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Abstract

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Copper and lithium are essential to the global energy transition, each playing distinct roles in enabling low-carbon technologies. However, their supply chains are highly vulnerable to geopolitical risks, posing a threat to the stability and resilience of future clean energy systems. This study proposes strategic stockpiling as a cost-effective instrument to mitigate supply disruptions due to geopolitical risks in copper and lithium supply chains. First, we develop and apply novel, stage-specific, measures of geopolitical risk for copper and lithium for each of the four key phases of their supply chain: proven reserves, extraction, refining and end-use consumption. Second, we construct forward-looking stockpiling scenarios for both minerals, grounded in projected demand under the International Energy Agency's Announced Pledges (APS) and Net Zero Scenario (NZS) pathways. Our estimates indicate substantial supply shortfalls by 2040 when strategic stockpiling is incorporated. Specifically, we project the shortfall in lithium supply to increase by a factor of 7.8 under APS and 9.8 under NZS, while copper shortages are projected to grow by 4.6 and 6.1 times, respectively. We consider Artificial Intelligence (AI)-driven productivity gains and recycling as alternative ways to alleviate shortages in both copper and lithium markets. We show that while enhanced recycling can significantly contribute to closing the supply gap for copper, its impact remains limited in the case of lithium due to technological, geological, and geographical constraints. We conclude that AI-driven productivity gains are essential to close the supply gap for both critical minerals.

Keywords: Critical Minerals; Copper; Lithium; Geopolitical Risk; Stockpiling

JEL Codes: C14; Q20, Q41; Q43

The accelerating global shift toward net-zero emissions has placed unprecedented emphasis on securing reliable and sustainable access to critical minerals. Among these, copper and lithium have distinct, yet complementary, roles in the clean energy transition. Copper, with its superior electrical conductivity and durability, is foundational to renewable power grids, electric vehicle (EV) infrastructure, and energy-efficient buildings. Lithium is the linchpin of electrochemical storage, underpinning the production of high-performance lithium-ion batteries essential for EVs and grid stabilization. While both minerals are vital to decarbonization pathways, they differ markedly in their supply chains, end-use applications, and exposure to geopolitical risks. This study examines how the geopolitical vulnerability of these two minerals differ across proven reserves, production, refining, and consumption stages of the supply chain, illuminating how their divergent roles in the energy transition produce distinct geopolitical risk profiles with implications for global energy security. We propose strategic stockpiling as a cost-effective way to mitigate supply disruptions in resource-constrained and geographically concentrated markets, constructing forward-looking stockpiling scenarios for copper and lithium based on projected demand under International Energy Agency (IEA) pathways.

Recent super cycles and persistent price volatility in lithium and copper markets underscore the structural fragility of critical mineral supply chains, which are increasingly characterized by recurring shortages and disruption risks. These instabilities reflect deeper supply-demand mismatches, driven not only by the slow responsiveness of upstream production, but also by geopolitical tensions, concentrated refining capacities, and the absence of sufficient stockpiles. Notably, lithium markets have exhibited substantially greater instability than copper, as evidenced by extreme price movements and higher geopolitical exposure across all supply chain stages[1,2]. Between 2020 and 2022, lithium prices surged by over 1,100 per cent, with lithium carbonate rising from under USD 6,000 per tonne to over USD 70,000 before partially correcting in 2023[1,3]. Copper also experienced more modest price fluctuations, rising from around USD 4,800 per tonne in early 2020 to over USD 10,700 in 2022, before declining to approximately USD 8,400 by mid-2024. These swings reveal how tight market conditions, combined with geopolitical events, can propagate volatility through the global economy. The resulting price shocks impact downstream industries—raising input costs for battery and EV manufacturers and stalling infrastructure investment—ultimately undermining the pace, and prospects for success, of the clean energy transition[1,4].

These developments highlight the urgency for structural interventions, such as strategic stockpiling, to mitigate the macroeconomic effects of supply instability and enhance market resilience. In 2021, the IEA issued a stark warning about the geopolitical risks associated with the clean energy transition, advising that Western governments should consider stockpiling critical battery metals such as cobalt and lithium to stabilize supply chains.[5]

Recent global developments point to a growing emphasis on strategic stockpiling of critical minerals as countries seek to mitigate geopolitical risks and secure supply chains essential for the clean energy transition. In 2021, the Japanese Government announced a new International Resource Strategy following public consultation. The resource strategy covers oil and LNG security, critical minerals, and climate change action[6]. In the United States, the National Defense Authorization Act (FY 2024) directs the Department of Defense to reduce reliance on strategic adversaries, such as China and Russia, while enhancing the National Defense Stockpile to safeguard against future supply disruptions[7]. The European Union (EU) has passed the Critical Raw Materials Act, which mandates that by 2030 the EU should domestically extract at least 10 per cent, process 40 per cent, and recycle 25 per cent of its critical raw material consumption[8]. Australia has committed AU$1.2 billion to establish a Critical Minerals Strategic Reserve, including funding for both stockpiling and processing capacity, aiming for full operation by mid-2026[9]. India is accelerating amendments to the Mines and Minerals (Development and Regulation) Act to promote domestic production of rare earth permanent magnets, particularly in response to China's recent export restrictions[10]. Meanwhile, China has tightened controls over exports of rare earths and related technologies, reinforcing its geopolitical leverage and prompting further diversification efforts by importing countries[11]. These policies reflect a broader international recognition of the strategic value of critical minerals and the potential important role of national stockpiles in buffering against supply shocks arising from geopolitical risks, ensuring industrial resilience.

Although it is widely acknowledged that geopolitical risk plays a critical role in shaping the clean energy transition, its specific impact on copper and lithium across each stage of the supply chain remains poorly understood. Furthermore, despite calls by the IEA to mitigate the macroeconomic consequences of supply disruptions to critical minerals through strategic stockpiling, we lack forward-looking projections that quantify the likely supply shortfalls due to stockpiling designed to mitigate geopolitical risks in the supply chain. In the absence of such information, policymakers are ill-equipped to allocate scarce resources effectively, making it difficult to design optimal stockpiling strategies across competing critical minerals. This, in turn, hampers efforts to support downstream industries and undermines the stability and predictability required for long-term investment in mineral development.

This paper makes the following contributions to the literature on critical minerals and energy security. First, we develop and apply novel measures of geopolitical risk for copper and lithium across each of the four main stages of their supply chains: proven reserves, production, refining, and consumption. These measures suggest that lithium is subject to consistently higher geopolitical risk than copper in each of the four stages of the supply chain. In addition, we show that the refining and consumption stages exhibit greater geopolitical vulnerability, relative to the upstream stages of proven reserves and production, which underscores the importance of downstream dependencies in global supply chain stability.

Second, we construct forward-looking stockpiling scenarios for copper and lithium based on the IEA's Announced Pledges Scenario (APS) and Net Zero Scenario (NZS). Assuming optimal conditions and excluding any offset from recycling or future technological advancements, our estimates suggest that over the next 15 years there will be substantial supply-demand imbalances when strategic stockpiling projections are incorporated. Specifically, 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 grow will by 4.6 and 6.1 times, respectively.

Third, we consider Artificial Intelligence (AI)-driven productivity gains and recycling as alternative ways to alleviate shortages in both copper and lithium markets. We show that while enhanced recycling can significantly contribute to closing the supply gap for copper, its impact is likely to be limited in the case of lithium, reflecting a combination of technological, geological, and geographical constraints. We show that AI-driven productivity gains will be essential to close the supply gap for both critical minerals, but particularly for lithium.

