Critical Minerals in an Age of Geopolitical Rivalry:
Stockpiling, Refining Constraints, and the Limits of Friend-Shoring★

Jamel Saadaoui[a,d], Russell Smyth[b,d], Joaquin Vespignani[c,d], Yitian Wang[b]

[a] *Paris 8 University, LED, Paris, France*
[b] *Monash University, Department of Economics, Monash Business School, Caulfield, Australia*
[c] *University of Tasmania, Tasmanian School of Business and Economics, Australia*
[d] *Centre for Applied Macroeconomic Analysis, Australian National University, Australia*

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Abstract

US–China geopolitical tensions pose significant risks to global critical-mineral supply chains, particularly because refining capacity for most critical minerals, including aluminum, copper, nickel, tin and zinc, is overwhelmingly concentrated in China. Using monthly data from 1995–2025 and a structural VAR-local projection framework, we estimate the dynamic effects of exogenous shocks to the US–China Political Relations Index (PRI) on mineral markets. We find that geopolitical deterioration systematically induces significant precautionary stockpiling. We then construct a multidimensional friend-shoring index incorporating reserves, alignment, regime type and distance, showing that only a narrow set of United States partners, primarily Australia and Canada, offer feasible pathways for refining diversification. The policy recommendation stemming from our findings is that the United States should make strategic stockpiling of refined critical minerals, rather than raw ores, the centerpiece of its strategy to build supply chain resilience, while negotiating long-term bilateral packages for the supply of refined critical minerals with Australia and Canada.

Keywords: Geopolitical risk; Critical minerals; Friend-shoring
JEL Codes: Q34; Q37; F51

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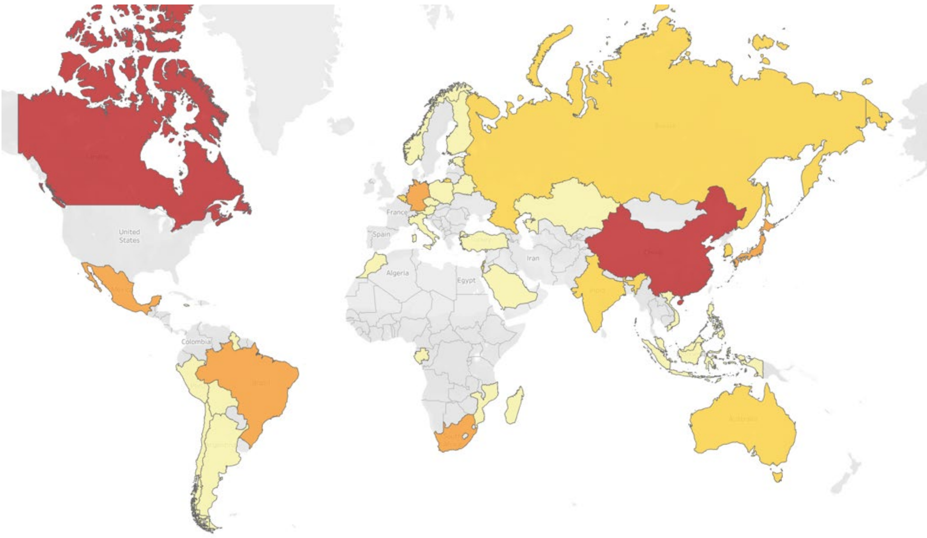
1. Introduction

Critical minerals are defined as those that are both essential in a modern technology and subject to supply-chain risk; both conditions are necessary for a mineral to be designated as critical (Adam, Arezki, and van der Ploeg, *forthcoming*; National Research Council, 2008). In this article, we focus on aluminum, copper, nickel, tin, and zinc because they are key inputs into electrification, digitalization, advanced manufacturing, and defense-related applications, while their refined supply chains are exposed to substantial concentration risk. Their strategic importance has risen sharply with the expansion of batteries, semiconductors, transmission infrastructure, electric vehicles, and aerospace systems (IEA, 2021; U.S. Department of Energy, 2023; Hidayat, 2025). For the United States, securing reliable access to these refined critical minerals has become increasingly difficult. Domestic refining capacity remains limited relative to downstream demand, reflecting high energy costs, environmental regulation, and local opposition to large industrial projects (EIA, 2021; Blum and Melvin, 2022; Vasquez, 2023). As a result, the United States Geological Survey's *Mineral Commodity Summaries* show that the United States is structurally dependent on global supply chains for several critical minerals, especially in refined form.

The United States' dependence on global supply chains for critical minerals is illustrated in Figure 1, which maps its net import reliance for non-fuel mineral commodities between 2020 and 2023. Figure 1 shows that the United States relies on a concentrated group of suppliers, most notably Canada and China, for more than half of its net imports across approximately twenty minerals. A second tier of suppliers, including Japan, Mexico, Brazil, South Africa and Germany, account for five to twelve minerals. This pattern underscores two structural challenges. First, supply is anchored in a narrow set of trading partners, providing few alternatives in the event of diplomatic or logistical shocks. Second, China functions simultaneously as a major supplier and the United States' principal geopolitical rival, reinforcing why bilateral relations have direct implications for critical-mineral security.

A major bottleneck hindering global supply chains of critical minerals is the configuration of global refining capacity. Although mining of critical minerals is geographically dispersed, midstream processing (i.e., the conversion of ores into high-purity industrial inputs) is overwhelmingly concentrated in China. China accounts for between one-half and three-quarters of global refining across aluminum/alumina, copper, nickel, zinc and tin (IEA, 2024; Chen & Tongurai, 2022; U.S. Geological Survey, 2025a,b). This dominance reflects decades of targeted industrial policy, subsidized energy, and economies of scale, coupled with the retreat of refining in advanced democracies. Recent work suggests that China's control of midstream capacity constitutes a strategic chokepoint, with exports of rare-earth magnets, battery precursors and other midstream products responding predictably to geopolitical tensions (Depraiter et al., 2025; Hidayat, 2025; Zhou, Crochet & Wang, 2025).

Figure 1: Leading Import Sources (2020-2023) of Nonfuel Mineral Commodities for which the United States was Greater than 50% Net Import Reliant



Note: Net import reliance (NIR), reported by the U.S. Geological Survey, is measured as net imports (imports minus exports), adjusted for changes in government and industry stocks, expressed as a percentage of apparent U.S. consumption. Apparent consumption is generally computed as domestic production plus imports minus exports, with adjustments for stock changes. Countries shown in color indicate foreign sources of nonfuel mineral commodities for which the United States was more than 50% net import reliant. Different colors indicate the number of nonfuel mineral commodities for which a country is a leading supplier to the United States: light yellow (1-3), dark yellow (4-6), orange (7-12), and red (19-21). Countries with net import reliance below 50% (or unavailable data) are shown in grey. Sources: U.S. Geological Survey (Mineral Commodity Summaries).

These risks have intensified as the US–China geopolitical rivalry has deepened. Diplomatic shocks can manifest in the form of tariffs, sanctions, export controls and human-rights disputes. These shocks intensify uncertainty in commodity and energy markets (Caldara & Iacoviello, 2022; Mignon & Saadaoui, 2024; Saadaoui, Smyth & Vespignani, 2025). The Political Relations Index (PRI) systematically tracks these shifts and has proven effective at isolating geopolitical turning points relevant to commodity-market behavior (Saadaoui, 2025). Yet despite the high stakes involved, little empirical evidence exists on whether bilateral geopolitical tensions translate into refined-mineral prices and how refined stockpiling and friend-shoring can be used to build supply chain resilience.

These vulnerabilities have become even more salient in recent months. China has tightened oversight and export controls over rare earth and other strategic mineral exports. In response to growing concerns over supply disruptions, the Trump administration announced ‘Project Vault’ in February 2026, a strategic critical-minerals stockpile intended to reduce the exposure of U.S. manufacturers to supply risks. Although these developments partly fall beyond our estimation window, they underscore the real-time relevance of the mechanisms analyzed in this research: stockpiling and supply restrictions have become central instruments in the geoeconomics of critical minerals.

This article contributes in three ways. First, we estimate the dynamic effects of deteriorations in US–China geopolitical relations on refined mineral markets using monthly data from 1995–2025 and an econometric approach combining a structural VAR with local projections (Jordà, 2005; Jordà & Taylor, 2025; Inoue, Jordà & Kuersteiner, 2025). This design allows us to identify how exogenous diplomatic shocks propagate through critical mineral markets via changes in production, prices and strategic stockpiling. We find that geopolitical deterioration reduces refined-mineral prices and induces substantial precautionary stockpiling, consistent with a global demand shock (see Kilian, 2009).

Second, to complement the empirical evidence and provide a forward-looking perspective, we develop a theoretical model which predicts that it is optimal for a country which is a net importer of refined critical minerals, such as the United States, to stockpile refined-mineral inventories under stochastic import disruptions, the probability of which increases with geopolitical tension. The theoretical model also examines the potential for such a net importer country to pursue friend-shoring as an alternative way to mitigate supply chain risk to stockpiling refined minerals. The model predicts that higher proven reserves of critical minerals in a friendly jurisdiction reduce the optimal stockpile requirement, while greater geopolitical distance and instances of critical mineral refining being located in a country with an authoritarian regime both raise the optimal stockpile.

Third, we construct a multidimensional friend-shoring feasibility index that incorporates geological endowments (U.S. Geological Survey, 2024), geopolitical alignment (Bailey, Strezhnev & Voeten, 2016; Correa da Cunha, Singh & Amal, 2024), regime type (Economist Intelligence Unit, 2025), and geographic distance. We find that only a narrow set of potential United States friend-shoring partners, mainly Australia and Canada, combine mineral scale and strategic alignment, while middle-feasibility candidates for friend-shoring, such as Brazil, Chile, Indonesia and Peru, face governance, institutional or logistical barriers. The policy recommendation stemming from this exercise is that the United States should make strategic stockpiling of refined minerals, rather than raw ores, the centerpiece of its resilience strategy, while negotiating long-term bilateral packages with Australia and Canada. Together, these contributions provide the first integrated framework linking geopolitical rivalry, refined-mineral market dynamics and the practical limits of diversification through friend-shoring.

The remainder of the article is organized as follows**.** Section 2 documents China's dominance in refined critical-mineral supply chains and details the evolution of US–China geopolitical relations using the

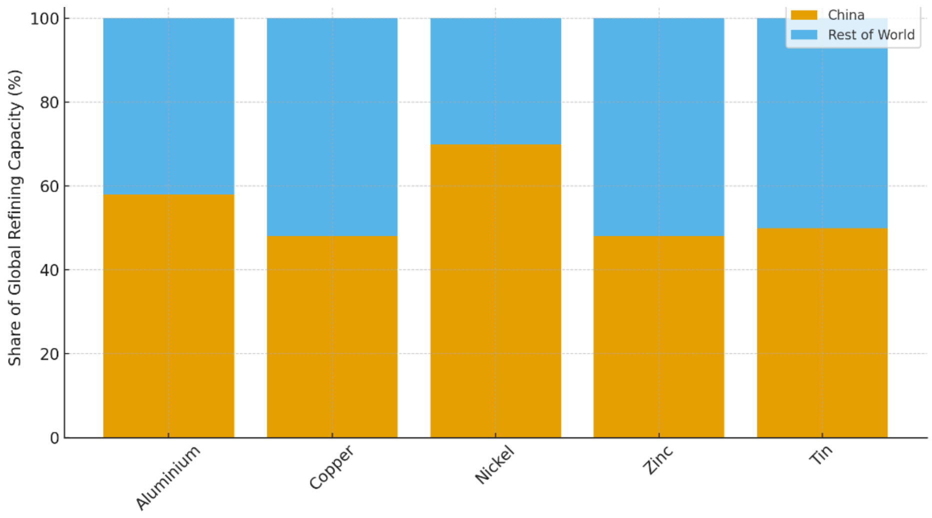
PRI. Section 3 presents the empirical strategy, combining a structural VAR with local projections to estimate the dynamic effects of exogenous diplomatic shocks on refined-mineral prices and stockpiling behavior. Section 4 presents a theoretical framework in which a net-importing country chooses its optimal refined-mineral stockpile under stochastic import disruptions and examines implications of friend-shoring for stockpiling. Section 5 introduces a multidimensional friend-shoring feasibility index incorporating geological endowments, geopolitical alignment, regime type and geographic distance. Section 6 concludes by discussing the policy implications for the US strategic stockpiling, supply-chain diversification and long-run coordination with geopolitical allies.

