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Mining or processing? Export restrictions, chokepoints and stockpiles in the cobalt value chain

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Abstract

In 2025, export controls were introduced at both ends of the cobalt value chain: at the mining stage by the DRC and at the processing stage by China. Existing studies map where supply is concentrated or model a disruption at one stage at a time, with one shock and one set of parameters, and cannot tell which stage is the real chokepoint or who bears its cost. To our knowledge, this paper is the first to compare mining- and processing-stage disruptions of a critical mineral in one general-equilibrium framework. We split cobalt intermediates, refined cobalt and batteries out of a global CGE model calibrated to GTAP 12 and combine Monte Carlo draws of supply shocks and elasticities with policy stress tests. Three findings have implications beyond cobalt. First, what makes a stage a chokepoint is the value of the trade it controls, not its concentration alone: cutting China's battery exports costs Japan, Korea, the US and the EU seven times as much as cutting the DRC's cobalt exports at the same rate, although the mining-stage restriction is more damaging per dollar. Second, the cost of an upstream restriction falls on the processing country rather than on final users. Third, losses from ordinary shocks grow in proportion to the shock, and easier substitution shifts them among importers rather than reducing them. Valuing stockpiles as insurance, we show that a 60-day cobalt stockpile breaks even at annual disruption probabilities of 2.7–10.7%.

Keywords: cobalt; critical minerals; export restrictions; value chain; stockpiling; computable general equilibrium

JEL codes: C68, F13, L72, Q31, Q37

1 Introduction

Cobalt is a small market with a large reach. Most cobalt demand now comes from lithium-ion batteries (Cobalt Institute 2026), which power electric vehicles and electronics. The cobalt value chain is also among the most concentrated in the world. The DRC mines about three quarters of the world's cobalt (USGS 2026), and China refines about four fifths of it and turns most of the refined metal into cathodes and batteries at home (Cobalt Institute 2026). In 2025, export controls were imposed at both stages. In February, the DRC suspended cobalt exports, and from October it replaced the suspension with quotas of 96,600 t per year for 2026–2027, well

below current production. In the same month, China announced export controls on high-performance lithium batteries and their key materials (MOFCOM 2025a), which it suspended before they took effect, first for one year and then to January 2027 (MOFCOM 2025b, 2026). For the first time, the mining stage and the processing stage became policy chokepoints in the same year.

Four gaps in the literature limit what can be said about these events. (i) Existing work measures where supply is concentrated (van den Brink et al. 2020; Gulley et al. 2019) or models a disruption at one stage at a time (Becker 2021), so it cannot say whether a disruption at the mining stage or at the processing stage does more damage to the economies that use cobalt. (ii) Studies of export restrictions focus on trade flows and prices in the restricted market (Kowalski and Legendre 2023); little is known about how the cost is shared along a value chain in which the main buyer of mined cobalt is a refiner, not a final user. (iii) Most analyses of mineral disruptions are deterministic, with one shock and one set of parameters, so they cannot distinguish ordinary year-to-year supply risk from rare policy shocks, or test whether losses rise sharply once buyers can no longer switch suppliers. (iv) Governments are building stockpiles of critical minerals, but the economics of stockpiling has been developed mainly for oil and food (Teisberg 1981; Wright and Williams 1982; Tanaka 2026), and a cobalt stockpile has not been valued in general equilibrium.

We address these gaps with four questions, each stated as a hypothesis and numbered to match the gaps:

- **(i) H1 (where the chokepoint is).** A disruption at the processing stage hurts the economies of Japan, Korea, the US and the EU more than a disruption at the mining stage.
- **(ii) H2 (who pays).** The cost of the DRC's export restriction falls mainly on China, the refiner, rather than on final users, while Indonesia, the alternative supplier, gains.
- **(iii) Condition (when it becomes severe).** Losses stay small while buyers can switch suppliers and rise sharply when they cannot.
- **(iv) Insurance (whether a stockpile pays).** A stockpile pays off if the losses it avoids in a disruption, weighted by the probability of disruption, exceed the cost of holding it.

To answer these questions, we build a global CGE model on the GTAP 12 database for 2023, in which we separate cobalt intermediates, refined cobalt and lithium-ion batteries from their parent sectors using trade and production data. We then analyse two kinds of shock. Ordinary variation in DRC output is drawn 1,000 times from its historical distribution, together

with the substitution elasticities and Indonesia's supply response, and summarised by Value-at-Risk. Export restrictions at the mining stage (the DRC's quota), at the processing stage (a restriction on China's battery exports at the same rate) and at both are treated as stress tests. Finally, we value a 60-day stockpile of refined cobalt in Japan, Korea, the US and the EU as an insurance contract.

This paper makes four contributions, one for each gap. First (i), it is, to our knowledge, the first study to compare disruptions at the mining and the processing stage of a critical-mineral value chain in one general-equilibrium framework, and it shows that what makes a stage a chokepoint is the value of the trade it controls, not its concentration alone. Second (ii), it traces the cost of an upstream export restriction along the value chain and shows that the cost falls on the processing country rather than on final users, while the restricting country and the alternative supplier gain. Third (iii), it combines random supply shocks with uncertain substitution elasticities and separates ordinary supply risk from rare policy shocks. This makes it possible to test, rather than assume, whether losses rise sharply when substitution is limited; we find that they do not, and that higher elasticities shift losses among countries rather than reduce them. Fourth (iv), it values a critical-mineral stockpile in general equilibrium and reports the disruption probability at which the stockpile breaks even, a simple threshold that policy makers can compare with their own view of the risk.