Results and discussion

Geographic concentration of copper and lithium in each stage of the supply chain

The macroeconomic fragility framework posits that economic systems become increasingly vulnerable when small shocks can trigger large and discontinuous effects due to inherent interdependencies[12]. Applying this to critical minerals, disruptions in any stage of the supply chain—whether in access to proven reserves, refining capacity, production volumes, or consumption demand—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., Chile) can destabilize the entire supply network. As highlighted by Kang, Smyth and Vespignani[2], these fragility mechanisms are particularly acute in critical mineral markets where substitution is limited, and geographic concentration is high. Thus, the macroeconomic fragility framework attributes systemic supply chain risks not to isolated events, but to the complex and nonlinear interactions among geopolitical exposure across all stages of the critical mineral value chain.

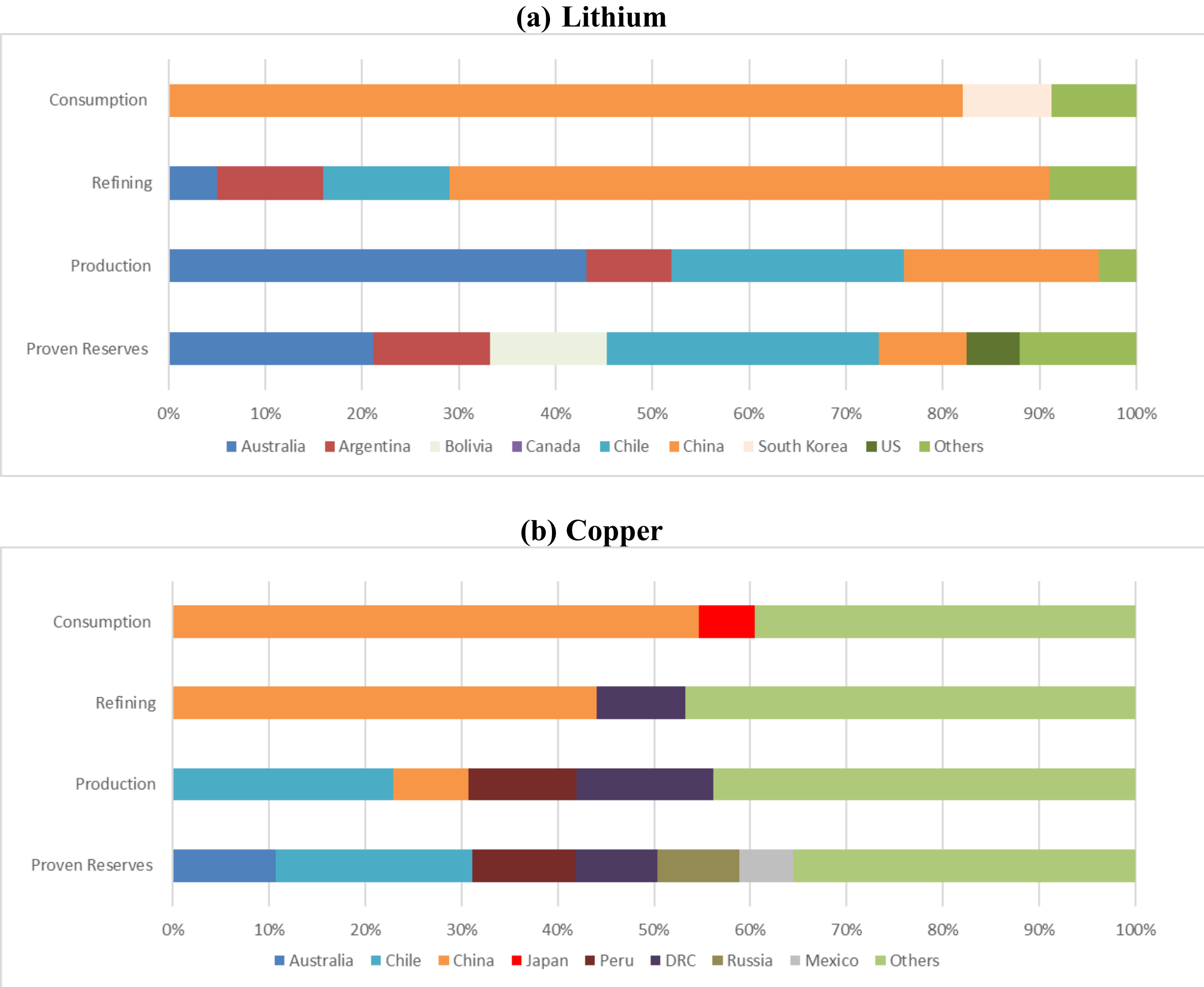


Fig. 1 | Global shares of proven reserves, production, refining and consumption in 2024 (percentage of global outputs). This figure presents the distribution of global shares for lithium and copper across the four key stages of the supply chain in 2024: proven reserves, primary production, refining, and final consumption.

Fig. 1 shows that copper's proven reserves are more geographically distributed, with significant shares in Chile, Australia, Peru, and other countries, while lithium reserves are highly concentrated in the so-called "Lithium Triangle" (Chile, Argentina, and Bolivia) and Australia. In terms of production, Australia dominates lithium output (around 43 per cent), while copper production is more balanced, with Chile, Peru, and the DRC playing major roles alongside Australia. The most striking contrast appears in refining, where China controls over 80 per cent of global lithium refining, reflecting its dominance in battery supply chains. Copper refining is also China-centric (around 44 per cent), but to a lesser extent, with some capacity in countries like the DRC and "others". Finally, consumption is more concentrated for lithium, with China accounting for over 80 per cent, driven by battery and EV manufacturing. China accounts for about one half of the consumption of copper, but other industrialized nations like Japan are also prominent consumers, indicating a broader industrial base for copper demand.

China's position in the global supply chains of critical minerals reveals a strategic imbalance. It dominates downstream refining and consumption, but remains heavily dependent on foreign sources for upstream stages, particularly proven reserves and raw material production. For both lithium and copper, China holds a relatively modest share of global reserves—approximately 9 per cent for lithium and just over 4 per cent for copper[13]—and produces less than 5 per cent of global copper and 9 per cent of lithium[1]. This upstream dependency exposes China to geopolitical vulnerabilities, especially in regions such as South America and Africa, where resource nationalism and foreign competition are intensifying[14]. As a result, China's efforts to secure stable supply—through overseas investment, bilateral agreements, and stockpiling—reflect the strategic imperative to mitigate risks associated with its limited control over the first two stages of the critical mineral value chain[15,16].

