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Critical minerals in an age of geopolitical rivalry: stockpiling, refining constraints, and the limits of friend-shoring

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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 aluminium, copper, nickel, tin, and zinc, is overwhelmingly concentrated in China. Using monthly data from 1995 to 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 centrepiece 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

I. 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 (National Research Council, 2008; Adam *et al.*, 2026). In this article, we focus on aluminium, copper, nickel, tin, and zinc because they are key inputs into electrification, digitalization, advanced manufacturing, and defence-related applications, while their refined supply chains are exposed to substantial concentration

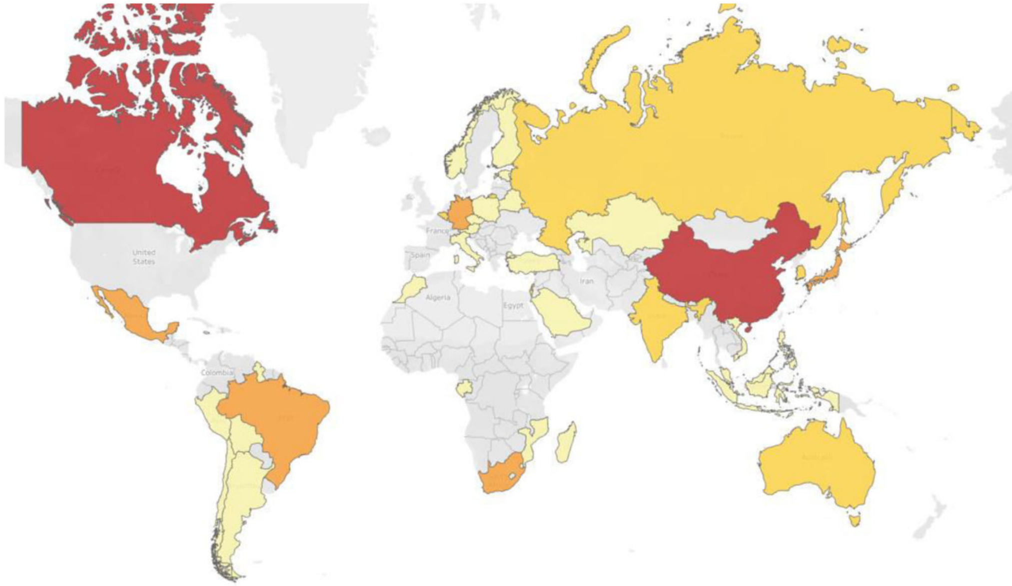

Figure 1 Leading import sources (2020–3) of nonfuel mineral commodities for which the United States was greater than 50% net import reliant.
Note: Net import reliance (NIR), reported by the US Geological Survey, is measured as net imports (imports minus exports), adjusted for changes in government and industry stocks, expressed as a percentage of apparent US consumption. Apparent consumption is generally computed as domestic production plus imports minus exports, with adjustments for stock changes. Countries shown in colour indicate foreign sources of nonfuel mineral commodities for which the United States was more than 50% net import reliant. Different colours 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: US Geological Survey (Mineral Commodity Summaries).

risk. Their strategic importance has risen sharply with the expansion of batteries, semiconductors, transmission infrastructure, electric vehicles, and aerospace systems (IEA, 2021; US Department of Energy, 2023; Hidayat, 2025a). 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 20 minerals. A second tier of suppliers, including Japan, Mexico, Brazil, South Africa, and Germany, account for 5–12 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 aluminium/alumina, copper, nickel, zinc, and tin (Chen and Tongurai, 2022; IEA, 2024; US 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; Zhou *et al.*, 2025; Hidayat, 2025b).

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 and Iacoviello, 2022; Mignon and Saadaoui, 2024; Saadaoui *et al.*, 2025). The Political Relations Index (PRI) systematically tracks these shifts and has proven effective at isolating geopolitical turning points relevant to commodity-market behaviour (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 US manufacturers to supply risks. Although these developments partly fall beyond our estimation window, they underscore the real-time relevance of the mechanisms analysed 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 to 2025 and an econometric approach combining a structural VAR with local projections (Jordà, 2005; Inoue *et al.*, 2025; Jordà and Taylor, 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 (US Geological Survey, 2024), geopolitical alignment (Bailey *et al.*, 2016; Correa da Cunha *et al.*, 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 centrepiece 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 II documents China's dominance in refined critical-mineral supply chains and details the evolution of US–China geopolitical relations using the PRI. Section III 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 stockpil-