Our main findings are as follows. The results support H1 with a qualification: a 58% cut in China's battery exports costs Japan, Korea, the US and the EU USD 24.2 bn per year, against USD 3.4 bn for the same cut in the DRC's exports of mined cobalt, but per dollar of restricted trade the mining-stage restriction is the more damaging (USD 1.5 against 0.7), so processing is the chokepoint because it controls far more value. H2 is also supported: under the DRC restriction, China loses USD 5.0 bn, more than the four users combined, while the DRC gains USD 3.7 bn from quota rents and Indonesia USD 1.8 bn. Ordinary supply shocks matter much less; China's 5% Value-at-Risk is USD 0.9 bn, the risk relative to GDP is highest in the cobalt-processing economies of Asia, and losses grow in proportion to the shock with no tipping point. Finally, a 60-day stockpile pays for itself if a disruption of the size of the DRC quota occurs with an annual probability above 2.7% in the US, 4.1% in Korea, 8.2% in Japan and 10.7% in the EU.

The rest of the paper is organised as follows. Section 2 reviews the literature. Section 3 describes the data, the model and the scenarios. Section 4 presents the results, Section 5 discusses the implications for policy, and Section 6 concludes.

2 Literature review

2.1 Supply risk in critical minerals and cobalt

Assessments of critical-mineral supply risk usually start from market concentration. Cobalt is among the most concentrated cases: the DRC dominates mining and China dominates refining (IEA 2021, 2025). Mapping the cobalt supply chain at the level of mines, refineries and firms, van den Brink et al. (2020) find high disruption risk at both stages. They also point to mitigating factors, such as artisanal production and a mine stage that is less concentrated at the level of companies. Gulley et al. (2019) show that country-level shares understate China's position. Through its ownership of mines abroad, mainly in the DRC, China controls much of the ore it does not mine at home. Supply risk for other countries is therefore not confined to minerals produced in China. These studies describe where supply is concentrated, but not what a disruption at each stage costs, or whom it costs.

2.2 Where in the value chain a disruption bites

A growing literature argues that the binding constraint in energy-transition minerals has moved from mining to processing, where China's share is larger and more persistent than in mining (IEA 2025; Gulley et al. 2018). Model-based evidence on this question is scarce. Becker (2021) uses a CGE model to simulate a Chinese restriction on refined cobalt and finds sizeable costs for the US economy, especially for vehicle production. Like most studies, however, it examines one stage at a time. Without a common framework, it is unclear whether a restriction at the mining stage or at the processing stage is more harmful to final users. Our first hypothesis (H1) addresses this gap by comparing the two stages in the same model.

2.3 Export restrictions by resource-rich countries

Export restrictions on industrial raw materials have spread rapidly. Between 2009 and 2020, the use of export restrictions on critical raw materials increased more than fivefold, and about a tenth of the value of their exports became subject to at least one measure (Kowalski and Legendre 2023). Producers use them to capture rents and to promote domestic processing. Indonesia's ban on nickel ore exports is the best-known recent case, and China's rare earth restrictions an earlier one (Mancheri 2015). Most evidence on these policies concerns trade flows and prices in the restricted market.

Less is known about who bears the cost along the value chain. In food markets, stochastic CGE analyses show that export restrictions by producers shift the burden of supply shocks to

importers and that the size of this shift depends on trade structure (Tanaka and Hosoe 2011; Tanaka and Karapinar 2019). For cobalt, the main buyer of DRC output is not the final user but the refiner. Our second hypothesis (H2) therefore asks whether the cost of the DRC's restriction falls on China rather than on battery users, and whether Indonesia, the alternative supplier, gains.

2.4 Modelling supply risk under uncertainty

Most CGE analyses of supply disruptions are deterministic: they report the effect of one shock under one set of parameters. Two strands of work address the uncertainty this leaves out. The first treats parameters as uncertain. Hertel et al. (2007) show that CGE results can be given confidence intervals by drawing trade elasticities from their estimated distribution. The second treats shocks as random. Stochastic CGE models draw supply shocks from their historical distribution and summarise the resulting welfare distribution with risk measures such as Welfare-at-Risk (Ünal et al. 2018). They have been applied mainly to food supply and food trade policy (Tanaka and Hosoe 2011; Tanaka and Vellinga 2025). Tanaka et al. (2022) show how many Monte Carlo draws such models need for stable results.

We combine the two strands. Shocks to DRC output are drawn from their historical distribution, and the substitution elasticities and Indonesia's supply response are drawn at the same time. This lets us test our condition hypothesis, namely whether losses grow sharply once buyers can no longer switch suppliers, rather than assume a single elasticity.

2.5 The economics of stockpiles

Public stockpiles are the standard insurance against supply disruptions. For oil, the literature derives optimal acquisition and release policies (Teisberg 1981). It also shows that public storage is justified mainly where private storage is distorted, for example by the expectation of price controls (Wright and Williams 1982). IEA (2018) compares the costs and benefits of emergency oil stocks and finds that financing is the largest cost. In food markets, stochastic CGE analyses have examined how trade policy buffers production shocks (Tanaka and Hosoe 2011; Tanaka and Vellinga 2025) and how release rules for international grain reserves should be designed (Tanaka 2026).

For critical minerals, the evidence is recent and mostly in working papers. Vespignani et al. (2025) find that stockpiling can reduce supply gaps for copper but much less for lithium. Wang et al. (2025) find that the best mix of stockpiling and recycling differs by country. We are not aware of studies that value a cobalt stockpile in general equilibrium, comparing what it saves in a disruption with what it costs to hold.