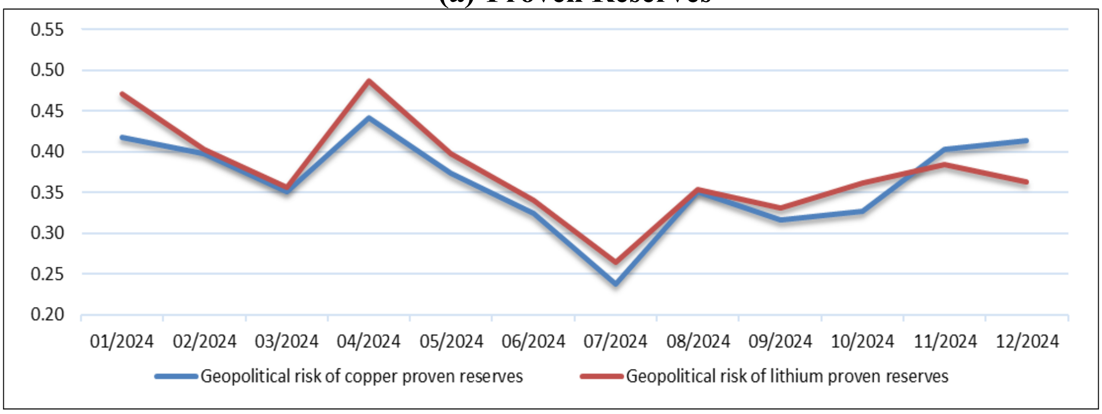
Geopolitical risk of copper and lithium in each stage of the supply chain

We define the geopolitical risk of a critical mineral as a weighted average of the geopolitical risk scores of the countries involved in each stage of the supply: proven reserves, refining, production, and consumption. Fig. 2 presents the monthly geopolitical risk indices for lithium and copper across each of the four stages of the supply chain for the period from January to December 2024. Lithium consistently exhibits higher geopolitical risk than copper in each stage, reflecting that each stage of the supply chain is more geographically concentrated, as reflected in Fig. 1, and that the countries which are more prominent in each stage of the lithium supply chain are geopolitically more sensitive. The refining and consumption stages show the highest risk levels for both minerals, with lithium's refining risk peaking above 0.65 and its consumption risk approaching 1.1. This largely reflects the dominance of China in these stages of the supply chain, given that China has a relatively high country geopolitical risk score.

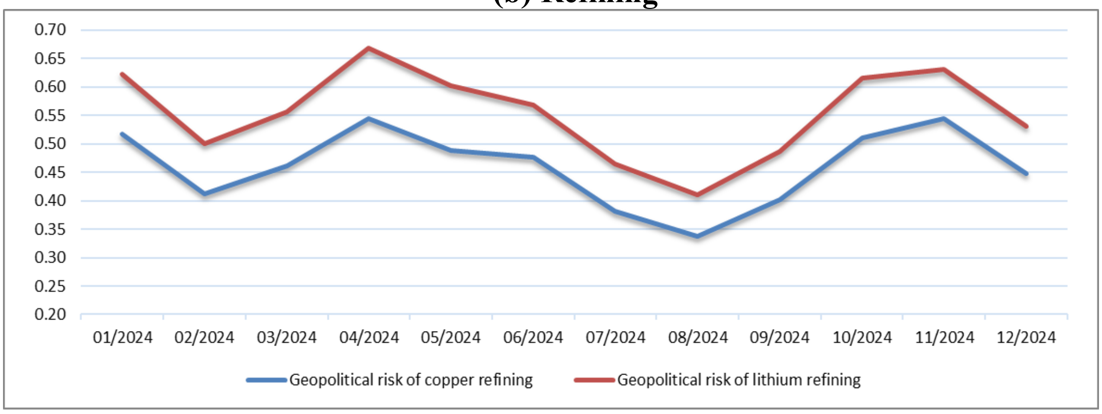
In contrast, geopolitical risk associated with production and reserves remains comparatively lower, particularly for copper. This reflects the fact that the largest shares of global reserves and production are located in countries with relatively low geopolitical risk such as Australia, Argentina, Bolivia, and Chile for lithium, and Australia and Chile for copper. Country-specific geopolitical risk scores are detailed in Supplementary Information 1.

As illustrated in Fig. 2(a–d), 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 four stages of the supply chain. Furthermore, geopolitical risk is globally correlated due to the outsized influence of major powers—particularly the United States and China—on global risk dynamics[17]. 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[18]. A second notable rise in geopolitical risk occurs in November and December 2024 following the election of Donald Trump as U.S. President. Trump's return to office signalled potential shifts in both domestic and foreign policy, leading to increased uncertainty in global markets and diplomatic relations[19]. 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 move uniformly across supply chain stages. For example, during April 2024, the geopolitical risk associated with copper production remained relatively stable, reflecting the political stability of major producing countries such as Chile, Peru, and Argentina (see Supplementary Information 1).

(a) Proven Reserves



(b) Refining



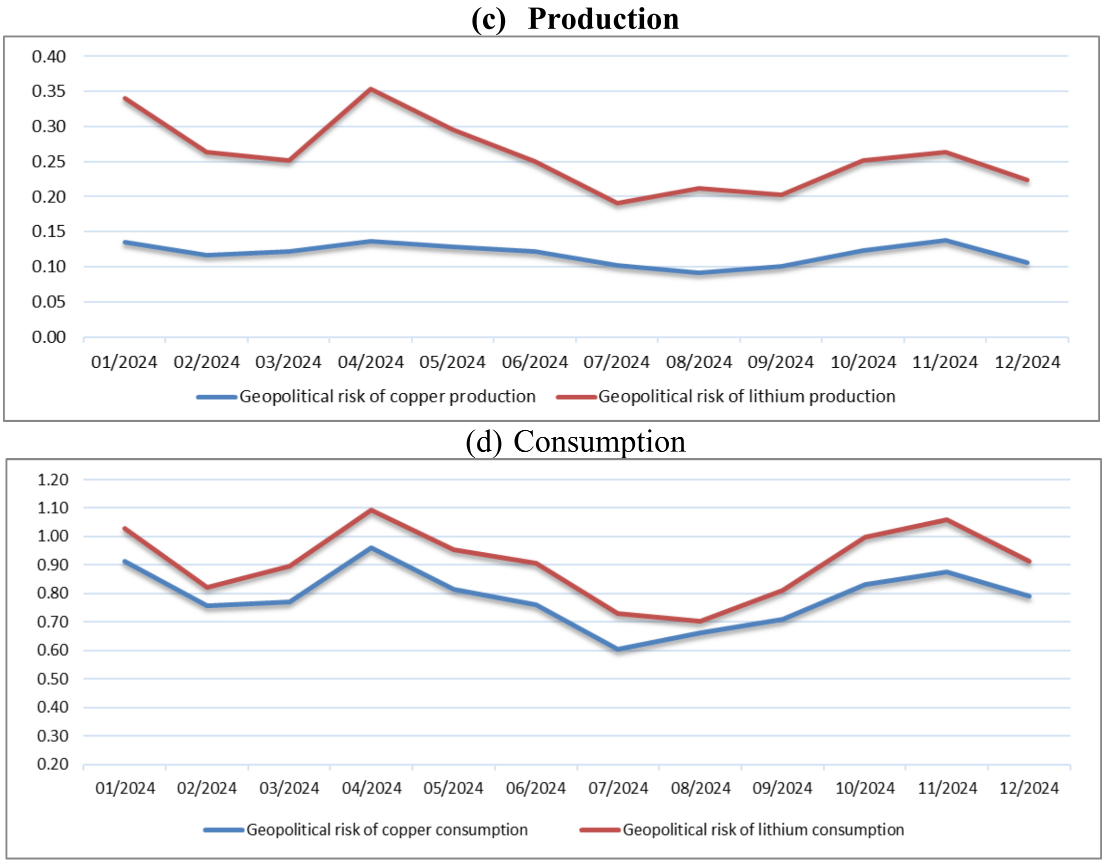


Fig. 2 | Geopolitical risk exposure across the lithium and copper supply chains (M1–M12 2024). This figure presents monthly geopolitical risk indices for lithium and copper from January to December 2024, disaggregated by the four key stages of their supply chains. Panel (a) shows geopolitical risk associated with proven reserves, panel (b) with primary production, panel (c) with refining, and panel (d) with final consumption.