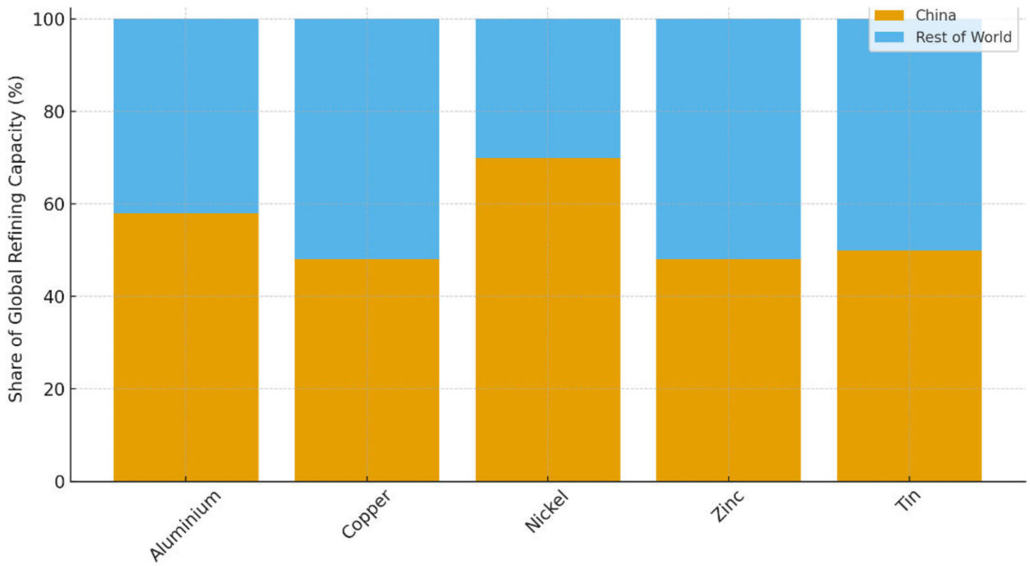

Figure 2a China vs the Rest of World refining capacity for aluminium, copper, nickel, zinc, and tin (2024).
Note: This figure shows the share of global refining capacity accounted for by China and the Rest of World for aluminium, copper, nickel, zinc, and tin in 2024. 'Rest of World' aggregates refining capacity outside China. The figure shows China's dominant position in global refining capacity across these key minerals.
Data sources: USGS *Mineral Commodity Summaries*; USGS *Global Maps of Critical Mineral Production*; IEA *Global Critical Minerals Outlook*; authors' calculations.

ing behaviour. Section IV 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 V introduces a multidimensional friend-shoring feasibility index incorporating geological endowments, geopolitical alignment, regime type, and geographic distance. Section VI concludes by discussing the policy implications for the US strategic stockpiling, supply-chain diversification, and long-run coordination with geopolitical allies.

II. 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 and 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, defence systems, and the clean-energy transition (IEA, 2025; Saadaoui *et al.*, 2025). This dominance creates a structural asymmetry: while the United States and its allies possess significant raw mineral reserves, according to the US 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 and Saadaoui, 2024; Saadaoui *et al.*, 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 behaviour and the resilience of United States critical minerals supply chains (IEA, 2024).

Figure 2a shows the distribution of global refining capacity for aluminium, copper, nickel, zinc, and tin, comparing China with the rest of the world. Across all five metals, China accounts for roughly one-half of

