Tasmanian School of Business and Economics
University of Tasmania

Discussion Paper Series N 2026-01

Where Geopolitical Risk Binds: Stockpiling and AI as Complementary Strategies for Mitigating Supply Chain Risk in Critical Minerals

Joaquin Vespignani
University of Tasmania, Australia

Russell Smyth
Monash University, Australia

Jamel Saadaoui
Paris 8 University, France

Yitian Wang
Monash University, Australia

ISBN 978-1-922352-24-8

Where Geopolitical Risk Binds: Stockpiling and AI as Complementary Strategies for Mitigating Supply Chain Risk in Critical Minerals

Joaquin Vespignani, [ac*] Russell Smyth, [bc] Jamel Saadaoui, [cd] and Yitian Wang [b]

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

Abstract

We develop novel, stage-specific, geopolitical risk indicators to examine how geopolitical risk is distributed across the supply-chain for lithium and copper, two minerals which are vital for low-carbon technologies. We find that refining is the geopolitical bottleneck for both minerals, reflecting that refining capacity is highly concentrated in China. We examine refining diversification, strategic stockpiling, and AI-driven productivity gains as complementary policy instruments for mitigating exposure to geopolitical risk at the refining stage. We show that reducing China's refining share substantially lowers refining-stage geopolitical risk, with larger gains for lithium than for copper. We find that stockpiling plays a critical role in buffering near-term geopolitical shocks, but significantly increases the projected shortfall in copper and lithium which is needed to realize the clean energy transition under alternative Net Zero pathways. We demonstrate that AI-driven productivity gains will be needed to narrow the projected supply gaps for both minerals. Our results suggest that ensuring effective security of critical minerals requires a coordinated policy mix, combining refining diversification, strategic stockpiling, and productivity-enhancing technological change.

Keywords: Critical Minerals; Copper; Lithium; Geopolitical Risk; Refining bottlenecks

JEL Codes: C14; Q20, Q41; Q43

*Correspondence and requests for materials should be addressed to Joaquin Vespignani, joaquin.vespignani@utas.edu.au, University of Tasmania, Private Bag 85, Hobart, TAS 7001, Australia.

1. Introduction

The clean energy transition is reshaping global demand for critical minerals and, in particular, those minerals that are essential inputs to low-carbon technologies. Lithium and copper have emerged as two of the most important critical minerals for facilitating the clean energy transition. Lithium is essential for energy storage in electric vehicles (EVs) and grid systems, and copper for power transmission, electrification, and renewable infrastructure.[1] Together, they represent approximately 60-65 per cent of all critical minerals by market value.[2]

The supply chains for copper and lithium are increasingly exposed to geopolitical volatility, high levels of supply chain concentration and long project development timelines—factors that pose systemic risks to realizing agreed carbon net zero timelines. Developing effective mitigation strategies to reduce exposure to geopolitical risk depends on pinpointing the stage at which the bottleneck in the supply chain emerges. We lack evidence, however, on how exposure to geopolitical risk varies across different stages of the supply chain and the effectiveness of alternative policy instruments to mitigate stage-specific supply chain risk. We address this gap by quantifying stage-specific geopolitical risk exposure for lithium and copper and examining refining diversification, stockpiling and productivity-enhancing technological change as complementary strategies to enhance resilience in mineral supply chains.

We contribute to the literature on critical minerals and energy security in two ways. First, we develop stage-specific measures of geopolitical risk across the stages of the critical mineral supply chain, focusing on proven reserves, mining, and refining.[3] This is important because, proven reserves, mining activity and refining capacity are unevenly distributed across countries with differing levels of geopolitical risk. Because aggregate indicators of exposure to geopolitical risk do not distinguish between risk at different points of the supply chain, there is the potential of misidentifying the stages at which geopolitical bottlenecks are most binding. We find that refining consistently emerges as the dominant geopolitical bottleneck for both copper and lithium, which reflects the high concentration of global refining capacity in a small

---

[1] Copper and lithium are chosen because they capture two distinct energy-transition functions and market structures: copper is a broad-use "electrification" input critical for grids, wiring, motors and renewable integration, whereas lithium is a use-specific "energy-storage" mineral primarily demanded for batteries in EVs and grid storage. This pairing allows us to compare supply-stage geopolitical exposure across a diffuse, infrastructure-driven metal versus a concentrated, specification-sensitive battery mineral.

[2] Copper represents approximately half of the market share of critical minerals, reflecting its scale of use, while the market share of lithium is approximately 10-15 per cent depending on volatility in lithium prices (IEA, 2024).

[3] We abstract from the consumption stage of the supply chain. While consumption patterns shape demand pressures, they are not a direct source of geopolitical risk, which is primarily associated with the geographic concentration and political conditions of proven reserve ownership, mining, and refining.

number of countries; most notably, China. Once the refining-stage is recognized as the primary source of geopolitical risk in critical mineral supply chains, there are three major strategies that can be employed to mitigate this risk. Our second contribution is to examine each of these strategies applied to copper and lithium supply chains.

One potential strategy for reducing refining-stage risk is via geographical diversification of refining capacity, whereby producing countries expand domestic refining and absorb part of China's dominant share. Our results indicate that greater diversification of refining capacity would reduce refining-stage geopolitical risk for both copper and lithium. The reduction is substantially larger for lithium, reflecting its stronger dependence on China-dominated refining capacity and the greater potential for diversification gains.

Another strategy to mitigate short-run vulnerability to refining-stage risk is through stockpiling of refined minerals, which provides an intertemporal buffer against supply disruptions when refining capacity cannot adjust quickly. We construct forward-looking stockpiling estimates for copper and lithium based on the IEA's Announced Pledges Scenario (APS) and Net Zero Scenario (NZS). Assuming optimal conditions and excluding offsets from recycling or technological advancements, our estimates suggest that over the next 15 years there will be substantial supply-demand imbalances when strategic stockpiling projections are incorporated. We project the deficit in lithium supply to increase by a factor of 7.8 under APS and 9.8 under NZS, while copper shortages will grow by 4.6 and 6.1 times, respectively.

While strategic stockpiling can provide short-term buffering, the substantial supply-demand imbalances projected under APS and NZS suggest that it is insufficient on its own to mitigate longer-run refining-stage risks. A third complementary option for alleviating longer-run exposure to refining stage risk is through productivity-enhancing technological change, most notably investment in artificial intelligence (AI), which increases effective supply by lowering marginal cost and accelerating capacity expansion. We show that AI-driven productivity gains will be essential to overcome the shortfall in supply for both critical minerals, but particularly for lithium, to realize net zero targets.

Taken together, we contribute to the literature by providing a unified and policy-relevant framework for understanding where geopolitical risk arises in critical mineral supply chains, how it evolves under the energy transition, and how it can be mitigated through complementary instruments that operate over different time horizons.

2. Geopolitical risk and supply-side stabilization in critical mineral markets

Fig. 1 illustrates three key mechanisms affecting price and quantity dynamics in critical mineral markets: (a) a surge in demand driven by the clean energy transition; (b) a reduction in supply elasticity due to elevated geopolitical risk, for example, due to a trade war, economic sanctions or a terror attack; and (c) the role of refining diversification, strategic stockpiling, and productivity-enhancing AI investment in enhancing supply responsiveness.

Panel (a) captures the sharp increase in demand for critical minerals—such as lithium, and copper—driven by the global push toward clean energy technologies. The transition from internal combustion engines to electric vehicles, the expansion of renewable energy infrastructure, and grid electrification are among the key drivers of higher demand. The demand curve shifts outward from D_{Low} to D_{High}, reflecting greater mineral consumption in order to satisfy these drivers. Given the relatively inelastic nature of short-run supply (depicted by $S_{Low\,GPR}$), this demand shock leads to a pronounced price increase—from P_{Low} to P_{High}—with a moderate quantity response from Q_{Low} to Q_{High}. Consequently, Panel A illustrates the potential inflationary pressure and supply stress associated with rapid decarbonization.

In Panel (b), we illustrate the role of geopolitical risk. This panel shows how the supply-side response differs according to whether the geopolitical risk for copper and lithium is relatively low ($S_{Low\,GPR}$) or high ($S_{High\,GPR}$). Heightened geopolitical tensions—such as resource nationalism, trade restrictions, or regional conflicts—reduce the responsiveness of supply to price increases. Even with the same demand curve D_{Hig} , the equilibrium shifts to a higher price level $P_{High\,GPR}$, with only a modest increase in quantity $Q_{High\,GPR}$.

Panel (c) provides a stylized illustration of how alternative policy interventions could be employed as general stabilization mechanisms to increase effective supply elasticity. In Panel (c), the policy intervention is represented by a shift from a steeper ($S_{No\,policy}$), to a flatter ($S_{With\,policy}$) supply curve. With the same elevated demand curve, D_{High}, the policy intervention results in a lower equilibrium price and a greater supply response (depicted in the movement from $Q_{No\,policy}$ to $Q_{With\,policy}$). Strategic reserves—held either by governments or firms— constitute one such potential intervention, acting as a buffer against market shocks and effectively increasing the elasticity of supply. The other two potential strategies that we consider for mitigating supply chain risk, geographical diversification of refining capacity and productivity-enhancing AI investment, work in a similar way to strategic stockpiling. Geographical diversification of refining capacity could reduce supply rigidity by lowering concentration and chokepoint risks, while AI-driven productivity gains flatten the supply curve by reducing marginal production costs. With each of these stabilization measures, higher effective supply elasticity dampens price volatility in the presence of elevated demand.

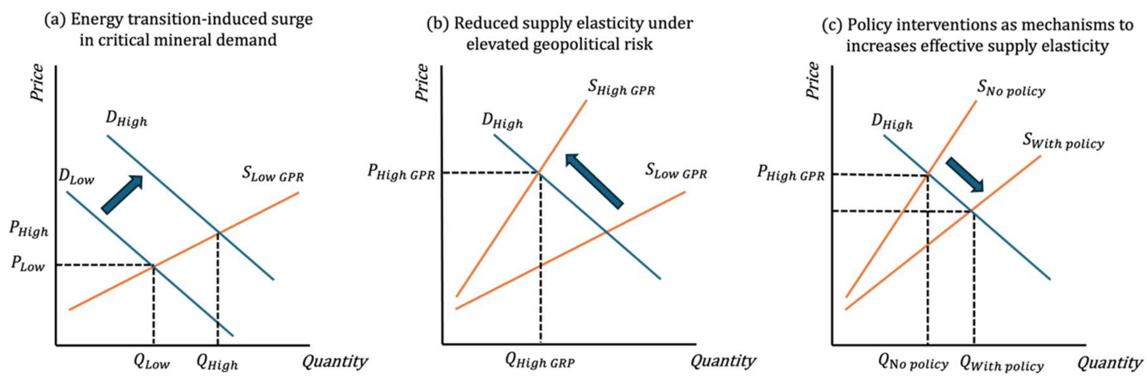


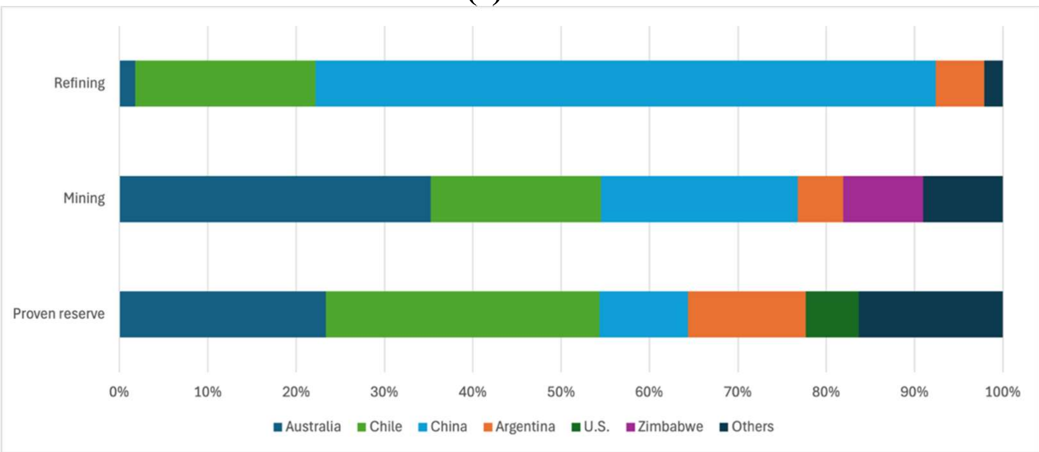
Fig. 1 | Critical mineral supply demand dynamics, geopolitical risk, and policy interventions. This figure illustrates three key mechanisms affecting price and quantity dynamics in critical mineral markets: (a) a surge in demand driven by the clean energy transition, (b) a reduction in supply elasticity due to elevated geopolitical risk, and (c) policy interventions, which act as general stabilization mechanisms that enhance the responsiveness of supply. Three complementary policy interventions are geographical diversification of refining capacity, strategic stockpiling, and productivity-enhancing AI investment, each of which are expected to operate through similar mechanisms in flattening the supply curve and increasing effective supply elasticity.