3 Methodology

3.1 Data

The model is calibrated to the GTAP 12 database for 2023 (Aguiar et al. 2025), aggregated to 8 regions, 20 commodities and activities, and 5 endowments (Table 1). The regions follow the cobalt value chain: the DRC (mining), China including Hong Kong (refining and battery production), Indonesia (the alternative supplier), four users (Japan, Korea, the US and the EU-27) and the rest of the world. Zambia, Namibia, South Africa and Tanzania, which re-export DRC cobalt, belong to the rest of the world. The endowments are land, unskilled labour, skilled labour, capital and natural resources.

Table 1 Regions and sectors

	Model aggregate	**Content**
Regions	DRC, China, Indonesia, Japan, Korea, US, EU, RoW	China includes Hong Kong; the EU excludes the UK
Cobalt and batteries	Cobalt intermediates (cob_int)	Hydroxide and oxides (HS 282200; HS 810520 from the DRC and transit countries); Indonesian MHP
	Refined cobalt (cob_met)	Metal, mattes and powders, waste and articles (HS 810520, 810530, 810590)
	Lithium-ion batteries (bat)	HS 850760
Downstream users	Non-ferrous metals, chemicals, electrical equipment, electronics, motor vehicles, other transport equipment	Users of refined cobalt and batteries
Other sectors	Agriculture, food, coal, crude oil, gas, petroleum products, electricity, other mining, other manufacturing, transport, services	Energy sectors kept separate for the energy nest

GTAP has no cobalt sector, so we split the three cobalt and battery goods out of their parent sectors at the level of the social accounting matrix (SAM). Cobalt intermediates and refined cobalt are taken from non-ferrous metals, which is where GTAP records DRC hydroxide, and batteries from electrical equipment.

- *Trade.* Bilateral trade comes from BACI (Gaulier and Zignago 2010), HS 2022 classification, averaged over 2022–2024. The DRC exports most of its hydroxide under HS 810520, so this code is assigned to cobalt intermediates when it comes from the DRC or a transit country and to refined cobalt otherwise. Exports from Namibia and Tanzania, which have no cobalt production of their own, are reassigned to the DRC.
- *Production.* Output of cobalt intermediates is set equal to exports, since almost all hydroxide is exported. For Indonesia, whose cobalt leaves the country inside nickel intermediates (MHP, HS 750120), output is USGS mine production valued at the DRC's export unit value (USD 22,602 per t of cobalt) and is exported along Indonesia's MHP trade. Output of refined cobalt is the larger of exports and USGS refinery production (USGS 2025; USGS, various years) valued at the 2023 US spot price of USD 17.20 per lb (USGS 2025). Battery output is cell production valued at the 2023 average cell price of USD 95 per kWh (BloombergNEF 2023) for China (905 GWh; WardsAuto 2024), the EU (110 GWh) and the US (70 GWh) (IEA 2024), and the official production value for Japan (METI 2024); for the other regions it is proxied by exports.
- *Uses.* Refined cobalt is allocated among batteries, superalloys (other transport equipment), non-ferrous metals and chemicals using the global end-use shares for 2025 of the Cobalt Institute (2026), and for the US the end-use shares of USGS (2026), which include no battery use. Batteries are allocated to their users in proportion to their use of electrical equipment.

To allow the CES functions to be calibrated, very small trade flows and domestic sales are raised to a minimum; the additions total USD 84 mn. Cobalt ores and concentrates (HS 260500) are left in other mining because their trade is small (USD 0.1 bn per year). Table 2 summarises the resulting benchmark. The DRC produces three quarters of the world's cobalt intermediates and China imports 84% of them, while China produces two thirds of refined cobalt and 60% of batteries. In the main battery producers, cobalt accounts for 2–6% of battery costs (China 5.6%, Japan 4.5%, the EU 2.7% and Korea 2.1%).

Table 2 Benchmark cobalt and battery markets, 2023 (USD mn)

Region	Cobalt intermediates: output	Cobalt intermediates: exports	Cobalt intermediates: imports	Refined cobalt: output	Batteries: output	Batteries: exports	Batteries: imports	Cobalt in battery cost (%)
DRC	3,849	3,912	0	0	0	0	29	–
China	145	149	4,032	5,467	82,517	62,145	2,459	5.6
Indonesia	507	470	3	11	196	159	426	1.6
Japan	1	1	39	192	6,257	3,170	2,615	4.5
Korea	3	3	189	8	6,826	6,794	6,152	2.1
US	2	2	65	401	6,490	3,774	21,504	0.0
EU	315	141	111	741	29,246	6,926	29,503	2.7
RoW	271	133	372	1,530	5,967	4,373	24,655	13.6
World	5,093	4,812	4,812	8,351	137,500	87,342	87,342	–

Note: Output is valued at basic prices, before production taxes, and trade at market prices, so exports of cobalt intermediates can exceed output (in the DRC, by the production tax on mining). Exports exclude trade within a region. The cobalt share of battery cost is zero in the US because USGS reports no use of refined cobalt in US battery production, and high in RoW because RoW's battery output is proxied by its exports while its use of refined cobalt follows the world end-use shares.

3.2 CGE model

We use a static multi-regional CGE model based on Hosoe, Gasawa and Hashimoto (2010), written in GAMS and solved with CONOPT. The model has 18,707 equations and reproduces the benchmark exactly when no shock is applied.