2. US–China Geopolitical Tension and Refined Critical Minerals Dominance

The strategic landscape of critical minerals is profoundly shaped by the evolving US–China geopolitical relationship (Mignon & Saadaoui, 2024; Saadaoui, 2025). This is most evident in the refining stage, where China holds a dominant global position across nearly all minerals essential for advanced manufacturing, defense systems and the clean-energy transition (IEA, 2025; Saadaoui, Smyth & Vespignani, 2025). This dominance creates a structural asymmetry: while the United States and its allies possess significant raw mineral reserves, according to the U.S. Geological Survey's (USGS) Mineral Commodity Summaries, they remain heavily dependent on Chinese refining capacity to convert these ores into usable, high-purity materials. Hence, geopolitical tension translates directly into heightened vulnerability for the United States to supply chains for critical minerals that it needs for national security (Mignon & Saadaoui, 2024; Saadaoui, Smyth & Vespignani, 2025). This section documents the scale of China's refining dominance, the channels through which US–China tensions amplify supply risk, as well as the implications for stockpiling behavior and the resilience of United States critical minerals supply chains (IEA, 2024).

Figure 2a shows the distribution of global refining capacity for aluminum, copper, nickel, zinc and tin, comparing China with the rest of the world. Across all five metals, China accounts for roughly one-half of global refining capacity, with nickel as high as almost 70 percent. The remaining capacity is fragmented across multiple countries, with no other producer able to match China's scale. The figure highlights the structural concentration of midstream processing in China and illustrates why friend-shoring efforts confront severe limitations: even if mining is diversified, most refined material still originates in China. Outside China, the remaining global refining capacity is distributed across a small group of countries; namely, Australia, India and Brazil for aluminum; Chile, Japan and the EU for copper; Canada, Norway and Australia for Class I nickel; South Korea, Canada and Japan for zinc; and Indonesia, Malaysia and Bolivia for tin; each typically accounting for only 3–12% of global capacity, far below China's share (USGS *Mineral Commodity Summaries*; USGS *Global Maps of Critical Mineral Production*; IEA *Global Critical Minerals Outlook*; authors' calculations).

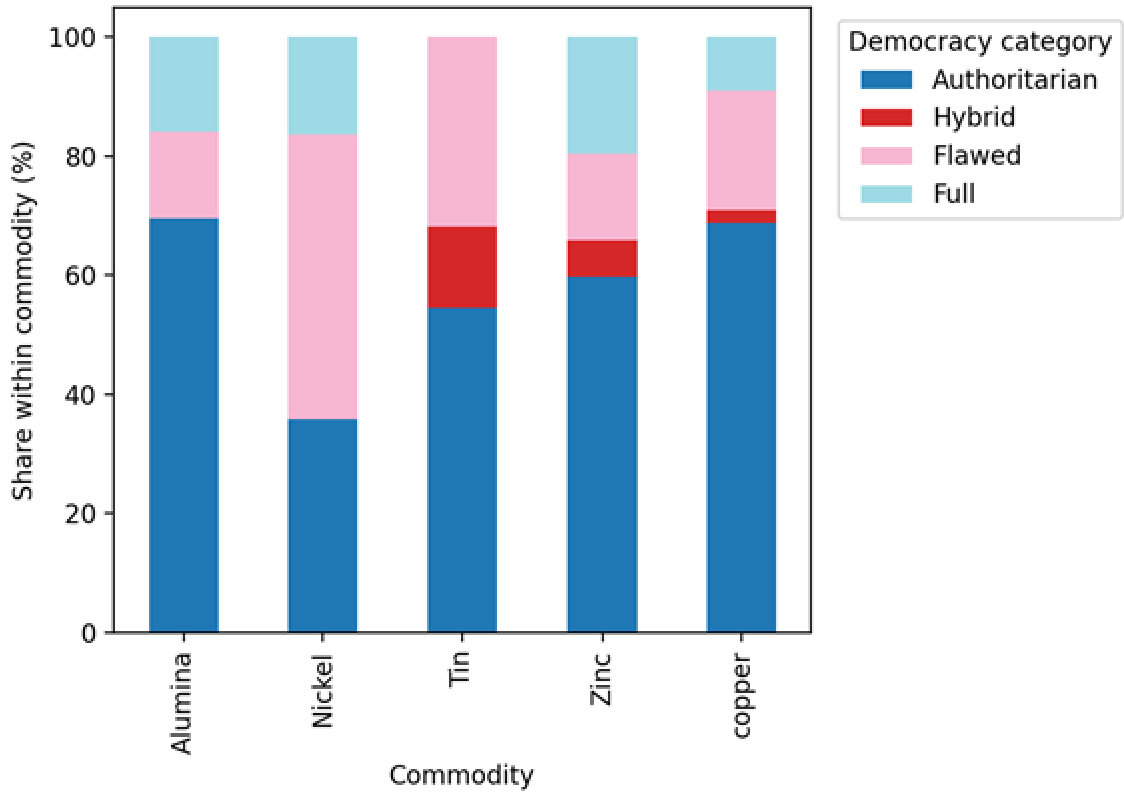
Figure 2a. China vs the Rest of World Refining Capacity for Aluminum, Copper, Nickel, Zinc and Tin (2024)



Note: This figure shows the share of global refining capacity accounted for by China and the "Rest of World" for aluminum, copper, nickel, zinc, and tin in 2024. "Rest of World" aggregates refining capacity outside China. The figure shows China's dominant position in global refining capacity across these key minerals. Data Source: USGS *Mineral Commodity Summaries*; USGS *Global Maps of Critical Mineral Production*; IEA *Global Critical Minerals Outlook*; authors' calculations.

Figure 2b illustrates that refining capacity across major critical minerals is overwhelmingly concentrated in authoritarian countries**.** For alumina, copper, zinc and tin, authoritarian regimes account for the single largest share of global refining output (typically ranging between 55% and 70%). Nickel shows a slightly more balanced distribution; however, authoritarian regimes still account for nearly 40% of global refining output. By contrast, full democracies account for generally below 15% of refining capacity for all five minerals. This distribution underscores a structural reality often overlooked in policy discussions. In advanced democracies, it is often impossible to sustain the environmental, regulatory and social trade-offs associated with large-scale refining**,** even when they possess resource endowments. The result is a geopolitical and industrial asymmetry: the United States and its democratic allies remain heavily dependent on refining capacity concentrated in authoritarian states and, in particular, China, limiting the practical scope of friend-shoring and making refined stockpiling a necessary, but insufficient, resilience strategy.

Figure 2b. Refining Capacities by Political Regime for Aluminum, Copper, Nickel, Zinc, and Tin (2024)



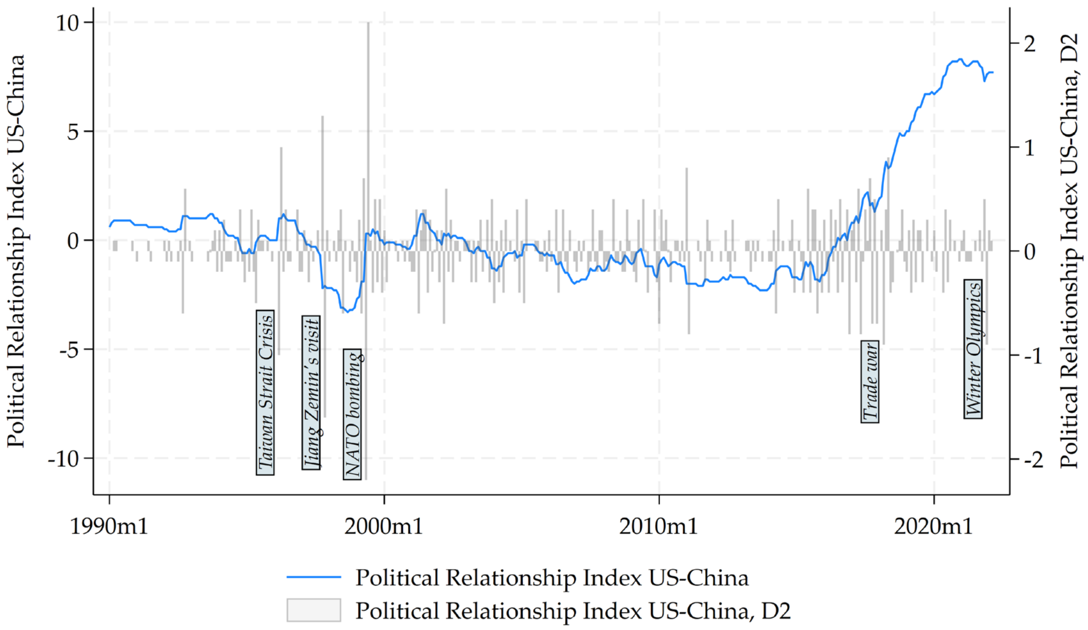
Note: Countries are classified by political regime using the Democracy Index, which measures the degree of democracy on a scale from 0 to 10 based on a broad set of political and institutional criteria. Following the standard categorisation, countries are grouped into four regime types: authoritarian regimes (scores less than 4), hybrid regimes (scores greater than 4, and less than 6), flawed democracies (scores greater than 6, and less than 8), and full democracies (scores greater than 8). The categorization follows the standard classification of the Economist Intelligence Unit (EIU) Democracy Index, which maps continuous democracy scores into discrete regime types. Data Source: EIU Democracy Index. https://www.eiu.com/n/campaigns/democracy-index-2024-confirmation/.

Figure 3 depicts the evolution of US–China geopolitical relations using the PRI, which was developed by Chinese political scientists (see Mignon and Saadaoui (2024) for a detailed description of the index) and is an established measure used to quantify bilateral diplomatic tensions and cooperation over time. The solid line reports the level of the PRI, where higher values denote less favorable geopolitical relations, while the vertical bars show the second difference of the index, which isolates discrete geopolitical turning points by capturing sharp accelerations or decelerations in bilateral tensions. This visualization allows us to distinguish gradual shifts in the relationship from abrupt geopolitical shocks, which are central to understanding the timing and magnitude of geopolitical risk transmission (Saadaoui, 2025; Mignon & Saadaoui, 2024).

Several significant events are captured in the PRI series depicted in Figure 3. In March 1996, the Third Taiwan Strait Crisis marked a substantial decline in relations between the two countries, as the United

States deployed aircraft carriers in response to Chinese missile tests near Taiwan. This event represents one of the most severe geopolitical confrontations of the post–Cold War period. A partial recovery was observed following President Jiang Zemin's visit to the United States in late 1997, which began on a diplomatically positive note in October but soured in November amid renewed tensions over Taiwan and human rights, leading to a sharp fall in the PRI.

Figure 3. US–China Geopolitical Relationship.



Note: The solid line reports the level of the Political Relations Index (PRI) for US–China relations, where higher values indicate more strained (deteriorating) bilateral relations. The bars plot the second difference of the PRI (the change in the first difference), which isolates sharp accelerations and reversals in the trajectory of relations — i.e., geopolitical turning points. In this representation, positive bar values correspond to abrupt deteriorations in US–China relations, whereas negative bar values indicate sudden improvements. The most significant geopolitical turning points are shown. The PRI index includes the full sequence of events as documented in Yan et al. (2010).

A further critical deterioration occurred in May 1999, when the NATO bombing of the Chinese embassy in Belgrade provoked intense public protests across China and resulted in a temporary suspension of bilateral diplomatic engagement. This event is reflected as a pronounced drop in the PRI, illustrating the fragility of relations during this period. The index remained relatively stable through the early 2000s but experienced a renewed and severe downturn beginning in March 2018, with the onset of the US–China trade war under the first Trump administration. The announcement of extensive tariffs on Chinese goods led to a major deterioration in the PRI, signaling a structural shift in economic and geopolitical relations.

The most recent downturn in Figure 3 is observed in December 2021, corresponding to the diplomatic boycott of the Beijing Winter Olympics by the Biden administration. The boycott, motivated by concerns over human rights issues in Xinjiang and Hong Kong as well as the disappearance of Chinese tennis player Peng Shuai, precipitated another sharp drop in the PRI.

Together, these turning points illustrate how exogenous geopolitical shocks (not anticipated by market participants) have punctuated the broader evolution of US–China relations, shaping the cyclical pattern of cooperation and confrontation evident in Figure 3.