2.1. Geographical diversification as a stabilization mechanism

Fig. 2 shows global shares of proven reserves, mining and refining in 2024. Copper's proven reserves are relatively evenly geographically distributed, with significant shares in Chile, Australia and Peru, while lithium reserves are highly concentrated in Chile, Australia, and Argentina. In terms of mining**,** Australia dominates lithium output (around 35 percent), while copper extraction is more balanced, with Chile, Peru, and the Democratic Republic of the Congo (DRC) playing major roles. The most striking contrast appears in refining**,** where China controls over 70 percent of global lithium refining**,** reflecting its dominance in battery raw mineral supply. Copper refining is also China-centric (around 44 per cent), but to a lesser extent, with some capacity in countries like Chile and 'other' countries.

The macroeconomic fragility framework posits that economic systems become increasingly vulnerable when small shocks can trigger large and discontinuous effects due to inherent interdependencies (Acemoglu & Tahbaz-Salehi, 2025). Applying this to critical minerals, disruptions arising along the stages of the supply chain—whether in access to proven reserves, mining/extraction or refining capacity—can propagate across the system, amplifying price volatility and investment uncertainty. Each stage acts as a potential chokepoint. For example, a geopolitical shock affecting refining in a country in which copper or lithium refining is highly concentrated (e.g., China) or a sudden regulatory shift in a major producer (e.g., Australia and Chile) can destabilize the entire supply network. As Kang et al. (2025) note, these fragility mechanisms are particularly acute in critical mineral markets where substitution is limited, and geographic concentration is high.

(a) Lithium



(b) Copper

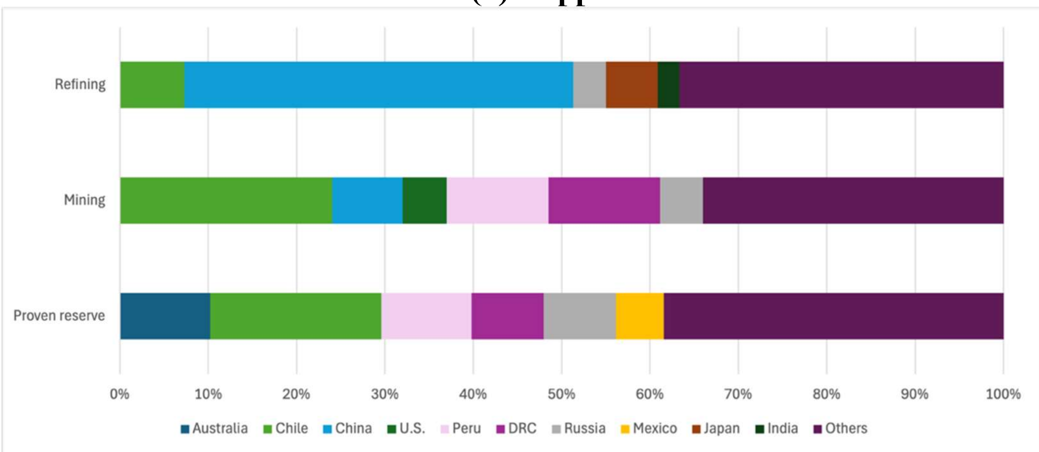


Fig. 2 | Global shares of proven reserves, mining and refining in 2024 (as a percentage of global output). This figure presents the distribution of global shares for lithium and copper across the three key stages of the supply chain in 2024: proven reserves, mining and refining.

One option for mitigating supply chain risk in copper and lithium is geographical diversification at the relevant chokepoint. Whether the chokepoint is at the proven reserves, mining or refining stages largely depends on the geopolitical risk in those countries in which the concentration in each stage is high. At the proven reserves and mining stages, diversification is dependent on finding more reserves of copper and lithium and mining them in countries other than Australia and parts of Africa and Latin America in which concentration is already high. At the refining stage, this would involve diversification away from China.

2.2. Stockpiling as a stabilization mechanism

Stockpiling resources or commodities is a strategic policy tool employed by governments to stabilize markets during periods of supply disruption, price volatility, or geopolitical uncertainty. The core principle rests on the countercyclical release and accumulation of reserves—governments accumulate stocks during periods of surplus or low prices and release them during supply shocks or demand surges to mitigate extreme price fluctuations and ensure continuity of supply (Newbery & Stiglitz, 1981; Wright & Williams, 1982). This mechanism enhances market predictability, discourages speculative hoarding, and provides a buffer against unforeseen global events such as wars, pandemics, or trade embargoes. Recent applications in critical minerals have been linked to national security and energy transition goals, as these materials are essential for low-carbon technologies and are often sourced from geopolitically concentrated regions (Saadaoui, et al., 2025). Strategic stockpiles not only serve to stabilize domestic markets but also enhance bargaining power in international negotiations and support industrial policy planning (OECD 2023).

Stockpiling is most effective when implemented at the refined stage of the supply chain. While proven reserves and raw ores determine long-run availability, disruptions to refining capacity directly constrain the flow of usable inputs to downstream industries. Refined minerals are immediately deployable in production and therefore provide an effective buffer against short-run geopolitical supply disruptions. By contrast, stockpiling upstream resources offers limited protection, as processing constraints, energy requirements and technological bottlenecks prevent rapid conversion into usable inputs during crises.

Fig. 3 demonstrates the role of strategic stockpiling in mitigating the effects of geopolitical risk on the supply of copper and lithium. As geopolitical risk increases**,** the probability of disruption to supply rises sharply—especially when stockpiling is low or absent. This reflects the vulnerability of critical mineral supply chains to political instability, export bans, conflict, and other geopolitical disturbances in producing regions.

However, as strategic stockpiling increases**,** the effective exposure to geopolitical risk is reduced. The surface drops steeply along the stockpile dimension, particularly in high-geopolitical areas, indicating that even modest stockpiles (e.g., 50–75% of annual production) can significantly mitigate supply chain risks. This effect is most pronounced in scenarios of elevated geopolitical tension, where stockpiling acts as a stabilizing buffer, smoothing price volatility and protecting downstream industries from supply shocks.

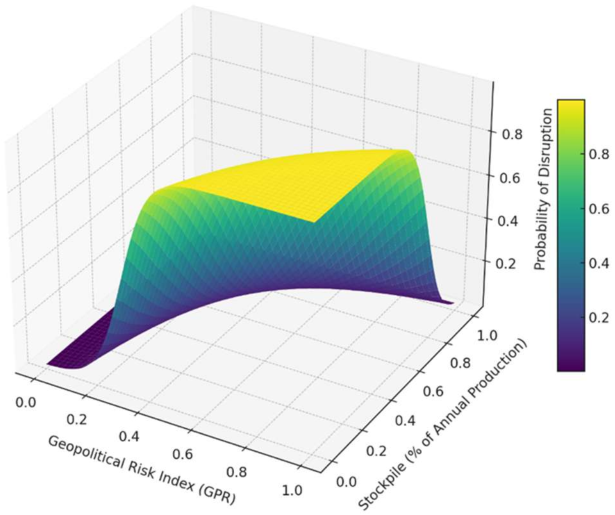


Fig. 3 | Geopolitical risk, refined mineral stockpiling and the probability of chain supply disruption. This figure presents a three-dimensional representation of how the probability of mining production disruption varies with changes in geopolitical risk and the level of strategic stockpiling. The x-axis measures the Geopolitical Risk Index (GPR)**,** which ranges from 0 (low risk) to 1 (high risk), while the y-axis represents the size of the strategic stockpile**,** expressed as a percentage of annual mineral production. The z-axis shows the probability of disruption**,** capturing the likelihood that geopolitical shocks result in halted or delayed production.

2.3. Productivity-enhancing AI investment as a stabilization mechanism

A third potential stabilization mechanism to mitigate supply chain risk is through productivity gains. There are multiple avenues through which AI is expected to deliver productivity gains across the supply chain from exploration through to refining (Vespignani & Smyth, 2024).

At the exploration stage, AI techniques, such as drone-based photogrammetry and remote sensing, enable automation of mineral mapping, making it easier to identify new deposits (Ali & Frimpong, 2020; Jooshaki et al, 2021).

At the mining stage, AI can improve productivity in several ways. AI techniques, particularly random forest, can be used to improve predictive recovery in copper (Flores et al., 2020). Machine learning methods have been used to improve recovery of lithium from unconventional water sources (Xu et al., 2024). One of the biggest challenges at the mining stage is that blasting and drilling efficacy depends on the rock fragmentation. AI can be used to predict rock fragmentation and provide real-time evaluation of drilling performance that improves efficiency (Ali & Frimpong, 2020). Automated drilling can be fitted with sensors that target specific ores that reduce extraction time (Onifade et al, 2023). AI can also be useful in reducing the prevalence of environmental disasters (You et al, 2021), which is particularly relevant to lithium mining from salt deserts or solar in the lithium triangle in Argentina, Bolivia and Chile, which has increased the prevalence of droughts (Ortiz, 2021).

At the refining stage, AI has been shown to enhance efficiency in copper and lithium production and reduce waste, including facilitating the recovery of useful secondary minerals from waste materials (Kenzhaliyev et al., 2025; Masouleh et al, 2024). AI is also revolutionising production lines in refineries, improving efficiency. For example, traditional manual inspections in copper tankhouses are labor-intensive and error prone. Recent developments in machine learning enable real-time defect detection, quality control, and process optimization in copper tankhouses (Howald, 2025).

Across all stages of the critical mineral supply chain, AI is expected to automate many functions in which labour intensive roles are replaced with capital intensive high-level machine intelligence, delivering productivity gains (Hyder et al, 2019).

3. Data and methods

In this section, we first describe how we calculated geopolitical risk for copper and lithium at each supply-side stage of the supply chain. We then proceed to describe the methods used to estimate diversification of refining capacity, strategic stockpiling and productivity enhancing AI investment as ways to mitigate refining concentration as a stage-specific supply chain risk.