Production. Each activity combines value added, an energy composite and other intermediate inputs in fixed proportions, scaled by a productivity term. Value added is a CES function of the endowments with the GTAP elasticity. The energy composite has two levels: electricity and a non-electric aggregate are combined with an elasticity of 0.231 (Sikl et al. 2025), and the non-electric aggregate combines crude oil, petroleum products, coal and gas with an elasticity of 1.334 (Stern 2009). Because intermediate inputs are fixed per unit of output, a battery maker cannot replace cobalt with other materials; it can only switch between suppliers of cobalt.

Trade. Domestic goods and imports are imperfect substitutes (Armington), with an elasticity σ_d between domestic goods and imports and an elasticity σ_m among import sources. Output is allocated between domestic and export markets, and exports among destinations, with

CET functions using the same elasticities. In the standard setting, σ_d is taken from GTAP and $\sigma_m = 2\sigma_d$, following the GTAP convention; the cobalt and battery goods use the values of their parent sectors. In the MC, σ_d and σ_m of the two cobalt goods are drawn independently (Section 3.3.1). International transport is supplied by a global pool.

Final demand and closure. A representative household in each region receives factor income, pays direct taxes, saves, and spends the rest with Cobb–Douglas preferences. Real government consumption and investment are fixed, and foreign savings are fixed in US dollars. Endowments are fixed and fully employed; unskilled labour moves across sectors, while the other endowments are sector-specific. Under this closure, losses from higher import prices appear mainly in household welfare rather than in real GDP.

Changes for this study. We make three changes to the standard model, each of which leaves the benchmark unchanged. First, export quotas fix bilateral export quantities and create a rent for the exporter (Section 3.3.4). Second, a stockpile release adds a quantity of refined cobalt to the importer's domestic market; the government sells it at the market price and receives the revenue. Third, we let the alternative supplier respond to prices. Indonesia's cobalt sector has no natural-resource endowment in the data, so its supply could otherwise expand only through mobile unskilled labour. Its capital and skilled labour h therefore respond to their return p_h^F relative to the wage w of unskilled labour:

$$F_h = F_h^0 \left(\frac{p_h^F}{w} \right)^{\eta} \tag{1}$$

where F_h^0 is the benchmark endowment. With $\eta = 0$ the sector behaves as in the standard model; in the MC, η is drawn from $U(0.1,2)$.

3.3 Scenarios

We consider two kinds of supply shock, both starting from the 2023 benchmark without restrictions (Reference). The first is the ordinary year-to-year variation in DRC mine output, which drives the Monte Carlo analysis (MC) and the Value-at-Risk measures. The second is a set of export restrictions modelled on the policies announced in 2025. Because these restrictions are far larger than anything the distribution of ordinary shocks would generate, we treat them as separate stress tests. Table 3 shows which shocks each scenario contains and which question it answers, and Appendix Table A1 gives the details of each shock.

Table 3 Scenario matrix

Scenario	DRC output shock	DRC export quota on cobalt intermediates	China export restriction on batteries	Stockpile release	Elasticities	Question
Reference	–	–	–	–	Standard	Benchmark
MC	✓	–	–	–	Random	Welfare at risk; condition
MC + stock	✓	–	–	✓	Random	Insurance
S1	–	✓	–	–	Standard	H1, H2
S1 + stock	–	✓	–	✓	Standard	Insurance
S2	–	–	✓	–	Standard	H1
S3	–	✓	✓	–	Standard	Combined restrictions

3.3.1 Ordinary supply shocks (MC)

Following the stochastic CGE literature (Ünal et al. 2018; Tanaka et al. 2022), we fit an ARIMA model to the log of DRC cobalt mine production for 2000–2025, taken from the USGS Minerals Yearbook for 2000–2022 (USGS, various years) and the Mineral Commodity Summaries for 2023–2025 (USGS 2026), and choose the orders by the corrected Akaike information criterion (Hurvich and Tsai 1989). The selected ARIMA(0,1,2) has a residual standard deviation of 0.147 (Ljung–Box p = 0.66). In each draw, the productivity of the DRC cobalt-intermediate sector is multiplied by $\exp(e)$, with $e \sim N(0, 0.147^2)$. At the same time, σ_d of the two cobalt goods is drawn from $U(0.5,4)$, σ_m from $U(1,8)$ and the Indonesian supply elasticity η from $U(0.1,2)$; the model is recalibrated for each draw. We run 1,000 draws with a fixed seed. Each draw starts from the benchmark, and a draw that fails is solved again in finer homotopy steps. In all, 998 draws solve; the two that do not ($e = -0.31$ and -0.26) are excluded.

3.3.2 Export restrictions (S1–S3)

S1 represents the DRC's export policy. The DRC suspended cobalt exports in February 2025 and replaced the suspension with quotas from 16 October 2025 (ARECOMS 2025). The quota of 96,600 t per year for 2026 and 2027 is 58% below 2025 production (USGS 2026), so S1 cuts DRC exports of cobalt intermediates, mainly hydroxide, by 58%. The scenario is stylised: it ignores how quotas are allocated among firms, and measured against 2024 shipments, as Argus (2025) does (the quota is 49% of 2024 shipments), the cut would be 51%.

S2 represents China's export controls on lithium batteries and battery materials (MOFCOM 2025a). Announced in October 2025, they were suspended for one year before taking effect (MOFCOM 2025b), and the suspension has since been extended to 10 January 2027 (MOFCOM 2026). China's exports of refined cobalt are small (USD 0.2 bn per year in the benchmark) because China turns almost all the cobalt it refines into cathodes and batteries at home, so the relevant chokepoint at the processing stage is China's exports of batteries, the products that embody refined cobalt. The controls are a licensing regime without a quantity cap, and they cover only high-energy-density cells (300 Wh/kg or more), a fraction of China's battery exports. S2 is therefore not a simulation of the announced measure but a hypothetical restriction at the processing stage: it cuts all of China's lithium-ion battery exports by the same 58% as S1, so that the two stages can be compared at the same rate. Its results should be read as an upper bound on the effect of the announced controls. S3 imposes S1 and S2 together.