Stockpiling for market stabilization

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[20,21]. 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[16]. Strategic stockpiles not only serve to stabilize domestic markets but also enhance bargaining power in international negotiations and support industrial policy planning[15].

Fig. 3 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 a terrorist attack, and (c) the role of strategic stockpiling 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_{High}, the equilibrium shifts to a higher price level $P_{High\ GPR}$, with only a modest increase in quantity $Q_{High\ GPR}$.

Panel (c) illustrates the role of stockpiling as a stabilizing policy intervention. Strategic reserves—held either by governments or firms—act as a buffer against market shocks, effectively increasing the elasticity of supply. This is represented by a shift from a steeper supply curve $S_{Low\ stockpile}$ to a flatter one $S_{High\ stockpile}$. With the same elevated demand curve D_{High}, the presence of stockpiles results in a lower equilibrium price and a greater supply response (depicted in the movement from Q_{Low} to $Q_{High\ stockpile}$).

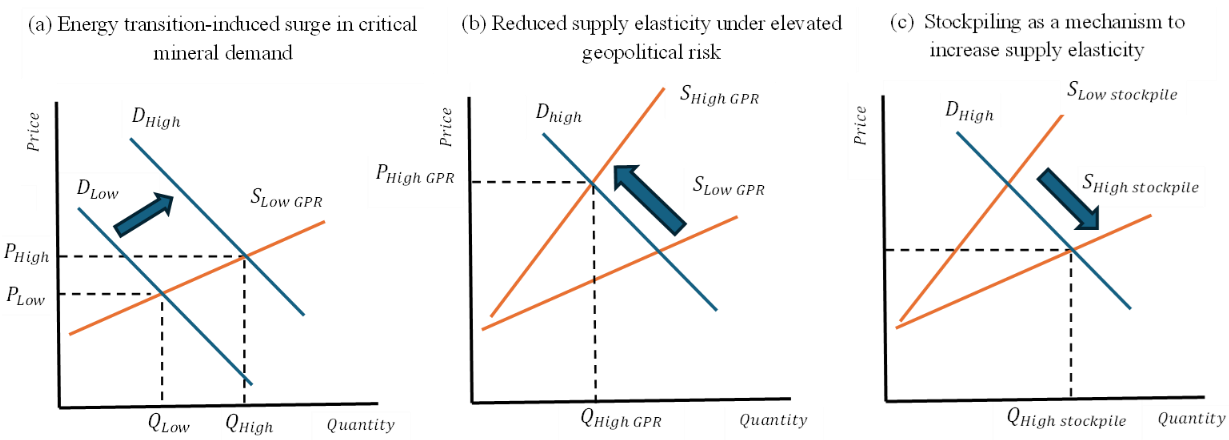


Fig. 3 The impact of geopolitical risk and stockpiling on supply of critical minerals. Fig. 3 illustrates three key mechanisms affecting price and quantity dynamics in critical mineral markets: (a) a surge in demand driven

by the energy transition, (b) a reduction in supply elasticity due to elevated geopolitical risk, and (c) the role of strategic stockpiling in enhancing supply responsiveness.

Fig. 4 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.

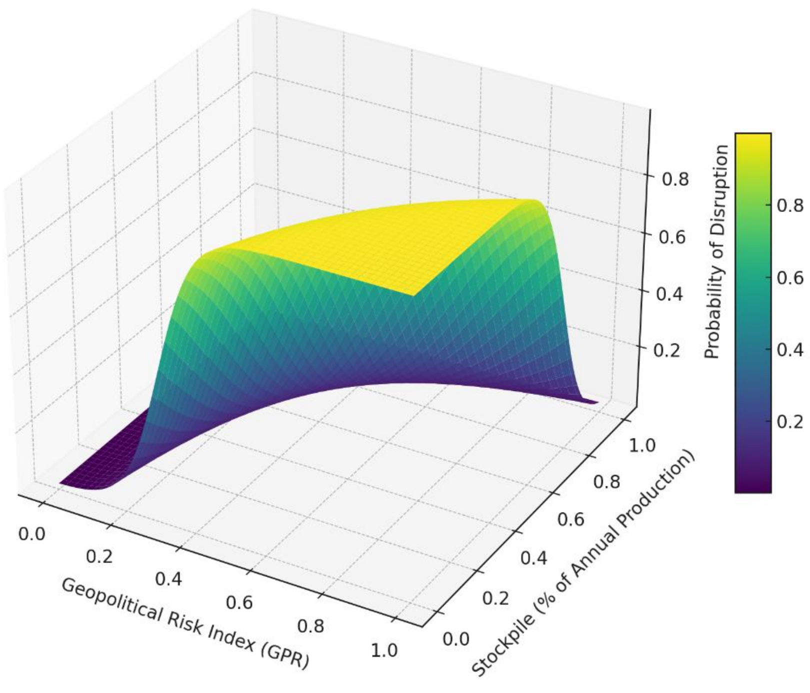


Fig. 4| Geopolitical risk, stockpiling and the probability of chain supply disruption. This figure presents a three-dimensional representation of how the probability of mining production disruption varies with changes in geopolitical risk and the level of strategic stockpiling. The x-axis measures the 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.

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

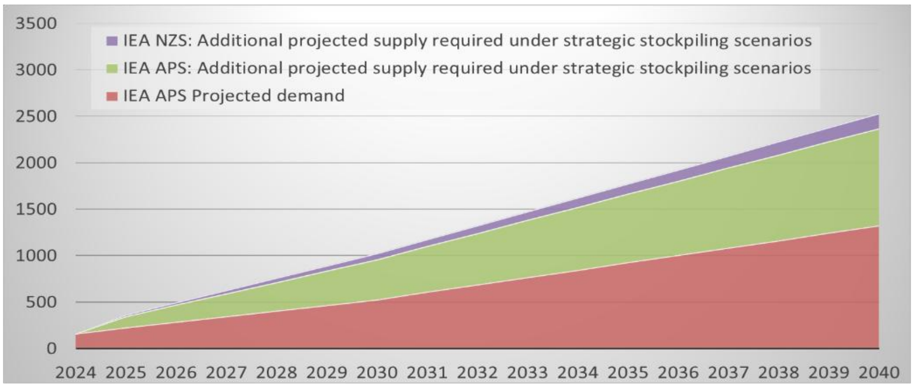
The extent to which stockpiling enhances supply elasticity is critically dependent on the volume of reserves held, often measured in terms of "days of supply." Stockpiles covering only a few days of consumption offer limited buffering capacity, whereas inventories sufficient to meet demand for several months can significantly flatten the supply curve 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 reserves. Stabilizing supply conditions for critical minerals—particularly lithium and copper—is essential to supporting the clean energy transition. However, current supply projections by the International Energy Agency (IEA) do not explicitly incorporate strategic stockpiling into their baseline scenarios. As such, mitigating the cyclical instability of critical mineral supply markets will require, large-scale public investment in critical minerals project developments at the global level.

The two panels in Fig. 5 illustrate the projected global demand and projected stockpiling scenarios for lithium and copper, under the two alternative IEA scenarios - APS and NZS - adjusted to include additional demand from strategic stockpiling initiatives.

