Australian National University
Crawford School of Public Policy

CAMA

Centre for Applied Macroeconomic Analysis

Recycling or Stockpiling? Country-Specific Strategies for Securing EV Battery Critical Minerals

CAMA Working Paper 70/2025
December 2025

Yitian Wang
Monash University

Joaquin Vespignani
University of Tasmania
Centre for Applied Macroeconomic Analysis, ANU

Russell Smyth
Monash University
Centre for Applied Macroeconomic Analysis, ANU

Abstract

Accelerating transport electrification is vital for net-zero goals, yet remains hindered by slow, uncertain development of battery minerals. We show how non-technical risk, such as policy, regulatory, social, and geopolitical risk, inflate capital costs, delay greenfield supply, and heighten price volatility for lithium, cobalt, nickel, manganese, graphite, and copper. Combining Fraser Institute investment scores with reserve shares of these critical minerals, we construct dynamic, mineral-specific risk premiums, derive an optimal stockpiling rule balancing risk and storage costs and introduce a distance-to-iso-cost map comparing recycling and stockpiling strategies. Our framework suggests that in 2040 recycling-led stabilization will be the optimal strategy for mitigating non-technical risk for Japan and Korea, strategic stockpiling will be the optimal strategy for China and the United States, and mixed outcomes for Europe. The method that we propose provides a tractable and updateable toolkit for deciding optimal stockpiles and prioritising recycling where it is most cost-effective.

Keywords

recycling, stockpiling, critical minerals, EV battery

JEL Classification

Q38, Q41, Q32, F51, G32

Address for correspondence:

(E) cama.admin@anu.edu.au

ISSN 2206-0332

Recycling or Stockpiling? Country-Specific Strategies for Securing EV Battery Critical Minerals

Yitian Wang [a], **Joaquin Vespignani** [b c], **and Russell Smyth** [a c]

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

Abstract

Accelerating transport electrification is vital for net-zero goals, yet remains hindered by slow, uncertain development of battery minerals. We show how non-technical risk, such as policy, regulatory, social, and geopolitical risk, inflate capital costs, delay greenfield supply, and heighten price volatility for lithium, cobalt, nickel, manganese, graphite, and copper. Combining Fraser Institute investment scores with reserve shares of these critical minerals, we construct dynamic, mineral-specific risk premiums, derive an optimal stockpiling rule balancing risk and storage costs and introduce a distance-to-iso-cost map comparing recycling and stockpiling strategies. Our framework suggests that in 2040 recycling-led stabilization will be the optimal strategy for mitigating non-technical risk for Japan and Korea, strategic stockpiling will be the optimal strategy for China and the United States, and mixed outcomes for Europe. The method that we propose provides a tractable and updateable toolkit for deciding optimal stockpiles and prioritising recycling where it is most cost-effective.

Keywords: Recycling; Stockpiling; Critical minerals; EV Battery
JEL Codes: Q38, Q41, Q32, F51, G32

Introduction

Battery technologies lie at the core of the global transition to clean energy. Unlike fossil fuels that store energy intrinsically, renewable energy sources require external storage systems to ensure stability and reliability, which makes batteries indispensable. As highlighted by the International Energy Agency (2025c), the rapid adoption of electric vehicles (EVs) as a climate mitigation strategy has generated a rapid increase in global battery demand. In 2024, demand from the energy sector—including EV batteries and stationary storage—surpassed an historic milestone of 1 TWh, with weekly average demand exceeding the entire annual demand recorded just a decade earlier. The acceleration in the shift toward clean energy, particularly through large-scale EV deployment, is expected to generate unprecedented demand for the critical minerals required in battery production (Horn et al., 2021; Dou et al., 2023; International Energy Agency, 2025b). According to the International Energy Agency (2021b), meeting the Paris Agreement target of limiting global warming to *"well below 2°C"* will necessitate a fourfold increase in mineral demand for clean energy technologies by 2040.

Despite robust demand projections, investment in critical mineral projects remains constrained by significant uncertainty (International Energy Agency, 2025b). A major source of this uncertainty lies in non-technical risks, such as regulatory uncertainty, political instability, permitting delays, community opposition, and environmental litigation, which can disrupt supply chains, increase prices, and ultimately constrain battery production, thereby slowing the clean energy transition (Kang et al., 2025). These risks are exacerbated by the geographic concentration and long development timelines characteristic of critical minerals, leaving their supply chains more fragile than those of traditional fossil fuels (IEA, 2021b).

One way to ensure a stable supply of these minerals is via strategic stockpiling. A complementary approach to ensuring energy security is through recycling. As recycling technologies improve and the availability of secondary feedstock (i.e., end-of-life batteries) expands, recovered materials can increasingly be reintegrated into new battery production (Ma et al., 2024). This process generates a valuable secondary supply and reduces reliance on new mining projects, which is an advantage over fossil fuels that cannot be reused. The International Energy Agency (2024a) estimates that successful scaling of recycling could reduce the need for new mining by 25-40 % by 2050 in a scenario consistent with national climate pledges.

Therefore, the energy transition raises a practical question for market design: how should countries combine secondary supply from recycling with buffer stockpiling to stabilize EV battery raw mineral markets when facing significant energy security challenges due to high non-technical risks and long development timelines? Development lead times for lithium, nickel and copper frequently span one to two decades, and rising geopolitical risks make project delays increasingly likely (Mejía & Aliakbari, 2023). These factors further raise required returns, delay investment, and contribute to price volatility. In this paper we combine risk-aware project economics with commodity-stabilization instruments to provide a tractable toolkit for sizing strategic stockpiles and prioritising recycling where it is most cost-effective.

Our first contribution is to construct time-varying global non-technical risk premiums for each of the six battery-related critical minerals: lithium, cobalt, nickel, manganese, graphite, and copper, and construct an integrated measure of non-technical risk premiums for major EV battery chemistries (LFP, NMC523, NMC622, NMC811, and NCA), enabling us to assess supply-chain vulnerabilities arising from policy and governance uncertainty.

Our second contribution is to develop an optimal stockpiling model that embeds these risk premiums. The model yields a closed-form rule in which the recommended reserve rises with risk exposure and falls with storage costs. We operationalize the optimal stockpiling model to produce country and regional specific stockpile requirements for 2030 and 2040, highlighting the critical role of graphite and nickel in future stabilization needs.

Our third contribution is to present a relative-cost classification for choosing between recycling and stockpiling as stabilization instruments. We develop two comparable indices—the relative cost of stockpiling (RCS) (a real-estate pressure proxy scaled by population density and target stockpiling) and the relative cost of recycling (RCR) (a logistics proxy scaled by country size and projected end-of-life battery flows)—and position each country/region–mineral pair in this two-dimensional space. Furthermore, we propose that the signed distance to the 45-degree iso-cost line provides a simple way for discerning which instrument is optimal: points below the line favour recycling and points above favour stockpiling, while the distance from the line measures the intensity of the incentive to engage in either response.

Using this framework, we find systematic cross-regional patterns with direct policy implications. Korea and Japan sit predominantly in the recycling-favourable region for lithium, cobalt, nickel, manganese, graphite, and copper, reflecting dense industrial ecosystems and recoverable end-of-life streams in these countries. China and the United States lie in the stockpiling-favourable region, with a stronger stockpiling advantage for the United States, consistent with higher implied collection and logistics costs relative to storage. The European Union demonstrates a moderate near-term advantage in stockpiling for nickel and graphite, though this position is expected to erode as recycling competitiveness strengthens with the scaling up of take-back systems. These findings reconcile the temporal supply mismatch: in the 2020s, stockpiling remains essential for managing EV battery supply chain risks; in the 2030s, recycling capacity and end-of-life flows will assume greater importance; and in the longer term, secondary supply can be expected to become the dominant stabilizer.

The remainder of the paper proceeds as follows. In the next section, we present a conceptual framework for understanding the relationship between non-technical risk premiums, storage and recycling for EV battery minerals. In the results section, we construct annual mineral- and battery-level non-technical premiums since 2011, report mineral- and region-specific optimal stockpiling requirements for 2030 and 2040, and compare the RCR and RCS for China, Europe, Japan, Korea and the United States to generate an interpretable set of country-by-mineral recommendations. We conclude this section with a policy discussion that translates the quantitative results into country-specific stabilization mixes and governance guidelines, and discuss how annual data updates can be employed, in order to recalibrate recommendations as technologies, deployments and policy settings evolve. Finally, the methods section details the computational steps used to estimate non-technical risk premiums, optimal stockpile requirements, and the RCR and RCS measures.

Conceptual framework

Battery-mineral mining: Non-technical risk premiums and the role of stockpiling

The development of battery-critical mineral projects is shaped not only by geological and technical factors but also by various non-technical risks significantly impacting investment decisions and supply outcomes. The non-technical risk premium of critical minerals relative to non-critical minerals represents the additional returns investors require on critical mineral projects to compensate for uncertainty arising from political instability, regulatory complexity, social opposition, and environmental litigation (Vespignani & Smyth, 2024). In mining critical minerals, non-technical risks are especially pronounced due to long project development horizons, high upfront capital requirements, and irreversible investment costs. Consequently, the cost of capital in high-risk jurisdictions can increase significantly, affecting both the feasibility and timing of new mining projects (Renaud & Kumral, 2021).

Mining projects for lithium, cobalt, nickel, graphite, manganese, and copper, which are key inputs for EV batteries, typically have development timelines ranging from seven to 25 years, from initial exploration to commercial production (American Battery Technology Company, 2022; Avocet Electrofoils, 2024; IEA, 2021b; IEA, 2022; Jones et al., 2023). During this period, capital investments remain exposed to regulatory delays, uncertainty around obtaining a social license, and changing market conditions (Manalo, 2024; Manalo, 2025).

Table 1 summarizes estimated global lead times from discovery to production for each of the six critical minerals, which is compiled based on recent industry reports from S&P Global, the IEA, and selected project case studies. The table reports both average lead times and observed ranges, highlighting variability across projects, with global average lead times for these six battery-related minerals typically exceeding 15 years.

Lead times vary by mineral. According to S&P Global, the average global lead time from discovery to production for lithium projects that became operational between 2020 and 2024 was 20.5 years (Manalo, 2025). The corresponding lead times for nickel and copper mines were 22.4 and 17.2 years, respectively (Manalo, 2025). Lead times vary significantly across countries and projects. Andrade et al. (2024) found regional differences in lead time for lithium projects ranging from four to 27 years, with the longest lead time in Europe. North America also had relatively long development timelines, while Australia had shorter timelines. For copper projects, Khan et al. (2016) reported longer lead times in Europe and Central Asia, with shorter durations in Sub-Saharan Africa. Individual mineral projects also exhibit variability. For example, in Indonesia, the Weda Bay nickel projects required 24 years, while the Oracle nickel project took 29 years (Manalo, 2025). Similarly, in the Democratic Republic of Congo (DRC), the Kisanfu copper project took 18 years from discovery to production, compared to only 12 years for the Pumpi copper project (Manalo, 2025).

Importantly, mine lead times are getting longer. According to Manalo (2025), the global average lead time for major mines that became operational between 1990 and 1999 was 6.4 years. This figure increased to 10.6 and 15.5 years for major mines that became operational from 2000-09 and 2010-19. For projects that came online between 2020 to 2024, the average lead time was 17.9 years, which is nearly three times longer than for projects that became operational between 1990 and 1999. The trend upwards in average mine lead times can be attributed to prolonged exploration, permitting, financing, and study phases, as well as the extended waiting period between the completion of feasibility studies and the start of construction (Manalo, 2025). Deloitte Global (2025) warned that without a radical reduction in development timelines, critical mineral shortages could emerge before 2030.

Extended project timelines pose greater challenges for battery critical minerals, resulting in longer pre-revenue periods, increased cumulative costs, and difficulties securing financing for early-stage discoveries with distant production prospects (Zadeh, 2025). Mitchell (2024) identified capital attraction and management as the top risk for mining companies in

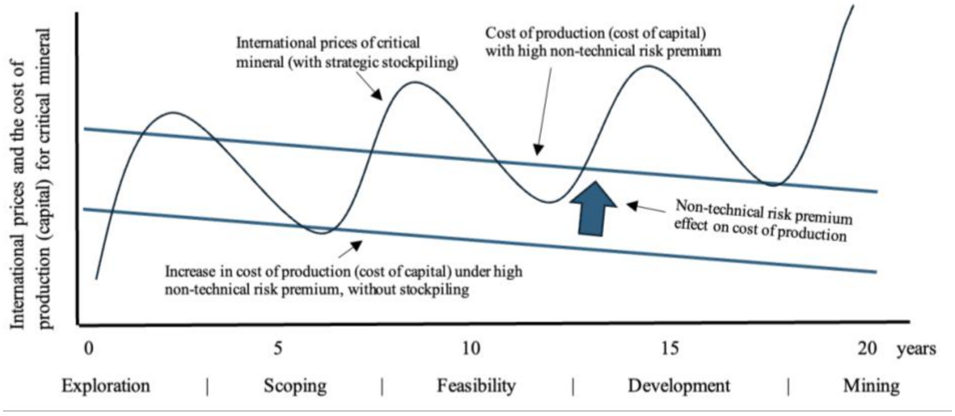
2025. Given the industry's capital-intensive nature, insufficient risk-adjusted returns can lead to adverse financial conditions for mining companies, potentially causing critical mineral project delays or cancellations, thus exacerbating future supply shortages and price volatility (Bullock & Mernitz, 2017; Azevedo et al., 2022; Kelly, 2025; Mack, 2025).

Mineral	Global Average Lead Time for Mines that Became Operational Between 2020-24[a]	Global Lead Time Range	Key Examples[g]
Lithium	20.5 years.	4-27 years[d]	- Finniss Lithium Project in Australia (Startup year 2023): 27 years. - Cauchari-Olaroz Lithium Project in Argentina (Startup year 2023): 14 years. - Altura Lithium Project in Australia (Startup year 2018): 9 years.
Cobalt	22.4 years[b]	11-29 years[e]	
Nickel	22.4 years.	11-29 years[e]	- The Celestial mine in the Philippines 29 years. - The Eagle Nickel Project in Michigan (Startup year 2014): 12 years. - Oracle Nickel Project in Indonesia (Startup year 2023): 29 years. - Weda Bay Nickel Project in Indonesia (Startup year 2020): 24 years. - Avebury Nickel Project in Indonesia (Startup year 2008): 11 years.
Manganese[c]	17.9 years.	6-32 years[e]	- Tshipi Borwa Manganese Project in South Africa: ~6 years.
Graphite[c]	17.9 years.	6-32 years[e]	- Molo Graphite Mine: ~12 years.
Copper	17.2 years.	8-32 years[f]	- Khoemacau Copper Project in Botswana (Startup year 2021): 24 years. - Kisanfu Copper Project in the DRC (Startup year 2023): 18 years. - Pumpi Copper Project in the DRC (Startup year 2020): 12 years. - Marcona Copper Project in Peru (Startup year 2021): 20 years. - Zhibula Copper Project in China (Startup year 2020): 14 years.

Table 1 | Average lead times from discovery to production for selected critical minerals. This table summarizes the global average development timelines for lithium, cobalt, nickel, manganese, graphite, and copper based on recent industry reports and selected project case studies. The lead time for mining projects encompasses discovery, exploration, technical and feasibility studies, a waiting period post-feasibility, and the construction-to-production phase. (a) Global average lead time data for lithium, nickel, and copper are sourced from S&P Global. (b) Nickel project lead times serve as proxies for cobalt due to their common co-mined occurrence. (c) Limited data availability necessitates using the general base-metal average lead time as proxies for manganese and graphite. (d) The lead times of 397 lithium projects across different regions, tracked between 2004 and 2022 (Andrade et al., 2024). (e) Tracked between 2002 and 2023 (S&P Global: Manalo, 2023). (f) Tracked between 2001 and 2015 (S&P Global: Manalo, 2025). (g) Key project examples for lithium, nickel and copper are from S&P Global (Manalo, 2025). Nickel project examples also apply to cobalt due to their co-mined occurrence. The manganese example is from Jupiter Mines Limited (2012), and the graphite example is from NextSource Materials (n.d.; 2025).

Fig. 1 illustrates the dynamic relationship between international prices and production costs (including the cost of capital) for EV battery critical minerals across the project development lifecycle. International EV battery critical mineral prices experience exogenous fluctuations driven by global business cycles and industrial demand shocks, introducing volatility independent of underlying project fundamentals (Jacks et al. 2011). Concurrently, baseline production costs gradually decrease over time due to cumulative technological advancements, economies of scale, and learning-by-doing throughout each of the exploration, development, and mining phases (Tilton & Guzmán, 2016).

(a) Impact of non-technical risk premium on production cost, cost of capital, and critical mineral prices



(b) Impact of stockpiling on production cost, cost of capital, and critical mineral prices

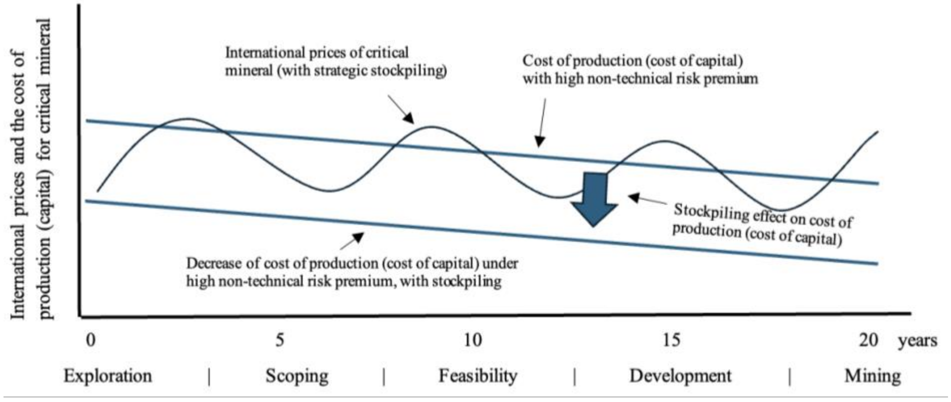
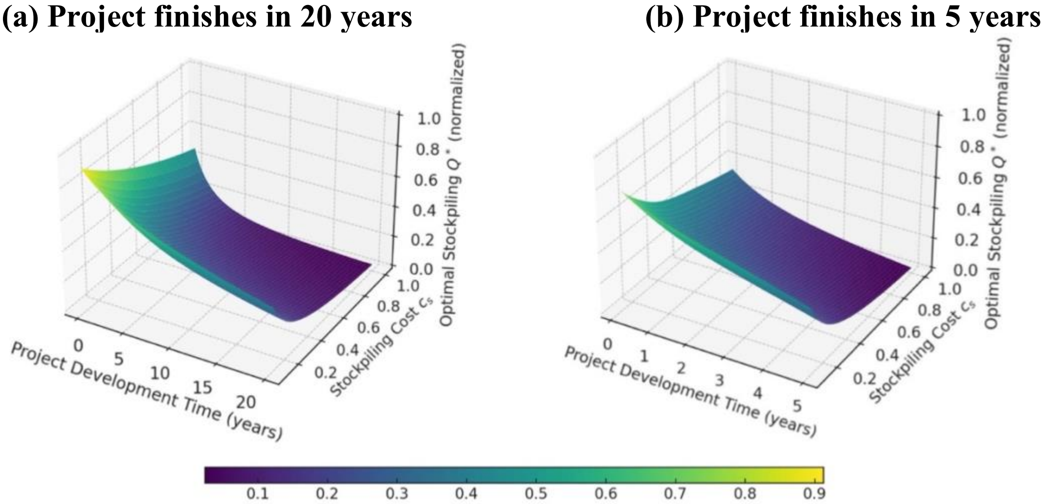


Fig. 1 | Dynamic relationship between international prices and production costs (including the cost of capital) for critical minerals across the project development lifecycle. Panel (a) depicts the effects of non-technical risk premiums on production, capital costs, and international critical mineral prices when no stockpiling is undertaken. Panel (b) shows how strategic stockpiling offsets production and financing costs in the presence of high non-technical risk premiums.

Panel (a) of Fig. 1 depicts the scenario without strategic stockpiling, where high non-technical risk premiums elevate the cost of capital. Higher capital costs drive up overall production costs and reduce investment certainty, generating wider and more volatile price-cost gaps. Over time, chronic supply constraints in such high-risk environments contribute to a persistent upward drift in prices, as investors demand higher returns to compensate for uncertain project timelines and risk exposure (Vespignani & Smyth, 2024; Kang et al; 2025).