3.3.3 Stockpile

In the stockpile variants, Japan, Korea, the US and the EU each hold refined cobalt equal to 60 days of their use, the standard stockpiling target for rare metals in Japan (METI 2020), and release it into their own market: in S1 throughout the restriction, and in the MC in years when DRC output falls by more than one standard deviation (about one year in six).

3.3.4 Implementation

Each restriction is modelled as a bilateral export quota. Every restricted flow is fixed at $(1-\kappa)$ times its benchmark quantity, where κ is the cut, and the gap between the domestic and export price is a quota rent that accrues to the exporting region. If a quota stops binding, so that its rent would turn negative, it is released. The cut is tightened in 30 to 60 steps, each solved from the previous solution; in S2, flows below USD 0.01 mn are left unrestricted. S3 is solved in two phases: S1's quota rent is first converted into an equivalent export tax, and an export tax on China's batteries equal to the rent rates of S2 is then added step by step. For S2 alone this tax method reproduces the quota solution exactly, but in S3 China's battery exports are not cut by exactly 58%. All scenarios except the MC use the standard GTAP elasticities.

Claude (Anthropic), a large language model, was used to write and run the data-processing and model code, to draft and edit parts of the text, to check the consistency between the text, tables and model output, and to prepare the figures and the Appendix. All code, results and text were reviewed by the author, who takes full responsibility for them.

3.4 Outcomes and risk measures

Welfare is measured by equivalent variation (EV), in US dollars at base prices and as a share of base-year GDP or household expenditure. Prices are the Armington composite prices that domestic users pay, relative to the Reference. Risk is measured on the loss side. The 5% Value-at-Risk (VaR) of welfare is the 5th percentile of EV across the solved draws, the loss exceeded in one year in twenty. For prices, we report the 95th percentile of the price change. Because shocks are symmetric in log output, the VaR of a region that gains from scarce cobalt, such as the DRC, comes from draws in which DRC output rises.

3.5 Conditions of risk: two-stage analysis

In the first stage, we regress each outcome y (EV as a percentage of expenditure, and the prices of refined cobalt and batteries) on the shock and its interactions with the drawn elasticities, separately for each region:

$$y = a + b_1 e + b_2 e\tilde{\sigma}_d + b_3 e\tilde{\sigma}_m + b_4 e\tilde{\eta} + c_1\tilde{\sigma}_d + c_2\tilde{\sigma}_m + c_3\tilde{\eta} + u \qquad (2)$$

where the tilde denotes a deviation from the sample mean. The coefficient b_1 is the region's sensitivity to the DRC shock at average elasticities, and b_2–b_4 show how the elasticities change it. A good fit with no need for higher-order terms indicates that losses grow in proportion to the shock, without a tipping point.

In the second stage, we compare the sensitivities b_1 of six regions (China, Japan, Korea, the US, the EU and RoW) with their characteristics in the benchmark SAM. The characteristics are:

- direct dependence on the DRC (imports of cobalt goods from the DRC divided by absorption);
- dependence including DRC cobalt embodied in imports from China;
- the Herfindahl–Hirschman index (HHI) of import sources;
- the use of cobalt goods relative to final demand;
- the share of battery absorption imported from China.

With six observations, a regression is not feasible, so we report Spearman rank correlations and treat them as tendencies.

3.6 Stockpile insurance

We value a stockpile as an insurance contract. The payout is the welfare gain from releasing the stock, net of the cost of buying it back at base prices, and the premium is the annual cost of holding it:

$$\text{Payout} = EV^{\text{release}} - EV^{\text{no release}} - V \tag{3}$$

$$\text{Premium} = hV \tag{4}$$

where V is the value of the stock and h covers financing and storage. We use $h = 5\%$ with a range of 3–7%, the real discount rates used by IEA (2018) to assess emergency oil stocks; the storage cost of refined metal is small relative to financing. In S1, the stockpile pays off if an S1-size disruption occurs with an annual probability above

$$p^* = \frac{hV}{\text{Payout}} \tag{5}$$

In the MC, we compare the expected annual payout, the mean payout over all draws including years without release, with the premium, and report how much the release reduces the 5% VaR. The MC with and without the stockpile uses the same draws, and the comparison is made over the draws that solve in both runs.

4 Results

Welfare is measured by equivalent variation (EV), in USD million per year at 2023 prices or as a percentage of base-year expenditure. Prices are composite (Armington) prices relative to the Reference. Scenario results use the standard GTAP elasticities; MC results come from the run with the Indonesian supply response, in which 998 of 1,000 draws solved.

4.1 The chokepoint is processing, not mining

A restriction of China's battery exports (S2) is far more damaging to the importing economies than the DRC's restriction of mined cobalt at the same rate (S1) (Fig. 1a; Appendix Table A2). The US loses USD 15.7 bn under S2 against 2.0 bn under S1, the EU 6.9 bn against 1.1 bn, and Korea 3.8 bn against 0.2 bn. Taken together, Japan, Korea, the US and the EU lose USD 24.2 bn under S2 and 3.4 bn under S1, which supports H1.