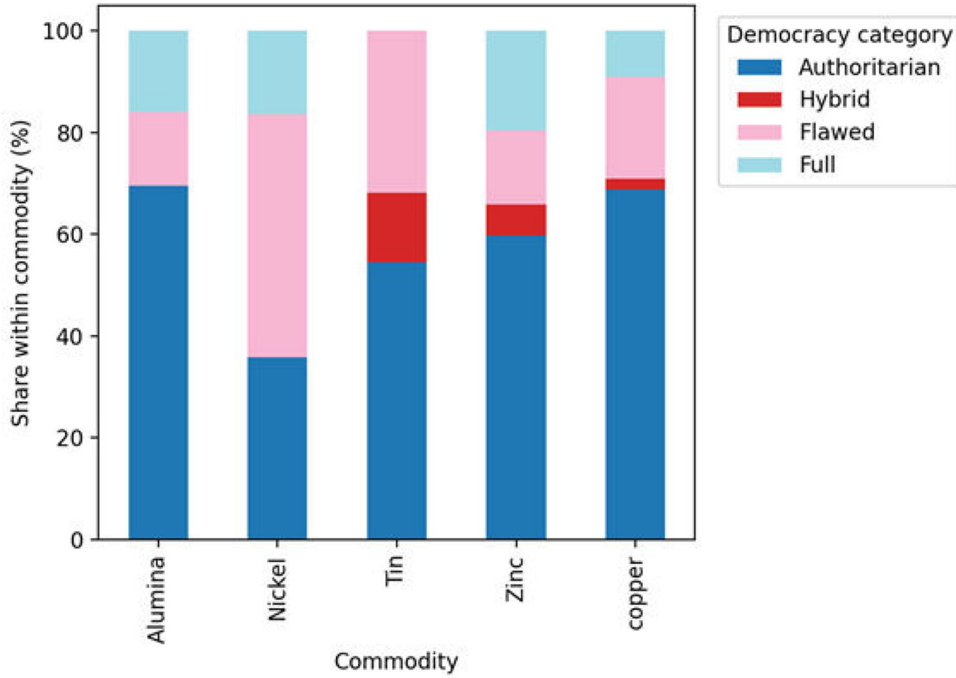

Figure 2b Refining capacities by political regime for aluminium, copper, nickel, zinc, and tin (2024).
Note: Countries are classified by political regime using the Democracy Index, which measures the degree of democracy on a scale from 0 to 10, based on a broad set of political and institutional criteria. Following the standard categorization, 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/.

global refining capacity, with nickel as high as almost 70%. 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 aluminium; 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 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

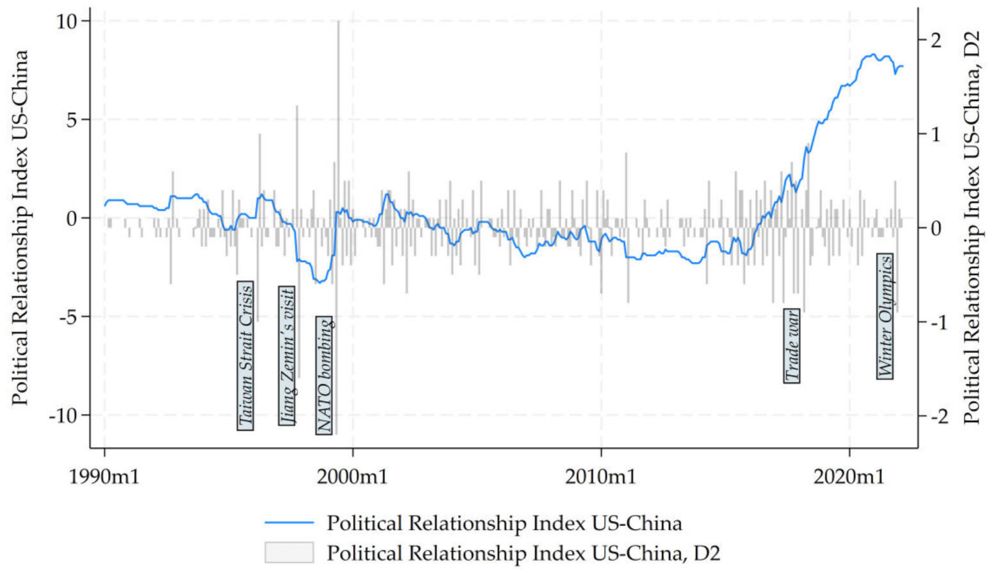

Figure 3 US–China geopolitical relationship.
Note: The solid line reports the level of the Political Relations Index (PRI) for US–China relations, where higher values indicate more strained (deteriorating) bilateral relations. The bars plot the second difference of the PRI (the change in the first difference), 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).

practical scope of friend-shoring and making refined stockpiling a necessary, but insufficient, resilience strategy.

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 favourable 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 (Mignon and Saadaoui, 2024; Saadaoui, 2025).

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.

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, signalling 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.

III. 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 aluminium, copper, nickel, tin, and zinc. We focus on these critical minerals for two reasons. First, aluminium, 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 II, 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 *et al.*, 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 *et al.* (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

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

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 *et al.* (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.