In contrast, panel (b) of Fig. 1 shows how strategic stockpiling mitigates these pressures**.** By lowering perceived investment risk, stockpiling reduces the non-technical risk premium, consequently lowering the cost of capital and production. Price fluctuations become less pronounced, stabilizing at lower levels compared to panel (a). This improves alignment between market prices and underlying costs but also reduces the overall economic burden of the energy transition**,** enhancing the affordability of clean energy technologies.

These dynamics highlight two critical channels through which non-technical risks impact critical mineral markets. The first is a risk-driven cost channel: elevated non-technical risk premiums increase the cost of capital, raising overall production costs. This effect contributes not only to higher marginal costs for projects but also to elevated and more volatile market prices, as investors demand greater returns for uncertainty. The second is the stabilization dividend of strategic stockpiling (Vespignani & Smyth, 2024; Kang et al; 2025): by reducing perceived supply-side risks, stockpiling lowers the non-technical risk premium, thereby decreasing the cost of capital and production costs. It also leads to lower overall price levels and dampens price volatility - stabilizing investment and improving affordability. In this way, stockpiling serves a dual role; it serves as both a financial stabilizer and market price anchor, lowering the economic cost associated with the clean energy transition.


(a) Project finishes in 20 years

(b) Project finishes in 5 years

Fig. 2 | Project development timelines, stockpiling costs, and optimal stockpiling levels. Panel (a) represents battery-critical minerals with a long project development timeline (20 years), while Panel (b) depicts minerals with a short development timeline (5 years). Both panels illustrate how varying project durations and stockpiling costs influence optimal strategic stockpiling levels.

Fig. 2 illustrates how the optimal level of strategic stockpiling required to ensure supply security and price stability is jointly determined by the duration of project development and the associated cost of maintaining reserves. When a project is at an early development stage or when the cost of maintaining reserves is relatively low, the optimal stockpiling quantity tends to increase, helping to ensure supply security and mitigate price volatility. Additionally, minerals with longer development horizons (panel (a)) exhibit greater vulnerability to supply shocks and investment delays, requiring a higher optimal stockpile to stabilize markets and mitigate investment risk. Conversely, minerals with shorter timelines (panel (b)) can more readily adjust to market dynamics, resulting in a lower optimal reserve size. Overall, when stockpiling costs and development stages are comparable, projects with longer development durations tend to require greater optimal stockpiling to mitigate risks over extended timelines.

In Supplementary Information Section 1, we develop a theoretical framework that links project development timelines, non-technical risk premiums and incentives for strategic stockpiling in critical minerals. The model captures the declining trajectory of non-technical risk premiums over the project timeline and shows that a higher premium raises the cost of capital for mining investment and increase the risk of project cancellation. To capture welfare losses arising from project delays, we introduce a stockpiling incentive function that increases with project duration. Its logarithmic form makes the function more sensitive to early delays, reflecting that small disruptions at initial stages can generate disproportionately large welfare impacts. The inclusion of a squared term ensures non-negative losses and emphasises that welfare losses escalate with longer development timelines. Building on this framework, we define an adjusted non-technical risk premium that incorporates the mitigating role of strategic stockpiling. The cost-minimization objective for determining the optimal stockpiling level of a battery-critical mineral balances two competing costs: the expected risk of disruption and the cost of holding inventory. Solving this problem yields a closed-form expression for the optimal stockpile size. Our theoretical model highlights that that optimal stockpiling increases with risk exposure and decreases with storage cost, highlighting that stockpiling is an effective strategy to mitigate non-technical risk and enhance investment resilience.

Geographical concentration and non-technical risk premiums

The geographical concentration of critical mineral proven reserves serves to further amplify non-technical risk premiums. Unlike coal and oil, which have relatively broad geographic distributions, critical energy-transition minerals are heavily concentrated in a few geopolitically riskier countries. Many of these nations experience significant political and regulatory instability. Consequently, geopolitical shocks disproportionately affect global supply chains for these minerals, raising the non-technical risk premium. Minerals exhibiting both high geographic concentration and elevated country-level non-technical risks are particularly vulnerable to investment delays, exacerbating supply bottlenecks.

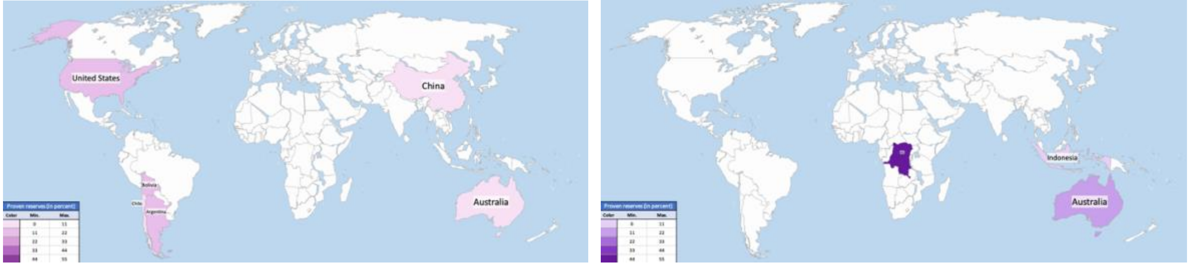
Fig. 3 shows that proven reserves of the six critical minerals essential for battery production were highly concentrated in relatively few countries in 2024, creating significant geopolitical and supply-chain vulnerabilities. Geographical concentration is most pronounced for cobalt, with the DRC holding a near-monopolistic position compared to secondary reserves in Australia. Lithium reserves are predominantly located in South America’s "Lithium Triangle" (Argentina, Bolivia, and Chile), creating a regional chokepoint. This distribution highlights significant geopolitical vulnerabilities. Nickel supply is similarly reliant on a single dominant nation, Indonesia, with Australia and Brazil holding substantial secondary shares.

China had the largest proven reserves of graphite in 2024, followed by Brazil. Given graphite’s crucial role as a battery anode material (Zhao et al., 2022; Robin, 2024; IEA, 2025b), the concentrated distribution underscores significant supply-chain vulnerability. In contrast, manganese and copper reserves are relatively more dispersed, yet still concentrated among a limited number of countries. Manganese primarily comes from South Africa, Australia, China, and Brazil. Copper reserves, though broader, are concentrated in Chile and Peru along South America’s west coast, with substantial reserves also found in Australia.

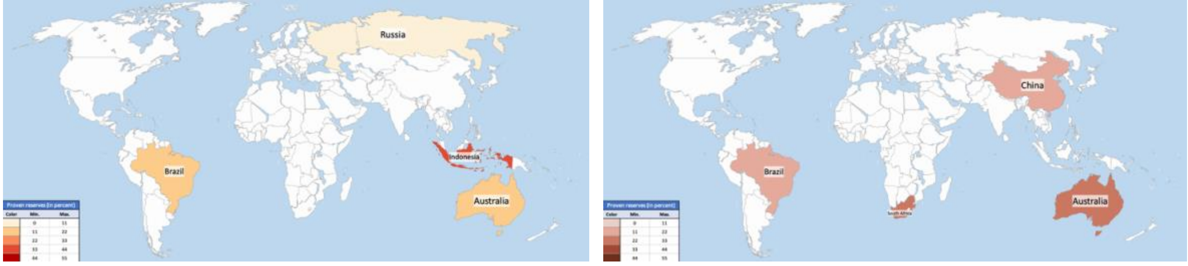
In Supplementary Information Section 2, detailed information is provided on the annual country-level percentage of proven reserves for these six critical minerals in countries with a proven reserve share of a given battery metal greater than 10 percent from 2011 to 2024. Proven reserve distributions fluctuate due to extraction activities, discovery of new deposits, changes in extraction viability, or revisions in resource classification standards. Over time, reserve concentrations have shifted, notably declining in favorable investment locations such as Australia and Chile, while rising in less attractive countries like Argentina, China, and Indonesia. Additionally, persistent dominance by countries with higher uncertainty, such as the DRC and South Africa, heightens geopolitical risks for battery-related minerals.

Supplementary Table S1 presents annual data on the proven reserve shares of the six critical minerals from 2011 to 2024 across countries with significant reserve holdings. Lithium reserves have become increasingly concentrated in Argentina over time, overtaking Chile in terms of reserve holdings. Moreover, although Bolivia’s share of global lithium reserves has been declining, as of 2024 its shares were still comparable to Argentina. Indonesia’s share of nickel reserves increased notably post-2017, overtaking Australia’s previous dominance. Since 2011, Brazil’s share of global graphite reserves has increased substantially, accompanied by a corresponding decline in China’s share. Nevertheless, as of 2024, China remains the country with the largest share of global graphite reserves. Unlike these shifting patterns, cobalt and manganese reserves remain consistently dominated by the DRC and South Africa, respectively. The distribution of copper reserves over the period has remained relatively stable, with Chile experiencing a notable decrease from 27.5 percent in 2011 to 19.4 percent in 2024.

(a) Lithium **(b) Cobalt**



(c) Nickel **(d) Manganese**



(e) Graphite **(f) Copper**

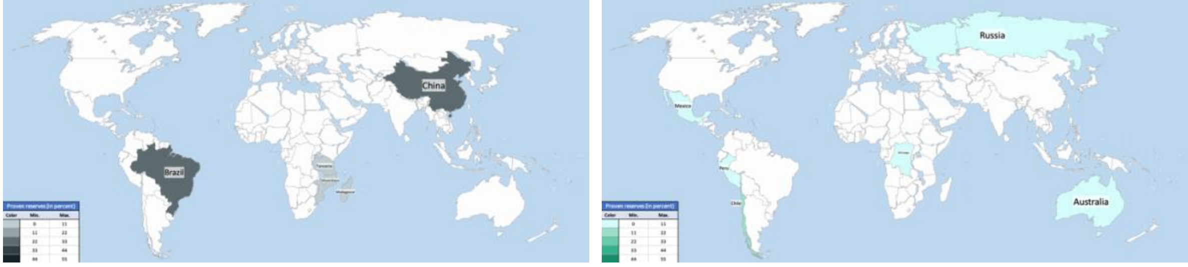


Fig. 3 | Geographic concentration of critical battery mineral reserves in 2024. This figure maps the global distribution of proven reserves in 2024 for (a) lithium, (b) cobalt, (c) nickel, (d) manganese, (e) graphite, and (f) copper. The heat maps highlight countries with major reserves, defined as possessing over 5 percent of the global total for each mineral.

The investment attractiveness of countries with significant mineral reserves

Since proven reserves of battery-related critical minerals are highly geographically concentrated, elevated political and regulatory uncertainty, geopolitical instability, and environmental constraints in these host countries increase non-technical risk premiums for these minerals. Fig. 4 presents the Fraser Institute's average Investment Attractiveness Index (IAI) scores for countries with major reserves of the six EV battery critical minerals from 2011 to 2024, with higher scores indicating more attractive investment conditions. Detailed annual IAI data by country from 2011 to 2024 are described in Supplementary Information Section 3. Over the period, Chile had the highest average IAI score among countries with major reserves, yet experienced considerable volatility, attributable to periodic policy uncertainty, tax regime reforms, constitutional changes, and episodes of social unrest (Cerda et al., 2016; Castiglioni, 2022). Countries like Australia and the United States demonstrate high, relatively stable IAI scores, attributed to political stability, transparent regulatory framework, ethical sourcing standards, and a skilled mining workforce (Schandl et al., 2023; Australian Trade and

Investment Commission, 2024). Although Australia and the United States experienced declines, they consistently maintained a high attractiveness level (see Supplementary Table S2).

Conversely, countries such as Bolivia, China, and the DRC show relatively low and volatile IAI scores, reflecting challenging investment environments. Supplementary Table S2 presents detailed trends in national IAI scores between 2011 and 2024. The DRC continues to struggle with political instability, weak governance, and significant extraction difficulties (Burnley, 2011; Denisova & Kostelyanets, 2023; Balyaminu et al., 2025). Bolivia's investment attractiveness has remained consistently low, briefly reaching a high point in 2019 before declining again to a persistently low level. Owing to an insufficient number of survey responses from China, the Fraser Institute did not report China's 2024 scores in its 2025 report (Mejía & Aliakbari, 2025). According to the 2024 report, China's IAI score had fallen sharply - by 69 percent compared to 2011 - making it the least attractive investment destination for mining countries among countries with significant EV battery mineral reserves by 2023.

```
SUMMARY STATISTICS

Top 3 Countries:
  1. Chile: 75.14
  2. United States: 72.15
  3. Australia: 71.78

Bottom 3 Countries:
  1. Bolivia: 43.77
  2. China: 48.78
  3. India: 49.89

Statistical Measures:
  Mean: 59.87
  Median: 58.63
  Std Dev: 9.67
  Range: 31.37

Tier Breakdown:
  Tier 1 (≥70): 3 countries
  Tier 2 (60-69): 3 countries
  Tier 3 (50-59): 4 countries
  Tier 4 (<50): 3 countries
```

Fig. 4 | Average Investment Attractiveness Index and volatility for key mineral reserve holders (2011-2024). This figure presents the average Fraser Institute Investment Attractiveness Index for major mineral reserve-holding countries from 2011 to 2024. The blue error bars in the top-left figure depict standard deviations, indicating the volatility of investment attractiveness within each country's mining sector. The analysis includes key mineral reserve holders, defined as countries with a proven reserve share greater than 10 percent for at least one critical battery mineral.

Supplementary Table S3 presents detailed subnational IAI values for the United States, Australia, and Argentina, which have significant concentrations of mineral reserves.[1] The

---

[1] These are the only three countries with significant reserves of these critical minerals for which the Fraser Institute produces subnational IAIs.

distribution of mineral reserves can also vary considerably across different regions within a country. Provincial or state governments can exert significant authority over mining policy, meaning that policy environments have the potential to be shaped more by subnational jurisdictions than by national governments (Mejía & Aliakbari, 2025).

Recycling and battery-mineral market stability

By building a predictable secondary supply of lithium, nickel, cobalt, manganese, copper and graphite, higher recycling rates can reduce dependence on primary extraction and help dampen price spikes (IEA, 2024a). In the near term, manufacturing scrap is likely to provide the primary means of stabilization, as end-of-life EV packs only begin to scale materially from the early-to-mid 2030s. Multiple assessments suggest that scrap will remain the dominant recycling feedstock until around 2040 (IEA, 2024b; IEA, 2025a; NREL, 2025). Accordingly, recycling and stockpiling should be viewed as complementary strategies for market stabilization. Expanding recovery and refining of recycled materials in the near-term can help to build a future secondary buffer, while simultaneously increasing targeted stockpiles to manage short-run volatility and safeguard the deployment of EVs (IEA, 2024a).

Results and discussion

Non-technical risk premium for battery storage minerals

The overall non-technical risk score for each mineral is derived from the IAI values, weighted by each jurisdiction's share of global proven reserves. We further decompose this score into two components—best practice and policy perception—corresponding to the respective dimensions of the IAI. These components capture policy-related and pure-mineral non-technical risks, respectively. Non-technical risk scores fluctuated over the period 2011-2024, with the policy perception score varying more strongly than the best practice score and, therefore, exerting a more dominant influence on overall non-technical risk.

The degree of volatility differs across minerals. For example, cobalt exhibits the greatest variability due to its high proven reserve concentration in the DRC, a politically less stable jurisdiction. Nickel remained relatively stable in earlier years, but its volatility has increased markedly in recent years as proven reserves shifted from Australia to Indonesia. Most minerals show a pronounced decline in scores after 2020, indicating rising non-technical risks in recent years. Details of the non-technical risk scores for each critical mineral are provided in the Methods, Supplementary Information Section 4, and in the Supplementary Data File.

Based on the non-technical risk score, the non-technical risk premium represents the additional returns required by investors to compensate for risks unrelated to technical operations, including political and regulatory uncertainty, geopolitical instability, and environmental constraints. These premiums are typically more pronounced in critical mineral projects compared to fossil fuel investments (Trench et al., 2014), reflecting differences in the investment characteristics and associated risks. As discussed above, critical minerals often face longer development timelines and have geographically concentrated reserves, especially when reserves are located in politically less stable countries, as depicted in Fig. 1.

We calculate the non-technical risk premium of each of the battery-related critical minerals. The methodology for calculating the non-technical risk premium of battery-related critical minerals is described in the Methods and the Supplementary Data File. Each critical mineral exhibits a non-technical risk premium relative to coal - a benchmark fossil fuel - indicating their comparative investment attractiveness. Higher non-technical premiums signify lower investment attractiveness. As Fig. 2 illustrates, investment attractiveness varies among countries with substantial mineral reserves. Minerals concentrated in countries with lower IAI score have higher non-technical risks and larger non-technical risk premiums.

Fig. 5 illustrates annual trends in non-technical risk premiums for the six critical minerals from 2011 to 2024, categorized into two panels based on their functional roles in battery production. Panel (a) comprises core cathode metals - lithium, cobalt, and nickel - which are predominantly used in battery cathodes and are partially substitutable depending on performance and cost. Panel (b) includes anode and support metals - manganese, graphite, and copper - which are essential in anodes or as conductive structural materials. In 2024, the non-technical risk premiums for all six critical minerals were positive. Trends in the non-technical risk premiums highlight significant investor concern as to their primary source countries.

Among cathode metals in Panel (a) of Fig. 5, cobalt's non-technical risk premium exhibits considerable volatility and is high for the majority of the time, notably spiking in 2019 and 2021 due to declining investment attractiveness in the DRC, which has approximately 50 percent of global reserves. Key factors include the late-2019 closure of Glencore's Mutanda mine, which is the world's largest cobalt operation, and subsequent COVID-19 disruptions in 2020, significantly increasing investor uncertainty which further drove up the non-technical risk premium in 2021 (Cobalt Institute, 2021; Ellis, 2020; Reid & Holland, 2020). Lithium's premium exhibits slight fluctuations, generally staying positive except for minor dips below zero in 2011 and 2023. Nickel's premium remains relatively stable, fluctuating around zero,

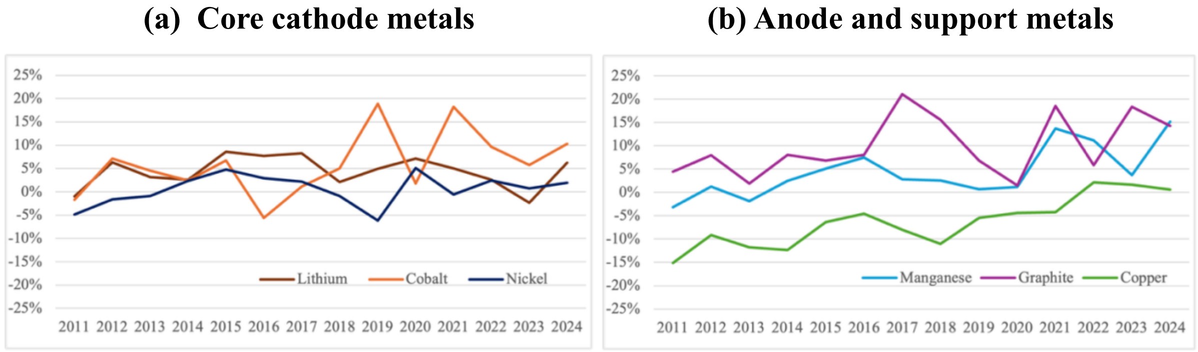


Fig. 5 | Annual non-technical risk premium for critical battery minerals (2011-2024). The figure illustrates annual overall non-technical risk premiums for six critical minerals from 2011 to 2024, grouped into two panels based on their primary functions in battery technology. Panel (a) consists of core cathode metals - lithium, cobalt, and nickel - used predominantly in lithium-ion battery cathodes. Panel (b) features anode and support metals - manganese, graphite, and copper - used primarily in anodes or as essential supporting materials within battery systems.