3.1. Method to calculate geopolitical risk at each stage of the supply chain

Vespignani and Smyth (2024) constructed non-technical risk indicators using a proven-reserve-based weighting scheme combined with the Fraser Institute's (2022) Investment Attractiveness Index, which they applied uniformly across the full mineral supply chain. We extend their approach to calculate geopolitical risk at each supply-side stage of the lithium and copper supply chain: ie. proven reserves, mining and refining. Let $GPR_{m,c,t}^{s}$ denote the geopolitical risk score of country c and mineral m at time t in supply-side stage s.

$$s \in S = \{proven\ reserve, mining, refining\}$$

We define:

1. Geopolitical risk of critical mineral m in country c in time t in the proven reserves stage:

$$GPR_{m,c,t}^{reserve} = \omega_{m,c,t}^{reserve} \times GPR_{c,t} \qquad (1)$$

Where $\omega_{m,c,t}^{reserve}$ is the share of global proven reserves of mineral m located in country c in time t. $GPR_{c,t}$ represents the geopolitical risk score of country c in time t.

We define the total geopolitical risk score for critical mineral m in time t at the proven-reserves stage as:

$$GPR_{m,t}^{reserve} = \sum_{c=1}^{i} GPR_{m,c,t}^{reserve} \qquad (2)$$

c =1,…,i, represents the set of all countries with proven reserves of mineral m.

2. Geopolitical risk of critical mineral m in country c in time t in the mining stage:

$$GPR_{m,c,t}^{extraction} = \omega_{m,c,t}^{extraction} \times GPR_{c,t} \qquad (3)$$

where $\omega_{m,c,t}^{extraction}$ is the share of global mine production of mineral m in time t in country c.

We define the total geopolitical risk score for critical mineral m in time t at this stage as:

$$GPR_{m,t}^{extraction} = \sum_{c=1}^{j} GPR_{m,c,t}^{extraction} \qquad (4)$$

c =1,…,j, represents the set of all countries with extraction capacity for mineral m.

3. Geopolitical risk of critical mineral m in country c in time t in the refining stage:

$$GPR_{m,c,t}^{refining} = \omega_{m,c,t}^{refining} \times GPR_{c,t} \qquad (5)$$

where $\omega_{m,c,t}^{refining}$ is the share of global refining capacity for mineral m in country c in time t.

We define the total geopolitical risk score for critical mineral m in time t at the refining stage as:

$$GPR_{m,t}^{refining} = \sum_{c=1}^{k} GPR_{m,c,t}^{refining} \qquad (6)$$

c =1,…,k, represents the set of all countries with refining capacity for critical mineral m.

Each ω term is a stage-specific weight, such that the sum of all country shares for a given stage equals 1:

$$\Sigma\, \omega^{s}_{m,c,t} \;=\; 1 \qquad (7)$$

Data on proven reserves of copper and lithium are sourced from the U.S. Geological Survey's Mineral Commodity Summaries. Data on mining and refining of copper and lithium are sourced from the International Energy Agency (IEA) (2025) Critical Minerals Dataset. The geopolitical risk data by country are from Caldara and Iacoviello (2022), who construct a monthly index of geopolitical risk based on automated text analysis of international news.

3.2. Method to construct alternative refining share diversification scenarios

This section outlines the construction of counterfactual scenarios in which China's dominant refining share for copper and lithium is exogenously reduced and reallocated to other countries.

Let $Refine_{t,CN}$ denote China's share of global refining capacity at time t. We consider a set of diversification scenarios indexed by the parameter $a \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$, which capture the proportional reduction in China's refining share, relative to its baseline level. Under each scenario, China's diversified refining share is defined as:

$$Refine^{diversify}_{t,CN} = \; Refine_{t,CN} \times (1 - a) \qquad (8)$$

The reduction in China's refining share is, therefore, given by:

$$Diff_{t} = Refine_{t,CN} - Refine^{diversify}_{t,CN} \qquad (9)$$

We assume that the reduced refining share is absorbed by other countries in proportion to their existing production capacity. Let $Product_{t,k}$ denote country k's share of global copper and lithium production at time t, where $k \neq CN$. To ensure that the reallocation preserves the adding-up constraint, production shares are renormalised after excluding China:

$$Product^{(-CN)}_{kt,} = \frac{Product_{t,k}}{(1 - Product_{t,CN}}), \quad k \neq CN \qquad (10)$$

By construction,

$$\sum_{k \neq CN} Product_{kt,}^{(-C\ \ )} = 1 \qquad (11)$$

The diversified refining share of country k is then given by:

$$Refine_{t,k}^{diversify} = Refine_{t,k} + Diff_t \times Product_{kt,}^{(-CN)}, \quad k \neq CN \qquad (12)$$

This reallocation mechanism ensures that total global refining shares remain unchanged while allowing China's refining dominance to decline exogenously. This approach captures a stylized diversification pathway in which copper and lithium producing countries expand domestic refining capacity and progressively absorb refining activity previously concentrated in China. These counterfactual refining-share configurations form the basis for evaluating refining-stage geopolitical risk under alternative China refining share scenarios.

3.3. Method for constructing refined stockpiling scenarios for copper and lithium

This section develops a scenario-based framework for refined mineral stockpiling. We model the optimal inventory strategy for refined critical minerals as a dynamic optimization problem. The goal is to minimize expected financial losses from geopolitical supply disruptions, while accounting for the cost of maintaining stockpiling.

We begin by considering a stylised dynamic optimization problem in which a social planner chooses the stock level of refined minerals to minimise the expected discounted cost of holding inventory and supply disruptions. The objective function is given by:

$$\min_{\{S_t\}} E_0 \left[\sum_{t=0}^{T} \beta^t (C_s(S_t) + I_{\{shock_t\}} \times L_t(S_t)) \right] \qquad (13)$$

Where S_t denotes the stock of refined minerals at time t, $C_s(S_t)$ is the cost of storage (assumed to be convex, and to include warehousing and depreciation costs), and $I_{\{shock_t\}}$ = is an indicator variable equal to one when a geopolitical supply disruption occurs and zero otherwise. The term $L_t(S_t)$ captures the financial loss associated with insufficient refined inventories during a disruption and is assumed to be decreasing in S_t.

Stockpiling is justified when the risk-adjusted expected financial loss from supply disruption is greater than the cost of maintaining inventory. The first-order condition of this problem implies that stockpiling is optimal when the marginal cost of storage does not exceed the marginal reduction in expected disruption losses:

$$\frac{dC_s(S_t)}{dS_t} \leq P(shock_t) \cdot \frac{dL_t(S_t)}{dS_t} \quad (14)$$

At the optimum, the stockpile level S_t^* satisfies:

$$\frac{dC_s(S_t^*)}{dS_t} = P(shock_t) \cdot \left|\frac{dL_t(S_t^*)}{dS_t}\right| \quad (15)$$

This condition highlights the core trade-off underpinning refined stockpiling decisions: inventories are accumulated up to the point at which the marginal storage cost equals the expected marginal benefit of mitigating supply disruptions.

We use this optimality condition to motivate a policy-relevant and transparent stockpiling rule. In practice, strategic stockpiling decisions are typically implemented through inventory targets rather than continuous optimisation. We, therefore, assume that stockpiles accumulate over time as a fixed proportion of contemporaneous demand. We calculate stockpiling accumulation over time using a simple discrete-time model.

Stockpiling accumulation at time t is defined as:

$$Stockpile_t = Stockpile_{\{t-1\}} + \alpha \times Demand_t \quad (16)$$

where α is the target stockpiling ratio (for example, 0.1 corresponds to stockpiling an amount equivalent to 10 per cent of annual demand), and $Demand_t$ denotes total demand for the refined mineral in period t. This recursive formulation implies that inventories increase proportionally with market size and reflect the scale of potential exposure to supply disruptions.

Cumulative stockpiling over a time horizon T can be expressed as:

$$Stockpile_T = \sum_{t=1}^{T}(\alpha \times Demand_t) \quad (17)$$

If demand grows over time at a constant growth rate g, such that

$$Demand_t = D^0(1 + g)^{t-1} \quad (18)$$

Then cumulative stockpiling becomes:

$$Stockpile_T = \alpha \times D^0 \times \frac{[(1+g)^T - 1]}{g} \qquad (19)$$

This formulation links stockpiling requirements directly to demand growth and highlights how longer adjustment horizons amplify the need for refined inventories.

To anchor the stockpiling scenarios in observed practices, we draw on evidence from existing strategic reserves. Copper stockpiles represent 37 per cent of annual consumption, equivalent to around 95 days of demand coverage (S&P Global Market Intelligence, 2024). While lithium stockpiling data is less clear, Pedersen and Jaswal (2024) estimate that lithium inventories account for roughly 21 per cent of total consumption, or about 51 days of demand as of 2024. The data on stockpiles are sourced from S&P Global's *Metals & Mining* database.

Drawing on the historical precedent of oil stockpiling, most notably the IEA benchmark of maintaining reserves equivalent to 90 days of net imports, we apply a similar logic to critical minerals. However, unlike oil, which can typically be developed within an average lead time of around four years, copper and lithium projects often require 12–15 years to progress from exploration to extraction. This substantially longer supply response suggests that strategic stockpiles of refined critical minerals must be considerably larger to offset prolonged development timelines and heightened exposure to geopolitical shocks.

Accordingly, we assume that the volume of net imports to be stockpiled is proportional to the average time required for a project to transition from exploration to extraction. This proportional approach provides a pragmatic framework for adjusting stockpiling targets to reflect the structural supply constraints inherent in critical mineral markets.

3.4. Calculating productivity growth via AI investment

This section outlines the methodology used to quantify potential supply gains from productivity-enhancing technological change, with a particular focus on the role of AI. Productivity-enhancing investments operate through a fundamentally different channel from either refining diversification or strategic stockpiling. Rather than reallocating existing capacity or buffering supply disruptions intertemporally, AI adoption increases effective supply, thereby relaxing binding supply constraints over the long run.

We treat productivity growth as an exogenous, technology-driven augmentation of baseline supply trajectories. This approach is deliberately reduced-form: it captures the aggregate supply implications of AI-enabled efficiency gains without modelling firm-level adoption decisions or endogenous technological change. The objective is not to forecast precise outcomes, but to assess the potential to meet supply shortfalls of copper and lithium, which can be met under plausible productivity growth scenarios.

Let S_t^{base} denote the baseline projected primary supply of a given mineral at time t, as reported by the International Energy Agency under the APS or the NZS. These projections incorporate anticipated capacity expansions and policy commitments, but do not explicitly account for additional productivity gains arising from accelerated AI adoption beyond current trends. We model AI-enabled productivity growth as a constant exponential increase in effective supply relative to the baseline trajectory. Augmented supply in period t is defined as:

$$S_t^{AI} = S_t^{base} \times (1 + \gamma)^{t-t_0} \quad (20)$$

Where $\gamma \in \{0.03, 0.04, 0.05\}$represents alternative annual productivity growth rates attributable to AI technologies, and t_0 denotes the initial projection year. These values are chosen to reflect conservative to moderately ambitious assumptions commonly discussed in the literature on digital transformation and mining productivity. The cumulative supply gain attributable to AI-driven productivity growth by time T is given by:

$$\Delta S_T^{AI} = S_T^{AI} - S_t^{base} \quad (21)$$

This formulation implies that productivity gains compound over time, yielding increasingly large supply effects in later periods.