3. Empirical Evidence on the Impact of Deterioration in US–China Geopolitical Relations

We leverage granular datasets for production, consumption, and stockpiling from the World Bureau of Metal Statistics for aluminum, copper, nickel, tin and zinc. We focus on these critical minerals for two reasons. First, aluminum, copper and zinc were the largest critical-mineral markets by value in 2024. Second, and importantly for our methodology, reasonably long monthly time series are available for each, spanning three decades from January 1995 to January 2025. We use the US–China PRI, described in Section 2, to capture ebbs and flows in the geopolitical tensions between the two countries. This index has been used to examine the effect of US–China geopolitical tensions on oil prices by Mignon and Saadaoui (2024).

An important advantage of the PRI is that it is available at monthly frequency, given that our identification strategy relies on the use of monthly data. Geopolitical turning points are not expected by market participants at monthly frequency. We use a SVAR model with 12 lags with the following ordering: US–China geopolitical relationship (measured by the PRI), production, consumption, price, and stocks to produce structural innovations for each selected critical mineral. In this way, we remove the influence of geopolitical events linked to critical mineral market dynamics and obtain a causal interpretation of our shocks in a time-series context.

We examine the dynamic causal effects of an exogenous bilateral deterioration in US–China relations on critical mineral markets. To do so we rely on the local projection methodology introduced by Jordà (2005) and surveyed in Jordà and Taylor (2025). This approach greatly simplifies the estimation and inference of impulse response functions in systems of equations (Inoue, Jordà & Kuersteiner, 2025). In our setting, the effect of an exogenous bilateral geopolitical tension shock is identified through a series of ordinary least squares regressions of the future values of each critical mineral price and the corresponding stockpile value at different horizons. This allows us to trace the dynamic causal effects of a deterioration in US–China relations on critical mineral markets. A novel feature of our framework is the explicit inclusion of stockpile values.

The identification strategy follows Saadaoui, Smyth, and Vespignani (2025). Let

$$y_t = (PRI_t, Q_t, C_t, P_t, S_t)'$$

denote the vector of endogenous variables, where PRI_t is the bilateral geopolitical relations index, Q_t denotes production, C_t consumption, P_t prices, and S_t stocks. The reduced-form VAR of order p is

$$y_t = A_1 y_{t-1} + \cdots + A_p y_{t-p} + u_t, \qquad E(u_t u_t') = \Sigma_u.$$

Our identification uses a recursive (Cholesky) structure with the ordering $(PRI_t, Q_t, C_t, P_t, S_t)$. This implies that the PRI is predetermined within the month: PRI_t does not respond contemporaneously to innovations in Q_t, C_t, P_t, or S_t. The remaining variables may respond contemporaneously to the identified PRI shock, and the ordering also imposes the usual lower-triangular restrictions on contemporaneous responses across Q_t, C_t, P_t, S_t. Structural shocks are obtained via a lower-triangular impact matrix, ensuring mutual orthogonality of the structural innovations.

This triangular structure follows the identification strategy of Saadaoui, Smyth, and Vespignani (2025), with the geopolitical risk index replaced by the bilateral geopolitical relations index, as also employed in Mignon and Saadaoui (2024).

A distinctive feature of the present article is the explicit inclusion of stocks S_t in the structural system. To the best of our knowledge, this is the first contribution in this literature to jointly identify bilateral geopolitical shocks and trace their dynamic effects on stocks alongside production, consumption, and prices. Including stocks allows us to capture stockpiling and buffer-stock adjustment mechanisms that are otherwise absorbed implicitly into price or production responses in existing VAR-based studies.

Impulse response functions are estimated using local projections following Jordà (2005). For each horizon $h \geq 0$, and for each outcome variable $x_t \in \{Q_t, C_t, P_t, S_t\}$, we estimate

$$x_{t+h} = \alpha_{x,h} + \sum_{j=0}^{12} \beta_{x,h,j}\, \varepsilon_{t-j} + \sum_{\ell=1}^{12} \Phi'_{x,h,\ell}\, y_{t-\ell} + \nu_{x,t+h},$$

where ε_t denotes the identified structural bilateral geopolitical shock and $y_t = (Q_t, C_t, P_t, S_t)'$. The impulse response of variable x at horizon h is given by the coefficient $\beta_{x,h,0}$ on the contemporaneous shock.

When correctly specified, and in large samples, local-projection impulse responses coincide with the corresponding SVAR impulse responses up to horizon p, the VAR lag length. Beyond this horizon, equivalence no longer holds: SVAR impulse responses are obtained by recursively iterating on the parametric VAR structure, whereas local projections estimate each horizon directly without imposing such dynamic restrictions.

The impulse responses documented in Figures 4 and 5 are consistent with the dynamics associated with a negative global demand shock in the sense of Kilian (2009): prices fall while inventories rise, production adjusts only gradually, and the imbalance is absorbed through temporary stock accumulation. In our setting, a deterioration in US–China relations acts as an adverse demand signal for the global economy rather than as an immediate physical disruption of supply. Market participants revise downward their expectations of future activity and tighten their financial conditions, which simultaneously reduces their purchases and strengthens the precautionary motive for holding inventories. This interpretation aligns with the classic distinction between aggregate demand shocks and supply shocks in commodity markets and supports viewing our estimated geopolitical shock as a global demand shock (i.e., not specific to critical minerals).

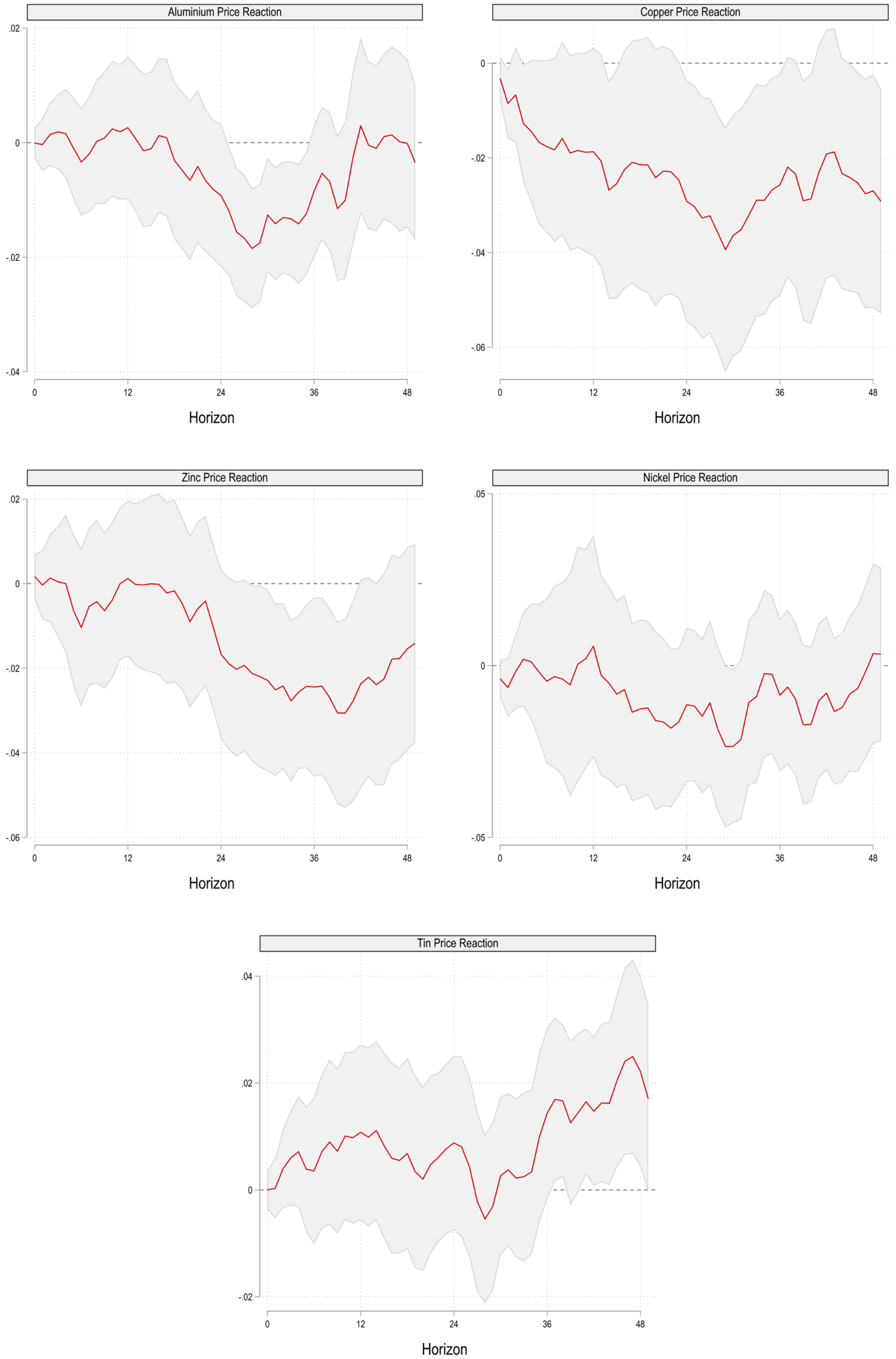
Taken together, the empirical results in this section provide a backward-looking characterization of how critical mineral markets have historically responded to unexpected deteriorations in US–China political relations. In particular, the joint response of inventories and prices documents a precautionary stockpiling margin that becomes salient when geopolitical tensions intensify. The remainder of the article adopts a forward-looking perspective. We develop a simple framework in which a planner (or an inventory-holding agent) chooses optimal inventories ex ante when facing geopolitical risk and constraints on accessing reliable refined supplies through friend-shoring.

4. Geopolitical Risk, Optimal Stockpiling and the Limits of Friend-shoring

Motivated by the backward-looking evidence in Section 3, in this section, we adopt a forward-looking, normative approach and derive the optimal inventory policy under anticipated geopolitical risk and alternative assumptions on the availability of friend-shored refined critical minerals.

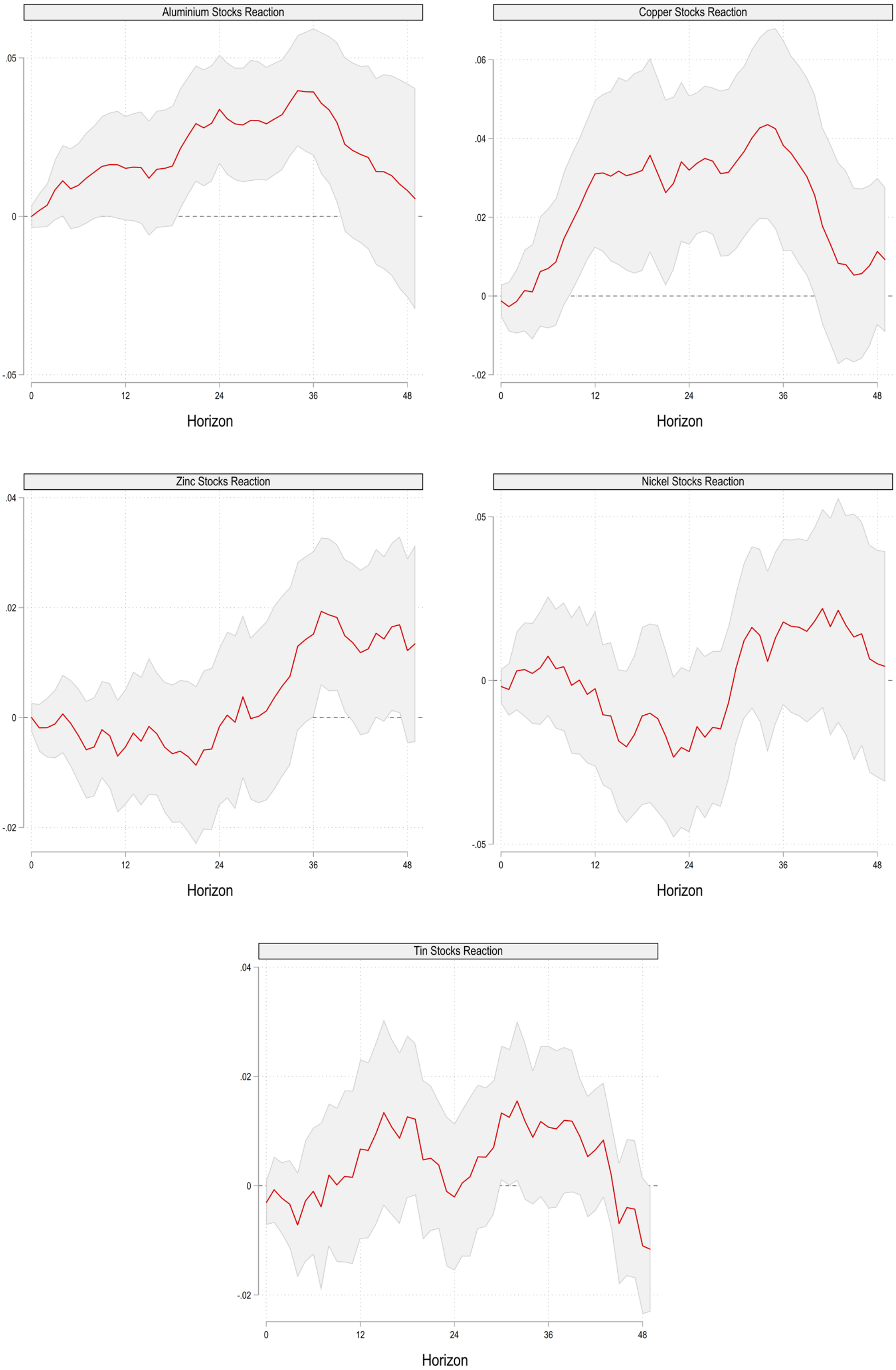
The empirical evidence in Section 3 shows that deteriorations in US–China geopolitical relations are associated with higher inventories, even as refined mineral prices fall, consistent with a broader demand-driven disturbance. At the same time, geopolitical rivalry can also generate supply-side disruptions, particularly when refining and export capacity are geographically concentrated. This section offers an intuitive framework for interpreting these competing perspectives in which inventories play an insurance role: stockpiles limit the economic losses from import shortfalls, the likelihood of which increases when geopolitical conditions worsen. The formal model, assumptions, and comparative statics are provided in Online Appendix B.