IV. Geopolitical risk, optimal stockpiling, and the limits of friend-shoring

Motivated by the backward-looking evidence in section III, 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 III 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.

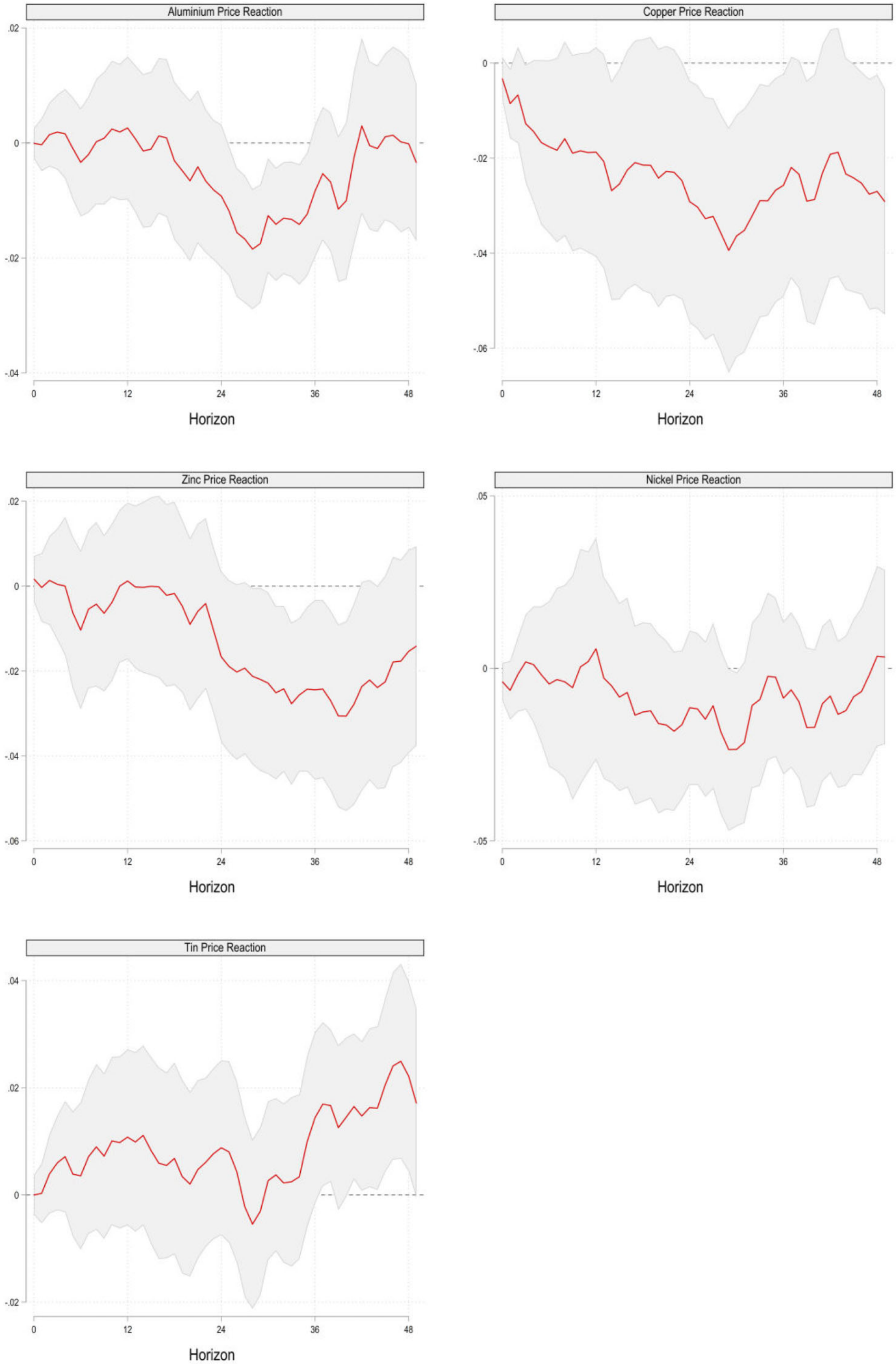

Figure 4 Response in prices of aluminium, copper, zinc, nickel, and tin to an exogenous deterioration in the US–China geopolitical relationship.

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.