In Fig. 5(a), we show demand for lithium under APS exhibits an exponential growth trajectory, with projected consumption increasing from under 165 kt in 2025 to over 1300 kt by 2040. The addition of strategic stockpiling leads to a significant upward shift, from 2370 kt to 2530 kt under the APS and NZS pathway, by 2040. This reflects lithium's vital role in battery technologies and the limited short-term flexibility in its supply chain.

In Fig. 5(b) we show copper demand under the APS pathway grows more gradually, increasing from around 26 Mt in 2025 to over 36 Mt by 2040. While strategic stockpiling also pushes copper demand to 59 Mt and 63MT under APS and NZS, respectively. The smaller impact on copper than for lithium is due to the broader availability of copper, its more established recycling infrastructure, and lower volatility in its supply-demand dynamics.

(a) Lithium



(b) Copper

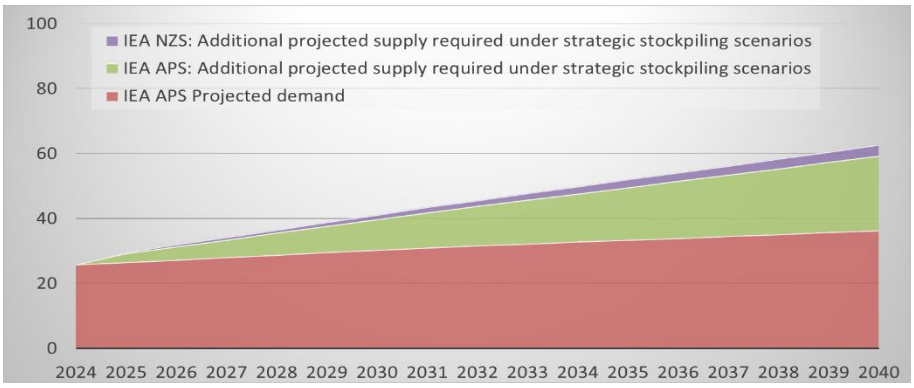
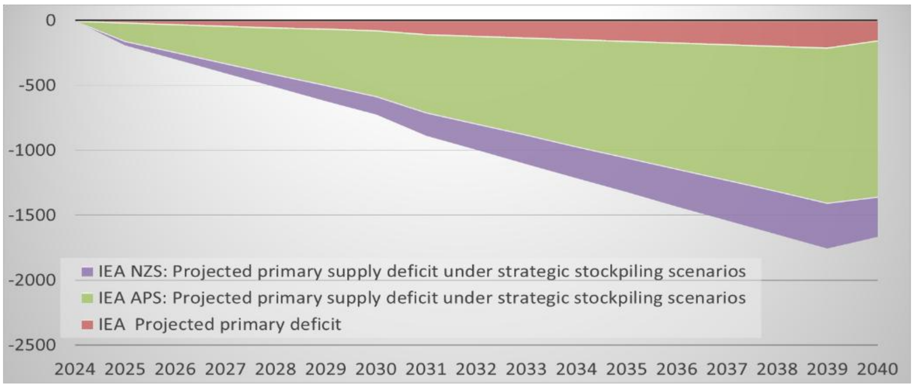


Fig. 5 | Projected supply requirements for copper under IEA APS and NZS, including global strategic stockpile accumulation. This figure illustrates the projected supply trajectory for copper under the IEA's APS pathway, together with the additional supply requirements generated by the inclusion of strategic 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.

In Figure 6, we show the projected shortfall for copper and lithium, Fig. 6(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 (purple area). By 2040, the lithium supply shortfall reaches nearly 2,000 kilotonnes under NZS, underscoring the scale of potential unmet demand even under optimistic policy scenarios. In Fig 6(b), copper's projected supply gap follows a similar pattern, though at a smaller scale. The baseline deficit (red area) gradually increases, with APS-related stockpiling (green area) and NZS-driven demand (purple area) exacerbating the shortfall. By 2040, the projected copper deficit is approximately 47 million tonnes under the NZS pathway, indicating significant pressure on copper supply chains despite better-established recycling systems compared to lithium.

(a) Lithium supply



(b) Copper supply

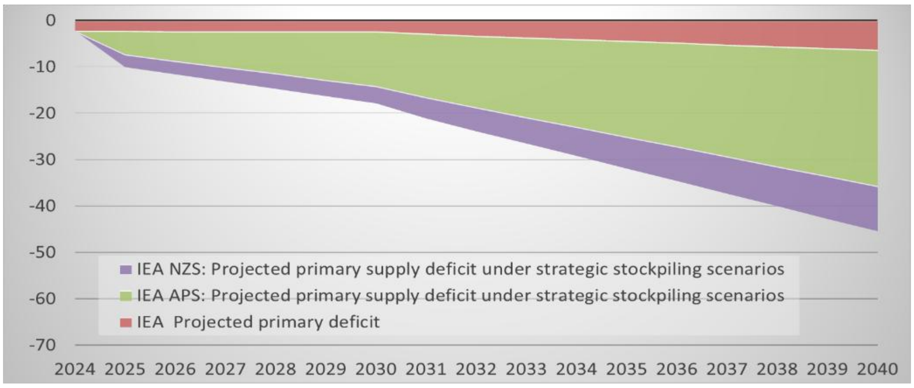


Fig. 6 | IEA current, APS, and NZS scenarios of supply shortfall of lithium and copper including global strategic stockpile. This figure projects supply-demand imbalances for lithium (top panel) and copper (bottom panel) under three IEA scenarios: the base demand, APS, and NZS, each adjusted to include 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.

In Supplementary Information 3, in Supplementary Fig.3, we present a sensitivity analysis of cumulative supply deficits for lithium and copper under the International Energy Agency's APS and NZS, incorporating additional demand from strategic stockpiling policies. Each panel models a different reserve accumulation pathway, equivalent to either 255 days (70% of annual production) or 474 days (130% of annual production) by 2040.

In Supplementary Information 3, in Supplementary Fig.3, panels (a) and (b) show the projected supply deficits for lithium under the APS and NZS, respectively. Comparing this to alternative stockpiling volumes, the deficit is lower under a 255-day scenario—rising by factors of 5.2 (APS) and 6.85 (NZS)—and more severe under a 474-day scenario, with supply shortfalls increasing by 10.4 (APS) and 12.8 (NZS). Panels (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).

Table 1 contains a summary of 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 pathways. The first row shows the primary supply projected by the IEA without additional stockpiling: 1,326 kilotons 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 and higher stockpiling scenarios (255 and 474 days) respectively 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.

The role AI and recycling 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? The projected shortfall in copper and lithium production—driven by both baseline demand and additional demand arising from strategic stockpiling for market stabilization—can be partially mitigated through enhanced recycling and productivity gains. In the case of copper, recycling presents a particularly viable pathway: the IEA estimates that copper recycling rates could increase by up to 37 per cent by 2040. [1] In contrast, lithium recycling is expected to grow by less than 22 per cent over the same period, reflecting substantial technological, geological, and geographical constraints[1]. Beyond recycling, improvements in productivity—particularly those enabled by AI and advanced digital technologies—offer promising avenues to accelerate exploration, optimize extraction, and improve operational efficiency across the critical minerals supply chain[14]. These complementary strategies are essential to reduce the scale of anticipated deficits and enhance the resilience of clean energy supply systems.

Fig. 7 shows the potential supply gains from productivity growth via AI investment and recycling 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 gains significantly narrow the projected supply gap, particularly under the more ambitious net-zero trajectory. However, recycling contributes only modestly to these gains due to technological and economic limitations, with the IEA estimating a maximum increase in lithium recycling of less than 21 per cent by 2040.