4. Results and discussion

4.1. Supply-side stage specific geopolitical risk in copper and lithium

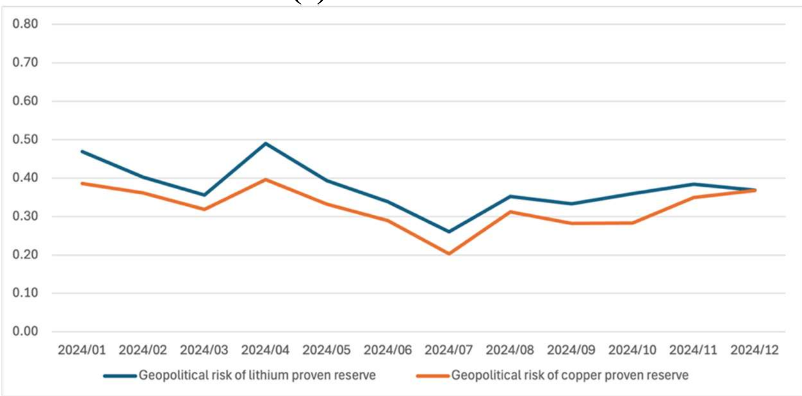
Fig. 4(a)-(c) presents the monthly geopolitical risk indices, defined as weighted averages of the geopolitical risk scores of the countries involved in each stage of the supply chain for lithium and copper across proven reserves, mining and refining for the period from January to December 2024. Fig. 4(a) shows that lithium consistently exhibits a relatively higher level of geopolitical risk than copper at the proven reserve stage. This reflects the fact that copper's proven reserves are more diversified, with larger shares of global reserves located in countries with relatively low geopolitical risk, such as Chile, Australia and Peru. In contrast, Fig. 4(b) shows that copper consistently exhibits relatively higher geopolitical risk than lithium at the mining stage. This is because global lithium extraction is highly concentrated in Australia, a country with relatively low geopolitical risk. Fig. 4(c) indicates that the refining stage has the highest risk levels for both critical minerals, with their refining risk peaking at 0.75 in April 2024. Country-specific geopolitical risk scores are detailed in Appendix A.

As illustrated in Fig. 4(a)-(c), the geopolitical risks of lithium and copper are strongly correlated, which can be attributed to the fact that many of the same countries are prominent across each of the three stages of the supply. Furthermore, geopolitical risk is globally correlated due to the outsized influence of major powers—particularly China and the U.S.—on global risk dynamics (Caldara & Iacoviello, 2022). The rise in geopolitical risk in April 2024 is associated with a terrorist attack in Sydney, resulting in Australia's geopolitical risk index rising sharply from 0.15 to 0.31 (Prosser, 2024). A second notable rise in geopolitical risk occurs in November 2024 following the election of Donald Trump as U.S. President (Smith & Pengally, 2024). Trump's return to office signalled potential shifts in both domestic and foreign policy, leading to increased uncertainty in global markets and diplomatic relations (Othman, 2024). This event notably affected China's geopolitical risk, which rose from 0.77 to 0.99 in response to anticipated trade and strategic tensions. It is also important to note that not all geopolitical risks uniformly affect each supply chain stage, highlighting the need to separate out each of the stages. For example, during August 2024, the geopolitical risk associated with lithium production remained relatively stable, reflecting the political stability of major producing countries such as Australia Chile, Peru, and Argentina.[4]

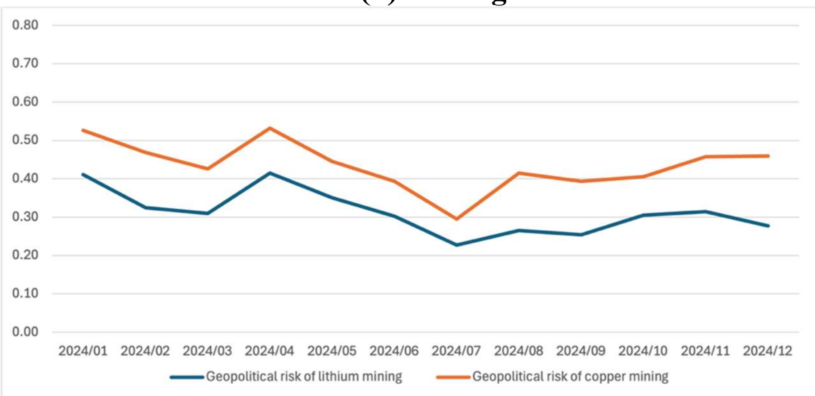
Fig. 4(d) highlights that that downstream processing represents the most vulnerable segment of the supply chain for copper and lithium, largely due to the high concentration of global refining capacity for these minerals in China, as evident in Fig. 2, where geopolitical risk is relatively elevated. Overall, the figure underscores that refining constitutes the key geopolitical bottleneck in the supply-side critical mineral supply chains.

[4] See Appendix A for more details.

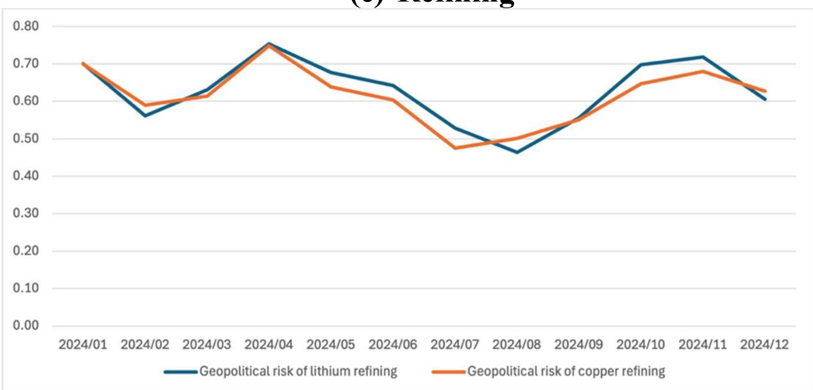
(a) Proven Reserves



(b) Mining



(c) Refining



(d) Global geopolitical risk by stage: 2024 average

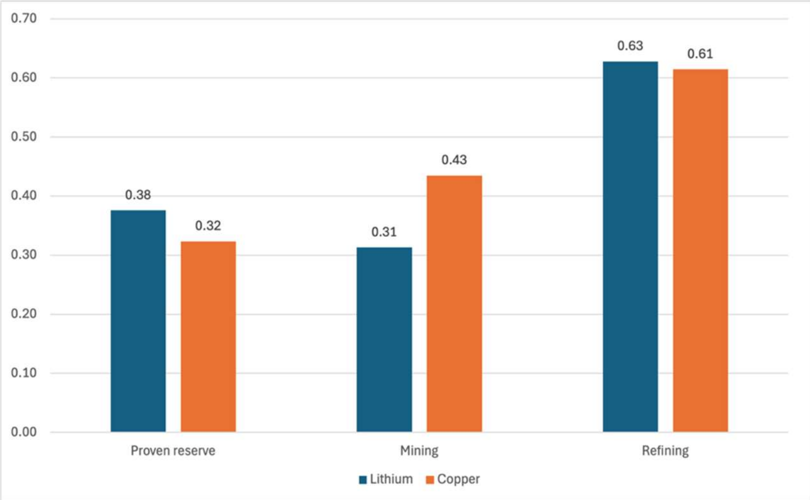


Fig. 4 | Geopolitical risk exposure across the lithium and copper supply chains). Panels (a) to (c) present monthly geopolitical risk indices for lithium and copper from January to December 2024, disaggregated by the three key stages of their supply chains. Panel (a) shows geopolitical risk associated with proven reserves, panel (b) geopolitical risk associated with mining, and panel (c) geopolitical risk associated with refining. Panel **(**d) shows the global average geopolitical risk in 2024 across each stage for lithium and copper.

4.2. Refining-stage geopolitical risk under alternative China refining share scenarios

In this section we examine geographical diversification as a way to mitigate supply stage geopolitical risk for copper and lithium. We focus on diversifying refining risk, given that our results in Fig. 4(d) indicate that the refining stage exhibits systematically higher geopolitical risk than both proven reserves and mining for copper and lithium.

Fig. 5 explores a counterfactual diversification scenario designed to alleviate refining-stage geopolitical risk. Specifically, we consider cases in which mining countries expand domestic refining capacity and progressively absorb part of China's refining share. Under this reallocation, global geopolitical risk at the refining stage declines monotonically as China's share is reduced. Importantly, the magnitude of risk mitigation differs across minerals. Lithium exhibits a substantially larger reduction in geopolitical risk than copper, reflecting its stronger initial dependence on China-dominated refining capacity and the greater scope for diversification gains. By contrast, copper's more geographically dispersed refining base implies that the marginal benefits from the same reallocation are more limited. These results highlight refining diversification as an important way for reducing geopolitical vulnerability, with particularly pronounced gains for lithium supply chains.

One practical proviso to this conclusion is that refining is environmentally costly. As such, there may be political opposition to developing copper and lithium refineries in some countries which mine large quantities of these minerals (Temper et al, 2020). For example, socioenvironmental justice concerns have been cited as a bar to increasing lithium refining capacity in Australia (Hine et al., 2023). This does suggest, however, that there may be more potential to expand copper refining in countries, such as DRC, which score lower on Freedom House measures of civil liberties and political rights and in which political opposition to refining is likely to be less. Supporting this conclusion is evidence that the DRC has increased copper refining in recent years, such as the Komoa-Kakala copper smelter.

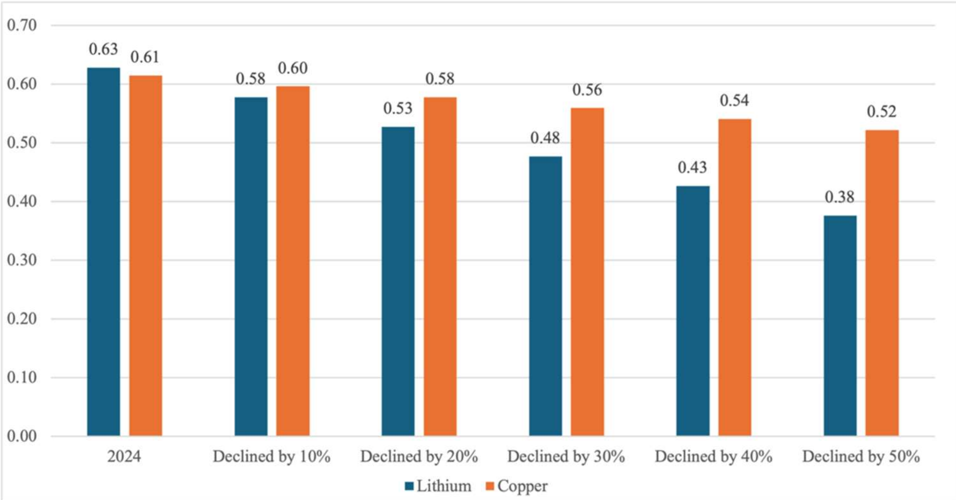


Fig. 5 | Refining-Stage Geopolitical Risk under China Refining Share Reduction Scenarios. This figure illustrates refining-stage geopolitical risk for lithium and copper under alternative scenarios where China's refining share declines by 10-50% relative to its 2024 level. Higher values indicate higher geopolitical risk.

4.3. Stockpiling scenarios for copper and lithium based on IEA pathways (2023-2040)

The effectiveness of stockpiling as a mechanism for mitigating supply disruptions depends critically on the scale of refined inventories, which we express in terms of days of refined supply. As formalised in Section 3.3, refined stockpiling operates as an intertemporal buffer: inventories accumulated during normal periods reduce expected losses when supply shocks materialise but require additional supply upfront to build and maintain stockpiles. Consequently, the implications of stockpiling are inherently dynamic and interact with projected demand growth. Stockpiles covering only a few days of consumption offer limited buffering capacity, whereas inventories sufficient to meet demand for several months can significantly flatten the supply curve as depicted in Fig.1(c) and mitigate price volatility. Accordingly, the effectiveness of stockpiling as a mechanism to increase supply responsiveness is a function of both the scale and duration of copper and lithium reserves.