Figure 4. Response in prices of aluminum, copper, zinc, nickel and tin to an exogenous deterioration in the US–China geopolitical relationship.



Note: The red line plots the estimated multiplier; the shaded grey band denotes the 90% confidence interval (robust standard errors). Online Appendix A presents the VAR estimation for the impulse response function. The results are qualitatively similar.

Figure 5. Critical mineral stockpiling response to an exogenous deterioration of the US–China relationship.



Note: The red line plots the estimated multiplier; the shaded grey band denotes the 90% confidence interval (robust standard errors). Online Appendix A presents the VAR estimation for the impulse response function. The results are qualitatively similar.

4.1 Stockpiling as insurance against disruption risk

Consider a net importing economy that requires refined mineral inputs for downstream production and strategic uses but faces uncertain import deliveries. Even if domestic production exists, it is typically insufficient to cover requirements in disruption states. In this environment, inventories provide a buffer: they raise available supply in every contingency and, therefore, reduce both the probability and the severity of shortages. This is the central mechanism underpinning the framework used in this article.

The economic tradeoff is straightforward. Holding refined inventories is costly, because it uses storage capacity, ties up capital, and can involve depreciation and quality loss. But inventories also have a benefit: they reduce expected shortage losses, where shortage losses are increasing in the size of the shortfall and may be especially steep when critical inputs are needed for defense, energy infrastructure, or high-value manufacturing. The optimal stockpile balances these benefits and costs. In practical terms, stockpiling is most valuable when shortages are both plausible and consequential, and least valuable when disruptions are rare and easily offset through spot purchases or rapid substitution.

Geopolitical tension enters this problem by shifting the distribution of import outcomes. When geopolitical relations worsen, the probability of a partial interruption, a delay, or a policy-driven restriction rises, and the expected economic loss from being caught short increases. Under mild regularity conditions, this implies a clear qualitative prediction: higher geopolitical risk raises the marginal value of inventories and, hence, increases the optimal stockpile. In Online Appendix B, we provide the formal statement of this result and the derivation from the optimization problem.

4.2 Friend-shoring as a partial substitute for inventories

A natural policy question is whether the United States can reduce the amount of refined stockpiling it needs by reallocating refined supply chains away from China and toward geopolitically aligned partners. This is the logic of friend-shoring. However, friend-shoring is not equally feasible across potential partners, because midstream refining requires scale, long-lived feedstock access, infrastructure, and predictable permitting and investment environments. To capture these constraints in a policy-relevant way, we treat friend-shoring feasibility as the likelihood that a given partner can deliver a stable stream of refined imports over time. Three determinants are central.

1. Geological scale: larger proven reserves make it easier to sustain a refining ecosystem and amortize large, fixed costs over long horizons.
2. Geopolitical alignment: greater political distance reduces the reliability of long-term supply commitments and increases contractual and sanctions risk.
3. Institutional and permitting frictions: in many high-income democracies, stricter environmental and social constraints can slow the expansion of large-scale refining capacity, even when resources are available.

In the formal model, these determinants shift the stability of non-Chinese import supply. The key implication is intuitive: as friend-shoring feasibility rises, expected vulnerability to disruptions falls, and the optimal stockpile declines because inventories are less often needed as insurance. Online Appendix B provides the formal comparative statics.

4.3 Why feasibility is nonlinear: geology, alignment, and constraints interact

A central takeaway for policy is that the determinants of friend-shoring feasibility interact rather than add mechanically. Large reserves help most when alignment is strong, because greater geopolitical distance sharply reduces the reliability of supply chains even when geological endowments are substantial. Likewise, when institutional and permitting constraints are tight, additional reserves translate less efficiently into near-term refining scale up, because project timelines and local acceptance become binding constraints rather than ore availability. These interactions underlie the shapes shown in Figures 6 and 7 and are formalized through the CES feasibility structure in Online Appendix C.

In Online Appendix C, Φ_i denotes partner i's friend-shoring feasibility index. It is a reduced-form measure of the ability to source refined critical-mineral supply from partner i in a way that is both technically scalable and geopolitically reliable. By construction, $\Phi_i$increases with geological reserves and decreases with geopolitical distance from the United States and with regulatory/permitting constraints.

In our calibration, these determinants are mapped into the transformed inputs $x_R = R_i$, $x_G = e^{-\kappa_G G_i}$, and $x_D = e^{-\kappa_D D_i}$, where the exponential transformations ensure that feasibility declines monotonically in geopolitical distance and regulatory constraints. The CES aggregator Φ_i then combines these components, allowing for imperfect substitution governed by the elasticity parameter σ(equivalently $\rho = (\sigma - 1)/\sigma$) and weights $\omega_R, \omega_G, \omega_D$ satisfying $\omega_R + \omega_G + \omega_D = 1$.

This perspective clarifies why friend-shoring is best viewed as a complement to, rather than a replacement for, refined stockpiling. Even where trusted partners exist, scaling refining is slow relative to the speed at which geopolitical conditions can deteriorate. Thus, a resilience strategy that relies only on reorganizing supply chains is exposed to a timing problem, while a strategy that combines focused friend-shoring with refined stockpiles can manage short run disruptions and longer run diversification.

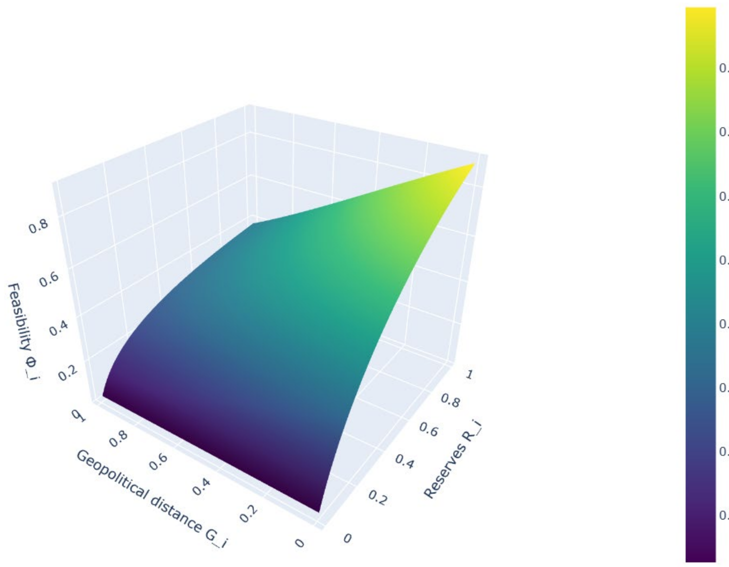
4.4 Policy implications for a stockpiling-centered strategy

The framework yields several policy-relevant implications. First, refined inventories should be the primary object of strategic stockpiling. Stockpiling ores does not resolve the binding midstream bottleneck when refining is concentrated abroad, so the insurance value of inventories is highest when materials are held in refined form and are immediately usable in domestic production.

Second, stockpile targets should be state contingent: when measured geopolitical risk rises, the marginal value of inventories rises, so stockpile benchmarks should adjust upward rather than remaining fixed. This logic supports linking stockpile rules to observable geopolitical risk indicators, while keeping the implementation simple enough to be operational.

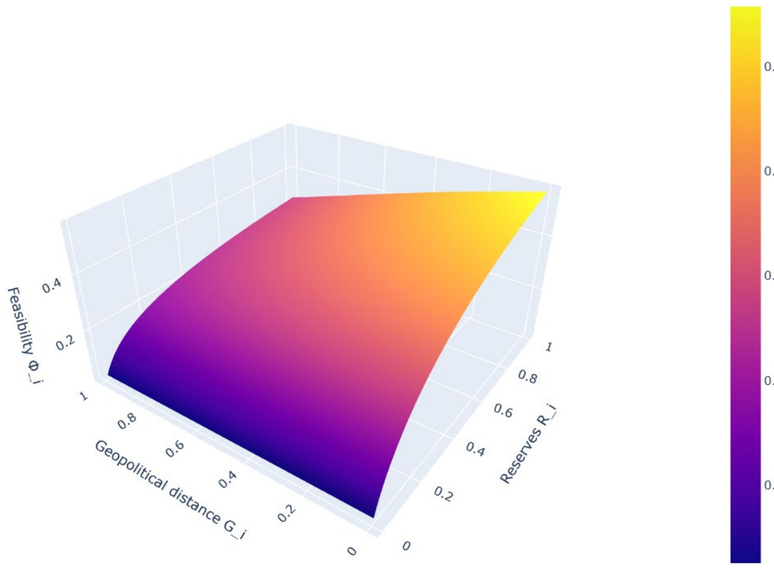
Third, friend-shoring should be targeted and realistic. Because feasibility is jointly constrained by reserves, alignment, distance, and institutional capacity, only a narrow set of partners can plausibly reduce US vulnerability at scale, and even then expansion is gradual. This motivates focusing on a small number of high feasibility partners for refined offtake arrangements and co-investment, while using stockpiles to manage the residual risk that diversification cannot eliminate quickly.

Figure 6: Feasibility Surface $\Phi(R_i, G_i)$ - Low Democratic Constraints ($D_i = 0.2$)



Note: This plot shows the feasibility function when democratic constraints are low. Feasibility increases sharply in reserves and decreases in geopolitical distance, yielding a convex upward-sloping ridge for aligned partners with substantial geological endowments. The surface is steep, indicating that reserves translate efficiently into refining potential when institutional constraints are weak. Online Appendix C describes the CES feasibility function and calibration.

Figure 7: Feasibility Surface $\Phi(R_i, G_i)$ - High Democratic Constraints ($D_i = 0.8$)



Note: Higher democratic constraints shift the entire feasibility surface downward, especially for partners with moderate or large geopolitical distance. Reserves become less effective in raising feasibility when stringent permitting and environmental rules slow investment. The curvature reveals that institutional frictions can sharply attenuate the benefit of geology. Online Appendix C describes the CES feasibility function and calibration.

5. Existing Refining, Proven Reserves and Alternatives for the US to Friend-shoring

Table 1 summarizes how heavily refining for five key metals is concentrated in China and what this implies for the feasibility of large-scale friend-shoring. Aluminum/alumina refining is dominated by China (around 55-60% of global output), but substantial capacity exists in Australia, India and Brazil. This makes friend-shoring "moderately" feasible, with Australia in particular offering scale, although high electricity prices and large upfront capital requirements slow the pace at which additional capacity could be brought online. Refined copper exhibits similar, though slightly less extreme, concentration (around 45–50% in China), with major smelters located in Chile, Japan and the EU. However, most of these plants already operate near capacity, and are tightly constrained by environmental regulation and high operating costs, so scope for rapid, large-scale friend-shoring is low.