Panel (b) of Figure 5 shows that graphite’s non-technical risk premium is both volatile and persistently positive, reaching its highest point in 2017 due to substantial drops in IAI scores in China, Turkey, and Brazil, which collectively hold nearly 80 percent of global graphite reserves. China’s IAI decline reflected investor concerns over land disputes, weak community agreements, and security issues (Stedman & Green, 2018). Additionally, the removal of China's 20 percent graphite export tax in 2017 boosted investor confidence and reduced premiums in the subsequent years until a renewed spike in 2021 due to COVID-19 disruptions (IEA, 2021a; Fortune Business Insights, 2024). In 2022, regulatory reforms in Brazil improved transparency, contributing to the reduction in graphite’s non-technical risk premium in that year (National Mining Agency, 2023). Copper’s premium follows an upward trajectory, turning positive in 2022. The nontechnical risk premium for Manganese has consistently been positive since 2014. In 2024, manganese’s non-technical risk premium rose sharply from 3.67 percent in 2023 to 15.21 percent. The significant increase in the non-technical risk premium of manganese can largely be attributed to a marked decline in the IAI scores of Australia and Brazil, both of which hold significant manganese reserves. In Brazil, investors have expressed growing concerns about uncertainty in the administration and enforcement of existing regulations, the taxation regime, and security conditions (Mejía & Aliakbari, 2025). Comparable concerns have been raised in Australia—particularly in Western Australia—where investors point to uncertainty over disputed land claims, regulatory duplication and inconsistencies, and the taxation framework (Mejía & Aliakbari, 2025).

We further decompose the overall non-technical risk premium for each critical mineral into “best practice” and “policy perception” components, using the corresponding dimensions of the IAI score, as detailed in Supplementary Information Section 5 and the Supplementary

Data File. The estimation covers four distinct phases—pre-Paris (2011-2014), post-Paris (2015-2019), Green Recovery (2020-2021), and Critical Materials Focus (2022-2024)—over the period 2011-2024.[2] We find that the policy-perception component accounts for most of the magnitude and variation in the non-technical risk premium across minerals and over time. In short, changes in the quality of regulatory and policy environments dominate the dynamics of overall non-technical risk premiums, relative to shifts in best practice conditions.

Non-technical risk premium for battery storage

The non-technical risk premiums associated with critical battery minerals contribute to input uncertainty in the battery storage sector, which ultimately shapes the non-technical risk premium of batteries. Batteries' non-technical risk premiums vary depending on their mineral compositions. The methodology used to calculate the non-technical risk premium for each battery type is detailed in the Methods and the Supplementary Data File. Fig. 6 indicates that each of the five main Li-ion battery chemistries had similar non-technical risk premium trends from 2011 to 2024, despite having differences in mineral composition. The non-technical risk premiums for all batteries exhibit an upward trajectory over the period, with consistently positive non-technical risk premiums since 2013.

Since these battery-level non-technical risk premiums are derived from the weighted risks of their constituent minerals, movements in these risk premiums are closely linked to the trends shown in Fig. 5. Lithium Iron Phosphate (LFP) batteries diverge slightly due to their distinctive composition—most notably the absence of cobalt and nickel. Batteries' non-technical risk premiums experienced significant spikes in 2017 and 2021, driven primarily by sharp increases in graphite's non-technical risk premiums—an essential material for anode across all battery types. Increases in non-technical risk premiums for cobalt and manganese in 2021 further contributed to the upward pressure on the premium for batteries that year. The Nickel-Cobalt-Aluminium (NCA90) battery recorded the lowest premium in 2021, benefiting

---

[2] This study covers the period from 2011 to 2024 because this is the period for which data are available. The pre-Paris period (2011-2014) corresponds to the years preceding the Paris Agreement, when climate policies were largely voluntary and fragmented. The post-Paris period (2015-2019) begins with the signing of the Paris Agreement, which emphasised net-zero emissions, energy transition and clean-energy investment. Its signing marked a new phase in the global energy transition, accompanied by a growing focus on the importance of critical minerals. The green recovery phase (2020-2021) refers to the period when many countries implemented environmentally sustainable recovery strategies to promote both economic recovery and energy transition during the COVID-19 pandemic. Finally, since 2022, global policy and investment have increasingly taken a critical mineral focus, driven by supply-chain disruptions and rising demand for EVs.

from its reliance on nickel, whose premium declined that year. Conversely, the premium of the LFP battery–which is heavily dependent on graphite–experienced a significant increase.

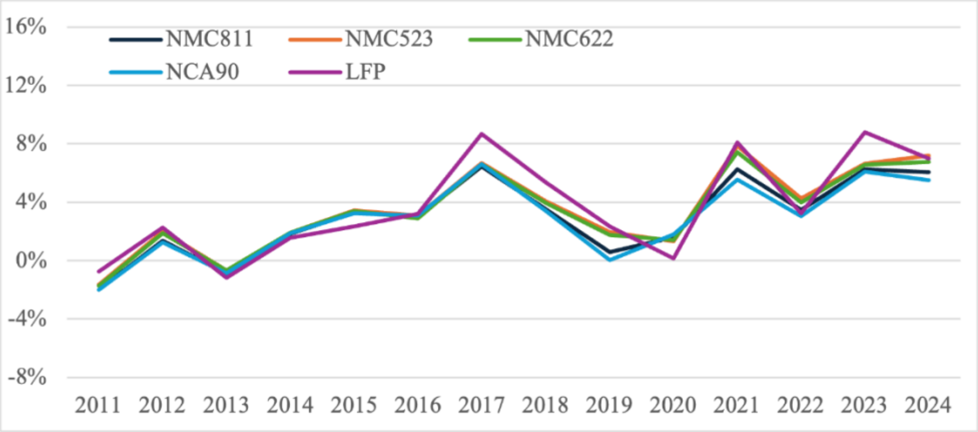


Fig. 6 | Non-technical risk premium for major battery chemistries (2011-2024). This figure shows the annual non-technical risk premium for five lithium-ion battery chemistries from 2011 to 2024. NMC811, NMC523, and NMC622 represent Nickel-Manganese-Cobalt chemistries with varying metal ratios (e.g., 5:2:3, 6:2:2, and 8:1:1), popular in electric vehicles due to their high energy density. Nickel-Cobalt-Aluminium (NCA90) batteries, known for longevity and thermal stability, and notably used by manufacturers like Tesla. Lithium Iron Phosphate (LFP) batteries, valued for safety, thermal stability, and cost-effectiveness, are cobalt-free.

In 2020, the non-technical risk premium for the LFP battery and the two types of Nickel-Manganese-Cobalt batteries (NMC523 and NMC622) declined, while those for NCM811 and NCA90 increased. These divergent trends can be primarily attributed to the rise in nickel's non-technical risk premium - which accounts for a higher proportion in the NCM811 and NCA90 batteries - and the decline in graphite's premium, which had a greater influence on the LFP, NMC523, and NMC622 batteries in that year. The LFP battery recorded the most substantial reduction in non-technical risk premium in 2020 due to its higher graphite content.

In 2024, the non-technical risk premiums for the NMC811, NCA90, and LFP batteries declined, primarily due to the drop in graphite's non-technical risk premium. The decrease in non-technical risk premium was particularly pronounced for LFP batteries, which have a high graphite content, but do not contain cobalt, nickel, or manganese - minerals whose non-technical risk premiums increased significantly in 2024. By contrast, the premiums for NCM523 and NCM622 batteries rose, largely due to their relatively high reliance on manganese, which exhibited a substantial increase in its non-technical risk premium that year.

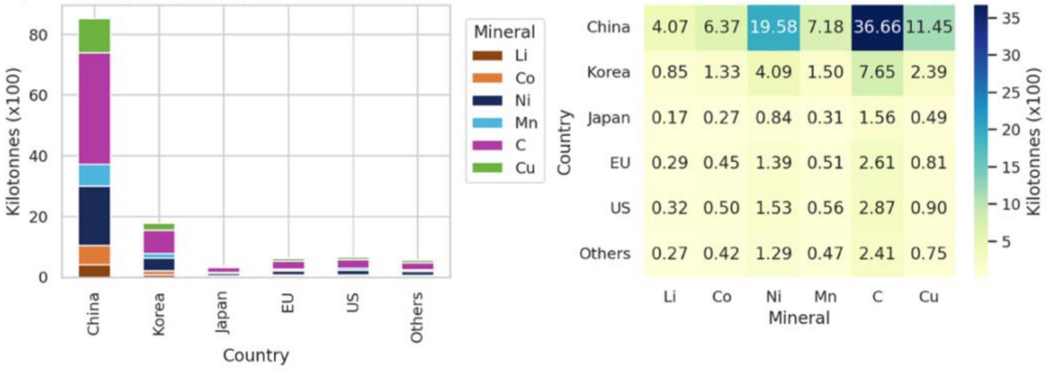
We further decompose the non-technical risk premium into "best practice" and "policy perception" components, using the respective dimensions of the IAI score, detailed in Supplementary Information Section 6 and the Supplementary Data File for each battery type. Overall, the battery non-technical risk best practice premium fluctuates around zero at the beginning of the period that we consider, but in recent years it has been above zero and has exhibited an upward trend. The battery non-technical risk policy perception premium has remained well above zero and has displayed a consistent and systematic upward trajectory. This indicates that policy-related risks play a significant and growing role in shaping the long-term upward trend of the overall non-technical risk premium for batteries, while in recent years mineral potential-related risks have also contributed to the increase in overall premium.

Optimal stockpiling for market stability

Strategic stockpiling of critical minerals represents a viable risk-management instrument. Precautionary reserves provide a buffer against supply disruptions arising from political or regulatory shocks. Despite the storage and opportunity costs involved, stockpiling serves as a hedge against underinvestment in high-risk jurisdictions. For the battery sector, such reserves help stabilize production, mitigate upstream volatility, and safeguard progress toward clean energy transition goals. We quantitatively estimate the optimal stockpiling requirements of battery-related critical minerals for market stabilization in terms of duration and the non-technical risk premium. The methodology for calculating the optimal stockpiling requirement of EV battery-related critical minerals for different regions are provided in the Methods and the Supplementary Data File. Briefly, considering duration and the non-technical risk premium ensures that the reserve size reflects both the long development lead times and resource scarcity characteristic of critical mineral projects and the geopolitical risks that can disrupt stable supply. The duration constraint captures potential long-term supply gaps arising from protracted project development, while the non-technical risk premium component quantifies the effects of geopolitical or policy shocks that could interrupt the supply of EV battery raw materials.

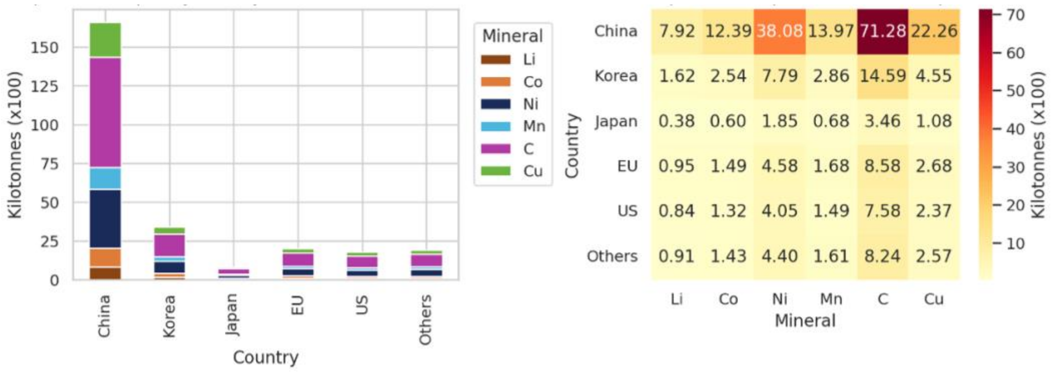
Fig. 7 Panel (a) compares the quantity of stockpiled material implied by our 2030 scenario for lithium, cobalt, nickel, manganese, graphite, and copper—across six countries or regions. China is projected to have the highest stockpiling requirement for every mineral, accounting for nearly half of the global total. Graphite represents the largest share of stockpiling in all regions, representing about two-fifths of the world total—followed by nickel and copper, with manganese and cobalt forming a middle tier and lithium the smallest component. Exact values are reported in the heatmap on the right and the Supplementary Data File.

(a) 2030



	Li	Co	Ni	Mn	C	Cu
China	4.07	6.37	19.58	7.18	36.66	11.45
Korea	0.85	1.33	4.09	1.50	7.65	2.39
Japan	0.17	0.27	0.84	0.31	1.56	0.49
EU	0.29	0.45	1.39	0.51	2.61	0.81
US	0.32	0.50	1.53	0.56	2.87	0.90
Others	0.27	0.42	1.29	0.47	2.41	0.75

(b) 2040



	Li	Co	Ni	Mn	C	Cu
China	7.92	12.39	38.08	13.97	71.28	22.26
Korea	1.62	2.54	7.79	2.86	14.59	4.55
Japan	0.38	0.60	1.85	0.68	3.46	1.08
EU	0.95	1.49	4.58	1.68	8.58	2.68
US	0.84	1.32	4.05	1.49	7.58	2.37
Others	0.91	1.43	4.40	1.61	8.24	2.57

Fig. 7 | Optimal stockpiling of battery-related raw materials for market stabilization. The figure illustrates the optimal stockpiled material implied by BNEF's Economic Transition Scenario across six critical minerals—lithium, cobalt, nickel, manganese, graphite, and copper—used in batteries and across six regions, based on average 2020 Li-ion battery chemistries with a capacity of 60 kWh. The total stockpiling requirements, expressed in hundreds of kilotonnes, reflect the long lead times of critical mineral projects and the non-technical risk premium component for these six minerals. Note that division by one hundred is applied to adjust the y-axis scale in Fig. 7. Panel (a) presents estimates for 2030, while Panel (b) presents estimates for 2040.

In 2030, China is the clear outlier, with a combined requirement of 85.32 (units as reported in hundreds of kioltonne), accounting for 68% of the global stockpiling requirement. The largest requirements are for graphite (36.66), nickel (19.58), and copper (11.45), while manganese (7.18), cobalt (6.37), and lithium (4.07) are smaller but still exceed the needs of any other region. Korea (17.80), the United States (6.68), and the European Union (6.07) form a second tier with Korea and the United States dominated by graphite (7.65 and 2.87) and nickel (4.09 and 1.53), respectively. Japan (3.64) has the smallest stockpiling requirements across all minerals. The top three countries (China, Korea, and the United States) account for over 87% of the world's total stockpiling needs, underscoring both the regional concentration of stockpiling needs and the pivotal role of graphite in non-technical risk-adjusted planning.

Panel (b) of Fig. 7 indicates that there will be a sharp escalation in stockpiling requirements by 2040 for each of the six critical minerals used in EV batteries. The global requirement by 2040 is 264.67 (units reported in hundreds of kilotonnes), representing an 111.5% increase from 125.12 in 2030. Graphite dominates the composition at 113.73 (43% of the total), followed by nickel at 60.75 (23%) and copper at 35.51 (13.4%). Manganese contributes 22.28 (8.4%), cobalt 19.77 (7.5%), and lithium 12.63 (4.8%). These results highlight a steadily rising demand for critical minerals—particularly graphite and nickel—pointing to the importance of prioritize these two materials in strategic stockpiling planning.

The regional profile remains highly concentrated in 2040. China's requirement is 165.89—62.68% of the world total—led by graphite (71.28), nickel (38.08), and copper (22.26), with manganese (13.97), cobalt (12.39) and lithium (7.92) smaller but still the largest across regions. In 2040, China is projected to continue dominating global stockpiling requirements, accounting for the majority share despite a slight decline relative to 2030. Korea forms the second tier at 33.95 (12.83% share), followed by the European Union at 19.97 (7.54%) and the United States at 17.64 (6.67%). Both Europe and the United States are expected to increase their shares compared with 2030, with Europe exhibiting a more pronounced rise than the United States. Japan remains the smallest at 8.06 (3.05%). Together, China, Korea, and the European Union account for 83% of the global requirement. Growth is broad-based but faster in the European Union, which is projected to increase by 229% relative to its 2030 level, and the United States which would more than double (+164%), relative to 2030, while China would still expand by around 94%. These results indicate a gradual diversification of stockpiling requirements across regions, although China remains dominant. They also reflect differences in the pace of EV development across countries and regions.[3]

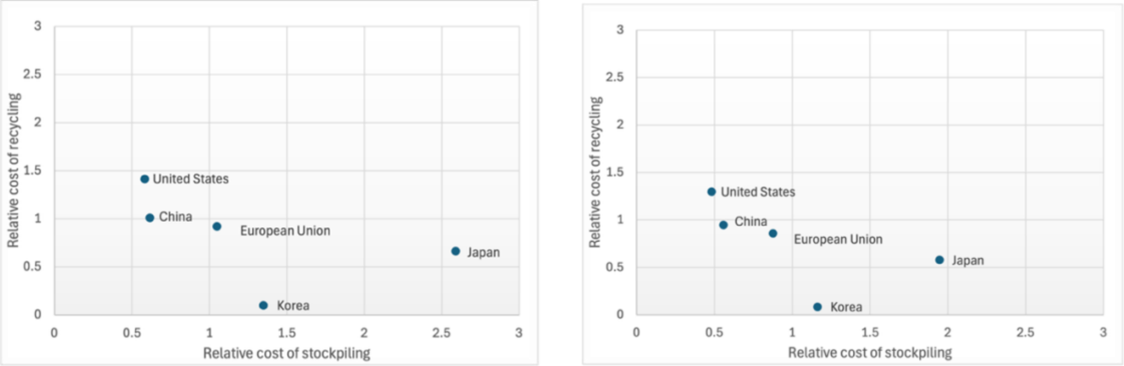
Recycling as a strategic reserve for EV battery materials

Since recycling and stockpiling can serve as complementary market-stabilization strategies, countries will differ in which option offers greater advantages depending on their EV deployment trajectories, battery manufacturing capacity, and other factors that influence the feasibility and cost-effectiveness of large-scale recycling. Therefore, we compare the RCR and the RCS across countries for different minerals. The methodology for calculating the RCR and

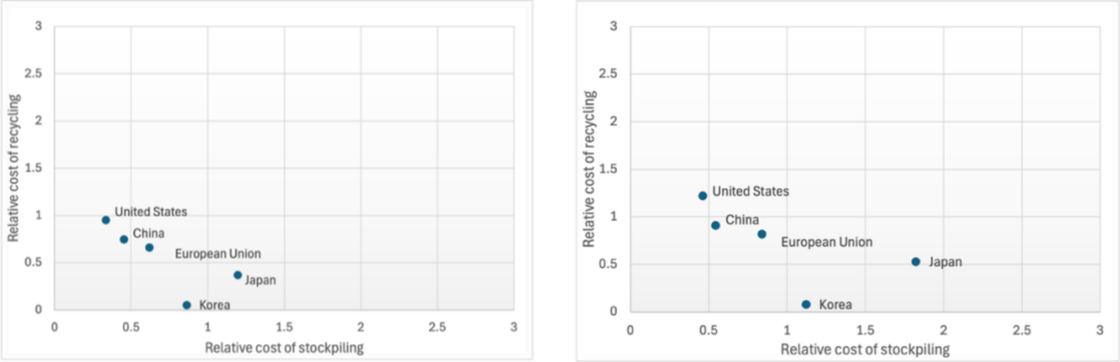
---

[3] This section reports results based on an eight-year warranty period for EV batteries, implying that batteries are expected to be replaced eight years after the vehicle is sold. With ongoing technological advancements and proper maintenance, modern EV batteries can last 10 to 20 years (Wu, 2025). Since EV sales data are only available from 2020 onwards, we conduct a sensitivity analysis assuming a ten-year warranty. A longer warranty period implies lower battery replacement demand, leading to slightly lower optimal stockpiling requirements for market stability compared with the eight-year warranty scenario. The overall conclusions remain consistent. Further details are provided in the Supplementary Data File.

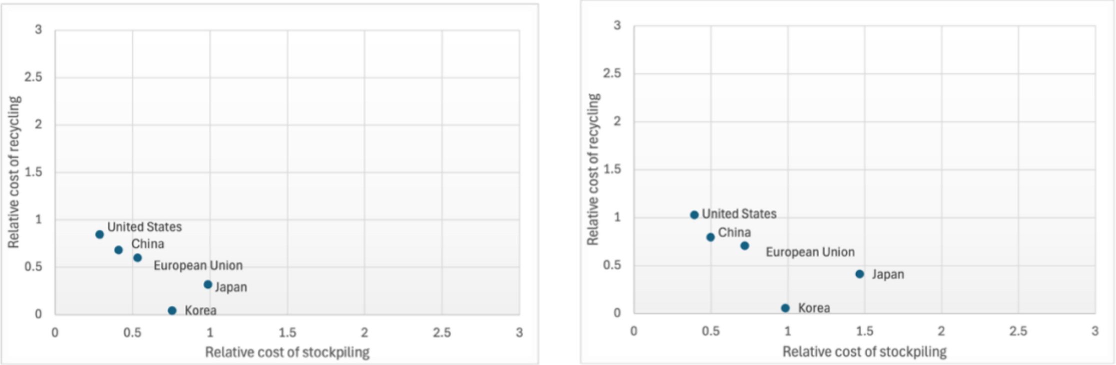
RCS for EV battery-related critical minerals in different regions is provided in the Methods and the Supplementary Data File.