In this section, we integrate the stockpiling accumulation rule derived in Section 3.3 with the IEA's, Announced Pledges Scenario (APS) and Net Zero Scenario (NZS) for the period 2023–2040. Importantly, the IEA's baseline projections do not explicitly incorporate strategic stockpiling. Hence, we augment projected demand by adding the additional refined supply required to accumulate strategic inventories under alternative stockpiling benchmarks.

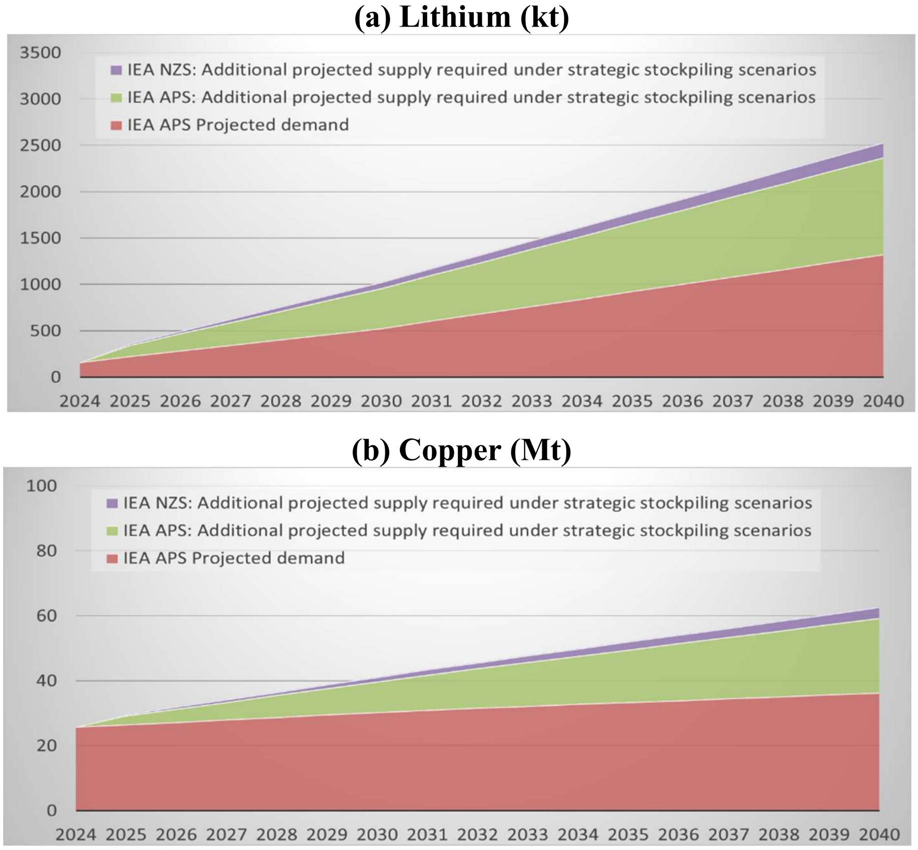


Fig. 6 | Projected supply requirements for lithium and copper under IEA APS and NZS, including global strategic stockpile accumulation. This figure illustrates the projected supply trajectory for lithium and copper under the IEA's APS pathway, together with the additional supply requirements generated by the inclusion of strategic stockpiling under both the APS and NZS. The red area represents baseline supply required under APS, while the green and purple areas reflect the additional supply needed to build strategic reserves under APS and NZS, respectively.

The two panels in Fig. 6 illustrate projected lithium and copper demand under the APS, together with the additional refined supply required to build strategic stockpiles under the APS and NZS. In Fig. 6(a), we show demand for lithium under APS exhibits a rapid, near-exponential, growth trajectory, with projected consumption increasing from under 165 kt in 2025 to over 1300 kt by 2040. Incorporating stockpiling substantially shifts this trajectory upward, to 2,374 kt and 2,531 kt under the APS and NZS pathways, respectively, by 2040. This amplification reflects the interaction between rapid demand growth and the strategic stockpiling accumulation rule: as demand expands, the volume of refined inventories required to maintain a fixed number of days of supply increases proportionally.

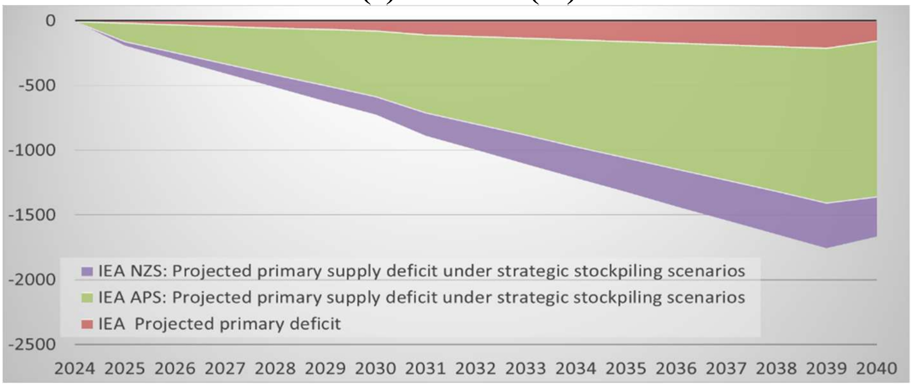
Fig. 6(b) presents the corresponding results for copper. In contrast to lithium, baseline copper demand grows more gradually, increasing from around 26 Mt in 2025 to just over 36 Mt by 2040 under the APS pathway. The inclusion of strategic stockpiling still raises cumulative supply requirements to approximately 59 Mt under APS and 63 Mt under NZS by 2040, but the relative impact is smaller than for lithium. The smaller relative impact on copper compared with lithium is due to the broader availability of copper, its more established recycling infrastructure, and lower volatility in its supply-demand dynamics, which collectively reduce the marginal benefit of additional inventories in mitigating expected losses.

In Fig. 7, we show the projected shortfall for copper and lithium, Fig. 7(a) reveals a widening supply deficit for lithium from 2025 to 2040. The red shaded area reflects the baseline IEA projected deficit (without additional stockpiling). When stockpiling is included, the deficit expands significantly under APS (green area) and even more steeply under NZS (green and purple areas). By 2040, the lithium supply shortfall reaches nearly 2,000 kt under NZS, underscoring the scale of potential unmet demand under optimistic policy scenarios. This result highlights that stockpiling, while reducing vulnerability to disruptions, places substantial pressure on supply when demand growth is rapid and supply responsiveness is limited.

In Fig. 7(b), copper's projected supply gap follows a similar pattern, though at a larger scale. While stockpiling amplifies projected shortfalls under both APS and NZS, the increase under APS is relatively more moderate. By 2040, the projected copper deficit is approximately 47 Mt under the NZS pathway, indicating significant pressure on supply chains.

To assess the sensitivity of these cumulative supply deficit results to the scale of strategic inventories, in Appendix B, Fig. B1 reports outcomes under alternative stockpiling benchmarks equivalent to 255 days (70% of annual production) and 474 days (130% of annual production) of consumption by 2040. Consistent with the accumulation rule in Section 3.3, higher stockpiling targets translate into proportionally larger cumulative supply requirements and wider projected supply deficits. In Fig. B1(a) and (b), for lithium, when compared with alternative stockpiling volumes, the deficit is lower under a 255-day scenario, rising by factors of 5.2 under APS and 6.85 under NZS, and more severe under the 474-day scenario, with supply shortfalls increasing by 10.4 under APS and 12.8 under NZS. Fig. B1 (c) and (d) present the projected supply deficits for copper under the APS and NZS, respectively. Under a 255-day stockpiling scenario, copper shortfalls increase by factors of 2.9 (APS) and 4.2 (NZS), while under a more extensive 474-day scenario, the deficits rise further—by 6.3 (APS) and 8.1 (NZS). These responses reflect the interaction between sustained demand growth and the need to maintain inventory coverage over longer time horizons.

(a) Lithium (kt)



(b) Copper (Mt)

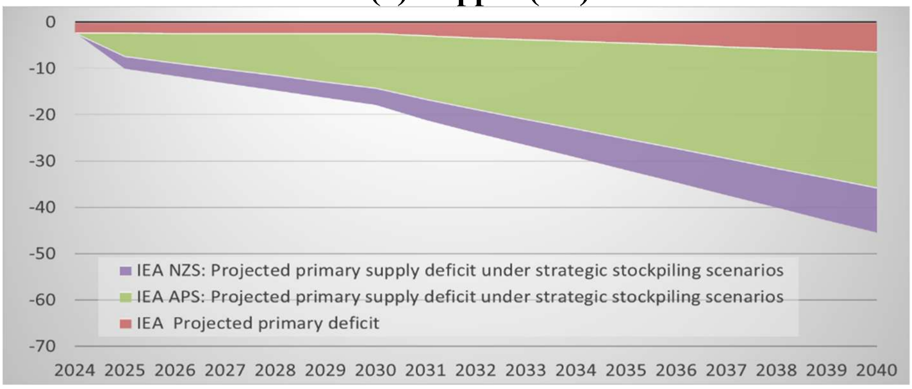


Fig. 7 | IEA current, APS, and NZS scenarios of supply shortfall of lithium and copper including global strategic stockpile. This figure projects supply-demand imbalances for lithium (top panel) and copper (bottom panel) under three IEA scenarios: the base demand, APS, and NZS, each adjusted to include global strategic stockpiling requirements. The red area represents baseline primary deficit required under APS, while the green and purple areas reflect the additional deficit if strategic reserves are built under APS and NZS, respectively.

Table 1 summarises the total refined supply required to balance global demand by 2040 under each stockpiling scenario. The first row shows the primary supply projected by the IEA without additional stockpiling: 1,326 kt for lithium and 36.38 million tonnes for copper. Subsequent rows reflect the increased supply required to accommodate strategic reserves equivalent to 255, 365, and 474 days of consumption**.** Under the 365-day stockpiling benchmark, our projections indicate that lithium supply must increase to 2,373 kt (APS) and 2,530 kt (NZS), while copper must rise to 59.3 Mt (APS) and 62.8 Mt (NZS). Lower (255 days) and higher (474 days) stockpiling scenarios reduce or intensify the required supply, underscoring the significant implications of stockpiling strategies on long-term supply planning for each of copper and lithium

	Lithium (kilotons, kt)		Copper (million tonnes, Mt)	
Primary supply (IEA)	1326		36.38	
Supply required under stockpiling scenarios to balance market				
	APS	NZS	APS	NZS
365 (Benchmark)	2373	2530	59.3	62.8
255	1975	2073	48.39	50.2
474	2771	2988	70.2	75.3

Table 1 | Projected supply requirements to balance global demand by 2040 under alternative stockpiling scenarios. This table summarizes the projected supply requirements for lithium and copper needed to balance global demand by 2040 under various strategic stockpiling scenarios, as defined by the APS and NZS.

4.4. The role AI in mitigating the supply shortage

The need for stockpiling to mitigate geopolitical risk considerably adds to the projected shortfall in copper and lithium by 2040 under IEA APS and NZS trajectories, raising the question of how the supply-demand imbalance will be overcome? In this section we explore the potential for the projected shortfall in copper and lithium production—driven by both baseline demand and additional demand arising from strategic stockpiling for market stabilization— to be offset through AI-enabled productivity gains.