The difference lies in how far each shock travels down the value chain (Fig. 1b, c). Under S1, cobalt prices rise sharply: the price of refined cobalt goes up by 37–43% in the importers and

by 135% in China, the main buyer of DRC hydroxide. Because cobalt accounts for only 2–6% of battery cost (Table 2), however, battery prices rise by just 4.6–7.5%, and the prices of electrical equipment, vehicles and aircraft by less than 0.3%. Under S2, the shock hits the final product directly. Battery prices rise by 31% in Japan, by 45–46% in the US and the EU, and by 134% in Korea. Japan, with a large battery industry of its own, actually gains USD 2.1 bn, as its battery output rises by 76% to replace Chinese supply.

This comparison holds the rate of restriction fixed, not its value. S2 removes about USD 36 bn of battery exports while S1 removes about USD 2.3 bn of hydroxide, and per dollar of restricted exports the four importers lose more under S1 (USD 1.5) than under S2 (USD 0.7). H1 therefore holds with a qualification: processing is the chokepoint because it controls a much larger flow of value than mining, not because each dollar of processed goods matters more to importers. Because S2 restricts all battery exports, whereas the announced controls cover only high-energy-density cells, these losses are an upper bound for the announced measure.

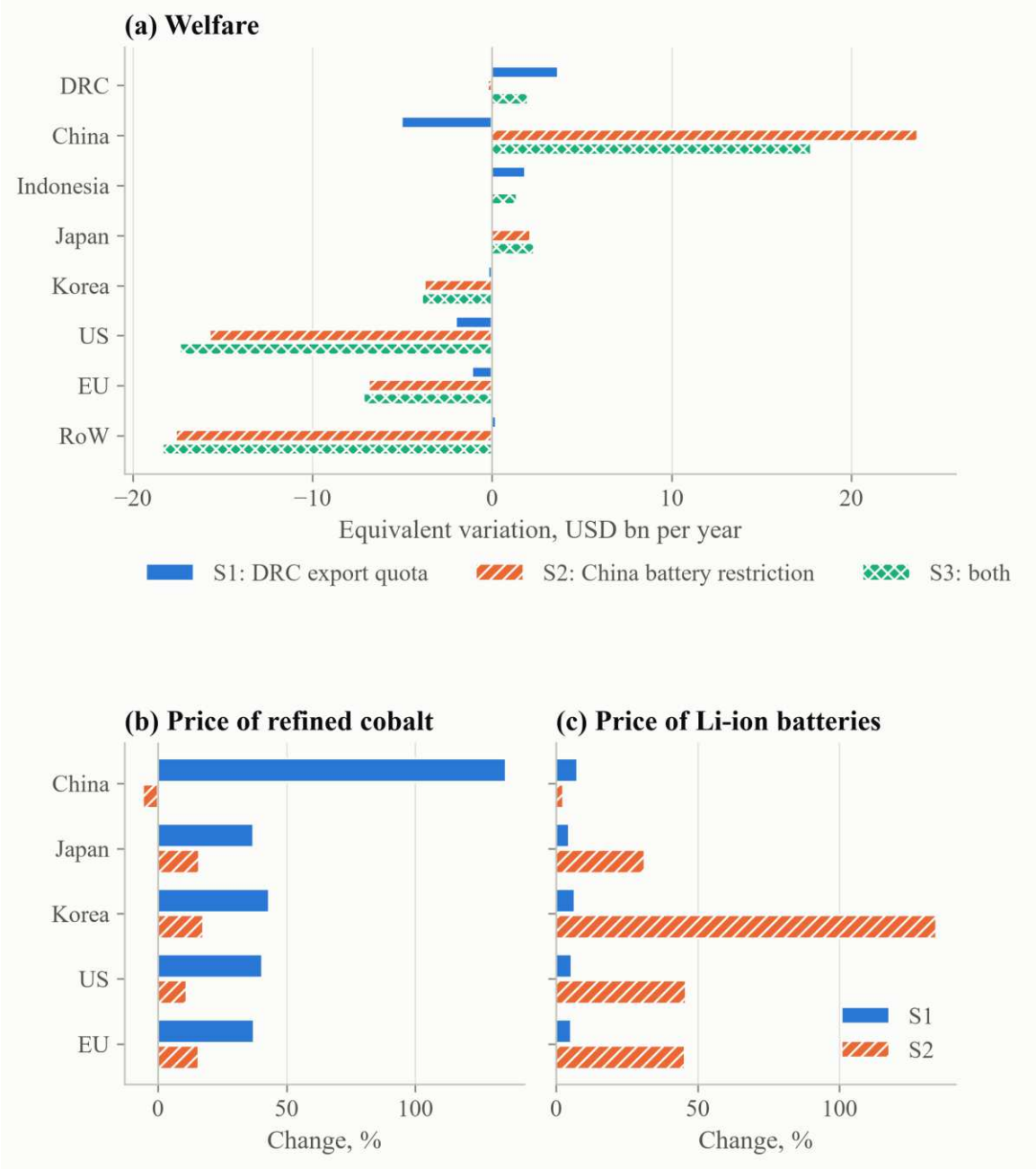


Fig. 1 Effects of the export restrictions: (a) welfare (EV, USD bn per year); (b) price of refined cobalt and (c) price of lithium-ion batteries under S1 and S2 (%)

4.2 China pays for the DRC restriction

The cost of S1 falls mainly on China, whose welfare falls by USD 5.0 bn, about 1.5 times the combined loss of the four importers (Appendix Table A2). As the main refiner of DRC hydroxide, China faces scarce and expensive feedstock: its output of refined cobalt falls by 21% and its battery output by 4.0%. The DRC gains USD 3.7 bn (9.9% of its expenditure), since a quota rent of USD 3.9 bn outweighs the loss in volume. Because only intermediates are restricted,

the DRC's own refining also expands, from a very small base, which is what the policy aims at. Indonesia gains USD 1.8 bn as buyers turn to MHP and its output of cobalt intermediates more than triples. These results support H2.