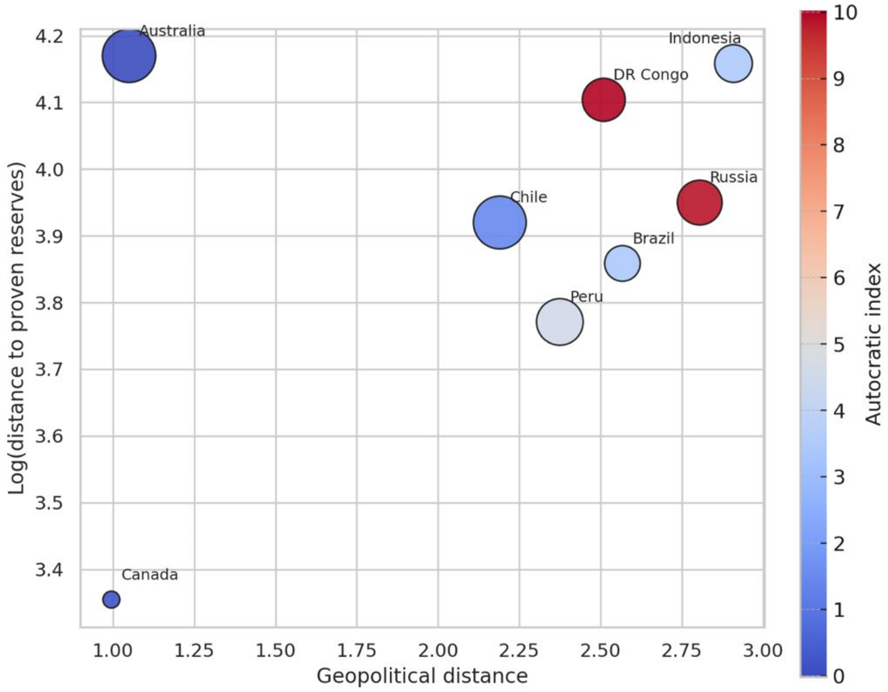
Table 1. Refining Concentration and Friend-Shoring Feasibility for Five Critical Metals.

Metal	China's Share of Global Refining (%)	Major Non-China Refiners	Feasibility of Large-Scale Friend-Shoring	Primary Constraint
Aluminum / Alumina	~55–60%	Australia, India, Brazil	**Moderate** – Australia has scale but high energy costs limit expansion speed	Energy-intensity; capital cost
Refined Copper	~45–50%	Chile, Japan, EU	**Low** – existing smelters operate near full capacity	Environmental regulation; high operating expenditure
Nickel	~70%	Canada, Norway, Australia	**Moderate to Low** – Canada viable; others constrained	Feedstock quality; emissions standards
Zinc	~45–50%	South Korea, Canada, Japan	**Low** – non-China capacity fragmented and small scale	Limited spare capacity
Tin	~50%+	Indonesia, Malaysia, Bolivia	**Very Low** – governance and cost issues in SE Asia	Weak institutional capacity

Note: Refining shares are indicative ranges based on USGS and IEA data. China's processing share for aluminum, copper, tin and zinc is from USGS *Global Maps of Critical Mineral Production in 2023* (Fact Sheet 2025-3038).

For nickel (Class I), China accounts for roughly 70% of global refining, with Canada, Norway and Australia as the main alternative sources. Friend-shoring is rated as "moderate to low" because, while Canada is a viable partner, other producers face constraints linked to feedstock quality and stringent emissions standards. Zinc refining, where China has 45-50% of capacity, is supported by smaller refineries in South Korea, Canada and Japan, but this capacity is fragmented and offers little spare room, yielding a low feasibility rating. Tin refining is the most problematic: China controls more than half of global output, and alternative centers in Indonesia, Malaysia and Bolivia are hampered by weak institutions, governance issues and cost pressures. As a result, Table 1 suggests that friend-shoring tin refining at scale has "very low" feasibility, underscoring how governance and institutional quality can be as binding as geology in shaping diversification options.

Figure 8: U.S. Friend-shoring Alternatives to Stockpiling for Key Critical Minerals.



Note: In Online Appendix D, we provide detail of the normalization of variables in this figure. This figure is equivalent to the baseline scenario in Figure 9.

How can the United States strengthen its refined stockpiling capacity when it remains structurally dependent on Chinese-refining of critical minerals? Addressing this question requires evaluating the feasibility of friend-shoring refining activities, that is, reallocating processing and refining stages of critical mineral supply chains toward trusted geopolitical partners with aligned strategic interests. In this section, we assess the extent to which allied producers possess the geological endowments, refining capabilities, geopolitical stability, and geographic proximity necessary to support a sustainable friend-shoring strategy that would enable the United States to expand its refined stockpiles, while reducing vulnerability to geopolitical shocks originating from China.

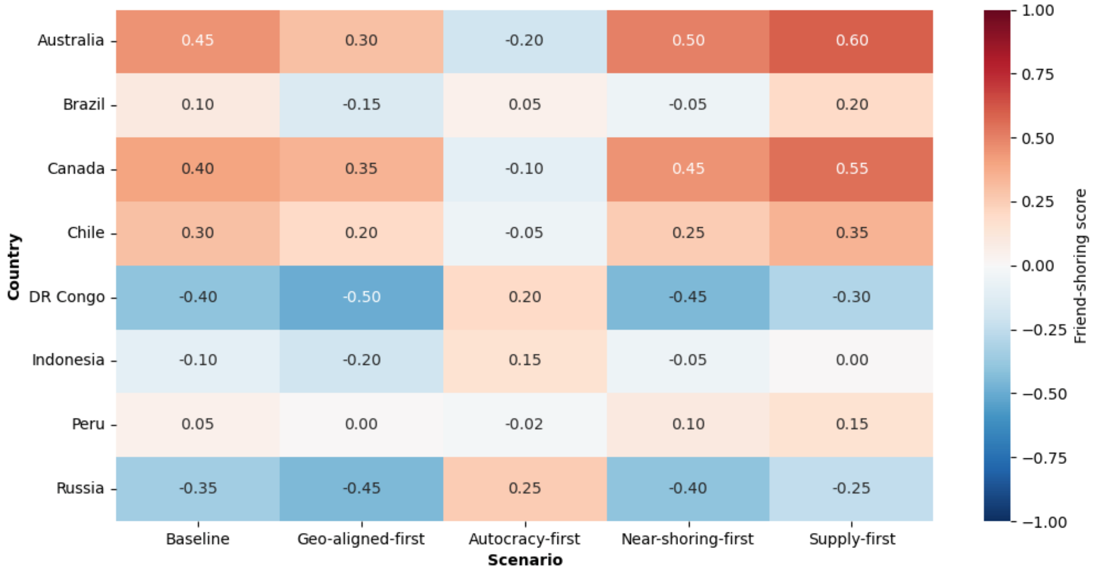
To provide empirical evidence on the predictions stemming from the intuition in Section 4.2, Figure 8 maps potential friend-shoring partners in a multidimensional strategic space defined by their geopolitical distance from the United States (horizontal axis), their log-distance to proven reserves from the United States (vertical axis), and the size of their geological endowment (bubble size), with color indicating the degree of autocracy. Note that autocracy is negatively related to the potential friend-shoring. Several patterns emerge. Australia stands out as the closest geopolitical partner with one of the largest reserve bases, placing it in the upper-left quadrant of the plot and making it the most attractive friend-shoring candidate. Canada also exhibits very close geopolitical alignment, but has comparatively smaller reserves, reflected in its lower position and smaller bubble. In contrast, countries such as Democratic Republic of Congo and Russia appear on the right-hand side of the chart, combining substantial reserves with high autocratic scores and greater geopolitical distance—factors that reduce the feasibility of near-term friend-shoring despite their geological importance. Indonesia, Brazil, Peru and Chile form an intermediate cluster: each has meaningful reserves, but their geopolitical distance and mixed autocratic profiles position them as moderately feasible options.

A further insight emerging from the figure concerns the role of reserve size, represented by the diameter of each bubble. Countries with larger geological endowments of copper, alumina (bauxite), nickel, tin and zinc, such as Australia, Democratic Republic of Congo, Russia, Chile, Peru, Brazil and Indonesia, occupy the largest positions in the plot. Australia's bubble reflects particularly large alumina, nickel and zinc reserves; Chile and Peru are heavily dominated by copper; Democratic Republic of Congo has large copper (and associated cobalt) deposits; Indonesia stands out for nickel and bauxite; Russia for nickel and copper; and Brazil for bauxite and iron-ore-linked copper potential. This scale is strategically significant because refining these minerals is a high-fixed-cost, capital-intensive activity where economies of scale are decisive. Large, concentrated deposits support stable ore supply over multiple decades, enabling operators to amortize expensive metallurgical facilities, maintain continuous throughput, and reduce per-unit processing costs. They also underpin complementary infrastructure (like chemical inputs, energy systems, transport networks and waste-management facilities) that all benefit from high-volume processing. As a result, countries that are better endowed with substantial reserves of copper, alumina, nickel, tin and zinc are structurally better positioned to host competitive and scalable refining hubs.

Figure 8 underscores core tensions in the friend-shoring strategy of the United States. Countries with the geological scale necessary to support efficient refining of these minerals are often less geopolitically distant from the United States or are autocratic regimes, while many of the United States' closest allies typically control smaller or more geographically dispersed deposits.

Figure 9 is a heatmap with overlaid numeric annotations that compares friend-shoring scores across the eight countries with the largest proven reserves of these minerals (excluding China and the United States) under five different weighting scenarios, called: baseline, geo-alignment-first, governance-first, nearshoring-first, and supply-first. A full description of this index is given in Online Appendix D. The five weighting scenarios are depicted on the horizontal axis, while the eight countries (Australia, Brazil, Canada, Chile, Democratic Republic of Congo, Indonesia, Peru, and Russia) are listed along the vertical axis. Each cell represents a specific country–scenario combination and reports the corresponding composite friend-shoring score s_i, displayed as a two-decimal numeric label.

Figure 9: Friend-Shoring Feasibility of Key Critical Minerals for the United States: Results from the Fourth-Dimensional Friend-Shoring Score (2024).



Note: This figure reports friend-shoring feasibility scores for key critical-mineral producers based on data for 2024. Scores are constructed using normalized indicators of proven reserve value, geographical distance, autocratic index and geopolitical distance. Columns correspond to alternative weighting scenarios (baseline, geo-alignment-first, governance-first, nearshoring-first, and supply-first). Higher values indicate greater feasibility as a friend-shoring partner. Online Appendix D describes the construction of the friend-shoring scores under different scenarios.

The baseline scenario in the first column applies equal weights to all criteria (namely, geopolitical alignment, political regime type, geographic distance, and mineral endowment) providing an unweighted benchmark of friend-shoring feasibility. Under this scenario, Australia, Brazil, Canada and Chile receive positive scores, reflecting their combination of resource availability and geopolitical alignment with the United States. However, even in this most neutral case, the pool of viable partners remains small. A key underlying challenge is that many of the world's largest refining hubs are in non-democratic or hybrid-regime countries, while advanced democracies often lack domestic refining capacity due to high costs, environmental restrictions, and regulatory barriers. As a result, the baseline already reveals a structural tension: the United States' closest democratic partners tend to be strong in raw mineral reserves, but weaker in processing capability, whereas countries with established refining infrastructure are often autocratic, poorly governed, or strategically misaligned.

In the second column we present the results for the geo-aligned-first scenario, in which diplomatic alignment with the United States dominates the weighting. The position of Australia and Canada are strengthened in this scenario, but it significantly penalizes countries such as Democratic Republic of

Congo, Russia and Indonesia, whose geopolitical distance from the United States reduces their suitability as partners. In the autocracy-first scenario, which discounts the drawbacks of refining being situated in authoritarian states, countries such as Russia and Democratic Republic of Congo experience a relative improvement in their ranking because democracy is no longer a binding requirement. Meanwhile, democratic and hybrid regimes show more marginal changes, illustrating how outcomes depend heavily on the strategic priorities imposed by policymakers.

The near-shoring-first scenario rewards geographic proximity to the United States. Canada becomes one of the highest-ranking options, while geographically distant producers such as Australia and Indonesia experience a decline in score, highlighting the logistical constraints associated with long-distance supply chains. Finally, the supply-first scenario prioritizes resource endowment and existing capacity. Here, Australia and Canada again emerge as the best-performing suppliers, reflecting their large proven reserves, stable regulatory environment, and ability to scale refining capacity. By contrast, Democratic Republic of Congo continues to score negatively despite large reserves, showing that geological advantage alone cannot offset governance and geopolitical risks.