(a)Lithium

(b) Cobalt


(c)Nickel

(d) Manganese


(e)Graphite

(f) Copper

Fig. 8 | The relative cost of stockpiling vs the relative cost of recycling using the distance-to-iso-cost approach. This figure plots, for each country–mineral pair, the relative cost of recycling (RCR) on the vertical axis against the relative cost of stockpiling (RCS) on the horizontal axis.

Fig.8 presents the RCS versus RCR in six panels—for (a) lithium, (b) cobalt, (c) nickel, (d) manganese, (e) graphite, and (f) copper—for each of China, Korea, Japan, the European Union, and the United States.[4] For each battery-related critical mineral, Japan and Korea are consistently located in the lower part of the figures, suggesting a lower RCR and a higher RCS.

---

[4] Note that data for other countries is not yet available.

This result can be attributed to their higher population density and smaller geographical size. Japan shows the highest RCS, whereas Korea appears to be the most cost-effective in recycling across all minerals. The difference in the relative costs of stockpiling and recycling is most pronounced for lithium, cobalt and manganese.

The United States and China exhibit higher RCR and lower RCS values for all minerals, which reflects their size. The United States has the highest RCR and is the most cost-effective in stockpiling. The difference in the relative costs of recycling and stockpiling is most pronounced for lithium. In the European Union, the results vary across minerals: nickel and graphite exhibit relatively higher RCR values, while the other four battery-related critical minerals display lower RCRs. This pattern reflects the relatively higher shares of nickel and graphite in EV batteries. although other minerals in Europe are generally better positioned for recycling, recycling remains relatively more costly for nickel and graphite due to the strong demand from EV battery production

In summary, for these minerals, the United States and China tend to be better positioned for stockpiling (relatively cheaper) than recycling (relatively costlier), whereas for Japan and Korea the opposite is the case. Within the European Union, nickel and graphite are more cost-effective to stockpile, while the other minerals are more cost-effective to recycle.

Policy recommendations

Building on the comparison of RCS and RCR across countries and minerals, we further assess the extent to which each country's cost structure favors stockpiling or recycling by measuring the distance from the 45° iso-cost line. This approach allows us to gauge the strength of each country's advantage and formulate corresponding policy recommendations. Fig. 9 ranks each country–mineral pair by how far it sits above or below the 45° iso-cost line in Fig.8. Points below the line indicate a recycling advantage, while points above indicate a stockpiling advantage, and the further the point is from the line, the stronger the incentive (low, moderate, or high) to engage in either recycling or stockpiling.

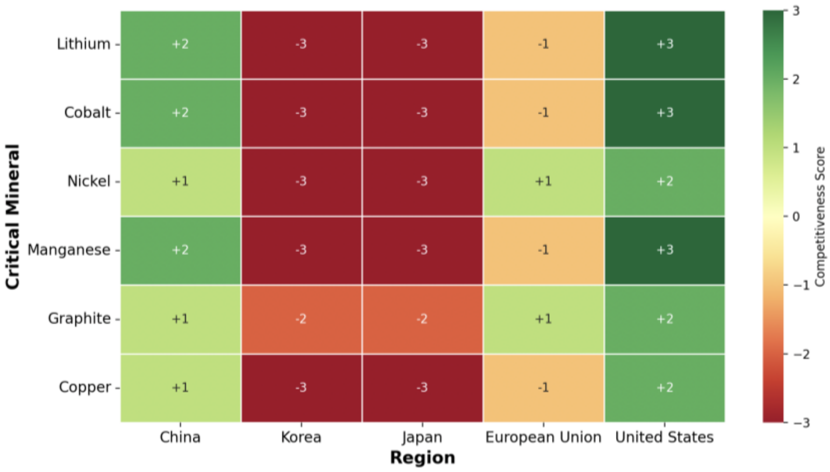


Fig. 9 | The distance-to-iso-cost relative cost approach. The country–mineral observation is placed in a plane where the horizontal axis is the relative cost of stockpiling, and the vertical axis is the relative cost of recycling. The 45° iso-cost line is $y = x$. For a point (x, y), the signed perpendicular distance to this line is $d = (y - x)/\sqrt{2}$. A negative value of d indicates that recycling is cheaper than stockpiling, while a positive value indicates the opposite. The absolute magnitude $|d|$ measures the strength of the incentive in either direction. To translate d into the qualitative ratings used in the paper, we classify by magnitude as follows. High incentive or disincentive when $|d| > 0.5$ (reported as "+3" for stockpile if $d > 0$, or "-3" for recycle if $d < 0$); moderate when $0.25 < |d| \leq 0.5$ (reported as "+/-2"); and low when $0 < |d| \leq 0.25$ (reported as "+/-1"). Values near zero indicate indifference between recycling and stockpiling.

The distance-to-iso-cost classification indicates that Japan and Korea are best positioned to rely on recycling as their primary stabilization instrument ("+2" for graphite and a consistent "+3" for the other five minerals). By contrast, China and the United States exhibit a strong stockpiling advantage. The United States shows the highest stockpiling advantage, with most battery minerals registering as "+2" or "+3". Thus, stockpiling is the more cost-effective near-term strategy in China and the United States, with recycling becoming competitive only as reverse logistics, feedstock (end-of-life battery), and recovery yields improve. For the European Union, the optimal strategy varies across minerals. The European Union should favour stockpiling for nickel and graphite (registering as "+1") and, to a lesser extent, lithium, while cobalt, manganese, and copper are better positioned to rely on recycling (registering as "–1"), albeit with narrower margins that could shift as recycling efficiency improves.

Methods

Measuring overall non-technical risk premium for each mineral

Following Vespignani and Smyth (2024), we calculate the overall non-technical risk score for lithium, cobalt, nickel, manganese, graphite, and copper, alongside coal - which serves as a benchmark due to its status as the most polluting fossil fuel - using the IAI from the Fraser Institute's Annual Survey of Mining Companies. This index is weighted by the jurisdiction-level proven reserves of each mineral, as sourced from the United States Geological Survey (see Supplementary Information Sections 2 and 3).

Formally, the global non-technical risk score is defined as:

$$NTR\ score_{m,t} = \sum_{c=i}^{n} (w_{c,m,t} \times IAI_{c,t}) \qquad (1)$$

Where $NTR\ score_{m,t}$ is the global non-technical risk score of critical mineral m in year t. $w_{c,m,t}$ represents the proven reserves of mineral m in country c in year t, expressed as a percentage of global proven reserves. $IAI_{c,m,t}$ denotes the Investment Attractiveness Index for country c in year t. The global non-technical risk score is the weighted sum across all relevant countries, with higher values indicating that a locale is a more attractive investment destination when it has lower non-technical risk. Further details of non-technical risk scores are provided in Supplementary Information Section 4. Additionally, we compute subnational-level non-technical risk scores for Argentina, Australia and the United States:

$$NTR\ score_{s,m,t} = w_{s,m,t} \times IAI_{s,t} \qquad (2)$$

Where $NTR\ score_{s,m,t}$ is the non-technical risk score of critical mineral m in state/province/territory s in year t. $w_{s,m,t}$ represents the proven reserves of critical mineral m in subnational unit s in year t, expressed as a percentage of global proven reserves. $IAI_{s,m,t}$ denotes the Investment Attractiveness Index for subnational unit s in year t. Further details on subnational-level IAI scores, proven reserve shares, and non-technical risk scores are provided in Supplementary Information Sections 2 and 3, as well as in the Supplementary Data File.

The IAI combines geological potential (BPMPI) and policy-related factors (PPI). Accordingly, we decompose the overall non-technical risk score into two components: the non-technical risk best practice score and the non-technical risk policy perception score, using the respective dimensions of the IAI. The non-technical risk policy perception score captures risks related to the policy environment, such as taxation, regulatory unpredictability, environmental regulations, political stability, and permitting processes. The non-technical risk best practice score assesses a jurisdiction's geological potential assuming an optimal regulatory framework and best-practice mining policies. Supplementary Information Section 4 provides further methodological details on the decomposition of the overall non-technical risk scores and the associated analysis.

Following Vespignani and Smyth (2024), we calculate the non-technical risk premium as the proportional difference between each critical mineral's non-technical risk score and the coal benchmark:

$$NTR\ premium_{m,t} = \frac{\left(NTR\ score_{coal,t} - NTR\ score_{m,t}\right)}{NTR\ score_{coal,t}} \qquad (3)$$

Where $NTR\ score_{m,t}$ represents the non-technical risk score for critical mineral *m* in year *t*, while $NTR\ score_{coal,t}$ is the non-technical risk score for coal. $NTR\ premium_{m,t}$ represents the overall non-technical risk premium of critical mineral *m* in year *t*. Higher non-technical risk premiums reflect greater non-technical risks relative to coal, indicating lower $NTR\ score_{m,t}$ and lower investment attractiveness. This premium can similarly be decomposed into non-technical risk best practice and non-technical risk policy perception components, detailed in Supplementary Information Section 5.

Measuring non-technical risk premium for specific battery chemistries

We further construct a battery-level non-technical risk premium by aggregating the weighted non-technical risk premiums of constituent critical minerals. The weighting is based on each mineral's share of the battery's total material content, derived from composition data provided by the European Environment Agency (Mathieu & Mattea, 2021). This dataset represents a typical 60-kilowatt-hour (kWh) battery pack used in a medium-sized EV. Formally, the battery non-technical risk premium is calculated as:

$$NTR\ premium_{b,t} = \sum_{m=1}^{6} \left(w_{m,b,t} \times NTR\ premium_{m,t}\right) \qquad (4)$$

Where $NTR\ premium_{m,t}$ is the non-technical risk premium for mineral m in year *t*. $w_{b,t}$ indicates the percentage share of critical mineral m in battery chemistry b. Thus, the battery's overall non-technical risk premium reflects the aggregated risk profile of its constituent minerals. A further decomposition of battery non-technical risk premiums into best practice and policy perception components is available in Supplementary Information Section 6.

Estimating optimal stockpiles of critical minerals for EV batteries

For each region and each critical mineral in 2030 and 2040, we first calculate the unadjusted total stockpiling requirement for critical minerals used in battery production as the sum of (i) the annual quantity required for primary battery production and (ii) the annual quantity needed to replace end-of-life batteries from EVs reaching the end of their eight-year warranty (Wu, 2025).[5] Formally, the unadjusted total stockpiling requirement for critical minerals used in battery production is expressed as:

$$D^{(t)} = Q^{primary} + Q^{replace} \tag{5}$$

Where t is equal to 2030 or 2040. $D^{(2030)}$ or $D^{(2040)}$ represent the annual requirement of critical minerals for production plus battery replacement in 2030 or 2040. $Q^{primary}$ is the annual quantity needed for primary battery production, and $Q^{replace}$ is the annual quantity required to replace end-of-life batteries from EVs reaching the end of their eight-year warranty.

For each critical mineral, the time-adjusted stockpiling ratio is defined as:

$$\alpha_m = oil\ inventory\ ratio * \left(\frac{t_{CM}}{t_{oil}}\right) \tag{6}$$

Where $oil\ inventory\ ratio$ is equal to 90/365, reflecting the oil sector's 90-day strategic reserve rule. According to the Agreement on an International Energy Programme (I.E.P.), each IEA member country is required to hold oil stocks equivalent to at least 90 days of net oil imports and to be prepared for a coordinated response to severe supply disruptions in the global oil market (IEA, 2025). We adopt this benchmark as the optimal inventory ratio for oil. The development time for oil, denoted as t_{oil}, is assumed to be seven years, reflecting the average energy development time for oil projects (Thunder Said Energy, 2025).

We then estimated the adjusted optimal stockpiling requirement in two steps. First, to account for the long lead times of critical mineral projects, we scaled the total critical mineral requirement by the benchmark oil development duration of seven years. This adjustment reflects the need to accumulate additional inventories for minerals with longer development

---

[5] The primary requirement is calculated as the expected number of new batteries produced, each with an average capacity of 60 kilowatt-hours (kWh), multiplied by the amount of each critical mineral contained in an average 2020 battery with the same capacity, representative of a medium-sized electric vehicle such as the Chevy Bolt (Transport & Environment, 2021). The replacement requirement is defined as the expected number of batteries replaced after the standard eight-year warranty period, multiplied by the same per-battery critical mineral content.

cycles relative to oil. Formally, the stockpiling requirement adjusted for project duration is defined as:

$$Q^*_{duration} = \alpha_m * D^{(t)} \tag{7}$$

Second, to capture the raw-materials requirements arising from non-technical risk premiums, we multiply the sum of the duration-adjusted stockpiling requirement and the total critical minerals requirement for battery production by the global non-technical risk premiums for 2024. This adjustment accounts for the extra material buffers needed to offset investment risks and potential supply disruptions associated with policy and governance uncertainty. Formally, the stockpiling requirement adjusted for the non-technical risk premium is defined as:

$$Q^*_{NTRP} = \left(Q^*_{duration} + D^{(t)}\right) * NTRP^{Global}_{2024} \tag{8}$$

Where $NTRP^{Global}_{2024}$ is critical mineral's global non-technical risk premium in 2024.

Finally, the adjusted optimal stockpiling requirement is obtained by summing the duration-adjusted requirement and the requirement arising from non-technical risk premiums. Formally, the total optimal stockpiling is defined as:

$$Q^* = Q^*_{duration} + Q^*_{NTRP} \tag{9}$$

Estimating the relative costs of stockpiling and recycling

The RCS is proxied by the opportunity cost of storage real estate, adjusted for each country's population density (where higher density implies higher land-value pressure). Specifically, we operationalize the stockpiling index as a real-estate pressure measure:

$$relative\ cost\ of\ stockpiling\ (RCS) = \frac{\log(population\ density)}{\log(optimal\ stockpile\ requirement)} \tag{10}$$

The RCR is proxied by the expected availability of feedstock for recycling (e.g. end-of-life battery), measured by the geographical concentration of battery use and industrial hubs—where greater dispersion implies higher collection and logistics costs. This recycling index captures the difficulty of collection and logistics, reflecting how geographic scale interacts with the depth of the 2040 recycling stream.[6] Formally, the relative cost of recycling is defined as:

$$relative\ cost\ of\ recycling\ (RCR) = \frac{\log(country\ size)}{\log(projected\ critical\ minerals\ to\ be\ recycled)} \quad (11)$$

This framework provides an initial, comparable lens for identifying country-specific comparative advantages between recycling and stockpiling, and can be refined as new data on recycling capacity, production, technology and spatial deployment become available. Both indices are unitless and comparable across countries, with higher values indicating higher relative costs.

---

[6] The projected quantity of batteries to be recycled in 2040 is estimated as the cumulative quantity of end-of-life batteries from 2020 to 2032, based on the eight-year warranty period of EV batteries. Due to data limitations, 2020 is used as the starting year. This represents the maximum limit of EV batteries that can be recycled. The analysis focuses on 2040, since the projected volume of batteries available for recycling by 2030 is still relatively limited.

References

American Battery Technology Company. (2022). *ABTC Accepts Presidential Challenge to Secure Domestic Supply of Critical and Strategic Battery Metals*. Available at: https://americanbatterytechnology.com/abtc-accepts-presidential-challenge-to-secure-domestic-supply-of-critical-and-strategic-battery-metals/ (Accessed: 13 September 2025).

Andrade, L. B., Frenzel, M., Bookhagen, B., Kresse, C., Schmidt, M., Nassar, N., ... & Sandmann, D. (2024). From exploration to production: Understanding the development dynamics of lithium mining projects. *Resources Policy*, 99, 105423.

Australian Trade and Investment Commission. (2024). *Why Australia benchmark report 2024*. Available at: https://international.austrade.gov.au/content/dam/austrade-assets/international/documents/reports/benchmark-report/atic-benchmark-report-2024.pdf (Accessed: 13 September 2025).

Avocet Electrofoils. (2024). *Understanding battery copper foil: Uses & key properties*. Avocet Electrofoils. Available at: https://www.batteryfoil.com/understanding-battery-copper-foil-uses-key-properties/ (Accessed: 13 September 2025).

Azevedo, M., Baczynska, M., Bingoto, P., Callaway, G., Hoffman, K., & Ramsbottom, O. (2022). *The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition*. McKinsey & Company. Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-raw-materials-challenge-how-the-metals-and-mining-sector-will-be-at-the-core-of-enabling-the-energy-transition (Accessed: 13 September 2025).

Balyaminu, J., Mphambukeli, T., & Magande, T. (2025). Regime Complexities in the Political Economy of Cobalt Mining in the DRC. In *URBAN INNOVATION: TO BOLDLY GO WHERE NO CITIES HAVE GONE BEFORE. Medium sized cities and towns as a major arena of global urbanisation. Proceedings of REAL CORP 2025, 30th Intl. Conference on Urban Development, Regional Planning and Information Society* (pp. 775-783). CORP–Competence Center of Urban and Regional Planning.

Bullock, R. L., & Mernitz, S. (2017). *Mineral property evaluation: Handbook for feasibility studies and due diligence*. Society for Mining, Metallurgy & Exploration.

Burnley, C. (2011). Natural resources conflict in the Democratic Republic of the Congo: a question of governance. *Sustainable Dev. L. & Pol'y*, 12, 7.

Castiglioni, R. (2022). Social policies, uncertainty and social unrest in Chile. *In Social Revolt in Chile* (pp. 69-84). Routledge.

Cerda, R., Silva, Á., & Valente, J. T. (2016). Economic policy uncertainty indices for Chile. *Economic Policy Uncertainty working paper*.

Cobalt Institute. (2021). *'State of the Cobalt market' report*. Cobalt Institute. Available at: https://www.cobaltinstitute.org/wp-content/uploads/2021/09/Cobalt-Institute-State-of-the-Cobalt-Market-Report_2020.pdf (Accessed: 13 September 2025).

Deloitte Global. (2025). *Tracking the trends 2025: Top 10 trends shaping the mining and metals sector*. Deloitte. Available at: https://www.deloitte.com/global/en/Industries/mining-metals/research/tracking-the-trends.html (Accessed: 13 September 2025).

Denisova, T. S., & Kostelyanets, S. V. (2023). The Democratic Republic of the Congo: Political instability and the Rwandan factor. *Vestnik RUDN. International Relations*, 23(1), 37-47.

Ellis, I. (2020). *DR Congo border closure and lockdowns to ravage copper and cobalt output. Verisk Maplecroft*. Available at: https://www.maplecroft.com/insights/analysis/dr-congo-border-closure-and-lockdowns-to-ravage-copper-and-cobalt-output/ (Accessed: 13 September 2025).

Fortune Business Insights. (2024). *Graphite mining market size, share, and industry analysis by mining type (open-pit and underground), by grade (crystalline and microcrystalline), and regional forecast, 2025–2032.* Fortune Business Insights. Available at: https://www.fortunebusinessinsights.com/graphite-mining-market-109424 (Accessed: 13 September 2025).

Heijlen, W., Franceschi, G., Duhayon, C., & Van Nijen, K. (2021). Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co). *Resources Policy*, 73, 102202.

Horn, S., Gunn, A. G., Petavratzi, E., Shaw, R. A., Eilu, P., Törmänen, T., ... and Wall, F. (2021). Cobalt resources in Europe and the potential for new discoveries. *Ore Geology Reviews*, 130, 103915.

IEA. (2021a). *The Role of Critical Minerals in Clean Energy Transitions*. IEA. Available at: https://www.iea.org/policies/16084-prohibition-of-the-export-of-nickel-ore (Accessed: 13 September 2025).

IEA. (2021b). *Total nickel demand by sector and scenario, 2020-2040*. IEA. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/reliable-supply-of-minerals (Accessed: 13 September 2025).

IEA. (2022). *Introducing the Critical Minerals Policy Tracker*. IEA. Available at: https://www.iea.org/reports/introducing-the-critical-minerals-policy-tracker (Accessed: 15 October 2025).

IEA. (2024a). *Recycling of Critical Minerals – Executive summar*y. Paris: International Energy Agency. Available at: https://www.iea.org/reports/recycling-of-critical-minerals (Accessed: 13 September 2025).