When both restrictions are imposed (S3), the importers' losses are close to the sum of S1 and S2 (US −17.4 bn against −17.8 bn; Korea −3.9 bn against −4.0 bn). The DRC's gain, however, shrinks to USD 2.0 bn, because the battery restriction lowers demand for cobalt and cuts its quota rent from 3.9 bn to 2.6 bn.

4.3 Welfare at risk from ordinary supply shocks

Ordinary variation in DRC output produces losses one to two orders of magnitude smaller than the stress tests (Fig. 2a; Appendix Table A3). In a 1-in-20 bad year (5% VaR), China loses USD 888 mn, followed by the US (308 mn), the EU (214 mn), Korea (59 mn) and Japan (31 mn). Relative to GDP, the ranking changes (Fig. 2b). China remains the most exposed (−0.0050% of GDP), but Indonesia (−0.0046%) and Korea (−0.0036%) come next, about three times the exposure of the EU (−0.0012%) and the US (−0.0011%), while Japan is the least exposed importer (−0.0007%). Absolute losses are thus concentrated in large economies, but the burden relative to the economy falls on the cobalt-processing economies of Asia. The shocks show up in cobalt prices but hardly in battery prices (Fig. 2c): in the worst 5% of draws, refined cobalt rises by 18% in China and by 4.6–5.7% in the importers, while batteries rise by less than 1%. The DRC is a special case. Because world demand for its cobalt is inelastic, it gains when its output falls, so its VaR comes from years of high output and low prices.

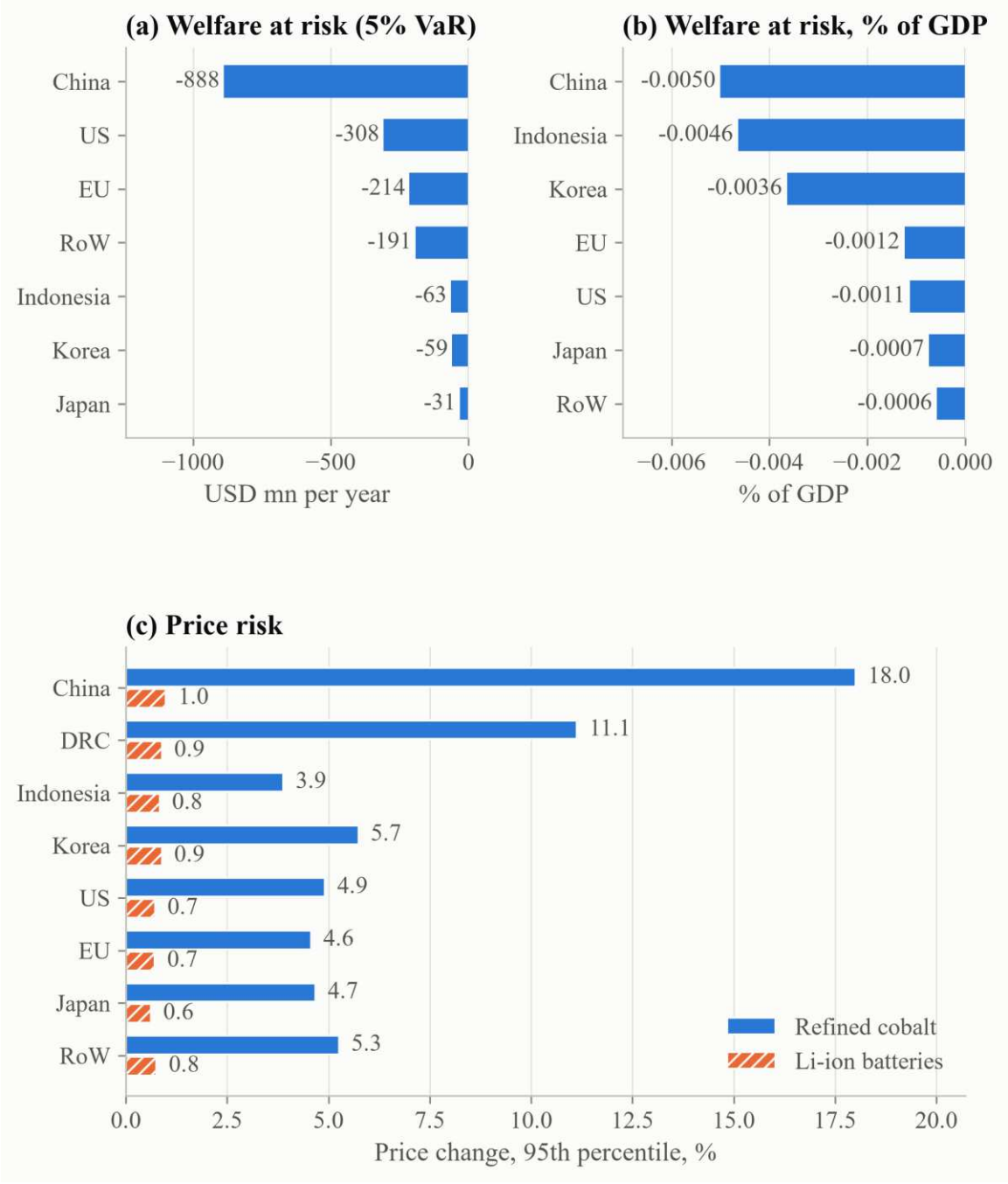


Fig. 2 Risk from ordinary DRC supply shocks (MC): 5% VaR of welfare (a) in USD mn per year and (b) in % of GDP; (c) 95th-percentile price changes of refined cobalt and lithium-ion batteries (%)