Friend-shoring feasibility in our framework is best interpreted as conditional and time-varying, rather than as an assumption of fixed geopolitical alignment. Short-run turbulence can occur even among close allies, but in a hierarchical international system shaped by US–China rivalry, the medium-run likelihood of reliable alignment remains systematically higher for treaty partners than for strategic rivals. Regime type enters the index as a reduced-form proxy for institutional constraints and policy predictability, not as a categorical exclusion. Likewise, reserves are necessary but not sufficient for supply security, as China's dominance in refining underscores the role of scale, processing capacity, and industrial organization. Extending the framework to incorporate direct measures of supply weaponization risk and supplier market power is a natural direction for future research.

6. Conclusion and policy recommendations

This article shows that US–China geopolitical tensions are a central driver of refined critical-mineral market dynamics. Using monthly data for aluminum, copper, nickel, tin, and zinc since the mid-1990s, and an SVAR–local projection framework, we find that adverse shocks to the bilateral US–China Political Relations Index (PRI) systematically trigger stockpiling of refined minerals. Our friend-shoring framework adds an important layer to this evidence. By combining proven reserves, geopolitical alignment, regime-type characteristics, and geographic distance into a composite friend-shoring score, we show that only a narrow set of partners — most notably Australia and Canada —

combine substantial geological endowments with close strategic alignment to the United States. Even for these preferred partners, high energy costs, stringent environmental regulation, social opposition to large industrial projects, and limited spare capacity restrict how quickly refining can be scaled. Middle-feasibility countries such as Brazil, Chile, Indonesia, and Peru have meaningful reserves, but are penalized by governance risks, regime characteristics, and greater geopolitical distance. The implication is that the pool of viable friend-shoring partners for refined critical minerals is small, and the most attractive candidates face structural constraints that make a rapid, large-scale reorientation of refining capacity away from China unlikely in the short to medium run.

These findings have direct policy implications. First, they imply that the United States should place strategic stockpiling of refined critical minerals — rather than raw ores — at the center of its resilience strategy. Refined inputs are less exposed to future processing bottlenecks and export controls; stockpiling rules should therefore be formulated in terms of refined inventories and linked explicitly to observable measures of geopolitical risk, as in our model. In practice, minimum refined-inventory benchmarks for defense, advanced manufacturing, and clean-energy supply chains could be adjusted in a rule-like manner in response to changes in US–China geopolitical relations, analogously to the way macroprudential instruments respond to systemic-risk indicators. Importantly, stockpiling can be implemented through distinct institutional channels: inventories may be accumulated as public strategic stockpiles managed by government agencies; they may be induced in the private sector through mandates, procurement rules, or targeted incentives that raise required working inventories; and they may also rise endogenously as market-driven precautionary stockholding by firms facing heightened geopolitical uncertainty and tail risks to supply chains. Distinguishing these channels helps clarify feasibility and accountability and disciplines the interpretation of observed inventory movements, even though we do not model institutional design explicitly.

Second, because friend-shoring cannot fully substitute for stockpiling, policy should prioritize a realistic expansion of allied refining capacity rather than an overly broad — and ultimately infeasible — diversification agenda. This requires negotiating long-horizon bilateral packages with Australia and Canada that directly address binding constraints on refining, including electricity prices, grid decarbonization trajectories, permitting delays, and community acceptance. A practical approach could be to combine long-maturity power contracts, infrastructure co-investment, and targeted use of Industrial policy instruments (including the IRA, the Defense Production Act, and the Minerals Security Partnership) to support brownfield expansions and upgrades to existing facilities.

Third, US policy should adopt a differentiated approach toward "middle-feasibility" producers. In countries such as Brazil, Chile, Indonesia, and Peru, the priority is not merely to secure additional ore, but to co-finance the environmental, governance, and logistical improvements that can make incremental refining capacity both politically acceptable and commercially viable. Concessional finance to modernize smelters, improve tailings management, and strengthen regulatory oversight can align local development objectives with US security concerns, provided these initiatives are embedded in long-term offtake agreements that prioritize refined-product exports. In parallel, domestic policies that support advanced recycling and material efficiency can play a complementary role. Expanding recycling for copper, aluminum, and nickel, together with support for less mineral-intensive technologies and efficiency standards, reduces demand vulnerability over time — even if it cannot replace refined stockpiles during acute geopolitical shocks.

Within the mechanism emphasized in this article, stockpiling is therefore a useful — and often necessary — instrument for mitigating short-run exposure to geopolitical disruptions in refined mineral supply. At the same time, it is not sufficient on its own to address deeper structural vulnerabilities, including refining bottlenecks, limited substitutability in downstream production, and concentrated capacity at critical stages of processing. These complementary margins lie beyond the scope of our formal model, but they are central to a comprehensive resilience strategy.

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Online Appendix

Online Appendix A. VAR(24) estimates for the impulse responses

For the sake of completeness, we investigate whether the dynamic responses are robust to the choice of estimation method. Figures A1 and A2 report impulse responses obtained from a standard VAR(24) specification using the same ordering and shock definition as in the baseline. The VAR responses are fully consistent with the LP estimates presented in Figures 4 and 5.

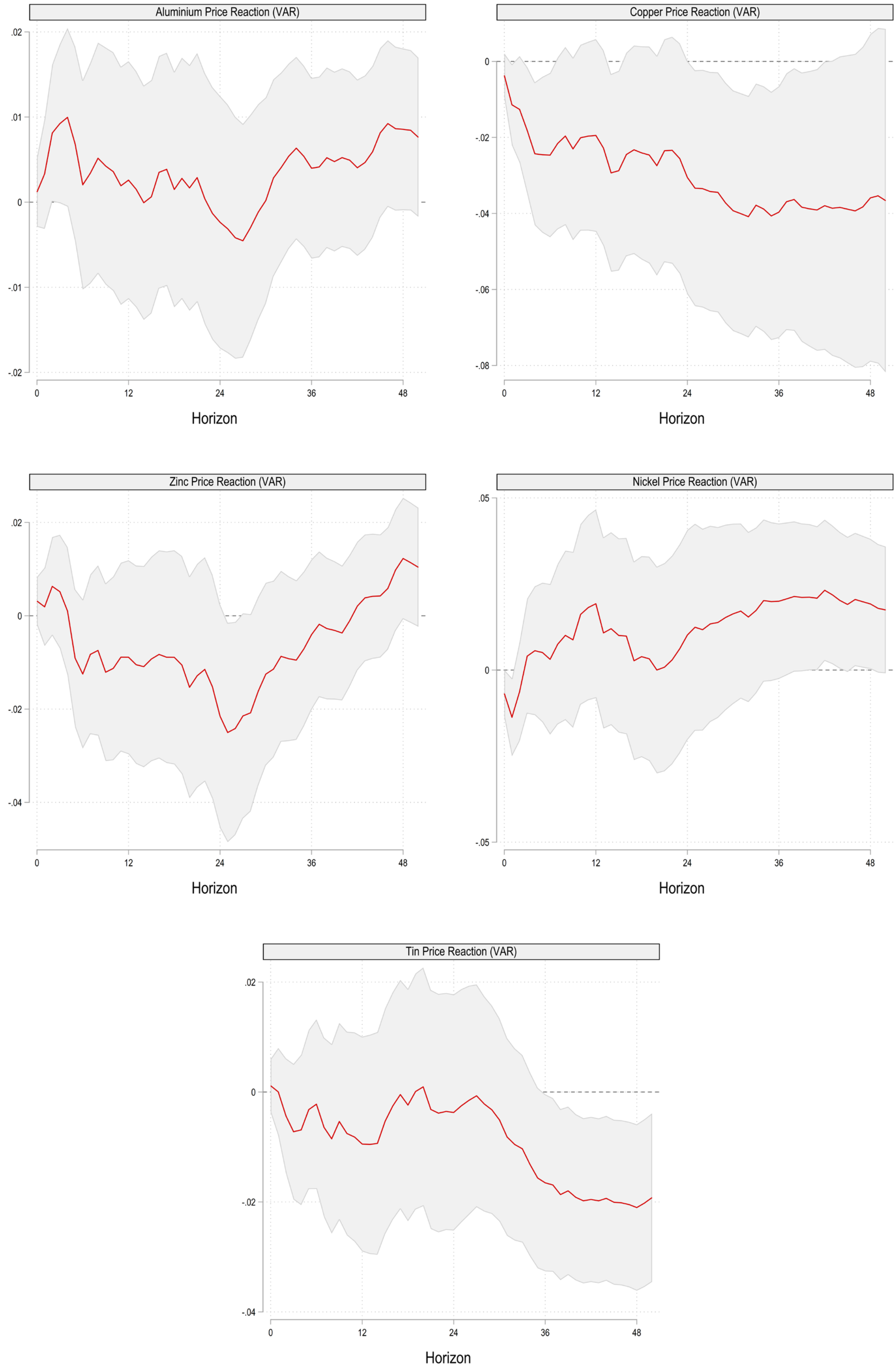
The VAR(24) also yields the following lag structure: prices responding immediately and stocks adjusting with a delay. This lag structure is a well-known implication of demand-driven disturbances: when global activity weakens, purchasing slows more rapidly than production, and the excess supply is absorbed into storage. This behavior is incompatible with a pure supply shock, which would instead generate declining inventories, but it is entirely consistent with the demand channel highlighted by the LP evidence.

Besides, the joint VAR responses of prices and inventories are economically coherent and replicate the identifying restrictions implied by Kilian's (2009) taxonomy. A negative demand shock lowers prices while raising inventories; a negative supply shock raises prices while reducing inventories; and a speculative demand shock raises both. Our VAR and LP estimates align precisely with the first case. The fact that two distinct estimation strategies recover the same dynamic pattern substantially reinforces the credibility of our interpretation.

Finally, the magnitudes and confidence bands of the VAR(24) responses are of comparable order to their LP counterparts, despite the differences in functional form and horizon-by-horizon estimation. This similarity suggests that our results are not driven by estimator-specific artefacts or the choice of horizon smoothing. Instead, the geopolitical shock identified from the PRI index consistently behaves like an adverse global demand disturbance across methods.

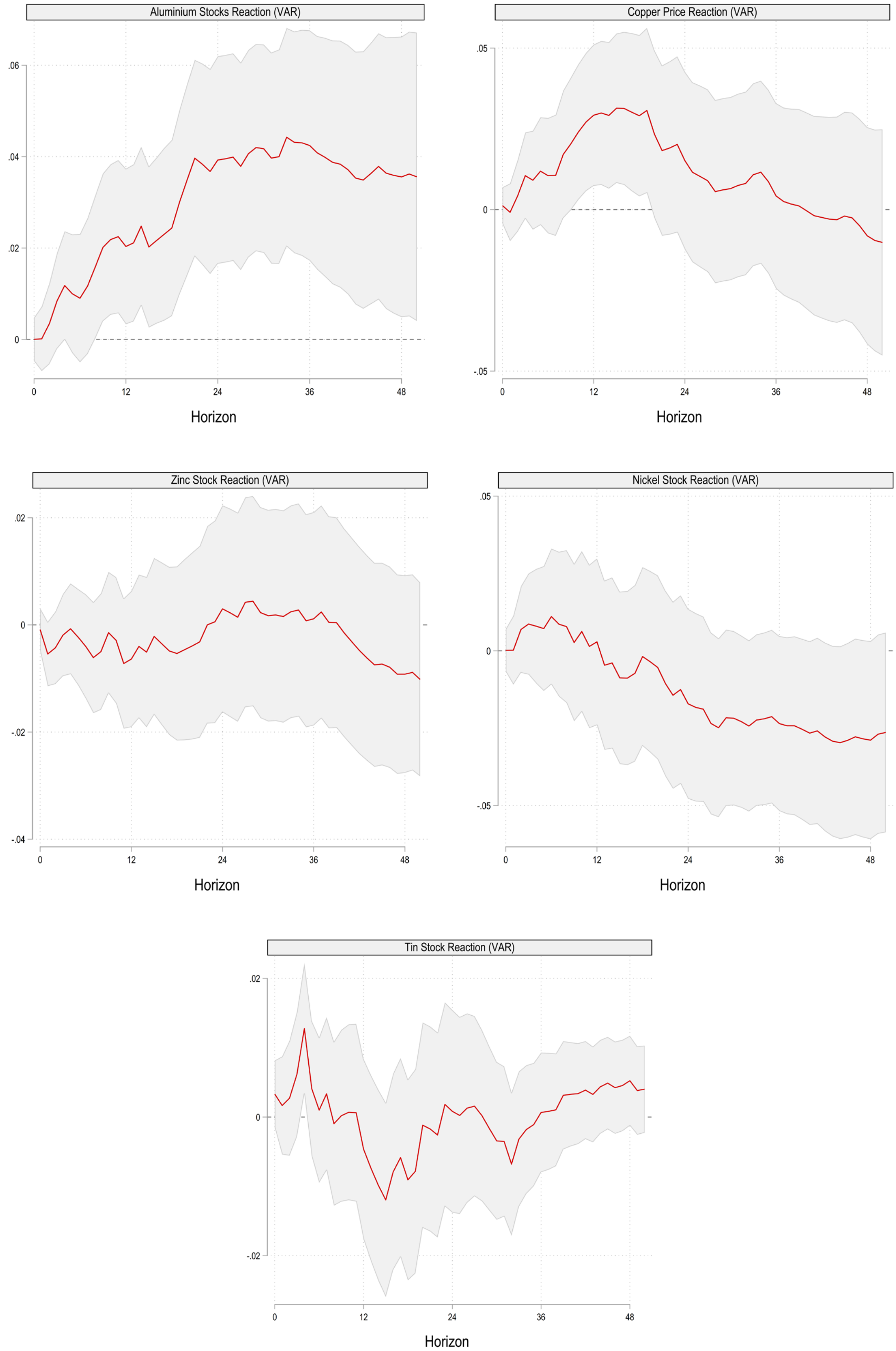
Taken together, the VAR(24) evidence confirms the robustness of the LP results and strengthens the conclusion that deteriorations in US–China geopolitical relations primarily transmit to critical mineral markets through an aggregate-demand channel, in line with the theoretical predictions of Kilian (2009). The VAR findings therefore serve as a strong external validation of the LP-based impulse responses.