IEA. (2024b). *Global EV Outlook 2024 – Outlook for battery and energy demand*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2024/outlook-for-battery-and-energy-demand (Accessed: 13 September 2025).

IEA. (2025a). *EV Battery Supply Chain Sustainability*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/ev-battery-supply-chain-sustainability (Accessed: 13 September 2025).

IEA. (2025b). *Global Critical Minerals Outlook 2025*. International Energy Agency. Available at: https://www.iea.org/reports/global-critical-minerals-outlook-2025 (Accessed: 13 September 2025).

IEA. (2025c). *Global EV Outlook 2025*. International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025 (Accessed: 21 September 2025).

Jacks, D. S., O'rourke, K. H., & Williamson, J. G. (2011). Commodity price volatility and world market integration since 1700. *Review of economics and statistics*, 93(3), 800-813.

Jones, B., Nguyen-Tien, V., & Elliott, R. J. (2023). The electric vehicle revolution: Critical material supply chains, trade and development. *The World Economy*, 46(1), 2-26.

Jupiter Mines Limited. (2012). *Investor Presentation*. Jupiter Mines Limited. Available at: https://www.jupitermines.com/cproot/48/3/jupiter---neiha.pdf (Accessed: 15 October 2025).

Kang, W., Smyth, R. and Vespignani, J. (2025) The Macroeconomic Fragility of Critical Mineral Markets. *Working paper*.

Kelly, J. (2025). *Miners warn only one in five major projects reaches completion*. Hancock Prospecting. Available at: https://www.hancockprospecting.com.au/miners-warn-only-one-in-five-major-projects-reaches-completion (Accessed: 13 September 2025).

Khan, T. S., Nguyen, T. T. T., Schodde, R., & Ohnsorge, F. (2016). From commodity discovery to production. *World Bank Policy Research Working Paper*, (7823).

Mack, J. (2025). *Mining shocks: A look at key disruptions*. White Noise Communications. Available at: https://whitenoisecomms.com/insights/mining-shocks-a-look-at-key-disruptions/ (Accessed: 13 September 2025).

Manalo, P. (2023). *Discovery to production averages 15.7 years for 127 mines.* S&P Global Market Intelligence. Available at: https://www.spglobal.com/market-intelligence/en/news-insights/research/discovery-to-production-averages-15-7-years-for-127-mines (Accessed: 13 September 2025).

Manalo, P. (2024). *Average lead time almost 18 years for mines started in 2020–23.* S&P Global Market Intelligence. Available at: https://www.spglobal.com/market-intelligence/en/news-insights/research/average-lead-time-almost-18-years-for-mines-started-in-2020-23 (Accessed: 13 September 2025).

Manalo, P. (2025). *From 6 years to 18 years: The increasing trend of mine lead times.* S&P Global Market Intelligence. Available at: https://www.capitaliq.spglobal.com/apisv3/spg-webplatform-core/news/article?id=88321260&redirected=1 (Accessed: 13 September 2025).

Mathieu, L., & Mattea, C. (2021). *From dirty oil to clean batteries*. Transport & Environment. Available at: https://www.transportenvironment.org/uploads/files/2021_02_Battery_raw_materials_report_final.pdf (Accessed: 13 September 2025).

Mejía, J., & Aliakbari, E. (2023). *Annual survey of mining companies, 2022*. Fraser Institute. Available at: https://www.fraserinstitute.org/sites/default/files/annual-survey-of-mining-companies-2022.pdf (Accessed: 13 September 2025).

Mejía, J., & Aliakbari, E. (2025). *Fraser Institute annual survey of mining companies 2024*. Available at: Fraser Institute. http://www.fraserinstitute.org (Accessed: 13 September 2025).

Mitchell, P. (2024). *Top 10 business risks and opportunities for mining and metals in 2025.* EY. Available at: https://www.ey.com/en_gl/insights/energy-resources/risks-opportunities (Accessed: 13 September 2025).

National Mining Agency. (2023). *RAL Guide 2023 - ANM*. National Mining Agency. Available at: https://www.gov.br/anm/pt-br/ral-2023-traz-mudancas-na-declaracao-de-recursos-e-reservas-minerais/guia-ral-2023-anm.pdf/view (Accessed: 13 September 2025).

NextSource Materials. (2025). *NextSource Materials Provides Quarterly Update and Announces Progress on Molo Mine Expansion Study and Battery Anode Facility Strategy*. NextSource Materials. Available at: https://www.nextsourcematerials.com/nextsource-materials-provides-quarterly-update-and-announces-progress-on-molo-mine-expansion-study-and-battery-anode-facility-strategy/ (Accessed: 15 October 2025).

NextSource Materials. (n.d.). *Energizer Resources Outlines 2013 Strategies and Timelines for Molo Mine Development*. NextSource Materials. Available at: https://www.nextsourcematerials.com/energizer-resources-outlines-2013-strategies-and-timelines-for-molo-mine-development/ (Accessed: 13 September 2025).

NREL. (2025). *Battery Recycling Supply Chain Analysis*. National Renewable Energy Laboratory. Available at: https://www.nrel.gov/transportation/battery-recycling-supply-chain-analysis (Accessed: 13 September 2025).

Reid, H., & Holland, H. (2020). *DRC: Mining minister warns against the social and economic impact of mine closures during the COVID-19 pandemic*. Business & Human Rights Resource Centre. Available at: https://www.business-humanrights.org/en/latest-news/drc-mining-minister-warns-against-the-social-and-economic-impact-of-mine-closures-during-the-covid-19-pandemic/ (Accessed: 13 September 2025).

Renaud, M., & Kumral, M. (2021). Out of the Comfort Zone: Quantifying Country Risk for Foreign Mining Project Investment Feasibilities. *Mining, Metallurgy & Exploration*, 38(6), 2323-2335.

Robin, R. J. (2024). Viability and Eco-consequences of synthetic and natural graphite for Li-ion battery anodes in the US. *IEEE Engineering Management Review*.

Schandl, H., Walton, A., Okelo, W., Kong, T., Boxall, N. J., Terhorst, A., & Porter, N. B. (2023). Australia's comparative and competitive advantages in transitioning to a circular economy. A Report to the Office of the Chief Scientist.

Stedman, A., & Green, K. P. (2018). *Fraser Institute Annual Survey of Mining Companies 2017*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Tilton, J. E., & Guzmán, J. I. (2016). *Mineral economics and policy*. Routledge.

Trench, A., Packey, D., & Sykes, J. P. (2014). Non-technical risks and their impact on the mining industry. *Mineral Resource and Ore Reserve Estimation*, 605-618.

Vespignani, J., & Smyth, R. (2024). Artificial intelligence investments reduce risks to critical mineral supply. *Nature Communications*, *15*(1), 7304.

Wu, S. (2025). *How long do electric car batteries last?* ConsumerAffairs. Available at: https://www.consumeraffairs.com/automotive/how-long-do-electric-car-batteries-last.html (Accessed: 30 October 2025).

Zadeh, J. (2025). *Understanding the Time Delay Between Mining Discovery and Development*. Discovery Alert. Available at: https://discoveryalert.com.au/news/widening-gap-discovery-development-mining-2025/ (Accessed: 13 September 2025).

Zhao, L., Ding, B., Qin, X. Y., Wang, Z., Lv, W., He, Y. B., ... & Kang, F. (2022). Revisiting the roles of natural graphite in ongoing lithium-ion batteries. *Advanced Materials*, 34(18), 2106704.

Supplementary Information Files:

Supplementary Information 1: Strategic stockpiling as a hedge against non-technical risk premiums in critical mineral project development

Let $t \geq 0$ denote the project development timeline (in years). The following components capture the relationship among project timelines, non-technical risk premiums, and incentives for strategic stockpiling.

Non-technical risk premium of invested capital

The non-technical risk premium per unit of invested capital, $R(t)$, is defined as:

$$R(t) = \frac{1}{t+1} \qquad (S1)$$

This function captures the inverse relationship between the project timeline and non-technical risk premium per unit of invested capital. It reflects the notion that earlier development stages in critical mineral project carry higher exposure to non-technical risks, such as regulatory and political risks, relative to coal, and that these risks diminish as projects mature (Acemoglu & Zilibotti, 1997; Caldara & Iacoviello, 2022).

Impact of non-technical risk premium on the cost of capital

Let r_0 represent the baseline cost of capital for mining investments. The effective cost of capital, adjusted for the non-technical risk premium, is expressed as:

$$r(t) = r_0 + \lambda \cdot R(t) \qquad (S2)$$

where λ quantifies the sensitivity of capital costs to the non-technical risk premium. A high $R(t)$ may increase the effective cost above profitability thresholds, risking project cancellation.

Stockpiling incentive

The stockpiling incentive function, capturing welfare losses from delayed supply, is formulated as:

$$S(t) = \frac{[\ln(1+t)]^2}{10} \qquad (S3)$$

The logarithmic form ensures higher early sensitivity to delays, which means that early delays have a large marginal impact on welfare losses. The square term ensures that losses are always non-negative and emphasizes the increasing importance of longer timelines. These align with views presented by the IEA (2023) and Vespignani and Smyth (2024). The denominator of ten is set for calibration and scaling purposes.

Adjusted non-technical risk premium of invested capital

The adjusted non-technical risk premium, accounting for strategic stockpiling effects over the project development timeline t, is given by:

$$\tilde{R}(t) = \frac{R(t)}{1+S(t)} = \frac{1}{t+1\left[1+\frac{(\ln(1+t))^2}{10}\right]} \qquad (S4)$$

The adjusted non-technical risk premium $\tilde{R}(t)$, incorporates the feedback effect where strategic stockpiling itself reduces overall risk, ensuring internal consistency in the optimization. As $t \to \infty, S(t) \to \infty$ and thus $\tilde{R}(t) \to 0$, demonstrating the effectiveness of strategic stockpiling in mitigating non-technical risks of invested capital.

Objective function

The cost-minimization objective for determining the optimal stockpiling Q of a battery-critical mineral balances two competing costs: the expected risk from supply disruptions (from inadequate stockpiling) and the direct cost of holding stockpiles.

Let $D^{(2040)}$ denote the projected demand (in kilotons) for the year 2040, according to IEA forecasts, and Q^* denote the optimal stockpile. The objective function to minimize financial loss from delay risk versus stockpiling cost is:

$$\min_{Q}\left\{R(t) \cdot \left(D^{(2040)} - Q\right) + c_{\mathrm{s}} \cdot Q\right\} \qquad (\mathrm{S5})$$

This expression represents the total expected cost of satisfying future demand for battery-critical minerals, balancing the financial risks from supply delays (driven by non-technical risk premiums) against the costs of stockpiling (financial risk). To derive the optimal stockpile Q^*, the first-order condition is computed as:

$$\frac{d}{dQ}\left[\, R(t)\big(D^{(2040)} - Q\big) + c_s \cdot Q \,\right] = -R(t) + c_s = 0 \qquad (S6)$$

Solving this condition yields the optimal stockpile:

$$Q^* = D^{(2040)} \cdot \frac{R(t)}{R(t)+c_s} \qquad (S7)$$

Using the adjusted non-technical risk premium $\tilde{R}(t)$, the optimal stockpile becomes:

$$Q^* = D^{(2040)} \cdot \frac{\tilde{R}(t)}{\tilde{R}(t)+c_s} \qquad (S8)$$

These results highlight that the optimal stockpile size is directly proportional to the adjusted non-technical risk premium and inversely proportional to the stockpiling cost, leading to the following implications:

- Higher non-technical risk premiums, compared with stockpiling costs, justify a larger optimal stockpile Q^*, indicating that greater stockpiling is optimal.
- Higher financial costs of stockpiling or lower non-technical risk premiums warrant a smaller optimal stockpile Q^*, indicating that less stockpiling is economically justified.

Supplementary Information 2: Proven reserve shares by country and subnational region

We calculate a country's non-technical risk score for each mineral based on its percentage share of the world's proven reserves. The geographical distribution of critical mineral reserves is dynamic, with annual data primarily sourced from the U.S. Geological Survey's (USGS) Mineral Commodity Summaries, detailed in Supplementary Table S1. According to USGS definitions, 'proven reserves' represent economically extractable quantities confirmed through exploration using current technology. Coal reserve data, serving as a benchmark, are sourced from the BP World Energy Report and the U.S. Energy Information Administration (EIA).

Supplementary Table S1 illustrates the changing geographical distribution of proven reserves of critical minerals from 2011 to 2024. Bolivia significantly increased its lithium reserve share in 2019, driven by enhanced partnerships with foreign entities (Ramos, 2019; Aguirre B, 2022; Sanchez-Lopez, 2023; Jepson & Baldakova, 2024). For instance, the state-owned Yacimientos de Litio Bolivianos (YLB) partnered with German’s ACI Systems GmbH in 2018, boosting lithium exploration (Szczesniak, 2021). Argentina similarly experienced a notable lithium reserve share increase in 2012 due to updated assessments from projects like the Cauchari-Olaroz Lithium Project (Lithium Americas, 2011). The Democratic Republic of Congo (DRC) has consistently maintained a dominant global position for cobalt, with its share increasing significantly in 2023. This followed the resolution of an export ban on China Molybdenum Company’s (CMOC) Tenke Fungurume mine - one of the largest cobalt operations, in the country, which had faced allegations of deliberately underreporting reserves to avoid additional royalty payments (Mining Technology, 2023; Cobalt Institute, 2024). The resolution led to a reassessment of resource estimates and an upward revision of the DRC’s cobalt reserves.

Indonesia’s nickel reserves share markedly rose after 2017, facilitated by policy changes such as the relaxation of its nickel export ban in 2017 and the implementation of the KCMI Code 2017 aligned with the CRIRSCO framework, standardizing the estimation and reporting of mineral reserves (Joint Committee of KCMI, IAGI, & PERHAPI, 2017; Warburton, 2017). The reforms improved classification accuracy, upgrading some economically recoverable resources to proven reserves. The adoption of High-Pressure Acid Leaching (HPAL) technology and increased Chinese investment post-2022 further enhanced exploration and reserve upgrades (Ginting & Moore, 2021; ChuanYu et al., 2024). Regarding manganese, South Africa experienced a substantial reserve increase in 2020, primarily driven by the development and expansion of the Kalahari Manganese Field (KMF), the largest land-based manganese deposit globally (Barradas, 2020). In 2022, China’s manganese reserve share rose markedly following the discovery of large Nanhuanian deposits in northeastern Guizhou (Zhou et al., 2022).

For graphite, Brazil saw a significant increase in 2013 following updated USGS estimates based on government and industry data, causing a corresponding decline in China’ reserve share. Turkey’s graphite reserves initially rose in 2015 following revised USGS estimates based on updated information from the Turkish government, but sharply declined in 2023 due to a downturn in the mining sector (Lahiri, 2024; U.S. Geological Survey, 2024). Copper reserves have been relatively stable, with the decline in Chile' share in 2017 following the implementation of a certification system, which led to reserve reclassification, aligning with CRIRSCO standards. Conversely, Peru's copper reserve increased in 2023 after Minerals and Metals Group (MMG) identified significant mineralisation at deeper levels of the Ferrobamba pit in Las Bambas, which is one of the world's largest copper mines (MMG Limited, 2023). Increased public and private investment in the Altamina copper project also contributed to the reserve growth (Aquino & Madry, 2023).

Subnational proven reserve data for Canada, the United States, Australia, and Argentina are sourced from various agencies. Australian subnational reserve data for the six critical minerals and coal are obtained from Australia's Identified Mineral Resources. Lithium, cobalt, and nickel reserves are predominantly located in Western Australia, with smaller cobalt and nickel deposits in New South Wales and Queensland. Australia's manganese-dominant reserves, initially concentrated in the Northern Territory, have shifted to Western Australia since 2022. Copper reserves are primarily in South Australia, with additional deposits in New South Wales, Queensland, and Western Australia.

Lithium reserves in the United States are primarily located in Nevada (Kennedy, 2024), while Argentina's lithium reserves are concentrated in Catamarca, Jujuy, and Salta (Gonzalez, 2021; Obaya et al., 2024). For this analysis, we assume that Argentina's reserves are equally distributed among these three provinces. Notably, subnational graphite analysis is omitted due to insignificant reserves across these countries. Subnational coal reserve data for the United States and Argentina are sourced from the EIA Annual Coal Report. Canada is excluded from the subnational analysis due to insignificant proven reserves for the minerals under consideration.

Proven reserves, rather than annual production, are used as weights in the analysis, as reserves better reflect long-term supply potential and strategic importance (Vespignani & Smyth, 2024). Production data, by contrast, capture only short-term output, which may fluctuate due to market conditions or temporary disruptions. Proven reserves represent economically extractable quantities confirmed under current conditions, unlike resources, which may not be economically viable. As such, reserves offer a more stable and strategic basis for assessing investment attractiveness and supply chain resilience.

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Lithium														
United States	11.8%	13.8%	13.8%	13.8%	16.3%	14.7%	12.6%	11.0%	8.5%	9.2%	10.2%	12.2%	13.3%	16.5%
Bolivia	26.5%	22.6%	22.6%	22.6%	22.0%	19.1%	16.7%	14.6%	26.3%	24.4%	23.6%	21.4%	21.9%	20.0%
Chile	22.1%	18.9%	18.9%	18.9%	18.3%	16.0%	15.6%	13.8%	11.3%	11.2%	11.0%	11.2%	10.5%	9.6%
China	15.9%	13.6%	13.6%	13.6%	12.4%	14.9%	13.0%	7.3%	5.6%	5.9%	5.7%	6.9%	6.5%	5.9%
Argentina	7.6%	16.3%	16.3%	16.3%	15.9%	19.1%	18.2%	23.9%	21.3%	22.5%	21.3%	20.4%	21.0%	20.0%
Brazil	2.9%	0.5%	0.5%	0.5%	0.4%	0.4%	0.3%	0.3%	0.5%	0.5%	0.5%	0.7%	0.8%	1.1%
DRC	2.9%	2.5%	2.5%	2.5%	2.4%	2.1%	1.9%	1.6%	3.8%	3.5%	3.4%	3.1%	2.9%	2.6%
Serbia	2.9%	2.5%	2.5%	2.5%	2.4%	2.1%	1.9%	1.6%	1.3%	1.4%	1.3%	1.2%	1.1%	1.0%
Australia	5.3%	4.3%	4.3%	4.3%	4.1%	4.3%	9.3%	12.5%	7.9%	7.5%	8.2%	8.1%	8.3%	7.7%
Canada	1.1%	2.5%	2.5%	2.5%	2.4%	4.3%	3.5%	3.2%	2.1%	3.4%	3.3%	3.0%	2.9%	5.0%
Others	1.0%	2.5%	2.5%	2.5%	3.2%	3.0%	6.9%	10.2%	11.4%	10.5%	11.5%	11.7%	11.0%	10.5%
Cobalt														
Australia	18.7%	16.0%	13.9%	15.3%	15.5%	14.3%	16.9%	17.4%	17.1%	19.7%	18.4%	18.1%	15.5%	15.5%
Canada	1.7%	1.9%	3.6%	3.5%	3.4%	3.9%	3.5%	3.6%	3.3%	3.1%	2.9%	2.7%	2.1%	2.0%
DRC	45.3%	45.3%	47.2%	47.2%	47.9%	48.6%	49.3%	49.3%	51.4%	50.7%	46.1%	48.2%	54.5%	54.5%
New Caledonia	4.9%	4.9%	2.8%	2.8%	2.8%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
Russia	3.3%	3.3%	3.5%	3.5%	3.5%	3.6%	3.5%	3.6%	3.6%	3.5%	3.3%	3.0%	2.3%	2.3%
Zambia	3.6%	3.6%	3.8%	3.8%	3.8%	3.9%	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%
Philippines	3.8%	3.8%	3.8%	3.8%	3.5%	4.1%	3.9%	4.1%	3.7%	3.7%	3.4%	3.1%	2.4%	2.4%
Indonesia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.9%	7.2%	4.5%	5.8%
Cuba	6.7%	6.7%	6.9%	6.9%	7.0%	7.1%	7.0%	7.2%	7.1%	7.0%	6.6%	6.0%	4.5%	4.5%
United States	0.4%	0.4%	0.5%	0.5%	0.3%	0.3%	0.3%	0.6%	0.8%	0.7%	0.9%	0.8%	0.6%	0.6%
Others	11.5%	14.1%	14.1%	12.8%	12.2%	13.4%	10.7%	9.5%	8.2%	6.8%	5.8%	6.1%	8.8%	7.6%
Nickel														
Australia	30.0%	26.7%	24.3%	23.5%	24.1%	24.4%	25.7%	21.3%	22.5%	21.3%	22.1%	21.0%	18.3%	18.3%
Brazil	10.9%	10.0%	11.4%	11.2%	12.7%	12.8%	16.2%	12.4%	12.4%	17.0%	16.8%	16.0%	12.2%	12.2%
Canada	4.1%	4.4%	4.5%	3.6%	3.7%	3.7%	3.6%	3.0%	2.9%	3.0%	2.1%	2.2%	1.7%	1.7%
China	3.8%	4.0%	4.1%	3.7%	3.8%	3.2%	3.9%	3.1%	3.1%	3.0%	2.9%	2.1%	3.2%	3.4%
Indonesia	4.9%	5.2%	5.3%	5.6%	5.7%	5.8%	6.1%	23.6%	23.6%	22.3%	22.1%	21.0%	42.0%	42.0%
New Caledonia	15.0%	16.0%	16.2%	14.8%	10.6%	8.6%	8.3%	8.1%	7.8%	7.6%	7.3%	7.1%	5.4%	5.4%
Philippines	1.4%	1.5%	1.5%	3.8%	3.9%	6.2%	6.5%	5.4%	5.4%	5.1%	5.1%	4.8%	3.7%	3.7%
Russia	7.5%	8.1%	8.2%	9.8%	10.0%	9.7%	10.3%	8.5%	7.8%	7.3%	7.9%	7.5%	6.3%	6.3%
South Africa	4.6%	4.9%	5.0%	4.6%	4.7%	4.7%	5.0%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%
Cuba	6.9%	7.3%	7.4%	6.8%	7.0%	7.1%	7.4%	6.2%	6.2%	5.9%	0.0%	0.0%	0.0%	0.0%
Others	11.0%	11.9%	12.2%	12.7%	13.9%	13.8%	6.9%	4.2%	4.2%	3.4%	9.4%	14.1%	2.9%	2.9%

