA analysis of the October 2025 restrictions, [2], documents that the inclusion of holmium was particularly significant because magnet manufacturers had been substituting it for the elements restricted in April 2025: the second-round restriction closed an escape valve on which the industry had relied.

4.5 A Shapley-Value Decomposition of REE Risk

We adopt the Shapley-value formulation used for explainable asset pricing in [10] and apply it to groups of features rather than to individual variables. Let f denote a gradient boosting predictor of the daily REMX return and let $N = \{C, G, T, M\}$ be the set of risk groups. The contribution of group $k \in N$ is

$$\phi_k = \sum_{S \subseteq N \setminus \{k\}} \frac{|S|!\,(|N| - |S| - 1)!}{|N|!} \big[f(S \cup \{k\}) - f(S) \big], \quad (1)$$

where $f(S)$ is the prediction obtained when only the groups in S are informative. The four groups are defined as follows.

(i) **Concentration risk** ϕ_C: China's refining share and the Herfindahl-Hirschman index of global REE mine production,

$$\mathrm{HHI}_t = \sum_{j=1}^{J} s_{j,t}^2, \quad (2)$$

where $s_{j,t}$ is the share of country j in year t;

(ii) **Geopolitical shock risk** ϕ_G: the geopolitical risk index (GPR) and its threats component (GPRT), [16];

(iii) **Technology demand risk** ϕ_T: AI adoption and semiconductor output indices;

(iv) **Macro-financial risk** ϕ_M: VIX, the USD index and interest rate differentials.

By the local accuracy property of SHAP, [9], the model prediction for each trading day t decomposes exactly as

$$\hat{r}_t = \phi_0 + \phi_{C,t} + \phi_{G,t} + \phi_{T,t} + \phi_{M,t}, \quad (3)$$

where ϕ_0 is the expected model output over the sample. Averaging the absolute contributions over a period of length T,

$$\bar{\phi}_k = \frac{1}{T} \sum_{t=1}^{T} \big| \phi_{k,t} \big|, \qquad k \in N, \quad (4)$$

yields the relative importance of each risk channel in that period. Local robustness of the attribution in (3) can be checked, as in [10], with an interpretable surrogate

$$\hat{g} = \arg\min_{g \in \mathcal{G}} \mathcal{L}\big(f, g, \pi_{x_0}\big) + \Omega(g), \quad (5)$$

where π_{x_0} weights observations by their proximity to the trading day x_0 and $\Omega(g)$ penalises the complexity of g.

Equation (1) guarantees a fair allocation of each prediction among the four channels, (2) supplies the structural input to the concentration channel, and (4) turns the daily decomposition (3) into a ranking that can be compared across regimes, while (5) provides a local check on that ranking. We hypothesise that $\bar{\phi}_C > \bar{\phi}_G > \bar{\phi}_T > \bar{\phi}_M$ during geopolitical stress, inverting to $\bar{\phi}_T > \bar{\phi}_M > \bar{\phi}_G > \bar{\phi}_C$ in tranquil regimes, a pattern consistent with the regime-dependent evidence in [7] and to be tested in the estimation outlined in Section 6.

5 Managerial and Governance Implications

5.1 Portfolio Construction

The 5-year beta of 1.55 for REMX, combined with the low-frequency lead of REE prices over AI equities, implies that REE exposure functions as an amplified beta factor rather than a diversifying hedge. AI-sector portfolios that ignore upstream REE exposure systematically underestimate their effective factor loading on technological and geopolitical risk.

Two prescriptions follow. AI-sector portfolios should include an explicit upstream REE allocation to hedge input cost shocks, with rebalancing rules robust to the non-smooth transitions induced by export restriction announcements. The channel ranking in (4) can, moreover, serve as an early-warning signal: a rising $\bar{\phi}_C$ relative to $\bar{\phi}_M$ indicates that concentration risk is displacing ordinary market drivers and that hedges should be reinforced.

5.2 Corporate Governance and Disclosure

The opacity of Tier-2 and Tier-3 REE dependencies represents a governance failure with material financial consequences. The 10% equity stake in USA Rare Earth taken by the US administration in January 2026, [17], underscores that sovereign risk management now extends to critical mineral supply chains in ways that affect corporate governance frameworks directly.

We recommend that AI-intensive firms adopt a Critical Mineral Dependency Disclosure (CMDD) framework analogous to the Scope 1/2/3 emissions structure in climate reporting. The additive attribution in (3) offers a quantitative template for such disclosures, since each firm could report the share of its return variability attributable to the concentration channel.

5.3 Digital Finance Infrastructure

The digital finance ecosystem (blockchain networks, AI-driven trading platforms, robo-advisory services, and decentralised autonomous organisations) faces a structural vulnerability: its hardware infrastructure is REE-intensive in ways not reflected in current regulatory frameworks. Regulators should require stress-testing scenarios incorporating critical mineral supply disruptions, analogous to the liquidity stress scenarios mandated for systemically important financial institutions.

6 Conclusion

This paper has argued that rare earth elements represent a financially material and insufficiently priced systemic factor in the AI and digital finance economy. The structural concentration of REE supply chains, the regime-dependent transmission of shocks to AI-sector equities, and the strategic use of export restrictions collectively create a risk landscape that conventional frameworks are not equipped to handle.

The empirical evidence documents exceptional REMX volatility (52-week ratio > 3), a beta of 1.55, and magnet rare earth demand projected to grow by 50-60% by 2040 even under stated policies. These findings, combined with the Shapley-value decomposition proposed here, provide foundations for a new generation of REE-aware portfolio management and governance practices.