Fig. 8 shows the potential supply gains from productivity growth via AI investment for lithium until 2040. Compared to the baseline projection without AI productivity gains, the 3 per cent, 4 per cent, and 5 per cent exponential annual growth scenarios yield supply increases of approximately 250 kt, 400 kt, and 550 kt, respectively under APS. Under the NZS, supply gains are even greater, rising by approximately 300 kt, 500 kt, and over 650 kt under the same growth assumptions. These AI-driven productivity gains significantly narrow the projected supply gap, particularly under the more ambitious net-zero trajectory.

Fig. 9 shows the corresponding AI projections for copper. It suggests that by 2040, potentially copper supply could increase under AI-driven productivity growth, though to a lesser extent than lithium. Relative to the baseline, the 3 per cent, 4 per cent, and 5 per cent productivity growth scenarios lead to increases of approximately 4 Mt, 6 Mt, and 8 Mt under APS. Under the NZS, supply gains are 5 Mt, 7 Mt, and nearly 9 Mt, respectively.

These conclusions are based on the assumption that AI continues to evolve. Most expect that it will. For example, in one survey of machine learning researchers, the consensus was that AI will perform many functions better than humans by 2030 (Grace et al., 2018). However, meta-studies suggest that some forecasts of AI potential may be overly optimistic due to data leakage and lack of reproducibility (Kapoor & Narayan, 2023; Rosenblatt et al, 2024). There are specific problems inhibiting the use of AI in critical minerals. These include the relative lack of high quality training data; that there is a skills deficit in the sector, meaning that there are not enough people who are trained in the use of AI; and that mining for critical minerals frequently occurs in remote locations and in conditions not well suited to the deployment of AI (see Vespignani & Smyth, 2024 for a discussion of these points).

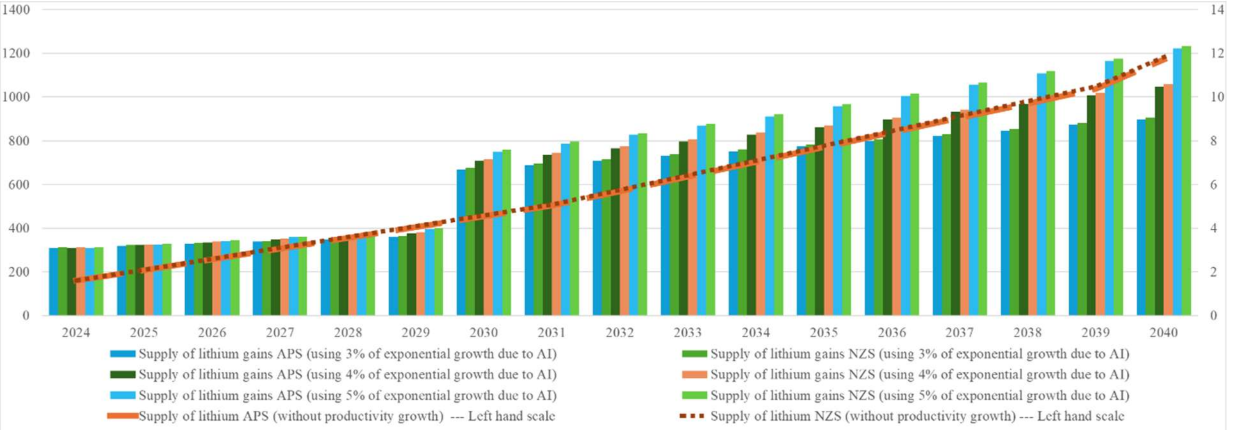


Fig. 8 | Supply gains from productivity growth via AI investment for lithium. This figure illustrates projected lithium supply under the APS and NZS, incorporating different assumptions about annual production gains enabled by AI. The right-hand y-axis (measured in tonnes) represents the total supply, while the left-hand y-axis applies to the baseline APS and NZS supply trajectories without productivity growth, shown as dashed lines. Bar segments represent lithium supply projections with 3 per cent, 4 per cent and 5 per cent annual exponential productivity growth due to AI, applied to both APS (blue, dark green, and light blue bars) and NZS (brown, orange, and light green bars) trajectories, respectively. The dotted lines show lithium supply in the absence of any productivity gains, under both APS (red dashed) and NZS (brown dashed).

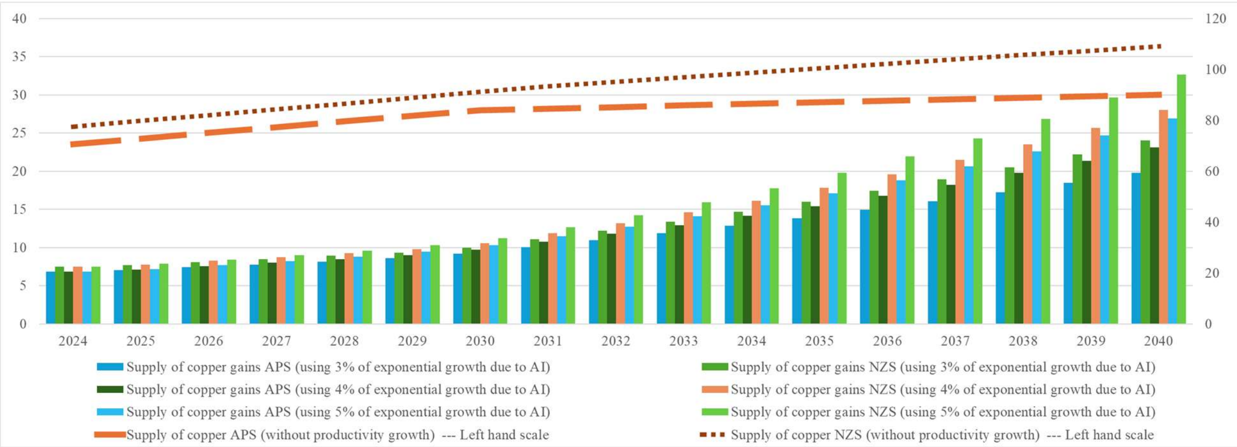


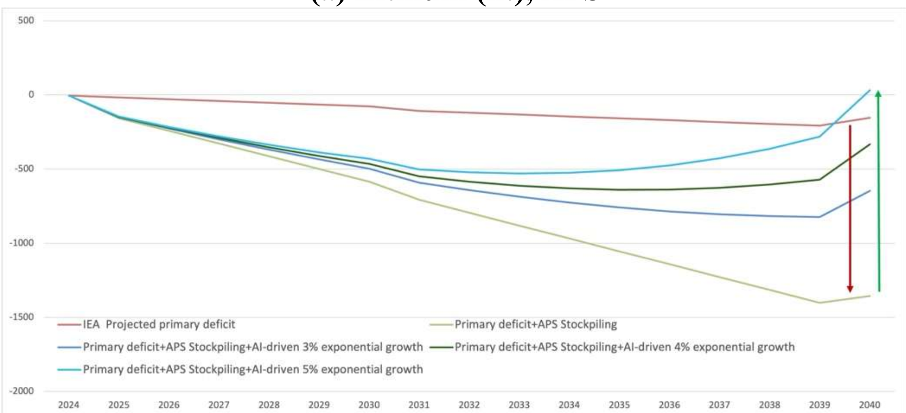
Fig 9 | Supply gains from productivity growth via AI investment for copper. This figure illustrates projected copper supply under the APS and NZS**,** incorporating different assumptions about annual production gains enabled by AI. The right-hand y-axis (measured in tonnes) represents the total copper supply, while the left -hand y-axis corresponds to the baseline APS and NZS supply trajectories without productivity growth, shown as dashed lines. Bar segments represent copper supply projections under 3 per cent, 4 per cent, and 5 per cent annual exponential productivity growth due to AI, applied to both APS (blue, dark green, and light blue bars) and NZS (brown, orange, and light green bars), respectively. The dotted lines indicate copper supply in the absence of any productivity gains, under the APS (red dashed) and NZS (brown dashed) trajectories.

Figure 10 shows the tightening effect of strategic stockpiling (red arrow) and the mitigating role of AI-driven productivity growth (green arrow, 5 per cent exponential growth case). Under the APS, Panel (a) shows that the IEA baseline projects a gradually widening lithium supply deficit. Incorporating stockpiling requirements substantially amplifies this deficit, reaching approximately 1400 kt by 2040. AI-induced productivity gains, modelled as exponential growth at annual rates of 3, 4, and 5 per cent, could help to mitigate the shortfall. Notably, a 5 per cent exponential annual productivity improvement could eliminate the supply deficit caused by rising demand and strategic stockpiling by 2040. This suggests that under the APS, high-level AI-led productivity gains could offset escalating supply-side pressures for lithium. In Panel (b), a similar pattern emerges for copper: stockpiling results in a projected shortfall of around 35 million tonnes by 2040, and AI-driven productivity growth could help mitigate this deficit by 2040.

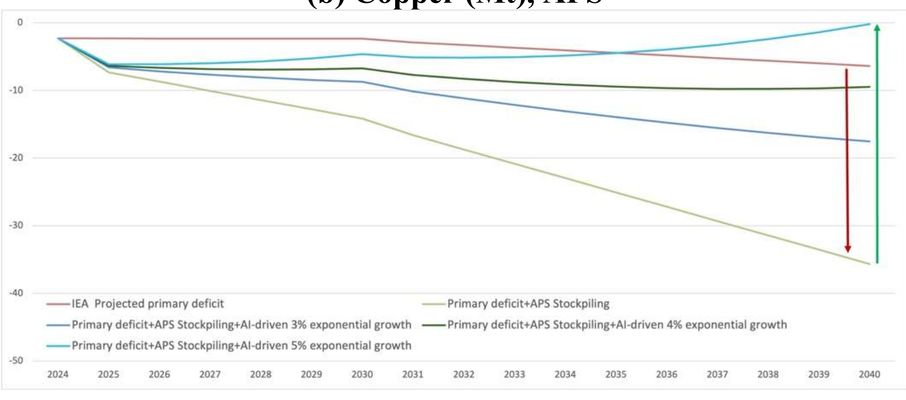
Under the NZS, Panels (c) and (d) show that supply deficits resulting from increased demand and stockpiling become even more pronounced than under APS. In Panel (c), AI-driven productivity growth could help to offset a significant portion of the lithium shortfall arising from these pressures. Panel (d) shows a similar effect for copper: while stockpiling leads to supply deficits, AI-driven productivity improvements narrow the supply gap.

Overall, these results illustrate a trade-off between short-term energy security and long-term supply tightness. While strategic stockpiling may enhance resilience in the near term, it systematically deepens future deficits. At the same time, AI-driven productivity growth serves as a powerful counterbalance, though its effectiveness is scenario- and mineral-specific.