Fig. 8 shows the corresponding AI and recycling 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. Importantly, the IEA projects copper recycling rates could increase by up to 37 per cent by 2040, providing a more substantial secondary supply channel than is currently feasible for lithium.

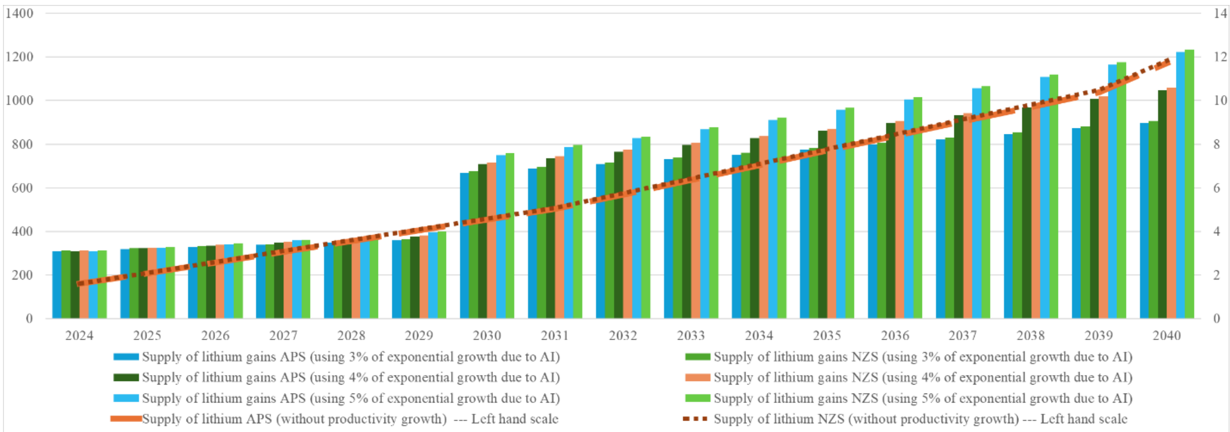


Fig. 7: Supply gains from productivity growth via AI investment and recycling for lithium. This figure illustrates projected lithium supply under the APS and NZS, incorporating different assumptions about annual production gains enabled by AI and recycling. The left-hand y-axis (measured in tonnes) represents the total supply, while the right-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).

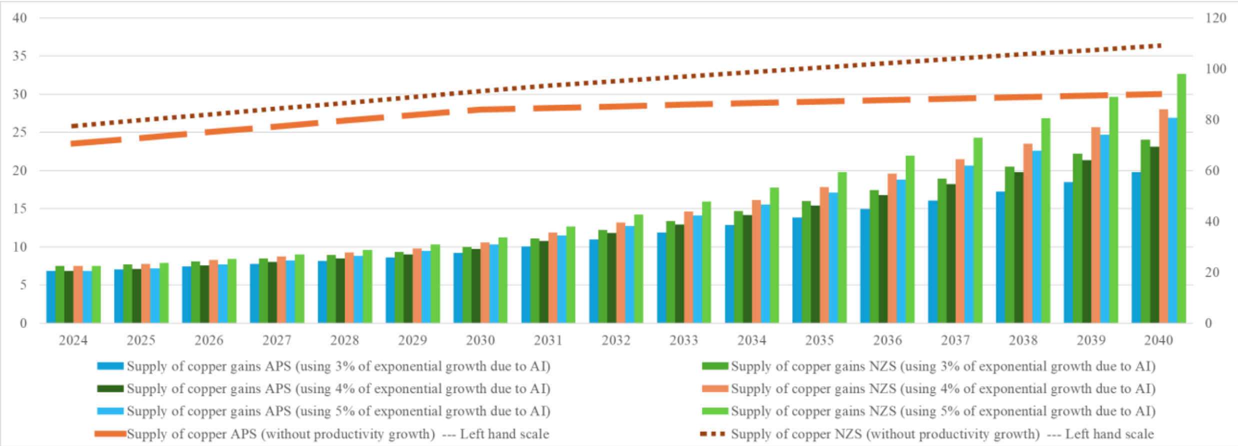


Fig 8: Supply gains from productivity growth via AI investment and recycling for copper. This figure illustrates projected copper supply under the APS and NZS**,** incorporating different assumptions about annual production gains enabled by AI and recycling. The left-hand y-axis (measured in tonnes) represents the total copper supply, while the right-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.

Summary finding and policy recommendations

Strategic stockpiling should be prioritised as a key policy instrument in order to ensure a stable and resilient supply of critical minerals amid rising demand and persistent geopolitical risks, Stockpiling can serve as a buffer against supply disruptions, reduce market volatility, and provide essential reserves during periods of geopolitical or economic instability.

Given the long lead times required to scale up production and the concentrated nature of global supply chains for both lithium and copper, government-led stockpiling schemes offer a cost-effective means to enhance energy security—particularly in resource-importing countries. This approach mirrors the logic underpinning historical strategic petroleum reserves, and is especially relevant under the IEA's NZS, where projected deficits are severe.

Table 2 summarises the potential to expand supply through technological and policy measures. For lithium, stockpiling must be complemented by significant gains in productivity, especially those enabled by AI. With recycling potential limited to less than 22 per cent by 2040[1] and substantial structural barriers—such as technological complexity, low recovery rates, and geographical concentration—AI-driven innovation is critical. Advances in exploration, automated extraction, and process optimisation are essential to reduce the projected supply gap, which may exceed 90 per cent by 2040 under the NZS.

For copper, the outlook is comparatively less constrained. While AI-driven productivity gains remain important, copper's stronger recycling potential—projected to increase by up to

37 per cent by 2040—provides a more robust pathway for mitigating shortages. Structural barriers are also lower, with established collection systems and widespread industrial reuse. Accordingly, a dual policy strategy that combines AI-enabled innovation with aggressive expansion of recycling and circular economy practices can significantly improve copper supply resilience. Meeting future mineral demand will require a three-pronged strategy: (1) the establishment of strategic stockpiles to manage risk and stabilise markets, (2) targeted investments in AI and digital technologies to improve productivity, and (3) accelerated development of recycling infrastructure, particularly for copper. Without coordinated action on all three fronts, critical mineral shortfalls will undermine global decarbonisation efforts.

Table 2: Summary of policy recommendations

Aspect	Lithium	Copper
Stockpiling	Critical	Critical
AI Productivity Gains	Critical	Very Important
Recycling Potential (IEA)[1]	<22% by 2040	Up to 37% by 2040
Structural Barriers	High (technological, geographical)	Low to moderate
Policy Priority	AI-driven innovation	AI-driven innovation and Recycling

Table 2 summarises the potential to expand supply through technological and policy measures. For lithium, stockpiling must be complemented by significant gains in productivity, especially those enabled by AI.

Methods

In this section we describe how we calculated geopolitical risk for copper and lithium at each stage of the supply chain and the underpinning assumptions and method used to estimate the stockpiling scenarios for copper and lithium under alternative IEA scenarios.

Geopolitical risk at each stage of the supply chain

Vespignani and Smyth[14] originally constructed non-technical/geopolitical risk indicators using proven reserve weights, by isolating the geopolitical component and applying it consistently across the full mineral value chain. We extend their approach to calculate geopolitical risk at each stage of the supply chain for copper and lithium. Let GPR_{res_m} denote the geopolitical risk score of country c. Then for a given mineral m, we define:

Geopolitical risk of proven reserves:

$$GPR_{res_m} = \Sigma \left[\omega_{res_c}, m \times G_c \right] \quad (1)$$

where ω_{res_c}, m is the share of global proven reserves of mineral m located in country c.