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Manganese														
Australia	14.6%	15.2%	16.7%	16.6%	14.6%	13.2%	13.8%	13.0%	12.3%	17.3%	18.0%	15.7%	26.2%	29.1%
Brazil	17.3%	17.2%	9.3%	9.2%	8.0%	16.8%	17.6%	14.5%	17.2%	20.3%	18.0%	15.7%	14.2%	15.7%
China	6.9%	6.9%	7.6%	7.5%	7.1%	6.2%	7.1%	7.1%	6.7%	4.1%	3.6%	16.3%	14.7%	16.3%
India	8.8%	7.7%	8.4%	8.9%	8.4%	7.5%	5.0%	4.3%	4.2%	2.6%	2.3%	2.0%	1.8%	2.0%
South Africa	23.6%	23.4%	25.8%	25.7%	32.2%	29.0%	29.4%	30.3%	32.0%	39.0%	42.7%	37.3%	31.4%	32.6%
Ghana	2.0%	2.0%	2.2%	2.2%	2.1%	1.7%	1.9%	1.7%	1.6%	1.0%	0.9%	0.8%	0.7%	0.8%
Gabon	3.3%	4.2%	4.1%	4.1%	3.5%	3.2%	2.9%	8.6%	7.5%	4.6%	4.1%	3.6%	3.2%	3.6%
Ukraine	22.0%	21.9%	24.1%	24.0%	22.5%	20.3%	20.6%	18.4%	17.2%	10.5%	9.3%	8.1%	7.3%	0.0%
Others	1.4%	1.6%	1.7%	1.7%	1.6%	2.0%	1.6%	2.1%	1.2%	0.8%	1.2%	0.6%	0.5%	0.0%
Graphite														
Brazil	0.5%	0.5%	44.6%	36.4%	31.3%	28.8%	25.9%	24.0%	24.0%	21.9%	21.8%	22.4%	26.4%	25.5%
China	71.4%	71.4%	42.3%	50.0%	23.9%	22.0%	20.4%	24.3%	24.3%	22.8%	22.8%	15.8%	27.9%	27.9%
India	14.3%	14.3%	8.5%	10.0%	3.5%	3.2%	3.0%	2.7%	2.7%	2.5%	2.5%	2.4%	3.1%	3.0%
Madagascar	1.2%	1.2%	0.7%	0.9%	0.4%	0.6%	0.6%	0.5%	0.5%	8.1%	8.1%	7.9%	8.6%	9.3%
Mexico	4.0%	4.0%	2.4%	2.8%	1.3%	1.2%	1.1%	1.0%	1.0%	1.0%	1.0%	0.9%	1.1%	1.1%
Russia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.2%	5.0%	4.8%
Turkey	0.0%	0.0%	0.0%	0.0%	39.1%	36.0%	33.3%	30.0%	30.0%	28.1%	28.1%	27.3%	2.5%	2.4%
Mozambique	0.0%	0.0%	0.0%	0.0%	0.0%	5.2%	6.3%	5.7%	8.3%	7.8%	7.8%	7.6%	8.9%	8.6%
Tanzania	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	6.3%	5.7%	6.0%	5.3%	5.6%	5.5%	6.4%	6.2%
Others	8.6%	8.6%	1.5%	0.0%	0.4%	0.9%	3.1%	6.1%	3.1%	2.5%	2.4%	6.0%	10.1%	11.2%
Copper														
United States	5.1%	5.7%	5.7%	5.0%	4.6%	4.9%	5.7%	5.8%	5.9%	5.5%	5.5%	4.9%	5.0%	4.8%
Australia	12.5%	12.6%	12.6%	13.3%	12.2%	12.4%	11.1%	10.6%	10.0%	10.1%	10.6%	10.9%	10.0%	10.2%
Canada	1.0%	1.5%	1.4%	1.6%	1.5%	1.5%	1.4%	1.3%	1.2%	1.0%	1.1%	0.9%	0.8%	0.8%
Chile	27.5%	27.9%	27.5%	29.9%	29.2%	29.2%	21.5%	20.5%	23.0%	23.0%	22.7%	21.3%	19.0%	19.4%
China	4.3%	4.4%	4.3%	4.3%	4.2%	3.9%	3.4%	3.1%	3.0%	3.0%	3.0%	3.0%	4.1%	4.2%
DRC	2.9%	2.9%	2.9%	2.9%	2.8%	2.8%	2.5%	2.4%	2.2%	2.2%	3.5%	3.5%	8.0%	8.2%
Indonesia	4.1%	4.1%	4.1%	3.6%	3.5%	3.4%	3.3%	6.1%	3.2%	3.0%	2.7%	2.7%	2.4%	2.1%
Kazakhstan	1.0%	1.0%	1.0%	0.9%	1.1%	1.4%	1.7%	2.0%	2.3%	2.3%	2.3%	2.2%	2.0%	2.0%
Mexico	5.5%	5.6%	5.5%	5.4%	6.4%	6.4%	5.8%	6.0%	6.1%	6.1%	6.0%	6.0%	5.3%	5.4%
Peru	13.0%	11.2%	10.1%	9.7%	11.4%	11.3%	10.3%	10.0%	10.0%	10.6%	8.8%	9.1%	12.0%	10.2%
Poland	3.8%	3.8%	3.8%	4.0%	3.9%	3.9%	3.9%	3.8%	3.8%	3.7%	3.5%	3.4%	3.4%	3.5%
Russia	4.3%	4.4%	4.3%	4.3%	4.2%	4.2%	5.8%	7.3%	7.0%	7.0%	7.0%	7.0%	8.0%	8.2%
Zambia	2.9%	2.9%	2.9%	2.9%	2.8%	2.8%	2.5%	2.3%	2.2%	2.4%	2.4%	2.1%	2.1%	2.1%
Others	12.0%	11.8%	13.8%	12.4%	12.3%	12.1%	21.0%	18.7%	20.2%	20.1%	20.9%	23.0%	17.9%	18.8%

Supplementary Table S1 | Country-level proven reserves of six critical minerals as a percentage of world reserves (2011-2024). This table reports the global percentage share of proven reserves for critical minerals by country from 2011 to 2024, based on data from the U.S. Geological Survey Mineral Commodity Summaries. Countries with negligible reserve shares are aggregated under "Others." These reserve shares serve as weights for calculating the non-technical risk scores.

Supplementary Information 3: Investment Attractiveness Index from the Fraser Institute

The Fraser Institute's Annual Survey of Mining Companies provides an extensive industry perspective on mining investment attractiveness across jurisdictions. The Investment Attractiveness Index (IAI), derived from this survey, combines two distinct indices: the Best Practice Mineral Potential Index (BPMPI) and the Policy Perception Index (PPI). Based on survey insights, investment decisions typically weigh mineral potential around 60 percent and policy factors about 40 percent (Mejía & Aliakbari, 2024). Consequently, higher IAI scores reflect jurisdictions that offer more appealing investment conditions. The BPMPI evaluates geological potential under optimal policy environment, while the PPI assesses the quality of regulatory and policy environments, such as taxation, regulatory efficiency, political stability, and environmental regulations. Both indices were formally introduced in the 2015 survey, with retrospective data provided back to 2011.

Following Vespignani and Smyth (2024), this study adopts the IAI as a proxy for overall non-technical risk, capturing mining companies' perceptions of political, regulatory, and environmental risks. We utilize national and subnational IAI values from 2011 to 2024 to calculate the non-technical risk scores. Supplementary Table S2 provides country- and region-level IAI values, while Supplementary Table S3 presents detailed subnational IAI values for the United States, Australia, and Argentina. We focus exclusively on jurisdictions that hold substantial reserves of the six critical minerals, as evaluating investment attractiveness is meaningful only where significant resource bases exist. Canadian provinces are excluded from the subnational analysis due to their limited reserve shares. Subnational analysis allows for a granular assessment of regional risk variations, particularly crucial given the geographic concentration of critical minerals within specific regions.

Supplementary Table S2 highlights significant changes in IAI scores at the national level. Chile's index declined by approximately 30 percent from 2018 to 2023, potentially impacting lithium and copper investment, as Chile is one of the key concentration areas for the reserves of both minerals. Chile's IAI scores rebounded in 2024, yet remained well below their 2011 levels. Bolivia's IAI fell around 52 percent post-2019, primarily affecting lithium investment due to Bolivia's substantial global lithium reserves. The DRC's IAI significantly decreased from 62.88 to a low of 29.67 in 2021 before partially recovering to 49.31 in 2024, adversely affecting cobalt investment attractiveness. Indonesia experienced a similar decline of 38 percent from 2019 to 2023, which heightened challenges in attracting investment to the nickel sector. Indonesia’s IAI score rose significantly from its 2023 level. Notably, China’s IAI plummeted from 61.07 in 2011 to 19.08 in 2023 - a 69 percent decline - introducing significant uncertainty for graphite investment, given China’s dominant global graphite reserves. Furthermore, China’s increasing share of global manganese reserves has also exposed manganese to greater uncertainty of investment.

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average	SD
Canada	78.77	74.58	77.46	78.38	73.99	77.37	74.67	78.32	71.52	74.52	72.59	73.62	72.52	65.96	74.59	3.46
United States	71.10	66.35	71.64	75.28	72.53	74.66	69.92	74.46	69.46	73.95	72.75	74.80	75.71	67.40	72.15	2.97
Australia	69.76	67.54	73.40	71.58	75.17	74.14	69.95	73.02	77.04	73.81	76.40	73.74	72.35	56.97	71.78	4.99
Argentina	61.37	50.45	47.67	55.59	43.52	43.33	51.67	53.21	53.18	58.14	57.56	61.53	63.88	67.60	54.91	7.32
Indonesia	66.04	61.96	58.01	55.24	65.16	50.16	66.84	63.10	73.09	44.32	57.84	51.03	45.17	62.90	58.63	8.55
New Caledonia	65.71	62.04	60.31	52.30	48.14	57.05	61.16	65.57	65.51	51.70	51.05	51.03	46.02	63.97	57.25	7.04
Philippines	64.12	59.36	64.54	48.78	56.59	58.97	50.32	55.55	65.51	51.70	51.05	51.03	36.89	77.11	56.54	9.64
DRC	62.88	50.39	54.86	58.38	59.37	72.80	61.51	54.92	39.20	58.12	29.67	48.52	42.97	49.31	53.06	10.89
Ghana	78.72	63.47	71.30	67.17	71.27	75.56	72.13	54.91	51.85	71.85	61.29	62.27	44.35	56.98	64.51	9.87
Madagascar	57.67	51.43	55.65	52.42	62.91	62.41	54.18	58.66	51.85	62.03	49.62	53.32	46.09	29.06	53.38	8.62
Mozambique	63.11	55.33	44.72	55.91	50.69	41.87	30.78	58.66	51.85	61.24	49.62	34.96	31.90	27.01	46.97	11.96
South Africa	59.56	53.76	61.50	56.49	58.04	53.62	62.06	65.30	64.79	56.33	37.88	44.76	41.84	41.12	54.07	9.13
Tanzania	66.16	62.53	58.40	63.82	57.46	60.45	46.79	55.04	32.82	42.08	45.76	52.90	46.38	62.75	53.81	9.75
Zambia	63.13	63.01	70.30	75.71	57.48	72.78	59.34	63.60	37.90	60.83	49.62	42.18	64.23	70.02	60.72	11.03
Bolivia	42.36	35.60	42.87	44.74	44.56	48.74	33.68	49.53	62.36	45.16	42.92	53.97	36.28	30.00	43.77	8.45
Brazil	75.45	64.99	65.63	69.27	61.45	62.51	55.12	58.63	63.36	69.29	56.20	68.98	68.50	51.23	63.62	6.65
Chile	85.16	78.52	82.54	81.86	79.81	69.66	81.51	84.90	77.72	72.11	69.33	60.34	59.76	68.75	75.14	8.53
Mexico	81.16	72.69	71.05	75.96	68.93	67.06	63.03	73.91	65.43	66.87	66.46	60.16	36.51	54.48	65.98	10.81
Peru	74.49	63.23	69.85	75.35	69.26	73.47	74.26	81.55	75.14	70.41	61.64	60.68	44.01	61.23	68.18	9.40
China	61.07	54.50	58.69	48.89	58.49	65.13	41.65	44.75	44.75	44.75	34.92	44.86	19.08	61.41	48.78	12.38
India	50.34	58.69	52.13	58.26	55.47	39.11	57.79	44.75	44.75	44.75	43.20	49.63	38.23	61.41	49.89	7.62
Kazakhstan	61.27	62.50	63.45	50.84	74.66	54.08	71.03	44.75	44.75	44.75	48.83	49.63	36.10	59.18	54.70	11.04
Poland	71.10	46.76	65.84	58.03	61.37	71.34	67.14	68.27	77.82	70.54	61.36	67.83	55.50	67.18	65.01	7.84
Russia	53.64	57.20	52.35	60.14	65.86	69.02	67.51	74.23	77.82	74.53	63.57	67.83	55.50	55.55	63.91	8.37
Serbia	67.29	67.46	63.21	58.74	63.20	62.54	68.34	68.65	77.82	70.54	61.36	67.83	56.50	48.68	64.44	7.01
Turkey	73.99	76.12	72.77	56.71	64.04	60.67	52.60	56.72	81.60	79.27	52.15	67.83	46.73	59.50	64.34	11.04
Others	62.98	57.66	57.98	58.28	58.68	60.10	58.18	59.99	59.47	60.10	53.52	58.43	47.97	56.20	57.82	3.55
Africa Mean	64.46	57.13	59.53	61.41	59.60	62.78	55.26	58.73	47.18	58.93	46.21	48.42	45.39	47.40	55.57	5.46
Europe Mean	66.51	61.89	63.54	58.41	63.62	65.89	63.90	66.97	78.77	73.72	59.61	67.83	53.56	67.18	66.14	5.12
Latin America and Caribbean Mean	71.72	63.01	66.39	69.44	64.80	64.29	61.52	69.70	68.80	64.77	59.31	60.83	49.01	49.79	54.87	4.34

Supplementary Table S2 | Investment Attractiveness Index by country (2011-2024). This table reports the Fraser Institute's Investment Attractiveness Index for all countries used to calculate the non-technical risk score, covering the period 2011-2024. The average and standard deviation in the last two columns highlight mean investment attractiveness and its volatility over the period. Countries with negligible reserve shares are aggregated under "Others," represented by the global mean. Missing country-level data are imputed using regional average. For countries with available subnational indices - Canada, the United States, Australia, and Argentina - the mean of their subnational indices is used.

Subnational	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Av	SD
Australia																
Western Australia	84.22	80.20	86.88	84.33	87.35	88.88	83.56	91.47	92.45	88.82	90.21	88.26	86.58	76.69	86.42	4.33
New South Wales	64.04	60.57	68.57	62.40	68.83	61.84	62.31	65.56	62.78	72.64	66.48	71.54	68.26	47.68	64.54	6.13
Northern Territory	74.56	74.48	76.49	73.89	81.90	77.61	70.47	75.93	81.43	77.27	78.35	84.64	81.72	62.62	76.53	5.52
Queensland	75.02	74.01	76.33	76.24	77.79	81.40	80.53	81.67	79.33	78.00	77.13	78.55	78.17	61.99	76.87	4.83
South Australia	81.49	74.73	75.97	79.71	79.83	81.03	79.30	75.46	83.31	85.64	81.70	83.37	75.60	63.14	78.59	5.56
Others	54.51	54.41	64.79	62.24	65.25	64.12	56.76	60.53	69.99	57.14	70.47	54.93	58.05	43.32	59.75	7.75
United States																
Nevada	86.41	82.68	87.47	88.38	85.39	87.48	85.45	92.99	87.54	91.05	87.64	92.17	87.93	88.69	87.95	2.73
Others	69.83	64.99	70.32	74.19	71.46	73.60	68.62	72.92	67.82	72.53	71.51	72.63	74.35	65.63	70.83	6.40
Argentina																
Catamarca	65.56	58.37	43.57	69.14	42.29	50.38	53.91	68.39	63.93	65.49	58.39	54.84	63.88	67.60	58.98	8.92
Jujuy	54.29	51.28	46.94	58.92	49.57	24.83	58.57	52.61	51.21	63.55	61.17	59.70	72.92	67.60	55.23	11.37
Salta	60.03	54.28	63.02	73.71	56.69	69.25	62.51	54.09	67.19	74.69	72.05	56.48	77.24	67.60	64.92	7.89
Others	62.21	48.65	46.17	50.58	40.94	40.92	48.35	50.64	49.93	53.26	54.41	68.31	52.68	67.60	52.85	10.45

Supplementary Table S3 | Investment Attractiveness Index by subnation (2011-2024). This table reports subnational Investment Attractiveness Index scores from 2011 to 2024, sourced from the Fraser Institute's Annual Survey of Mining Companies. Data focus on subnational regions in the United States, Australia, and Argentina, with Canada excluded due to negligible critical mineral reserves. Missing data are substituted with national averages. Regions with significant proven reserve are listed individually, while those with minor reserves are aggregated under "Others," and their mean values are used.