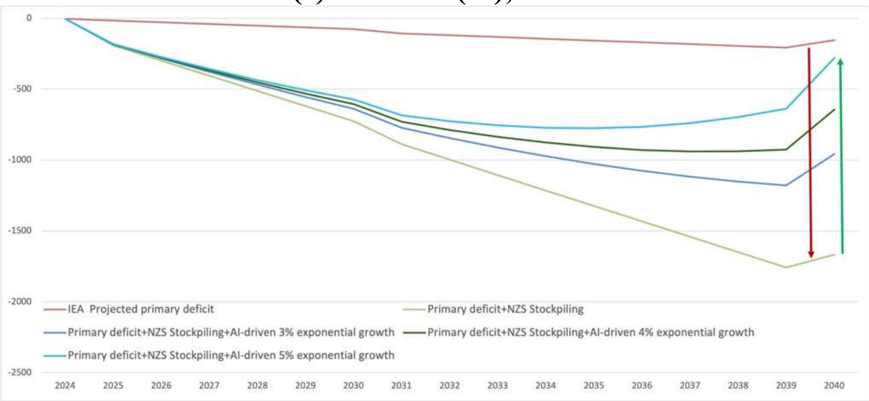
(a) Lithium (kt), APS



(b) Copper (Mt), APS



(c) Lithium (kt), NZS



(d) Copper (Mt), NZS

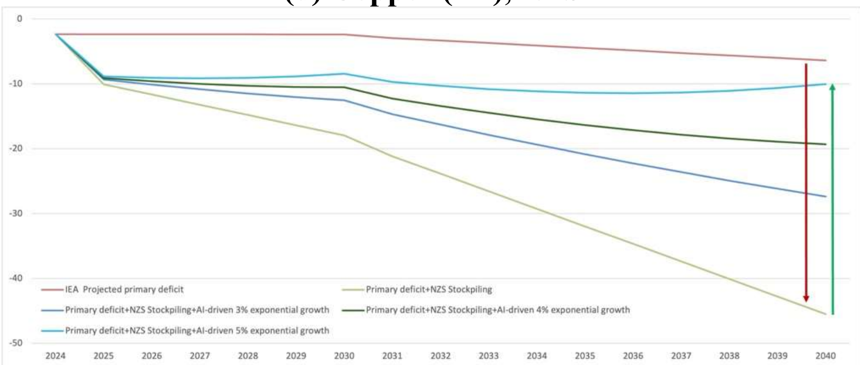


Fig. 10 | The amplifying effect of strategic stockpiling on supply deficits and the mitigating role of AI-driven productivity growth. Panels (a) and (b) show the baseline IEA projected deficits without additional stockpiling (red lines) and the expanded deficits under the APS when strategic stockpiling is included (light green lines), for lithium and copper, respectively. The dark blue, dark green, and light blue lines represent lithium and copper supply projections under 3 per cent, 4 per cent, and 5 per cent exponential annual productivity growth driven by AI, applied to the APS scenario, respectively. Panels (c) and (d) present the corresponding projections under the NZS scenario, showing the baseline IEA projected deficits without stockpiling (red lines) and the expanded deficits with stockpiling (light green lines), alongside AI-driven supply paths under the same productivity growth assumptions. The red arrow illustrates the increase in lithium and copper supply deficits driven by rising demand and strategic stockpiling requirements under different IEA scenarios. The green arrow indicates the (partial) narrowing of this deficit, highlighting the mitigating role of AI-driven productivity growth, with the 5 per cent exponential growth case shown as an illustrative example.

4.5. Summary of findings and policy recommendations

Table 2 summarises the potential to expand supply through technological and policy measures. For lithium, refining diversification and stockpiling must be complemented by significant gains in productivity, especially those enabled by AI. Advance in process optimisation is essential to reduce the projected supply gap, which may exceed 90 per cent by 2040 under the NZS. For copper, structural barriers are lower, meaning the outlook is comparatively less constrained. Table 2 suggests that meeting future demand for copper and lithium needed for the clean energy transition will require a three-pronged strategy: (1) the diversification of refining capacity to reduce supply concentration and chokepoint risks, particularly for lithium, (2) the establishment of strategic stockpiles to manage risk and stabilise markets, and (3) targeted investments in AI and digital technologies to improve productivity. Without coordinated action on all three fronts, critical mineral shortfalls will undermine global decarbonisation efforts.

Aspect	Lithium	Copper
Refining Diversification	Critical	Very Important
Stockpiling	Critical	Critical
AI Productivity Gains	Critical	Very Important
Structural Barriers	High (technological, geographical)	Low to moderate
Policy Priority	Refining diversification and AI-driven innovation	AI-driven innovation

Table 2 | Summary of policy recommendations. This table summarises the potential to expand supply through technological and policy measures.

5. Conclusion

Critical minerals, such as lithium and copper, are indispensable inputs to the clean energy transition, yet their supply chains are increasingly exposed to geopolitical risk, concentration, and long adjustment lags. An important beginning point for mitigating geopolitical risk is identifying the stage at which the bottleneck occurs. Aggregate risk measures that do not distinguish between reserves, mining, and refining understate the importance of downstream chokepoints in critical mineral supply chains. We provide a unified framework to identify the dominant geopolitical bottlenecks along the supply chain and to evaluate policy instruments capable of mitigating these risks across different time horizons.

Using novel stage-specific geopolitical risk indicators, we show that refining consistently emerges as the dominant geopolitical bottleneck across supply-side stages for both lithium and copper. This downstream vulnerability reflects the extreme concentration of refining capacity, particularly for lithium, in a small number of countries, most notably China, combined with limited short-run substitutability and long capacity expansion timelines.

Recognizing refining as the dominant bottleneck fundamentally reshapes the policy problem. We show that mitigation strategies operate along three distinct but complementary margins. First, geographical diversification of refining capacity can meaningfully reduce long-run geopolitical exposure, with particularly large gains for lithium due to its strong dependence on China-dominated refining. Second, strategic stockpiling of refined minerals provides an effective intertemporal buffer against short-run supply disruptions when refining capacity cannot adjust quickly. Third, productivity-enhancing technological change, most notably through AI adoption, relaxes supply constraints over the longer run by increasing effective supply and lowering marginal production costs.

Our forward-looking simulations highlight that while strategic stockpiling reduces vulnerability to geopolitical shocks, it also substantially amplifies supply requirements under the IEA's Announced Pledges and Net Zero scenarios. By 2040, projected lithium supply shortfalls increase significantly once stockpiling is incorporated, with copper deficits also widening, though to a lesser extent. These results underscore that stockpiling alone cannot resolve structural supply constraints and must be complemented by productivity-enhancing investment, such as AI investment, and refining diversification.

From a policy perspective, our findings imply that mineral security strategies should not rely on a single instrument. Geographical diversification of refining capacity is essential for building long-run resilience, strategic stockpiling plays a critical role in buffering near-term geopolitical shocks, and AI-driven productivity gains are important for closing projected supply gaps. These instruments differ in their channels and time horizons and should, therefore, be deployed as complements rather than substitutes.

The potential limitations on each of these instruments as ways to mitigate supply chain risk that we discuss in the paper reinforces the need to treat them as complementary policy tools. In this way, if, for example, geographical diversification of refining is not fully realizable for political reasons, AI projected gains can still reduce supply chain risk in the long run.

More broadly, the analysis highlights that safeguarding the clean energy transition requires moving beyond upstream resource availability toward a stage-specific understanding of supply chain fragility. Without coordinated action to address downstream bottlenecks, geopolitical risk will continue to undermine supply stability, investment incentives, and the pace of global decarbonisation. Strategic stockpiling, geographical diversification of refining, and productivity-enhancing technological change together form a coherent policy toolkit to manage these risks and support a resilient energy transition.

References

1. Acemoglu, D., Tahbaz-Salehi, A. The macroeconomics of supply chain disruptions. *Rev. Econ. Stud.* **92**, 656–695 (2025).
2. Ali, D., & Frimpong, S. (2020). Artificial intelligence, machine learning and process automation: Existing knowledge frontier and way forward for mining sector. *Artificial Intelligence Review*, *53*(8), 6025-6042.
3. Caldara, D., Iacoviello, M. Measuring geopolitical risk. *Am. Econ. Rev.* **112**, 1194–1225 (2022).
4. Flores, V., Keith, B., & Leiva, C. (2020). Using artificial intelligence techniques to improve the prediction of copper recovery by leaching. *Journal of Sensors*, *2020*(1), 2454875.
5. Fraser Institute (2022) Annual Survey of Mining Companies. Fraser Institute: Vancouver, BC.
6. Grace, K., Salvatier, J., Dafoe, A., Zhang, B. and Evans, O., 2018. When will AI exceed human performance? Evidence from AI experts. Journal of Artificial Intelligence Research, 62, pp.729-754.
7. Hine, A., Gibson, C., & Mayes, R. (2023). Critical minerals: rethinking extractivism? *Australian Geographer*, *54*(3), 233-250.
8. Howald, Q. (2025). Implementing Automated Inspection Systems in Copper Tankhouses. In: 12th International Copper Conference. COPR 2025. Springer, Cham. https://doi.org/10.1007/978-3-032-00102-3_30
9. Hyder, Z., Siau, K. and Nah, F., 2019. Artificial intelligence, machine learning, and autonomous technologies in mining industry. Journal of Database Management, 30(2), pp.67-79.
10. IEA (2024), *Global Critical Minerals Outlook 2024*, IEA, Paris https://www.iea.org/reports/global-critical-minerals-outlook-2024, Licence: CC BY 4.0
11. IEA (2025). Critical Minerals Dataset. https://www.iea.org/data-and-statistics/data-product/critical-minerals-dataset.
12. Jooshaki, M., Nad, A., & Michaux, S. (2021). A systematic review on the application of machine learning in exploiting mineralogical data in mining and mineral industry. *Minerals*, *11*(8), 816.
13. Kang, W., Smyth, R., Vespignani, J. (2025) The Macroeconomic Fragility of Critical Mineral Markets. CAMA Working Paper 21/2025
14. Kapoor, S., & Narayanan, A. (2023). Leakage and the reproducibility crisis in machine-learning-based science. *Patterns*, *4*(9), 100804.
15. Rosenblatt, M., Tejavibulya, L., Jiang, R. *et al.* Data leakage inflates prediction performance in connectome-based machine learning models. *Nat Communications* **15**, 1829 (2024). https://doi.org/10.1038/s41467-024-46150-w
16. Kenzhaliyev, B., Imankulov, T., Mukhanbet, A., Kvyatkovskiy, S., Dyussebekova, M., & Tasmurzayev, N. (2025). Intelligent System for Reducing Waste and Enhancing Efficiency in Copper Production Using Machine Learning. *Metals*, *15*(2), 186.

17. Masouleh, S. S. M., Sanz, C. A., Jansonius, R. P., Shi, S., Romero, M. J. G., Hein, J. E., & Hattrick-Simpers, J. (2024). Artificial intelligence-enabled optimization of battery-grade lithium carbonate production. *Digital Discovery*, *3*(11), 2320-2326.
18. Newbery, D.M., Stiglitz, J.E. The theory of commodity price stabilization. A study in the economics of risk. (1981).
19. OECD (2023). Critical minerals for the energy transition: Investment, trade, and geopolitical risks. Paris: OECD.
20. Onifade, M., Adebisi, J. A., Shivute, A. P., & Genc, B. (2023). Challenges and applications of digital technology in the mineral industry. *Resources Policy*, *85*, 103978.
21. Ortiz, E. M. (2021). The Role of the State and The Environmental Impacts of Lithium Mining in Jujuy, Argentina. PhD thesis, University of California, Los Angeles.
22. Othman, R, (2024) Analyzing Trump's Foreign Policy Expectations. Available at SSRN: https://ssrn.com/abstract=5075540 or http://dx.doi.org/10.2139/ssrn.5075540
23. Pedersen, A., Jaswal, M. A tale of a looming surplus in the lithium industry: sticky supply to stay? https://www.woodmac.com/news/opinion/a-tale-of-a-looming-surplus-in-the-lithium-industry-sticky-supply-to-stay/ (2024).
24. Prosser, D. (2024) ABC News. Sydney bishop among those stabbed in Wakeley church attack. https://www.abc.net.au/news/2024-04-15/wakeley-church-stabbing-terrorism-attack/102561234 (2024).
25. Saadaoui, J., Smyth, R., Vespignani, J. Ensuring the security of the clean energy transition: Examining the impact of geopolitical risk on the price of critical minerals. *Energy Econ.* **142**, 108195 (2025).
26. S&P Global Market Intelligence (n.d.). S&P Global Market Intelligence. https://www.spglobal.com/market-intelligence/en
27. Smith, D., Pengally, M. Donald Trump elected US president in stunning political resurrection. https://www.theguardian.com/us-news/2024/nov/06/donald-trump-wins-us-presidential-election (2024).
28. Temper, L., Avila, S., Del Bene, D., Gobby, J., Kosoy, N., Le Billon, P., ... & Walter, M. (2020). Movements shaping climate futures: A systematic mapping of protests against fossil fuel and low-carbon energy projects. *Environmental Research Letters*, *15*(12), 123004.
29. USGS. Mineral commodity summaries 2025. https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf (2025).
30. Vespignani, J., Smyth, R. Artificial intelligence investments reduce risks to critical mineral supply. *Nat. Commun.* **15**, 7304 (2024).
31. You, M., Li, S., Li, D. and Xu, S., 2021. Applications of artificial intelligence for coal mine gas risk assessment. Safety Science, 143, p.105420.
32. Wright, B.D., Williams, J.C. The economic role of commodity storage. *Econ. J.* **92**, 596–614 (1982).
33. Xu, Z., Ding, Y., Han, S. C., & Zhang, C. (2024). Predicting the performance of lithium adsorption and recovery from unconventional water sources with machine learning. *Water Research*, *266*, 122374.