Figure A1. Response of prices to an exogenous deterioration in the US–China relationship



The red line plots the estimated multiplier; the shaded grey band denotes the 90% confidence interval (robust standard errors).

Figure A2. Stockpiling response to an exogenous deterioration of the US–China relationship.



The red line plots the estimated multiplier; the shaded grey band denotes the 90% confidence interval (robust standard errors).

Online Appendix B. Optimal Stockpiling Under Geopolitical Risk for an Importer of Refined Critical Minerals

We develop a simple theoretical framework in which a net importing country chooses its optimal stockpile of a critical mineral in the presence of stochastic import disruptions. US–China geopolitical tensions are summarized by a parameter θ that affects the probability and severity of import shortfalls. Higher geopolitical risk increases the expected marginal value of inventories because shortages become more likely and more costly. As a result, the welfare maximizing stockpile is increasing in θ.

Consider a country that consumes a critical mineral and has access to domestic production $Q \geq 0$. Imports X arrive with uncertainty and follow a cumulative distribution $F(x; \theta)$, where θ indexes the state of US–China geopolitical relations. A higher value of θ represents worse relations and therefore a higher risk of disruption. Before observing the realization of X, the country chooses a stockpile $I \geq 0$.

Total available supply is

$$Y = Q + X + I. \qquad \text{(B1)}$$

Required domestic use is denoted $D > 0$. The country experiences a shortage of size

$$S = \max\{0, D - (Q + X + I)\}. \qquad \text{(B2)}$$

Shortages generate welfare losses. Let $L(S)$ denote the loss associated with a shortage of magnitude S, where $L(\cdot)$ is increasing and convex, reflecting diminishing marginal benefits of stockpiling as inventories expand. Expected vulnerability for a given stockpile I and geopolitical risk θ is defined as

$$V(I; \theta) = \mathbb{E}[\, L(\max\{0, D - (Q + X + I)\})]. \qquad \text{(B3)}$$

Expected vulnerability is decreasing in inventories whenever shortages occur with positive probability.

Proposition 1 (Stockpiling reduces vulnerability).

If there is a positive probability that $D > Q + X$, then

$$\frac{\partial V}{\partial I} < 0. \qquad \text{(B4)}$$

Intuitively, a higher stockpile I shifts total supply Y upward in all states, which reduces both the likelihood that a shortage occurs and its size when it does occur. The marginal effect of an additional unit of inventory on expected vulnerability is therefore negative.

Stockpiling is costly. Let $h > 0$ denote the per unit holding cost of inventory, capturing physical storage, financial, and depreciation costs. Total expected cost is

$$C(I;\theta) = hI + V(I;\theta). \qquad \text{(B5)}$$

The country chooses I to minimize $C(I;\theta)$. The first order condition for an interior optimum is

$$\frac{\partial C}{\partial I} = h + \frac{\partial V}{\partial I} = 0. \qquad \text{(B6)}$$

This condition equates the marginal holding cost $h$to the marginal reduction in expected vulnerability from one more unit of inventory, $-\,\partial V/\,\partial I$. For the optimum to be well defined, we assume convexity:

$$\frac{\partial^2 C}{\partial I^2} = \frac{\partial^2 V}{\partial I^2} > 0. \qquad \text{(B7)}$$

Convexity reflects diminishing marginal benefits of stockpiling: as inventories grow, each additional unit prevents increasingly unlikely or small shortages.

We now characterize how geopolitical tensions affect the optimal stockpile. Higher θ increases expected vulnerability at any given I:

$$\frac{\partial V}{\partial \theta} > 0. \qquad \text{(B8)}$$

Moreover, when geopolitical risk is high, an extra unit of inventory is more valuable, because it averts more severe or more likely disruptions. Formally, we assume

$$\frac{\partial^2 V}{\partial I\,\partial \theta} < 0. \qquad \text{(B9)}$$

To obtain the comparative static for the optimal stockpile $I^*(\theta)$, differentiate the first order condition (6) with respect to θ. Using the chain rule,

$$\frac{\partial^2 V}{\partial I^2}\,\frac{\partial I^*}{\partial \theta} + \frac{\partial^2 V}{\partial I\,\partial \theta} = 0. \qquad \text{(B10)}$$

Solving for $\partial I^* / \partial\theta$ gives

$$\frac{\partial I^*}{\partial\theta} = -\frac{\frac{\partial^2 V}{\partial I\,\partial\theta}}{\frac{\partial^2 V}{\partial I^2}} > 0, \qquad \text{(B11)}$$

where the inequality follows from $\partial^2 V/\partial I^2 > 0$ and $\partial^2 V/(\partial I\ \partial\theta) < 0$.

Proposition 2 (Geopolitical tension and optimal stockpiling).

Under assumptions (7) and (8), the optimal stockpile is increasing in geopolitical tension:

$$\frac{\partial I^*}{\partial\theta} > 0. \qquad \text{(B12)}$$

When geopolitical frictions raise the likelihood and cost of import shortages, the welfare maximizing response is to maintain a larger stockpile. The model therefore formalizes the idea that higher US–China tensions strengthen precautionary demand for inventories in critical mineral markets.

B.1. Stockpiling, Geopolitical Risk, and Friend-Shoring Feasibility

How can the United States, as a structural net importer of most refined critical minerals, expand its refined stockpiling capacity without relying on China's dominant position in global refining? One possible strategy is to reallocate refined supply chains toward geopolitical allies and trusted trade partners. The feasibility of such friend-shoring, however, varies considerably across potential partners. Countries differ in geological endowments, geopolitical alignment with the United States, and their institutional capacity to scale refining operations.

We model the main determinants of friend-shoring feasibility in a manner consistent with the empirical evidence. First, feasibility increases with a partner's proven reserves R_i, reflecting that large geological endowments support viable refining industries by enabling economies of scale and long operational lifetimes (Tilton and Guzmán 2016; Humphreys 2015; IEA 2024). Second, feasibility declines with geopolitical distance G_i, in line with evidence that trade, foreign investment, and supply-chain integration sharply weaken as geopolitical alignment deteriorates (Bailey, Strezhnev and Voeten 2016; Leeds 2015). Third, feasibility decreases with the democratic index D_i, consistent with Figure 2b and empirical research showing that democratic institutions tend to impose stricter environmental, social, and permitting constraints, slowing the expansion of refining capacity (Povitkina 2018).

B.1.1. Friend-Shoring Feasibility

Let the United States consider a set of potential friend-shoring partners indexed by $i = 1, \ldots, N$. Each partner is characterised by:

- $R_i \geq 0$: proven reserves of the relevant critical mineral

- $G_i \geq 0$: geopolitical distance from the United States (higher values indicate weaker alignment)
- $D_i \geq 0$: democratic index (higher values indicate more democratic institutions)

Define $\Phi_i \in [0,1]$as the probability that friend-shoring with partner $i$yields a reliable stream of refined imports. Let feasibility satisfy

$$\Phi_i = \Phi(R_i, G_i, D_i), \qquad \text{(B13)}$$

with partial derivatives

$$\frac{\partial \Phi}{\partial R_i} > 0, \frac{\partial \Phi}{\partial G_i} < 0, \frac{\partial \Phi}{\partial D_i} < 0. \qquad \text{(B14)}$$

The first derivative reflects that larger reserves facilitate refining. The second indicates that greater geopolitical distance reduces the probability of a stable friend-shoring relationship. The third reflects that most refining capacity for critical minerals is located in non-democratic jurisdictions, where permitting and environmental constraints are lighter, making rapid scale-up more feasible.

B.1.2. Import Structure with Friend-Shoring

Total refined imports are decomposed into flows from China and flows from friend-shoring partners:

$$X = X^C + X^F, \qquad \text{(B15)}$$

where X^Cfollows a distribution $F^C(x^C;\theta)$shaped by geopolitical tensions θ, and X^Ffollows a distribution $F^F(x^F;\Phi)$shaped by friend-shoring feasibility $\Phi = (\Phi_1, \dots, \Phi_N)$.

The joint distribution of total imports is therefore:

$$X \sim F(x;\theta,\Phi).$$

Total available supply and shortage definitions remain as in the baseline model. Expected vulnerability now depends on geopolitical tensions and friend-shoring feasibility:

$$V(I;\theta,\Phi) = \mathbb{E}[L(\max\{0, D - Y\})]. \qquad \text{(B16)}$$

Partial derivatives satisfy:

$$\frac{\partial V}{\partial I} < 0, \frac{\partial V}{\partial \theta} > 0, \frac{\partial V}{\partial \Phi_i} < 0, \qquad \text{(B17)}$$

for any partner i for which shortages occur with positive probability. Improved friend-shoring feasibility lowers expected vulnerability by stabilising non-Chinese refined supply.

B.1.3. Optimal Stockpiling with Friend-Shoring

The cost function becomes

$$C(I;\theta,\Phi) = hI + V(I;\theta,\Phi), \qquad \text{(B18)}$$

and the first-order condition is

$$\frac{\partial C}{\partial I} = h + \frac{\partial V}{\partial I} = 0. \qquad \text{(B19)}$$

Convexity requires:

$$\frac{\partial^2 C}{\partial I^2} = \frac{\partial^2 V}{\partial I^2} > 0. \qquad \text{(B20)}$$

Proposition 3: Friend-Shoring Reduces Optimal Stockpiling

Assume

$$\frac{\partial V}{\partial \Phi_i} < 0, \frac{\partial^2 V}{\partial I\ \partial \Phi_i} > 0. \qquad \text{(B21)}$$

Differentiating the first-order condition with respect to Φ_i:

$$\frac{\partial^2 V}{\partial I^2}\frac{\partial I^*}{\partial \Phi_i} + \frac{\partial^2 V}{\partial I\ \partial \Phi_i} = 0,$$

which yields:

$$\frac{\partial I^*}{\partial \Phi_i} = -\frac{\frac{\partial^2 V}{\partial I\ \partial \Phi_i}}{\frac{\partial^2 V}{\partial I^2}} < 0. \qquad \text{(B22)}$$

Thus, higher friend-shoring feasibility lowers the optimal stockpile. Greater access to reliable, non-Chinese refined supply reduces expected vulnerability to import disruptions.