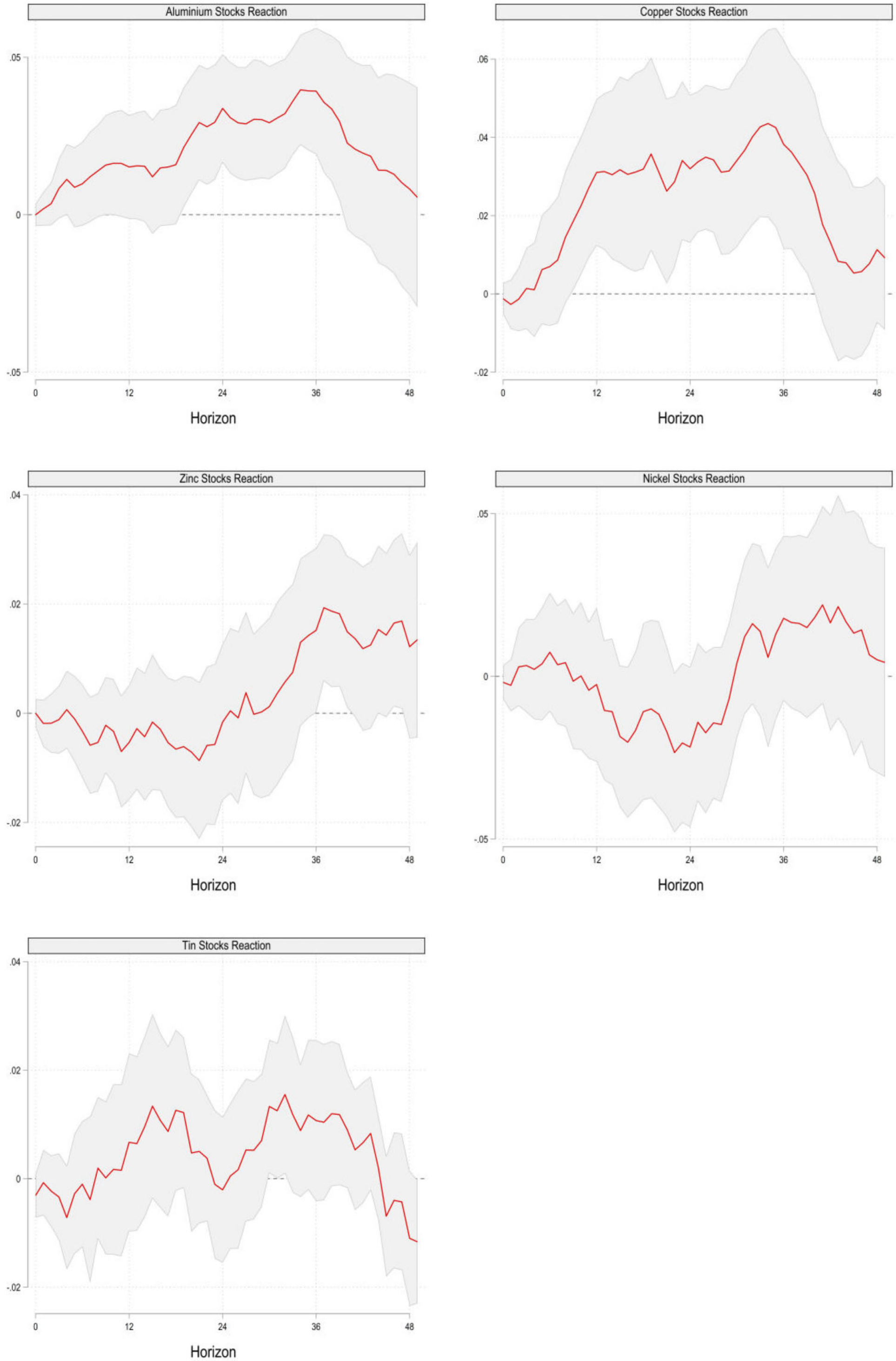

Figure 5 Critical mineral stockpiling response to an exogenous deterioration of the US–China relationship.
Note: The red line plots the estimated multiplier; the shaded grey band denotes the 90% confidence interval (robust standard errors). Online Appendix A presents the VAR estimation for the impulse response function. The results are qualitatively similar.

(i) 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 trade-off 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 defence, 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.

(ii) 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.