Supplementary Information 4: Estimation and decomposition of non-technical risk scores for battery minerals

Decomposing the non-technical risk score

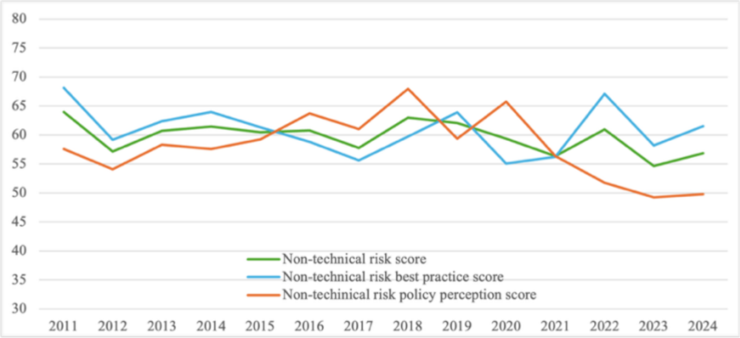
The IAI combines the PPI, measuring policy influences on exploration investment, and the BPMPI, evaluating pure geological attractiveness (Mejía & Aliakbari, 2024). We decompose the overall non-technical risk score into the non-technical risk best practice score and non-technical risk policy perception score, represented formally as:

$$NTRBP\ score_{m,t} = \sum_{c=i}^{n}(w_{c,m,t} \times BPMPI_{c,t}) \qquad \text{(S9)}$$

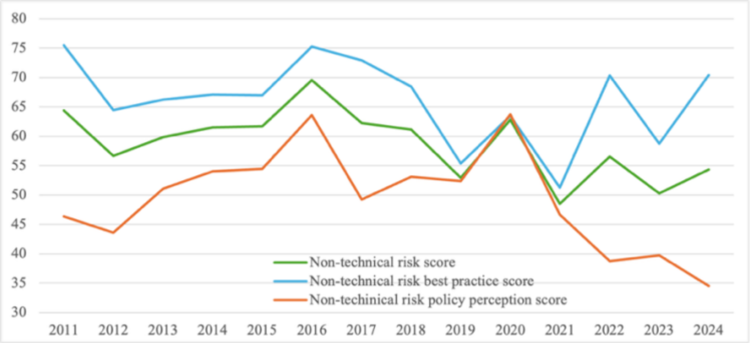
$$NTRPP\ score_{m,t} = \sum_{c=i}^{n}(w_{c,m,t} \times PPI_{c,t}) \qquad \text{(S10)}$$

Where $NTRBP\ score_{m,t}$ denotes the global non-technical risk best practice score for critical mineral m in year t, and $NTRPP\ score_{m,t}$ denotes the global non-technical risk policy perception score for critical mineral m in year t. $w_{c,m,t}$ represents the percentage share of proven global reserves for critical mineral m in country c in year t. The $BPMPI_{c,t}$ is the Best Practices Mineral Potential Index for country c in year t, and $PPI_{c,t}$ is the Policy Perception Index for country c in year t. Lower values are associated with high pure mineral- or policy-related non-technical risks.

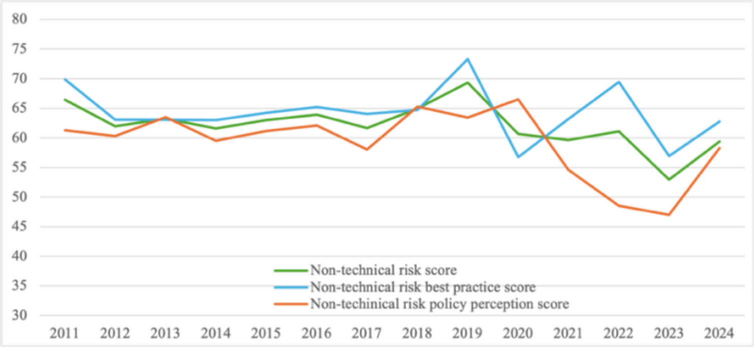
(a) Lithium



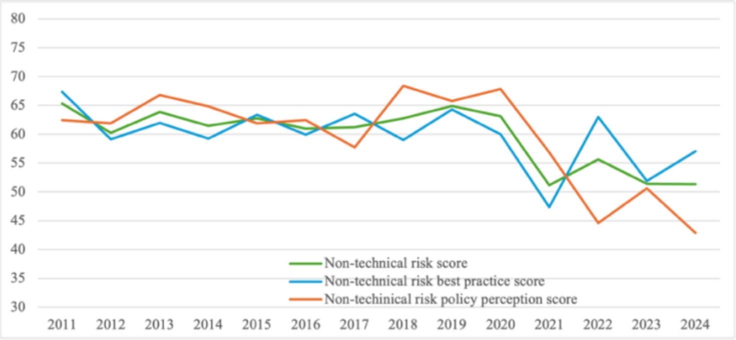
(b) Cobalt



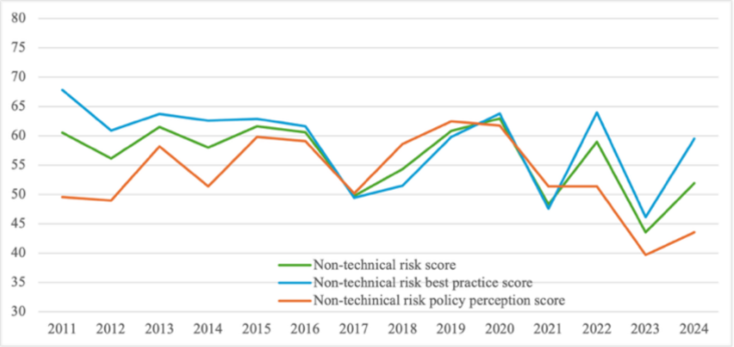
(c) Nickel



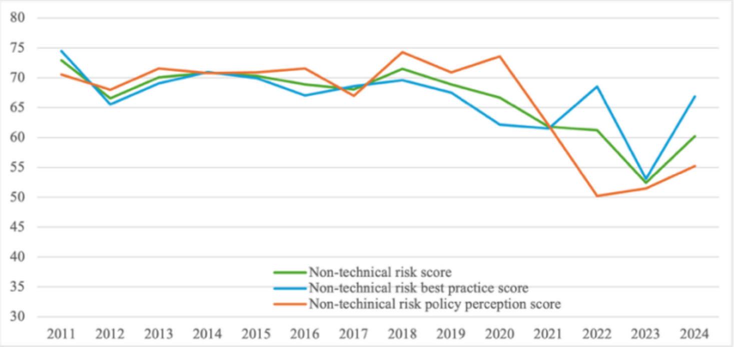
(d) Manganese



(e) Graphite



(f) Copper



Supplementary Fig 1 | Annual non-technical risk scores and their two constituent components - best practice and policy perception scores - for six critical minerals from 2011 to 2024. Following Vespignani and Smyth (2024), overall non-technical risk scores are calculated by weighting the Fraser Institute's Investment Attractiveness Index by global proven reserve distributions. The decomposition reflects the Investment Attractiveness Index's weighting scheme: 40 percent Policy Perception Index, 60 percent Best Practices Mineral Potential Index (Mejía & Aliakbari, 2024). Note that the non-technical risk score is inversely related to non-technical risk premium: lower non-technical risk score indicates higher non-technical risks and greater non-technical risk premiums.

Supplementary Fig. 1(a) illustrates how lithium's non-technical risk profile is shaped by the interplay between policy perception and best practice scores. The overall non-technical risk scores rose in 2018, driven by a shift in proven lithium reserves from China to Australia, which is a more stable jurisdiction. After 2020, policy perception score declined sharply, reaching its lowest point in 2023 due to increased regulatory uncertainty in key lithium countries such as Argentina, Chile, and Bolivia. In Chile, constitutional reform initiated in 2020 and concession proposals introduced by the new government in 2022 contributed significantly to uncertainty and unclear regulatory framework (Yunis & Aliakbari, 2022; Mejía & Aliakbari, 2023). Argentina's investment climate similarly deteriorated due to restrictive foreign exchange regulations, inconsistent environmental assessments, and mandatory local service contracting (Mejía & Aliakbari, 2023; Mejía & Aliakbari, 2024). The notable dip in the best practice score during 2020 reflected temporary operational disruptions and project delays resulting from COVID-19 pandemic lockdowns in key regions such as Bolivia, Chile and Australia (International Energy Agency, 2021).

Supplementary Fig. 1(b) shows cobalt's volatile non-technical risk profile, primarily influenced by fluctuations in the DRC, which holds half of the world's proven cobalt reserves (see Supplementary Table S2). The policy perception score improved steadily from 2012 to 2016, following increased transparency linked to revisions of the 2002 Mining Code since 2012 (Jackson & Green, 2016). However, the policy perception score dropped sharply in 2017 due to concerns over trade barriers, corruption, arbitrary license decisions, and unpredictable taxes in the DRC (Stedman & Green, 2018). A temporary rebound occurred in 2020 after the DRC resumed cooperation with the IMF in late 2019, restoring some investor confidence Yet, by 2024, the policy perception score fell to its lowest level, driven by a sharp decline in the DRC's PPI score. Contributing factors included the absence of property rights, government confiscation of mining equipment without legal basis, cash repatriation restrictions, poor data accessibility, corruption in licensing, and land tenure disputes (Yunis & Aliakbari, 2022; Mejía & Aliakbari, 2023; Mejía & Aliakbari, 2024; Mejía & Aliakbari, 2025). The best practice score saw notable declines in 2019 and 2021, reflecting disruptions from the closure of Glencore's Mutanda mine - the world's largest cobalt operation - and COVID-19-related shutdowns across the DRC (Cobalt Institute, 2021; Ellis, 2020; Reid & Holland, 2020).

Supplementary Fig. 1(c) highlights nickel's increasingly volatile non-technical risk profile, culminating in its lowest overall score in 2023. Policy perception score deteriorated significantly after 2020, driven by Indonesia's reintroduction of a nickel export ban and price-setting regulations (IEA, 2024; Harsono, 2020), and political instability in Brazil exacerbated by weakened institutions and widespread protests (Exman, 2021). In contrast, the best practice score increased significantly after 2020 due to foreign investments in Indonesia, notably from China, supporting advanced exploration technologies and world-class processing facilities such as Indonesia Morowali Industrial Park (Ginting & Moore, 2021). Technological advancements in nickel ore exploration, particular HPAL projects, also significantly improved perceptions of

Indonesia's geological potential (Critical Minerals, 2024). Additionally, policy perception score increased markedly in 2024, largely due to a sharp rise in Indonesia’s PPI score - from 32.16 in 2023 to 59.75 in 2024.

Supplementary Fig. 1(d) shows manganese’s relatively stable non-technical risk profile until 2019, after which volatility increased sharply. Policy perception score peaked in 2018 following positive developments in South Africa, such as the withdrawal of the controversial Mineral and Petroleum Resources Development Amendment Bill and the introduction of clearer regulations under Mining Charter III. However, manganese’s policy attractiveness declined drastically from 2020 to 2022 due to burdensome ownership requirements and infrastructure challenges, notably electricity load shedding (Mejía & Aliakbari, 2023; Ngoepe-Ntsoane, 2024). A partial recovery in 2023 was facilitated by Australia’s increased reserve share after USGS revisions. Policy perception score declined again in 2024, reaching its lowest level since 2011, primarily due to a 52 percent drop in South Africa’s PPI score. According to Mejía and Aliakbari (2025), this decline reflects growing investor concerns over political instability, weak socioeconomic agreements, and a deteriorating geological database. Geoscience Australia (2025) reported strong growth in Australia’s manganese reserves, attributed to advances in geological exploration and resource assessment. The dip in the best practice score in 2021 reflects operational disruptions caused by COVID-19 lockdowns (Fastmarkets, 2020). A notable rebound in 2022 was driven by a significant upward revision of China’s reserve share, given China’s high BPMPI in that year.

Supplementary Fig. 1(e) depicts graphite’s notably volatile non-technical risk profile, heavily influenced by China and Brazil’s reserve distributions. The overall non-technical risk score dropped significantly in 2017, primarily driven by declines in China’s policy perceptions due to socioeconomic disputes, community development disputes, land-claim controversies, and security issues (Stedman & Green, 2018). Concurrent reductions in geological attractiveness exacerbated this decline. Conversely, the significant rebound in 2022 was largely attributed to regulatory reforms in Brazil, aligning mineral resource classification standards with international practices, thereby enhancing transparency and geological perceptions (National Mining Agency, 2023).

Supplementary Fig. 1(f) shows a deteriorating trend in copper’s non-technical risk profile over the past decade. The best practice score had been gradually declining due to long-term industry challenges, such as falling ore grades and fewer major discoveries (International Energy Agency, 2021; Marjolin et al., 2022). However, it rose sharply in 2024, driven by increases in the BPMPI scores of both Peru and Chile. The policy perception score experienced sharp volatility, dropping dramatically between 2020 and 2022, primarily influenced by development in Chile - home to the world's largest copper reserves. Chile's protracted constitutional reform (2019-2022) created considerable policy uncertainty and regulatory confusion for the mining sector, compounded in 2022 by proposals for high copper royalties and additional income-based levies, unsettling investors (Yunis & Aliakbari, 2021; Yunis & Aliakbari, 2022; Mejía & Aliakbari, 2023).

Subnational decomposition of non-technical risk scores

We further decompose subnational non-technical risk score into subnational non-technical risk best practice score and non-technical risk policy perception score, calculated as follows:

$$NTRBP\ score_{s,m,t} = w_{s,m,t} \times BPMPI_{s,t} \tag{S11}$$

$$NTRPP\ score_{s,m,t} = w_{s,m,t} \times PPI_{s,t} \tag{S12}$$

Where $NTRBP\ score_{s,m,t}$ and $NTRPP\ score_{s,m,t}$ denote the non-technical risk best practice score and policy perception score, respectively, for mineral m in state/province/territory s in year t. $w_{s,m,t}$ represents the percentage share of global proven reserves for mineral m in state/province/territory s in year t. $BPMPI_{s,t}$ and $PPI_{s,t}$ represent the Best Practices Mineral Potential Index and the Policy Perception Index at the subnational level in year t, respectively. The resulting scores reflect detailed regional geological and policy non-technical risk profiles for each critical mineral. Further details on subnational-level BPMPI and PPI scores, proven reserve shares, and non-technical risk scores - including best practice and policy perception components - are provided in the Supplementary Data File.

Supplementary Information 5: Decomposing the non-technical risk premium for minerals

Using the decomposed non-technical risk best practice and non-technical risk policy perception scores for the six key battery metals and coal, we further decompose the overall non-technical risk premium into its components with the following equations:

$$NNTRBP\ premium_{m,t} = \frac{\left(NTRBP\ score_{coal,t} - NTRBP\ score_{m,t}\right)}{NTRBP\ score_{c,coal,t}} \qquad (S13)$$

$$NTRPP\ premium_{m,t} = \frac{\left(NTRPP\ score_{coal,t} - NTRPP\ score_{m,t}\right)}{NTRPP\ score_{coal,t}} \qquad (S14)$$

Where $NTRBP\ score_{m,t}$ represents the non-technical risk best practice score for critical mineral m in year t, and $NTRBP\ score_{coal,t}$ represents the corresponding coal benchmark score. Similarly, $NTRPP\ score_{m,t}$ denotes the non-technical risk policy perception score for critical mineral m in year t, with $NTRPP\ score_{coal,t}$ as its coal benchmark equivalent. Thus, $NTRBP\ premium_{m,t}$ and $NTRPP\ premium_{m,t}$ indicate the mineral-specific best practice and policy perception premiums, respectively.

We decompose overall non-technical risk premium into non-technical risk policy perception premium and non-technical risk best practices premium over the period 2011-2024. This timeframe encompasses four distinct policy phases that align with major shifts in climate policy, market sentiment, and supply-chain priorities. The pre-Paris period (2011-2014) serves as the baseline, characterized by relatively compressed non-technical risk premiums and limited cross-mineral differentiation, as global frameworks were still nascent. The post-Paris period (2015-2019) marks a structural re-rating: clearer policy signals and stronger investor alignment drove a broad uplift in perceived non-technical risk premiums, visible as step-like increases across many minerals. The Green Recovery period (2020-2021) functions as a stabilization bridge—elevated levels persist as stimulus effects and COVID-19 pandemic-related uncertainty are absorbed, yielding modest incremental changes. Finally, the Critical Materials Focus period (2022-2024) intensifies differentiation: energy-transition-critical minerals display firmer or rising premiums as supply security, ESG standards and industrial policy sharpen attention on upstream risks.

Supplementary Fig. 2 reports the evolution of the overall non-technical risk premium for six battery-related critical minerals (lithium, cobalt, nickel, manganese, graphite and copper) over 2011-2024. Across minerals, the non-technical risk premium generally exhibits an upward trend, though with varying degrees of volatility. During the pre-Paris period (2011-2014), overall non-technical risk premiums hovered around zero, indicating a relatively uniform and moderate level of perceived non-technical risk amid fragmented global frameworks. In the post-Paris period (2015-2019), premiums edged up for several minerals, reflecting a gradual increase in non-technical risk premium as the global energy transition entered a new phase and the strategic importance of critical minerals became more pronounced. During the Green Recovery phase (2020-2021), premiums remain elevated, suggesting that stimulus measures and pandemic-related uncertainty sustained higher levels of perceived risk.

In the most recent Critical Mineral Focus period (2022-2024), premiums increased noticeably—most visibly for cobalt, manganese and graphite—signalling a deterioration in non-technical risk premium amid supply-chain tightness and renewed policy emphasis on critical minerals. Specifically, lithium fluctuates around 0.1-0.2, showing a slight increase since 2022. Cobalt and manganese display greater volatility, with a pronounced rise in 2024. Nickel follows a gradual upward trajectory, peaking around 2022–2023 before declining in 2024. Graphite exhibits a clear rising pattern after 2022, while copper shows a gradual increase, peaking around 2022-2023.

Supplementary Figs. 3 and 4 decompose the overall non-technical risk premium into itss best practice and policy perception components. In Supplementary Fig. 3, the non-technical risk best practice premium remains relatively low and stable across all six minerals over 2011-2024, indicating that it contributes only modestly to the overall non-technical risk premium. Supplementary Fig. 4 isolates the policy perception premium and shows that it is the dominant driver of overall non-technical risk premiums. The patterns closely mirror those in Supplementary Figs. 2, with sharp increases for cobalt, manganese, and graphite during the recent Critical Materials Focus period, suggesting heightened perceptions of policy uncertainty and regulatory risk for these battery-related critical minerals. Overall, the comparison of components shows that the policy perception premium accounts for most of the increase in the overall premium, while the best practice premium follows a slower and steadier upward path. These results indicate that the recent rise in non-technical risk premium has been driven primarily by deteriorating policy perception.

Supplementary Fig 2 | Non-technical risk premium for six battery-related critical minerals over 2011-2024. The figure plots annual premiums from 2011 to 2024 on the x-axis, with four shaded policy periods—pre-Paris (2011-2014, blue), post-Paris (2015-2019, green), Green Recovery (2020-2021, orange), and Critical Materials Focus (2022-2024, pink)—corresponding to their respective year ranges. The y-axis is shared across all six mineral panels: lithium, cobalt, nickel, manganese, graphite, copper.

Supplementary Fig 3 | Non-technical risk best practices premium for six battery-related critical minerals over 2011-2024. The figure plots annual premiums from 2011 to 2024 on the x-axis, with four shaded policy periods—pre-Paris (2011-2014, blue), post-Paris (2015-2019, green), Green Recovery (2020-2021, orange), and Critical Materials Focus (2022-2024, pink)—corresponding to their respective year ranges. The y-axis is shared across all six mineral panels: lithium, cobalt, nickel, manganese, graphite, copper.

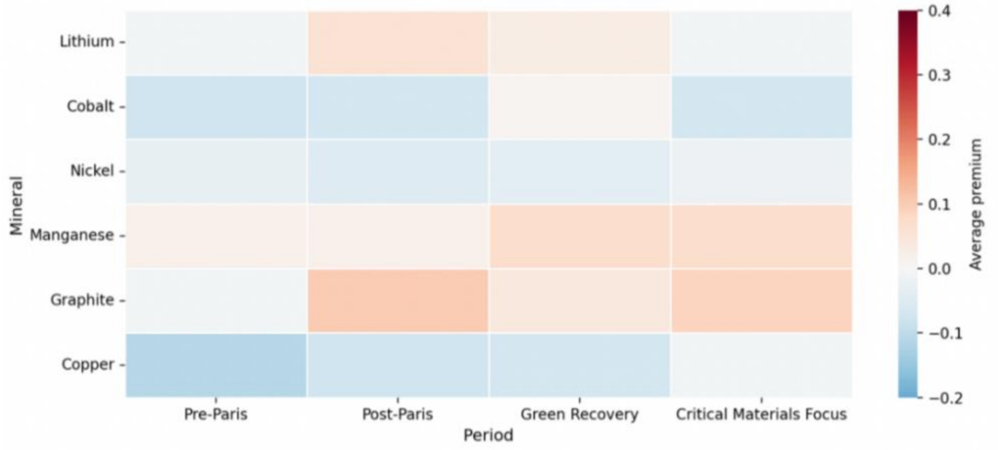
Supplementary Fig 4 | Non-technical risk policy perspective premium for six battery-related critical minerals over 2011-2024. The figure plots annual premiums from 2011 to 2024 on the x-axis, with four shaded policy periods—pre-Paris (2011-2014, blue), post-Paris (2015-2019, green), Green Recovery (2020-2021, orange), and Critical Materials Focus (2022-2024, pink)—corresponding to their respective year ranges. The y-axis is shared across all six mineral panels: lithium, cobalt, nickel, manganese, graphite, copper.