Geopolitical risk of refining:

$$GPR_{ref_m} = \Sigma \left[\omega_{ref_c}, m \times G_c \right] \quad (2)$$

where ω_{ref_c}, m is the share of global refining capacity for mineral m in country c.

Geopolitical risk of production:

$$GPR_{prod_m} = \Sigma \left[\omega_{prod_c}, m \times G_c \right] \quad (3)$$

where ω_{prod_c}, m is the share of global mine production of mineral m in country c.

Geopolitical risk of consumption:

$$GPR_{cons_m} = \Sigma \left[\omega_{cons_c}, m \times G_c \right] \quad (4)$$

where ω_{cons_c}, m is the share of global consumption of mineral m in country c.
Each ω term is a stage-specific weight such that the sum of all country shares for a given stage equals 1: $\Sigma\ \omega_c^j, m = 1\ for\ each\ stage\ j \in \{res, ref, prod, cons\}$. Data on weights are sourced from the U.S. Geological Survey[13] *Mineral Commodity Summaries*. The geopolitical risk data by country are obtained from Caldara and Iacoviello[17], who construct a monthly index of geopolitical risk based on automated text analysis of international news.

Stockpiling scenarios for copper and lithium

While the theoretical rationale for optimal stockpiling strategies is to minimize expected financial losses from geopolitical supply disruptions while accounting for the cost of storage (see Supplementary Information 2), empirical estimation is complicated by the heterogeneity of individual commodities. Differences in geopolitical exposure, geological complexity, geographic concentration, taxation and policy regulations and community attitudes toward mining present significant obstacles to designing uniform stockpiling frameworks. Drawing on the historical precedent of oil stockpiling—particularly the IEA's standard of maintaining reserves equivalent to 90 days of net imports - we apply similar logic to critical minerals. However, unlike oil, which can typically be developed within an average lead time of four years, the project development cycle for copper and lithium projects often exceeds 12 to 15 years[1,13]. This substantial discrepancy in supply responsiveness suggests that the required level of strategic reserves for critical minerals should be considerably larger to compensate for prolonged development timelines and heightened exposure to supply shocks[18]. Adopting this logic, we assume that the volume of net imports to be stockpiled should be proportional to the average time required for a project to progress 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.

We calculate stockpiling accumulation over time using a simple discrete-time model. Let $Stockpile_t$ represent the stockpile level at time t. The accumulation equation is given by:

$$Stockpile_t = Stockpile_{\{t-1\}} + \alpha \times Demand_t \qquad (5)$$

where α is the target stockpiling ratio (for example, 0.1 for 10 per cent of annual demand), and $Demand_t$ is the total demand in period t. This equation recursively accumulates stockpile levels by adding a fixed proportion of current demand each period.

To compute cumulative stockpiling over a time horizon T, the formula is expressed as:

$$Stockpile_T = \Sigma\ (from\ t = 1\ to\ T)\alpha \times Demand_t \qquad (6)$$

If demand grows over time at a constant growth rate g, such that $Demand_t = D^0(1 + g)^{t-1}$, then cumulative stockpiling becomes:

$$Stockpile_T = \alpha \times D^0 \times \frac{[(1+g)^T - 1]}{g} \qquad (7)$$

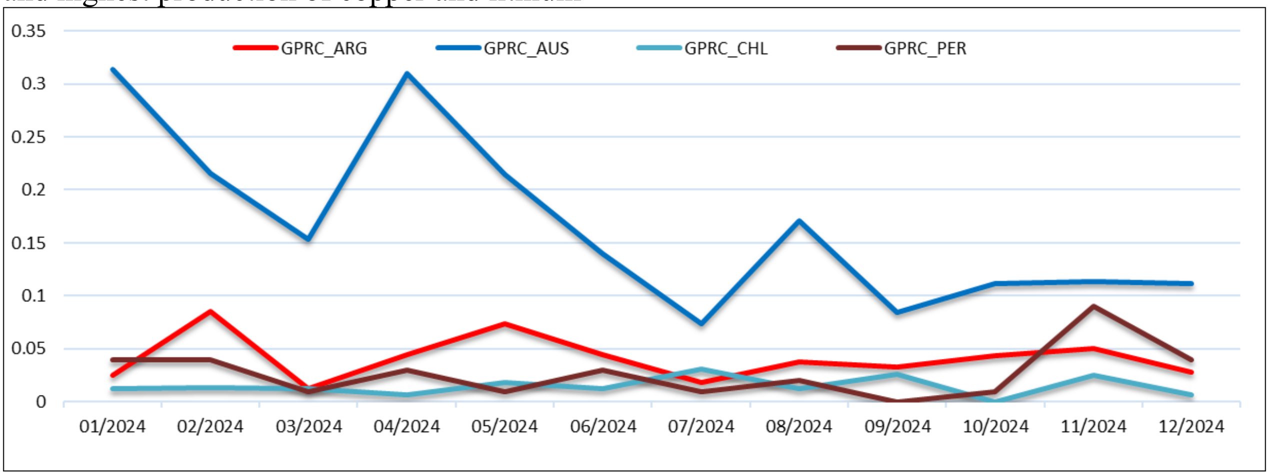
According to S&P Global Market Intelligence[22] copper stockpiles represent approximately 37 per cent of annual consumption, equivalent to around 95 days of demand coverage. While lithium stockpiling data is less clear, Pedersen and Jaswal[23] estimate that lithium inventories account for roughly 21 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.

Supplementary Information:

1. Geopolitical risk indicators (2024)

Supplementary Fig. 1 shows geopolitical risk indicators for the countries with the most reserves and highest production of copper and lithium in 2024. 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 consistently 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 Argentina coincides with broader regional uncertainty and the global impact of Trump's U.S. presidential election victory. Overall, the Fig. highlights important cross-country differences in geopolitical exposure, which are crucial for understanding vulnerabilities in the upstream stages of critical mineral supply chains.

Supplementary Fig. 1: Geopolitical risk indicators for the countries with the largest reserves and highest production of copper and lithium