(iii) 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 effi-

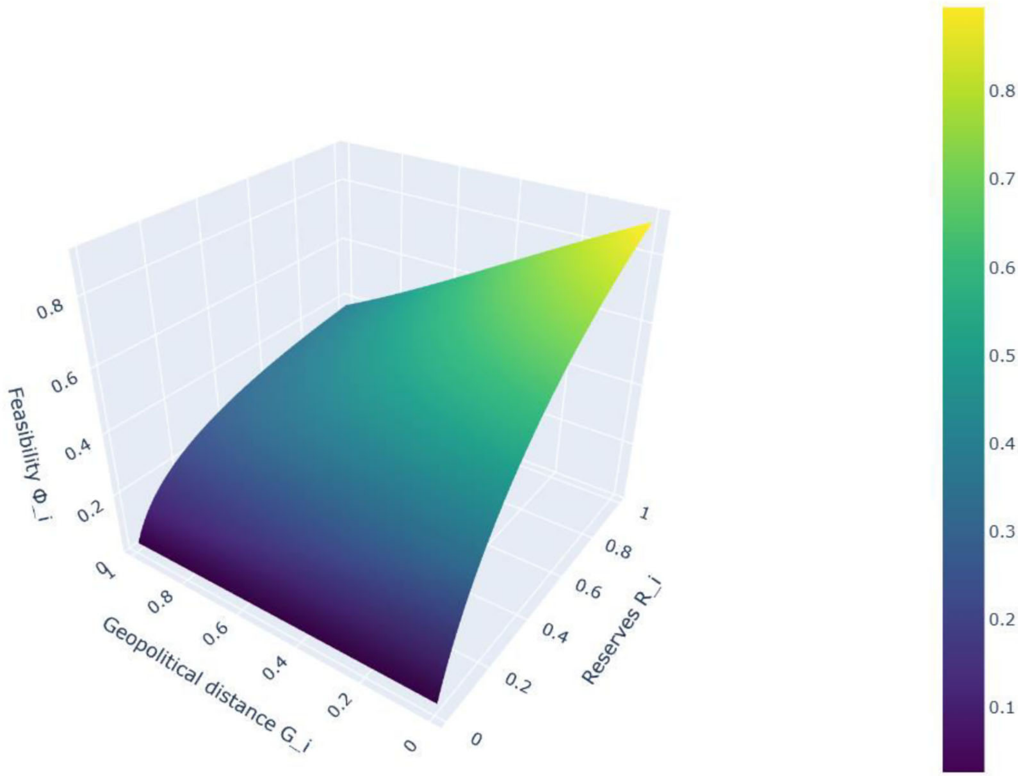

Figure 6 Feasibility surface $\Phi(R_i, G_i)$—low democratic constraints ($D_i = 0.2$).
Note: This plot shows the feasibility function when democratic constraints are low. Feasibility increases sharply in reserves and decreases in geopolitical distance, yielding a convex upward-sloping ridge for aligned 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.

ciently 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, Φ_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.