Supplementary Fig. 5 presents heatmaps of average non-technical risk premiums for six battery-related critical minerals across four policy periods. Panel (a) shows the results for the non-technical risk best practice premium. Average values remain close to zero in the pre-Paris years. In the post-Paris period, the best practice premiums for lithium and graphite increased markedly from negative to positive values, followed by increases for cobalt and manganese during the Green Recovery phase. In the Critical Materials Focus period, the best practice premiums for manganese and graphite remained relatively high. Overall, Panel (a) suggests that the non-technical risk best practice premium remains at a relatively low level and increases only gradually over time.

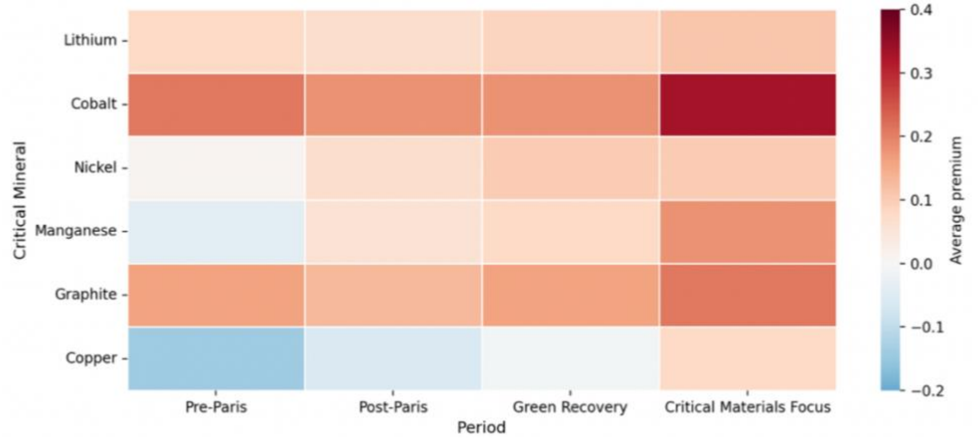
Panel (b) displays the non-technical risk policy perception premium, which is higher and shows more pronounced and widespread increases, particularly for cobalt, manganese and graphite. The average values for cobalt and graphite were relatively high during the pre-Paris years. In the post-Paris period, the policy perception premiums for nickel and manganese increased significantly. During the Green Recovery phase, all six critical minerals experienced increases in their policy perception premiums. In the Critical Materials Focus period, all premiums remained positive, with cobalt, manganese and graphite exhibiting particularly elevated values. The strong upward shifts in the policy perception premium indicate heightened perceptions of policy-related risks and regulatory uncertainty.

Comparing across panels reveals that the overall non-technical risk premium in Panel (c) largely mirrors the pattern observed in the policy perception premium, with the best practice component contributing more modestly. This further supports our conclusion that the escalation of average non-technical risk premiums across periods is driven primarily by deteriorating policy perception.

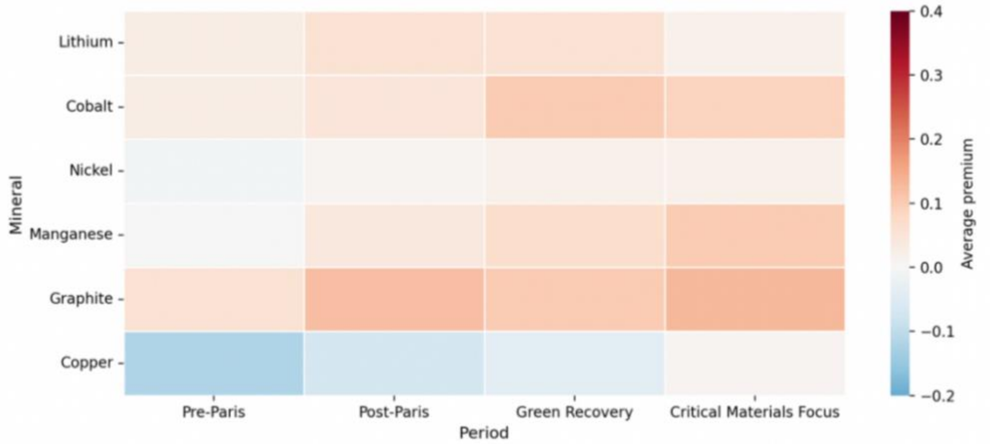
(a) Non-technical risk best practice premium



(b) Non-technical risk policy perception premium



(c) Non-technical risk premium



Supplementary Fig 5 | Non-technical risk premium for critical minerals – Average by value and era (2011-2024). This figure shows heatmaps with a categorical x-axis labelled Period, consisting of four columns—pre-Paris (2011-2014), post-Paris (2015-2019), Green Recovery (2020-2021), and Critical Materials Focus (2022-2024)—and a categorical y-axis labelled Critical Mineral, listing Lithium, Cobalt, Nickel, Manganese, Graphite, and Copper from top to bottom. There are no numeric tick marks, as both axes are categorical; instead, the grid is formed by the intersection of critical minerals and periods. A color bar on the right, labelled Average premium, displays a diverging scale ranging approximately from about −0.2 (blue) through white near zero to +0.4 (red), indicating lower to higher average premium values for each mineral-period cell.

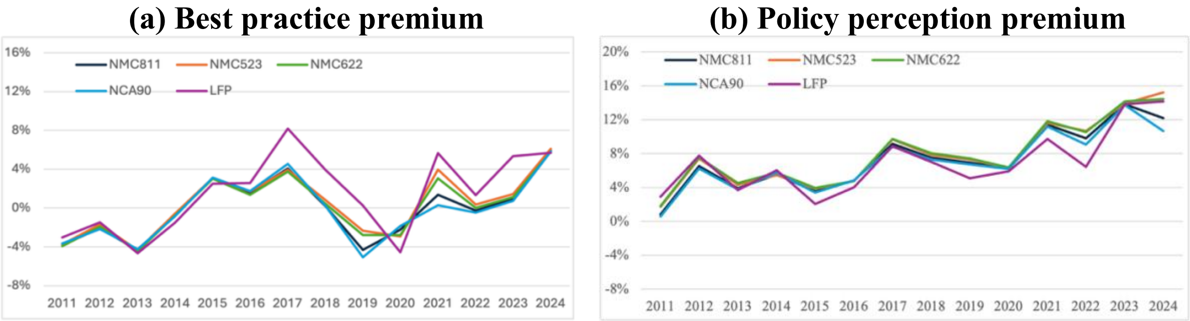
Supplementary Information 6: Decomposition of the non-technical risk premium for batteries

The battery-specific non-technical risk premiums can similarly be decomposed into non-technical risk best practice and non-technical risk policy perception components as follows:

$$NTRBP\ premium_{b,t} = \sum_{m=1}^{6} (w_{m,b,t} \times NTRBP\ premium_{m,t}) \qquad (S15)$$

$$NTRPP\ premium_{b,t} = \sum_{m=1}^{6} (w_{m,b,t} \times NTRPP\ premium_{m,t}) \qquad (S16)$$

Where $w_{m,b,t}$ is the share of critical mineral *m* in battery *b* in year *t*, expressed as a percentage of the battery's total mineral content. $NTRBP\ premium_{m,t}$ and $NTRPP\ premium_{m,t}$ represent the respective premium for each critical mineral, and $NTRPP\ premium_{m,t}$ and $NTRBP\ premium_{b,t}$ denote the corresponding battery-level premiums.



(a) Best practice premium

(b) Policy perception premium

Supplementary Fig 6 | The decomposition of the overall non-technical risk premium into two components for five major battery chemistries. Panel (a) shows the non-technical risk best practice premium, reflecting geological and mineral potential risks. Panel (b) illustrates the non-technical risk policy perception premium, highlighting risks related to regulatory and policy environments.

Supplementary Fig. 6 illustrates the evolution of the non-technical risk best practice and non-technical risk policy perception premiums across five major lithium-ion battery chemistries from 2011 to 2024. Both premium dimensions increased over the analysis period, though with distinct patterns. The non-technical risk best practice premium in Panel (a), reflecting non-technical risks related purely to mineral potential, is notably volatile, with marked spikes in 2017 and 2021. These spikes are predominantly driven by fluctuations in the best practice premium for graphite, indicating heightened perceived geological risks under ideal policy conditions. Among battery chemistries, Lithium Iron Phosphate (LFP) batteries exhibit the highest volatility due to their strong reliance on graphite.

Additionally, in Panel (a), all battery types experienced a sharp increase in their non-technical risk best practice premium in 2024, except for the LFP battery, which showed only a slight rise. This difference is primarily attribute to their composition: unlike other battery types that rely heavily on nickel - whose best practice premium rose sharply in 2024 - the LFP battery contains no nickel. Instead, it relies more heavily on graphite than the other four batteries, and graphite was the only one of the six key battery minerals to record a decline in its best practice premium that year.

In contrast, as shown in Panel (b), batteries' non-technical risk policy perception premium have remains consistently positive, demonstrating a steady upward trajectory. Major increases in policy-related risks occurred notably in 2012, 2017, 2021, and 2023, largely driven by rise in the policy perception premium of graphite - a critical mineral common to all battery chemistries. Nickel-Manganese-Cobalt523 (NMC523) batteries experienced the most significant increase, rising from 1.73 percent in 2011 to 15.20 percent in 2024

In 2024, the policy perception premiums of NMC523, NMC622, and LFP batteries increased, while those of NMC811 and Nickel-Cobalt-Aluminum (NCA90) batteries declined slightly. These variations can be explained by differences in mineral composition. NMC811 and NCA90 contain relatively higher shares of nickel, whose policy perception premium fell sharply in 2024. Additionally, among the three battery types with rising policy premium, NMC523 recorded the largest increase, owing to its relatively higher manganese content. Manganese's policy perception premium rose dramatically in 2024.

References to supplementary information

Acemoglu, D., & Zilibotti, F. (1997). Was Prometheus unbound by chance? Risk, diversification, and growth. *Journal of Political Economy*, 105(4), 709-751.

Aguirre B, F. (2022). The lithium triangle–the importance of Bolivia. *Journal of Energy & Natural Resources Law*, 40(2), 183-202.

Aquino, M., & Madry, K. (2023*). Peru will mine more copper in 2023, lithium permits pending*. MINING.COM. Available at: https://www.mining.com/web/peru-sees-copper-production-boost-in-2023-lithium-permissions-pending/ (Accessed: 13 September 2025).

Barradas, S. (2020). *Tshipi Borwa manganese mine expansion project, South Africa - update*. Mining Weekly. Available at: https://www.miningweekly.com/article/tshipi-borwa-manganese-mine-expansion-project-south-africa-update-2020-10-02 (Accessed: 13 September 2025).

Caldara, D., & Iacoviello, M. (2022). Measuring geopolitical risk. *American economic review*, 112(4), 1194-1225.

ChuanYu, J., Manurung, H., Anggara, F., & Petrus, H. T. B. M. (2024). Indonesian Nickel Overview: Potential, Development and Future Prospects. In *Conference of Metallurgists* (pp. 753-763). Cham: Springer Nature Switzerland.

Cobalt Institute. (2021). *'State of the Cobalt market' report*. Cobalt Institute. Available at: https://www.cobaltinstitute.org/wp-content/uploads/2021/09/Cobalt-Institute-State-of-the-Cobalt-Market-Report_2020.pdf (Accessed: 13 September 2025).

Cobalt Institute. (2024). *Cobalt market report 2023*. Cobalt Institute. Available at: https://www.cobaltinstitute.org/resource/cobalt-market-report-2023/ (Accessed: 13 September 2025).

Critical Minerals. (2024). *Indonesia's nickel dominance and price slump create supply chain concerns*. Critical Minerals. Available at: https://criticalminerals.id/indonesias-nickel-dominance-and-price-slump-create-supply-chain-concerns/ (Accessed: 13 September 2025).

Ellis, I. (2020). *DR Congo border closure and lockdowns to ravage copper and cobalt output. Verisk Maplecroft*. Available at: https://www.maplecroft.com/insights/analysis/dr-congo-border-closure-and-lockdowns-to-ravage-copper-and-cobalt-output/ (Accessed: 13 September 2025).

Exman, F. (2021). *Brazil has setbacks on the fight against corruption*. Valor International. Available at: https://valorinternational.globo.com/politics/news/2021/06/13/brazil-has-setbacks-on-the-fight-against-corruption.ghtml (Accessed: 13 September 2025).

Fastmarkets. (2020). *South Africa lockdown: How Covid-19 is affecting ores & alloys supply [Updated]*. Available at: https://www.fastmarkets.com/insights/south-africa-lockdown-how-covid-19-is-affecting-ores-alloys-supply-updated/ (Accessed: 13 September 2025).

Geoscience Australia. (2025). *Australia's Identified Mineral Resources*. Geoscience Australia. Available at: https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/aimr (Accessed: 13 September 2025).

Ginting, P., & Moore, E. (2021). *Indonesia Morowali Industrial Park (IMIP)*. The People's Map of Global China. Available at: https://thepeoplesmap.net/project/indonesia-morowali-industrial-park-imip/ (Accessed: 13 September 2025).

Gonzalez, E. (2021). *Explainer: Latin America's Lithium Triangle*. Americas Society/Council of the Americas. Available at: https://www.as-coa.org/articles/explainer-latin-americas-lithium-triangle (Accessed: 13 September 2025).

Harsono, N. (2020). *Indonesia sets price floor for nickel ore to protect small miners*. The Jakarta Post. Available at: https://www.thejakartapost.com/news/2020/04/24/indonesia-sets-price-floor-for-nickel-ore-to-protect-small-miners.html (Accessed: 13 September 2025).

IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. IEA. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary (Accessed: 13 September 2025).

IEA. (2023). *World Energy Investment 2023*. IEA. Available at: https://www.iea.org/reports/world-energy-investment-2023 (Accessed: 15 October 2025).

IEA. (2024). *Prohibition of the export of nickel ore*. IEA. Available at: https://www.iea.org/policies/16084-prohibition-of-the-export-of-nickel-ore (Accessed: 13 September 2025).

IEA. (2025). *Oil security and emergency response: Ensuring quick and effective response to major supply disruptions*. International Energy Agency. Available at: https://www.iea.org/about/oil-security-and-emergency-response (Accessed: 13 September 2025).

Jackson, T., & Green, K. P. (2016). *Fraser Institute annual survey of mining companies 2015*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Jepson, N., & Baldakova, O. (2024). Chinese state capital as a partner for resource-based structural transformation? The Belt and Road Initiative and downstream linkages in Bolivia and Kazakhstan. *The European Journal of Development Research*, 36(3), 718-745.

Kennedy, A. (2024). *White Gold: Mapping U.S. lithium mines*. Visual Capitalist. Available at: https://www.visualcapitalist.com/sp/us-lithium-mines-map/ (Accessed: 13 September 2025).

Lahiri, I. (2024). *Here's why Turkey's industrial activity fell sharply in November 2023*. Euronews. Available at: https://www.euronews.com/business/2024/01/10/heres-why-turkeys-industrial-activity-fell-sharply-in-november-2023 (Accessed: 13 September 2025).

Lithium Americas. (2011). *Preliminary Assessment and Economic Evaluation of the Cauchari-Olaroz Lithium Project, Jujuy Province, Argentina*. Lithium Americas. Available at: https://cdi.mecon.gob.ar/bases/docelec/az2160.pdf (Accessed: 13 September 2025).

Joint Committee of KCMI, IAGI, & PERHAPI. (2017). *KODE KCMI 2017: Code for reporting of exploration results, mineral resources and mineral reserves*. Indonesian Joint Committee for Mineral Reserves. Available at: https://mrmr.cim.org/media/1051/5111-kcmi-code-2017.pdf (Accessed: 13 September 2025).

Marjolin, A., DeCoff, S., & DeCoff, S. (2022). *Copper by the numbers: Exploration, development & operations*. S&P Global Market Intelligence. Available at: https://www.spglobal.com/market-intelligence/en/news-insights/research/copper-by-the-numbers-exploration-development-operations (Accessed: 13 September 2025).

Mejía, J., & Aliakbari, E. (2023). *Annual survey of mining companies, 2022*. Fraser Institute. Available at: https://www.fraserinstitute.org/sites/default/files/annual-survey-of-mining-companies-2022.pdf (Accessed: 13 September 2025).

Mejía, J., & Aliakbari, E. (2024). *Fraser Institute annual survey of mining companies 2023*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Mejía, J., & Aliakbari, E. (2025). *Fraser Institute annual survey of mining companies 2024*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Mining Technology. (2023). *CMOC and Congo settle royalties dispute over Tenke Fungurume mine*. Mining Technology. Available at: https://www.mining-technology.com/news/cmoc-congo-royalties-dispute/?cf-view (Accessed: 13 September 2025).

MMG Limited. (2023). *Report of exploration results from Las Bambas and Rosebery*. Available at: https://www.mmg.com/wp-content/uploads/2023/07/e_2023-07-13_Report-of-Exploration-Results-from-Las-Bambas-and-Rosebery.pdf (Accessed: 13 September 2025).

National Mining Agency. (2023). *RAL Guide 2023 - ANM*. National Mining Agency. Available at: https://www.gov.br/anm/pt-br/ral-2023-traz-mudancas-na-declaracao-de-recursos-e-reservas-minerais/guia-ral-2023-anm.pdf/view (Accessed: 13 September 2025).

Ngoepe-Ntsoane, M. (2024). The load shedding impact on the South African economy: Analyzing price inflation and strategies for post-load shedding price reductions. *Journal of Electrical Systems*, 20(11s). https://doi.org/10.52783/jes.7984

Obaya, M., Freytes, C., & Delbuono, V. (2024). Driving regional development through critical minerals: a case study of the lithium policy mix in Argentina. *Mineral Economics*, 37(3), 645-659.

Ramos, D. (2019). *Bolivia picks Chinese partner for $2.3 billion lithium projects*. Reuters. Available at: https://www.reuters.com/article/idUSKCN1PV2F6/ (Accessed: 13 September 2025).

Reid, H., & Holland, H. (2020). *DRC: Mining minister warns against the social and economic impact of mine closures during the COVID-19 pandemic*. Business & Human Rights Resource Centre. Available at: https://www.business-humanrights.org/en/latest-news/drc-mining-minister-warns-against-the-social-and-economic-impact-of-mine-closures-during-the-covid-19-pandemic/ (Accessed: 13 September 2025).

Sanchez-Lopez, M. D. (2023). Geopolitics of the Li-ion battery value chain and the Lithium Triangle in South America. *Latin American Policy*, 14(1), 22-45.

Stedman, A., & Green, K. P. (2018). *Fraser Institute Annual Survey of Mining Companies 2017*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Szczesniak, P. A. (2021). *The mineral industry of Bolivia, 2016*. U.S. Geological Survey. Available at: https://www.usgs.gov/media/files/mineral-industry-bolivia-2016-pdf (Accessed: 13 September 2025).

Thunder Said Energy (2025). *Energy development times: first consideration to full production?*. Thunder Said Energy. Available at: https://thundersaidenergy.com/downloads/energy-development-times-first-consideration-to-full-production/ (Accessed: 13 September 2025).

Transport and Environment. (2021). *From dirty oil to clean batteries*. Transport and Environment. Available at: https://tecdn.ams3.cdn.digitaloceanspaces.com/files/2021_02_Battery_raw_matrials_report_final.pdf (Accessed: 13 September 2025).

U.S. Geological Survey. (2024). *Mineral commodity summaries 2024*. Available at: https://doi.org/10.3133/mcs2024 (Accessed: 13 September 2025).

Vespignani, J., & Smyth, R. (2024). Artificial intelligence investments reduce risks to critical mineral supply. *Nature Communications*, *15*(1), 7304.

Warburton, E. (2017). *Resource nationalism in post-boom Indonesia: The new normal?*. Lowy Institute. Available at: https://www.lowyinstitute.org/publications/resource-nationalism-post-boom-indonesia-new-normal (Accessed: 13 September 2025).

Yunis, J., & Aliakbari, E. (2021). *Fraser Institute annual survey of mining companies 2020*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Yunis, J., & Aliakbari, E. (2022). *Fraser Institute annual survey of mining companies 2021*. Fraser Institute. Available at: http://www.fraserinstitute.org (Accessed: 13 September 2025).

Zhou, Q., Wu, C., Hu, X., Yang, B., Zhang, X., Du, Y., ... & Wang, J. (2022). A new metallogenic model for the giant manganese deposits in northeastern Guizhou, China. *Ore Geology Reviews*, 149, 105070.