Appendix:

Appendix A. Geopolitical risk indicators (2024)

Fig. A1 shows geopolitical risk indicators for the countries with the most reserves and highest production of copper and lithium in 2024. China consistently records elevated levels of geopolitical risk over the year. In addition, Australia exhibits the highest levels of geopolitical risk throughout most of the year, with sharp peaks in January, April, and August 2024, reflecting both domestic and global geopolitical events. In contrast, Argentina and Peru show moderate volatility, with notable increases in February, May, and November, potentially linked to political unrest or external shocks in the Latin American region. Chile generally displays the lowest geopolitical risk among the group, maintaining stable and minimal risk levels across the year, which aligns with its relatively stable political environment in 2024. The spike in Australia's risk in April 2024 corresponds to a terrorist incident in Sydney, while the elevated risk in November 2024 in Peru and Chile coincides with broader regional uncertainty and the global impact of Trump's U.S. presidential election victory. Overall, Fig. A1 highlights important cross-country differences in geopolitical exposure**,** which are crucial for understanding vulnerabilities in the upstream stages of critical mineral supply chains.

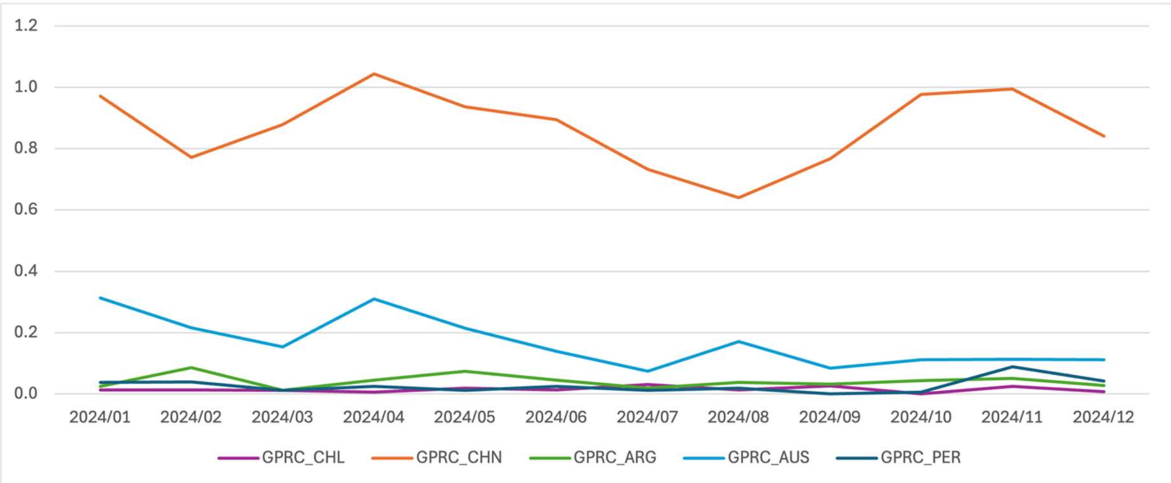


Fig. A1 | Geopolitical risk indicators for principal reserve and producer countries for copper and lithium. This figure displays the monthly geopolitical risk indicators for four major copper and lithium reserve and producer countries—Chile (GPRC_CHL), China (GPRC_CHN), Argentina (GPRC_ARG), Australia (GPRC_AUS), and Peru (GPRC_PER)—from January to December 2024.

Fig. A2 illustrates the monthly geopolitical risk indicators for key refining countries of copper and lithium—China and Chile—from January to December 2024. China exhibits persistently high geopolitical risk throughout the year, with noticeable fluctuations and several pronounced peaks. Risk levels increase in the final quarter of 2024, likely reflecting anticipation of renewed trade frictions under a Trump presidency. Chile maintains low geopolitical risk throughout the year, with limited volatility, consistent with its comparatively stable political environment in 2024.

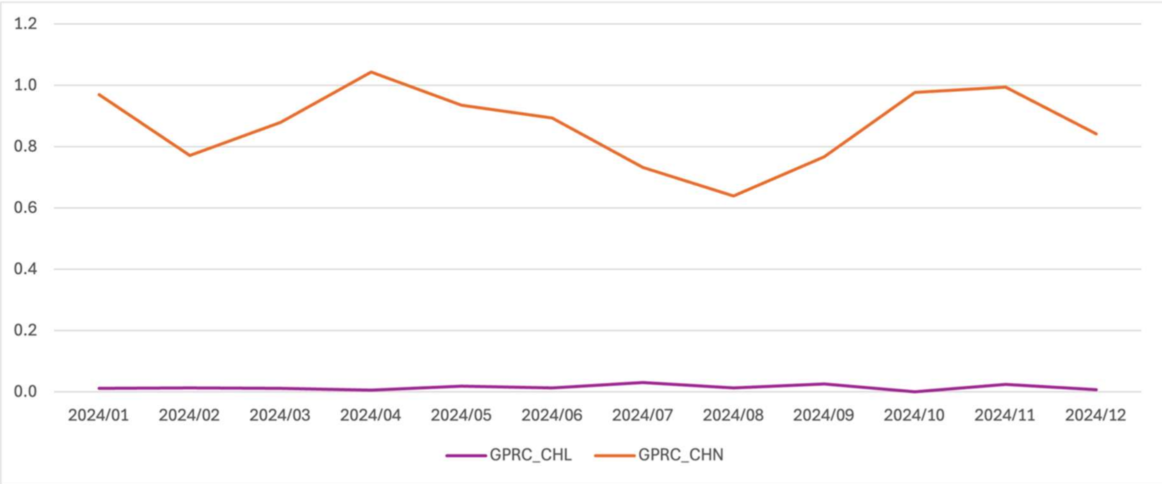


Fig. A2 | Geopolitical risk indicators for principal refining countries for copper and lithium. This figure displays the monthly geopolitical risk indicators for four major copper and lithium refining and consumption countries—China (GPRC_CHN) and Chile (GPRC_CHL)—from January to December 2024.

Appendix B. Projected supply deficits under alternative strategic stockpiling scenarios, expressed in days of consumption

Fig. B1 presents supply deficits under alternative strategic stockpiling scenarios, expressed in days of global consumption. Panels (a) and (b) show projected deficits for lithium. Under APS, the cumulative deficit is approximately 820 kt in the 255-day scenario (panel a) and 1,200 kt in the 474-day scenario (panel b). Under NZS, the shortfalls increase significantly to around 1,500 kt and 2,000 kt, respectively. Panels (c) and (d) display the corresponding projections for copper. In the 255-day scenario (Panel c), the cumulative deficits is approximately 20 million tonnes (Mt) under APS and 60 Mt under NZS. For the 474-day case (Panel d), these values rise to approximately 40 Mt and 85 Mt, respectively. These results highlight the growing strain on supply chains from strategic reserve accumulation, particularly for lithium, where limited recycling capacity and concentrated production amplify the impact of ambitious stockpiling policies under net-zero-aligned demand trajectories.

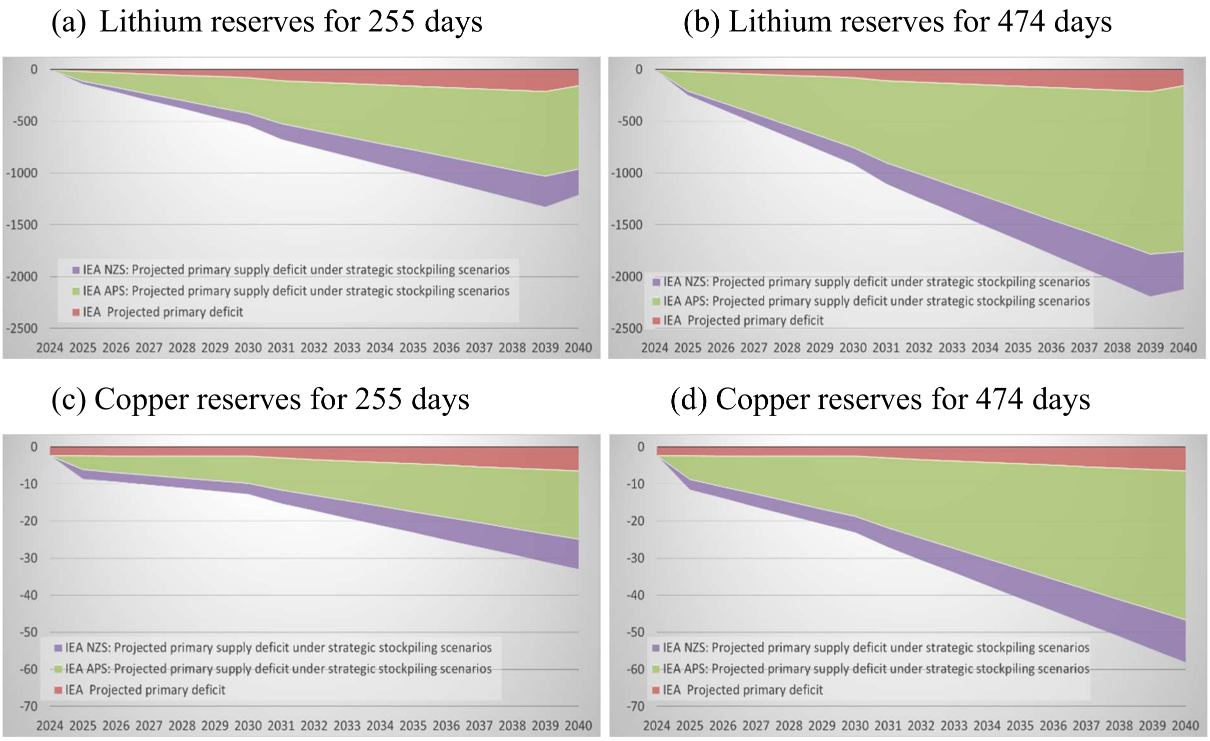


Fig. B1 | Projected supply deficits under alternative strategic stockpiling scenarios, expressed in days of global consumption. This figure presents a sensitivity analysis of cumulative supply deficits for lithium and copper under the APS and NZS, accounting for additional demand generated by strategic stockpiling policies. Each panel corresponds to a different reserve accumulation pathway, with stockpiles equivalent to either 255 days (70% of annual production) or 474 days (130% of annual production) by 2040. Panels (a) and (b) show projected deficits for lithium, while panels (c) and (d) display the corresponding projections for copper.