Future research should pursue three directions: econometric estimation of the decomposition in (1)-(4) on the full 2020-2026 REMX daily series; extension of the framework to gallium, indium, and cobalt; and integration of REE concentration risk into ESG scoring methodologies.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References

[1] International Energy Agency, *Global Critical Minerals Outlook 2024*, IEA, Paris, 2024, Licence: CC BY 4.0, [Online]. https://www.iea.org/reports/global-critical-minerals-outlook-2024 [Access Date: October 3, 2026].

[2] T.-Y. Kim, S. Dhir, A. Dasgupta, and A. Scanziani, "With new export controls on critical minerals, supply concentration risks become reality," IEA Commentary, International Energy Agency, Paris, October 23, 2025, Licence: CC BY 4.0, [Online]. https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality [Access Date: October 3, 2026].

[3] T.E. Graedel, E.M. Harper, N.T. Nassar, and B.K. Reck, "On the materials basis of modern society," *Proceedings of the National Academy of Sciences*, vol. 112, no. 20, pp. 6295–6300, 2015, https://doi.org/10.1073/pnas.1312752110.

[4] N.T. Nassar, T.E. Graedel, and E.M. Harper, "By-product metals are technologically essential but have problematic supply," *Science Advances*, vol. 1, no. 3, e1400180, 2015, https://doi.org/10.1126/sciadv.1400180.

[5] J. Vespignani and R. Smyth, "Artificial intelligence investments reduce risks to critical mineral supply," *Nature Communications*, vol. 15, Article 7304, 2024, https://doi.org/10.1038/s41467-024-51661-7.

[6] O. Panazan and C. Gheorghe, "Strategic risk spillovers from rare earth markets to critical industrial sectors," *International Journal of Financial Studies*, vol. 13, no. 3, Article 156, 2025, https://doi.org/10.3390/ijfs13030156.

[7] M.M. Islam, F. Ahmed, A. Al Mahmud, and M. Shahbaz, "The role of rare earth and metallic mineral prices and sovereign inflation-linked bonds in AI-driven fintech industrial development amid the Russia-Ukraine conflict: A dynamic quantile analysis approach," *Financial Innovation*, vol. 11, Article 140, 2025, https://doi.org/10.1186/s40854-025-00888-4.

[8] International Energy Agency, *Global Critical Minerals Outlook 2025*, IEA, Paris, 2025, Licence: CC BY 4.0, [Online]. https://www.iea.org/reports/global-critical-minerals-outlook-2025 [Access Date: October 3, 2026].

[9] S.M. Lundberg and S.-I. Lee, "A unified approach to interpreting model predictions," in *Advances in Neural Information Processing Systems 30 (NIPS 2017)*, Long Beach, CA, USA, 2017, https://doi.org/10.48550/arXiv.1705.07874.

[10] M. Ferrara and T. Ciano, "Improving the interpretability of asset pricing models by explainable AI: A machine learning-based approach," *Economic Computa-*

tion and Economic Cybernetics Studies and Research, vol. 58, no. 4, pp. 5–20, 2024, https://doi.org/10.24818/18423264/58.4.24.01.

[11] VanEck, "REMX: VanEck Rare Earth and Strategic Metals ETF, holdings and performance," VanEck, New York, [Online]. https://www.vaneck.com/us/en/investments/rare-earth-strategic-metals-etf-remx/ [Access Date: October 3, 2026].

[12] Yahoo Finance, "VanEck Rare Earth and Strategic Metals ETF (REMX): Quote, holdings and historical data," [Online]. https://finance.yahoo.com/quote/REMX/ [Access Date: October 3, 2026].

[13] U.S. Geological Survey, *Mineral Commodity Summaries 2025*, U.S. Geological Survey, Reston, VA, 2025, https://doi.org/10.3133/mcs2025.

[14] K. Siddiqui, "Rare earth critical minerals: Geopolitics, supply chains, and emerging tensions," *The World Financial Review*, September 23, 2025, [Online]. https://worldfinancialreview.com/rare-earth-critical-minerals-geopolitics-supply-chains-and-emerging-tensions/ [Access Date: October 3, 2026].

[15] A. Leader, A. Doris, A. Juani, and A. Carlson, "Artificial intelligence and the critical minerals crunch: Strategies for resilient supply chains," FP Analytics issue brief with support from JCDREAM, July 18, 2025, [Online]. https://fpanalytics.foreignpolicy.com/2025/07/18/artificial-intelligence-critical-minerals-supply-chains/ [Access Date: October 3, 2026].

[16] D. Caldara and M. Iacoviello, "Measuring geopolitical risk," *American Economic Review*, vol. 112, no. 4, pp. 1194–1225, 2022, https://doi.org/10.1257/aer.20191823.

[17] Reuters and CNBC, "Trump administration to take 10% stake in USA Rare Earth in $1.6 billion deal, sources say," *CNBC*, January 24, 2026, [Online]. https://www.cnbc.com/2026/01/24/us-rare-earths-miner.html [Access Date: October 3, 2026].

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Valeria Isgrò contributed to the conceptualisation, literature review, empirical design, and the XAI risk decomposition framework. Massimiliano Ferrara contributed to the formal Shapley-value specification, the portfolio and governance implications, and overall manuscript supervision. Both authors approved the final version.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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