Finally, because $\Phi_i = \Phi(R_i, G_i, D_i)$, applying the chain rule yields:

$$\frac{\partial I^*}{\partial R_i} = \frac{\partial I^*}{\partial \Phi_i} \frac{\partial \Phi}{\partial R_i} < 0, \qquad \text{(B23)}$$

$$\frac{\partial I^*}{\partial G_i} = \frac{\partial I^*}{\partial \Phi_i} \frac{\partial \Phi}{\partial G_i} > 0, \qquad \text{(B24)}$$

$$\frac{\partial I^*}{\partial D_i} = \frac{\partial I^*}{\partial \Phi_i} \frac{\partial \Phi}{\partial D_i} > 0. \qquad \text{(B25)}$$

Thus, holding θ constant, larger partner reserves reduce the optimal United States stockpile, while greater geopolitical distance and higher democratic constraints increase it.

Online Appendix C. Exploring the interaction between determinants of friend-shoring feasibility

C.1. CES Feasibility Function

Let partner i be characterised by three determinants of friend-shoring feasibility:

- $R_i \geq 0$: geological reserves
- $G_i \geq 0$: geopolitical distance from the United States
- $D_i \geq 0$: democratic index, capturing permitting and regulatory constraints

These are mapped into transformed inputs

$$x_R = R_i, x_G = e^{-\kappa_G G_i}, x_D = e^{-\kappa_D D_i},$$

so that feasibility increases in reserves and decreases in distance and regulatory constraints. Feasibility is modelled as a CES aggregator:

$$\Phi_i = (\omega_R x_R^\rho + \omega_G x_G^\rho + \omega_D x_D^\rho)^{1/\rho}, \rho = \frac{\sigma - 1}{\sigma},$$

where σ is the elasticity of substitution and $\omega_R + \omega_G + \omega_D = 1$.

C.2. Interpretation of the Interactions

The CES structure generates systematic interactions among the three dimensions of feasibility:

1. **Reserves × Distance interaction.**

   The marginal effect of reserves is larger when geopolitical distance is small. Aligned resource-abundant countries (e.g., Australia, Canada) appear on the upper ridge of the surface. By contrast, large reserves in distant countries yield only a modest increase in feasibility.

2. **Reserves × Democratic constraints interaction.**

   When D_i is low, reserves map almost directly into feasibility; when D_i is high, regulatory bottlenecks reduce the contribution of geology. This explains why the high-democracy surface is flatter despite identical geological inputs.

3. **Distance × Democratic constraints interaction.**

   Democratic constraints dampen the effect of geopolitical proximity: among highly democratic states, even close allies face institutional frictions that reduce the feasibility of rapidly scaling refining capacity.

These interactions arise directly because the CES aggregator deviates from linearity unless $\sigma \to \infty$. When $\sigma = 1$, the aggregator takes the Cobb–Douglas limit and yields imperfect but positive substitution; when $\sigma \to 0$, the function becomes Leontief and feasibility is dominated by the weakest dimension.

C.3. Calibration

The baseline calibration uses

- $\omega_R = 0.4$, $\omega_G = 0.35$, $\omega_D = 0.25$, reflecting the relative empirical importance of geology, alignment, and institutional frictions.
- $\kappa_G = 2$ so that geopolitical distance reduces feasibility sharply beyond moderate misalignment.
- κ_D is calibrated so that the upper quartile of democratic countries exhibit lower feasibility than the median non-OECD autocracies, consistent with observed differences in permitting delays, regulatory approval rates, and environmental review processes.
- $\sigma = 1$ in the benchmark, corresponding to the Cobb–Douglas (intermediate substitutability) case. This choice matches the non-linear but not fully complementary empirical relationship between reserves and alignment.

In the main text, Figures 6 and 7 correspond to two versions of $\Phi(R_i, G_i)$ obtained by holding D_i fixed at low and high-values, thereby isolating how democratic constraints reshape the feasibility landscape. These calibrated surfaces directly inform the comparative-statics analysis in Section 4, including the sensitivity of the optimal stockpile I^* to improvements in partner geology or alignment.

Online Appendix D: Description of the Estimations for Friend-Shoring Index

Estimates in Figures 8 and 9 quantify a composite friend-shoring score for eight countries with high proven reserves of the five critical minerals (F_i) under a set of alternative weighting schemes. The objective is to summarize, into a single index, how attractive each country is as a friend-shoring partner for the United States once we jointly consider supply potential (proven reserves), geopolitical alignment, the autocracy index, and geographic distance (representing cost of transportation).

For each country i, we first construct a small set of underlying indicators (e.g., proven reserve value, geographical distance, autocratic index and geopolitical distance). Proven reserve quantity and price are obtained from the United States Geological Survey's Mineral Commodity Summaries. The Autocratic Index is a continuous measure of political regime type that ranges from 0 to 10, where higher values indicate more autocratic governance and lower values correspond to more democratic systems. It captures institutional features, such as executive constraints, electoral competitiveness, civil liberties, and political pluralism. This index is widely used to assess the degree of political authoritarianism across countries and to compare governance structures in the context of economic and geopolitical analysis. The Democracy Index, which is employed in constructing the Autocratic Index, is taken from the Economist Intelligence Unit database.

Based on the spatial theory approach, Bailey, Strezhnev and Voeten (2016) proposed an indicator to estimate the ideal-point distance between countries on subsets of geopolitical issues, called geopolitical distance (GPD). Ideal point estimates based on the United Nations General Assembly (UNGA) voting behavior refer to a widely used dataset in political science that measures each country's ideological position or foreign policy orientation within the UNGA (Caldara & Iacoviello, 2022; Correa da Cunha, Singh & Amal, 2024). These ideal points are derived from UN voting patterns and reflect a country's foreign-policy preferences. Therefore, a higher GPD indicates weaker geopolitical alignment and fewer shared priorities between two countries. In our study, we define a bilateral geopolitical distance of each country as the absolute difference of each country score with the US. A larger value indicates a greater geopolitical distance from the United States, as well as a higher degree of divergence or opposition in foreign-policy preferences.

In Figures 8 and 9, each of these raw indicators is normalized so that they are dimensionless and comparable in magnitude (Figure 8 is the baseline scenario in the first column of Figure 9). The main analysis uses min–max normalization, which rescales each variable to the [-1,1] interval based on the minimum and maximum observed in the sample. This normalization preserves the relative spacing of values and fully stretches the most extreme observations to 0 and 1, respectively. Normalized variables are then combined linearly using scenario-specific weights to obtain F_i.

The scenarios differ only in their weights, not in the underlying data. In the baseline scenario, the four aspects (geopolitical alignment, political regime type, geographic distance, and mineral endowment) receive roughly equal weight. In the geo-alignment-first scenario, the weight on geopolitical alignment is increased, so that countries that are geopolitically closer to the United States gain in relative importance. In the political regime-first scenario, higher weight is placed on quality of governance and rule of law, penalizing countries with weak institutions or high autocratic scores. The nearshoring scenario increases the weight placed on geographic/logistical proximity, favoring countries geographically closer to the United States. The supply-first scenario prioritizes physical and economic reserves, emphasizing countries with large proven reserves or high reserve values.

The following sections provide the mathematical definitions and conventions used to construct the friend-shoring heatmaps and scenario-specific scores. It defines the data structure, normalization, democratic-index inversion, scenario transformations, and the final heatmap matrix.

D.1. Data structure and notation

Let countries be indexed by

$i \in \{1, \dots, N\}$

and scenarios by

$$s \in S = \{\text{baseline, geo-aligned-first, autocracy-first, near-shoring first, supply-first}\}.$$

For each country i and scenario s, define the friend-shoring score

$F_{i,s} \in \mathbb{R}$

which appears as a cell in the heatmap.

The heatmap is, therefore, the matrix

$F = (F_{i,s})_{i=1,\dots,N;\ s \in S}.$

Each $F_{i,s}$ is constructed from the following baseline variables:

- G_i represents the geopolitical distance between country i and the United States;
- D_i represents the geographic/logistical distance between country i and the United States;
- D_i^{dem} represents the democracy index of country i;
- R_i represents the reserves or supply capacity of country i.

D.2. Constructing the autocracy index

Suppose the original democracy index is D_i^{dem}, in which higher values indicate more democratic regimes, range from 0 (authoritarian regime) to 10 (full democracy). To align the autocracy-first logic (where higher values indicate more autocratic), we define the autocracy index A_i by:

$A_i = 10 - D_i^{\text{dem}}$

Alternatively, for a normalized autocracy index on [0,1], let

$D_{min}^{\text{dem}} = \min_i D_i^{\text{dem}} \qquad and \qquad D_{max}^{\text{dem}} = \max_i D_i^{\text{dem}}$

and define

$A_i^{norm} = \frac{D_{max}^{\text{dem}} - D_i^{\text{dem}}}{D_{max}^{\text{dem}} - D_{min}^{\text{dem}}}$

Higher A_i^{norm} always corresponds to more autocratic countries.

D.3. Baseline friend-shoring score

In the baseline scenario, the score is a function of geopolitical alignment and geographic distance:

$F_{i,\text{Baseline}} = f_{\text{base}}(G_i, D_i)$

A simple linear specification is:

$F_{i,\text{Baseline}} = \beta_G G_i + \beta_D D_i + \beta_0$

or including autocracy index:

$F_{i,\text{Baseline}} = \beta_G G_i + \beta_D D_i + \beta_A A_i^{norm} + \beta_0$

D.4. Geo-aligned-first scenario

This scenario gives extra weight to geopolitical alignment:

$F_{i,\text{Geo}} = (1+\lambda_G)\beta_G G_i + \beta_D D_i + \beta_A A_i^{norm} + \beta_0,$
with $\lambda_G > 0$.
Equivalently:
$F_{i,\text{Geo}} = f_{\text{geo}}(G_i, D_i, A_i^{norm}),$
where f_{geo} increases sensitivity to G_i.

D.5. Autocracy-first scenario
Here, the autocracy index A_i^{norm} becomes a primary driver. A general linear form is:
$F_{i,\text{Auto}} = \gamma_A A_i^{norm} + \gamma_G G_i + \gamma_D D_i + \gamma_0$
with $\gamma_A > 0$.
A simplified autocracy-driven form is:
$F_{i,\text{Auto}} = \gamma_A A_i^{norm} + \gamma_0$

D.6. Near-shoring-first scenario
Let d^* denote the distance threshold distinguishing "near" from "far", and $\phi > 0$ measure the strength of near-shoring.
Define the adjusted distance:
$$D_i^{(\text{near})} = \begin{cases} D_i - \phi, & D_i \le d^*, \\ D_i + \phi, & D_i > d^*. \end{cases}$$
The score becomes:
$F_{i,\text{Near}} = f_{\text{near}}(G_i, D_i^{(\text{near})}, A_i^{norm})$
or explicitly:
$F_{i,\text{Near}} = \beta_G G_i + \beta_D D_i^{(\text{near})} + \beta_A A_i^{norm} + \beta_0$

D.7. Supply-first scenario
Let R_i denote reserves or supply capacity, and let $h(R_i)$ be a transformation of R_i such as a normalisation. One convenient choice is:
$$R_i^{norm} = \frac{R_i - R_{\min}}{R_{\max} - R_{\min}}$$
with: $R_{\min} = \min_i R_i, \qquad R_{\max} = \max_i R_i.$
A general linear score is:
$F_{i,\text{Supply}} = \delta_R R_i^{norm} + \delta_G G_i + \delta_D D_i + \delta_A A_i^{norm} + \delta_0$
with $\delta_R > 0$.
A simplified supply-driven score is:
$F_{i,\text{Supply}} = \delta_R R_i^{norm} + \delta_0$

D.8. Construction of the heatmap
For each country i and scenario $s \in S$, compute:
$$F_{i,s} = \begin{cases} f_{\text{base}}(G_i, D_i, A_i^{norm}), & s = \text{Baseline}, \\ f_{\text{geo}}(G_i, D_i, A_i^{norm}), & s = \text{Geo-aligned-first}, \\ f_{\text{auto}}(G_i, D_i, A_i^{norm}), & s = \text{Autocracy-first}, \\ f_{\text{near}}(G_i, D_i^{(\text{near})}, A_i^{norm}), & s = \text{Near-shoring-first}, \\ f_{\text{supply}}(G_i, D_i, A_i, A_i^{norm}), & s = \text{Supply-first}. \end{cases}$$
These values populate the matrix F, which is rendered as a heatmap:

- rows correspond to countries i;
- columns correspond to scenarios s;
- cell color is a monotone function of $F_{i,s}$;
- the color scale is typically centered at zero for comparability.

This structure ensures that differences across columns reflect scenario-driven transformations while differences across rows reflect variation in country fundamentals.

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