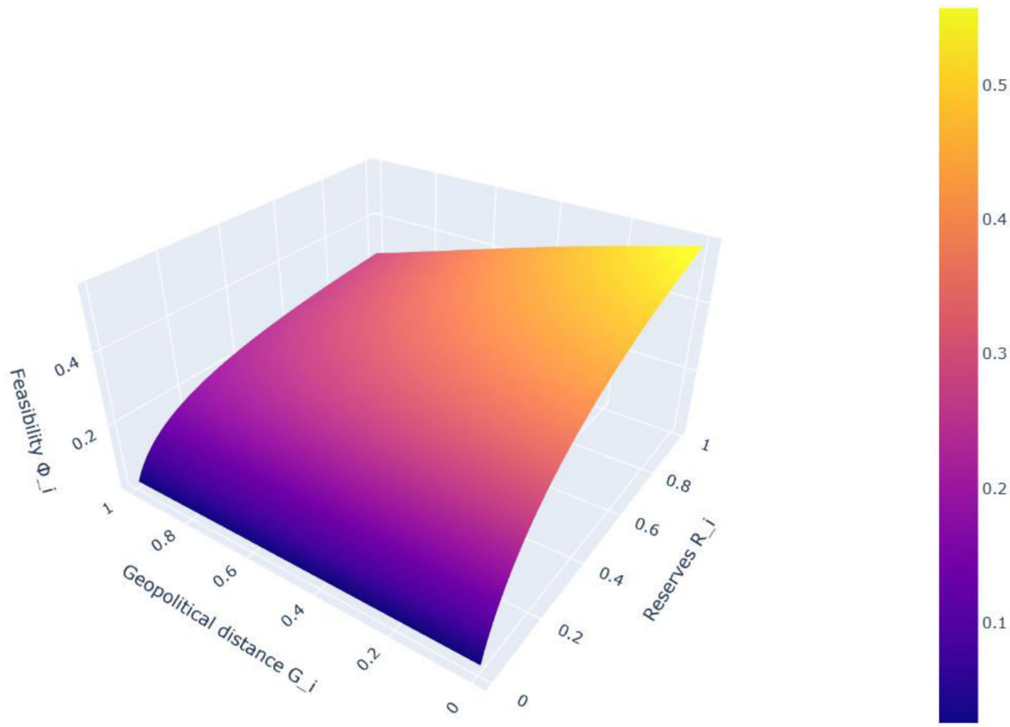

Figure 7 Feasibility surface $\Phi(R_i, G_i)$—high democratic constraints ($D_i = 0.8$).
Note: Higher democratic constraints shift the entire feasibility surface downward, especially for partners with moderate or large geopolitical distance. Reserves become less effective in raising feasibility when 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.

(iv) Policy implications for a stockpiling-centred 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.

V. 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. Aluminium/alumina refining is dominated by China

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
Aluminium/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 aluminium, copper, tin, and zinc is from USGS *Global Maps of Critical Mineral Production in 2023* (Fact Sheet 2025–3038).

(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.

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 centres 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.

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 towards trusted geopolitical partners with aligned strategic interests. In this

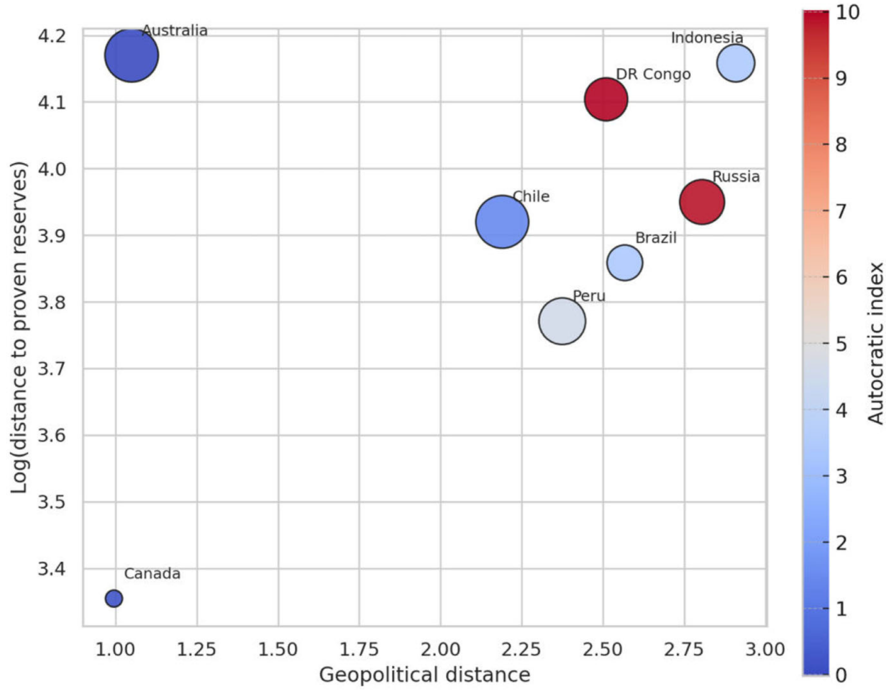

Figure 8 US friend-shoring alternatives to stockpiling for key critical minerals.
Note: In Online Appendix D, we provide detail of the normalization of variables in this figure. This figure is equivalent to the baseline scenario in Figure 9.

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 IV(ii), 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 colour 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

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.

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 $\boldsymbol{s}_i$, displayed as a two-decimal numeric label.

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 policy-makers.

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.

VI. 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 aluminium, 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 centre 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 defence, 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 towards '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, aluminium, 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.

Supplementary material

Supplementary material is available at *ECOPOL* Journal online.

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