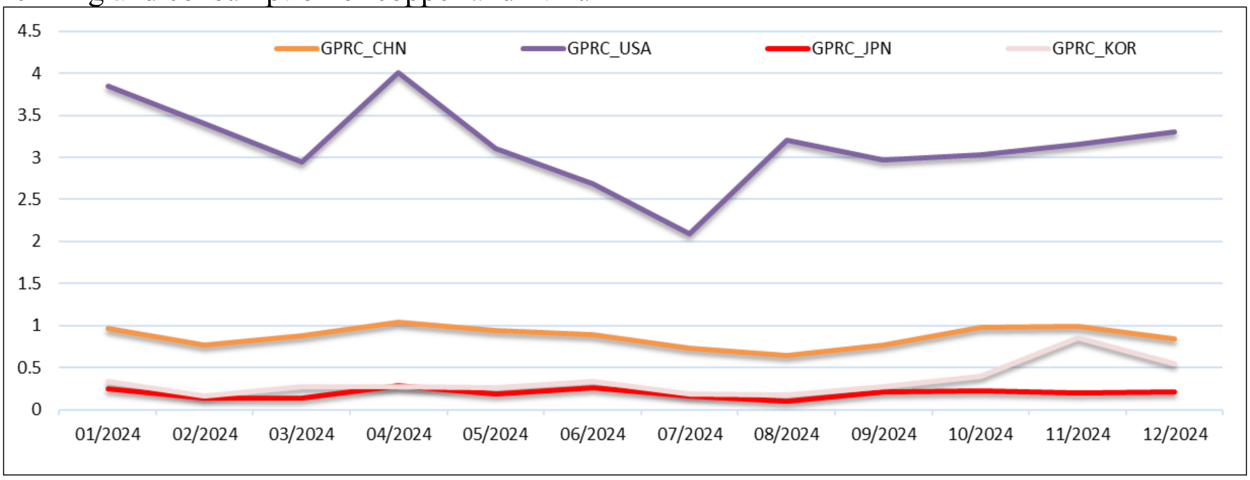


Supplementary Fig. 1 Geopolitical risk indicators for principal reserve and producer countries for copper and lithium. This figure displays the monthly geopolitical risk indicators for four major copper and lithium reserve and producer countries—Argentina (GPRC_ARG), Australia (GPRC_AUS), Chile (GPRC_CHL), and Peru (GPRC_PER)—from January to December 2024.

Supplementary Fig. 2 illustrates the monthly geopolitical risk indicators for key refining and consuming countries of copper and lithium—China (GPRC_CHN), the United States (GPRC_USA), Japan (GPRC_JPN), and South Korea (GPRC_KOR)—from January to

December 2024. The United States (GPRC_USA) consistently registers the highest geopolitical risk across the year, with a notable peak in April 2024, coinciding with heightened Middle East tensions and the Iranian attack on Israel, and again rising in November and December 2024 following the U.S. presidential election outcome. These fluctuations underscore the U.S.'s central role in global geopolitical dynamics. China (GPRC_CHN), while substantially lower than the U.S. in absolute terms, shows a steady risk profile with moderate fluctuations and a relative increase in the final quarter of 2024, likely reflecting anticipation of renewed trade frictions under a Trump presidency. South Korea (GPRC_KOR) displays an uptick in geopolitical risk around October–November 2024, possibly linked to security tensions with North Korea, while Japan (GPRC_JPN) maintains a low and stable risk profile throughout the year. Overall, Supplementary Fig. 2 highlights the heightened geopolitical exposure of major downstream actors in critical mineral supply chains. It reinforces the strategic importance of geopolitical diversification and the role of macro-political uncertainty—especially in the U.S. and China—in shaping global mineral market stability.

Supplementary Fig. 2: Geopolitical risk indicators for the principal countries involved in the refining and consumption of copper and lithium



Supplementary Fig. 2 Geopolitical risk indicators for principal refining and consumption 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), USA (GPRC_USA), Japan (GPRC_JPN), and South Korea (GPRC_KOR)—from January to December 2024.

2. Optimal stockpiling rule

We model the optimal storage strategy for 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 storage. The objective function is to minimize the total expected cost of either holding or not holding stock, which can be represented as follows:

$$\min_{\{S_t\}} E_t\left[C_{s(S_t)} + I_{\{shock_t\}} \cdot L_{t(S_t)} \right] \quad \text{S.1}$$

Where:
S_t = stock level at time t
$C_{s(S_t)}$ = cost of storage (convex, includes warehousing and depreciation)
$I_{\{shock_t\}}$ = indicator function (1 if geopolitical shock at time t, 0 otherwise)
$L_{t(S_t)}$ = financial loss due to insufficient stock during shock (decreasing in S_t)

Condition for Optimality:

The marginal cost of storage must be less than or equal to the marginal expected loss from insufficient reserves:

$$\frac{dC_{s(S_t)}}{dS_t} \leq P(shock_t) \cdot \frac{dL_{t(S_t)}}{dS_t} \quad \text{S.2}$$

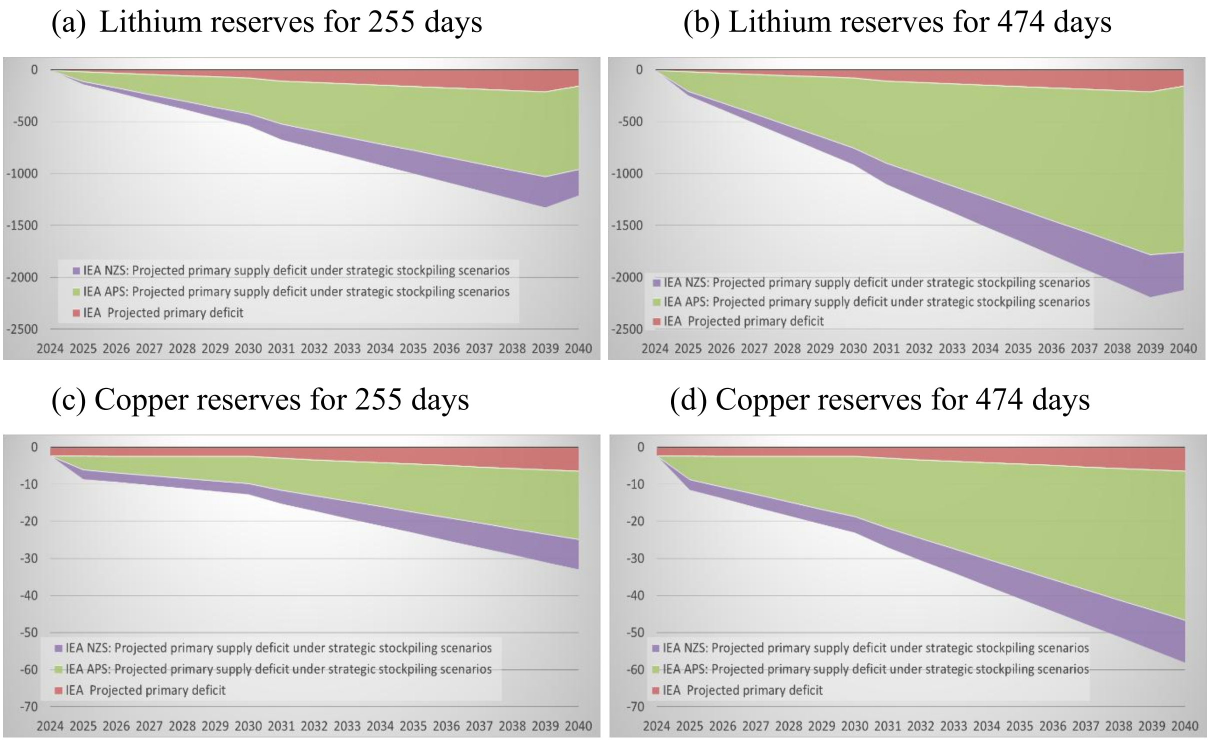
Optimal stockpile level S*_t is defined by the condition:

$$\frac{dC_{s(S*_t)}}{dS_t} = P(shock_t) \cdot \left|\frac{dL_{t(S*_t)}}{dS_t}\right| \quad \text{S.3}$$

Stockpiling is justified when the risk-adjusted expected financial loss from supply disruption is greater than the cost of maintaining inventory. The optimal storage strategy minimizes financial losses by balancing the probability-weighted impact of geopolitical shocks against storage costs.

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

Supplementary Fig. 3. present 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 kilotonnes (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.



Supplementary Fig. 3 | 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.

Data availability: The data is available in Excel format in the Source Data. Data sources are also provided in the Excel file.

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