4.4 Losses scale with the shock, with no tipping point

The stage-1 regressions (Section 3.5; Appendix Table A4) show that losses are almost linear in the shock. R^2 exceeds 0.98 in every importer, and the relation shows no curvature over the whole range of draws, from $e = -0.42$ to $+0.40$ (Fig. 3). A 10% fall in DRC output lowers

welfare by 0.005% of expenditure in China, 0.003% in Korea and 0.001% or less in Japan, the US and the EU, and raises the importers' price of refined cobalt by about 2%. The condition hypothesis is therefore only partly supported: substitution elasticities change the size of losses but, within the ranges we sample, do not produce a point where losses suddenly accelerate.

Higher elasticities also redistribute the shock rather than reduce it. When import sources are easier to switch (higher σ_m), the price rise in China is smaller but the rise in the importers' refined-cobalt price is 2–6% larger per unit of σ_m. Moving from the lowest to the highest third of σ_m, China's loss per unit of shock falls by 9% and the US and EU losses by 2–4%, while Korea's rises by 13% and Japan's by 69%, as buyers move away from Chinese refined cobalt towards other suppliers.

Indonesia's supply response matters little. A 10% fall in DRC output raises Indonesian output by 25–34%, depending on η, but over the full range of η this changes the importers' metal-price response by only about ±5%. Japan is the one case where Indonesian supply worsens the VaR (from −19 to −31 USD mn): as an exporter of refined cobalt (about USD 190 mn per year), Japan gains less from high prices when Indonesia expands.

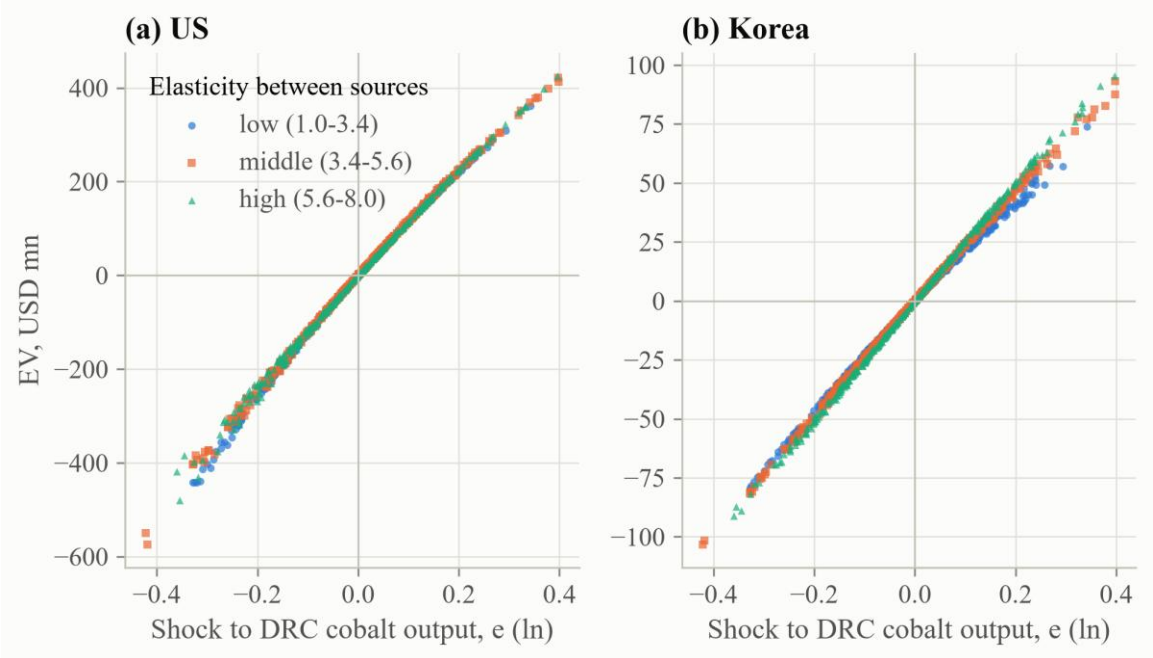


Fig. 3 Welfare change against the DRC shock, by elasticity among import sources: (a) US, (b) Korea (EV in USD mn)

4.5 Which importers are exposed

Comparing the stage-1 sensitivities of China, Japan, Korea, the US, the EU and RoW with their structural characteristics (Appendix Table A5, Fig. 4), welfare sensitivity rises with how much cobalt an economy uses relative to final demand (Spearman $\rho = 0.71$) and with its direct dependence on the DRC (0.66; 0.60 when DRC cobalt embodied in Chinese imports is included). The concentration of import sources (HHI) is a weaker predictor (0.49), because Japan and the US have concentrated imports but from suppliers other than the DRC, and dependence on Chinese batteries is unrelated (−0.26). The metal-price sensitivity is most closely related to direct DRC dependence ($\rho = -0.83$): the more an economy depends on the DRC, the more its price rises. With only six regions, a correlation needs $|\rho| > 0.89$ to be significant at 5%, so these are tendencies.

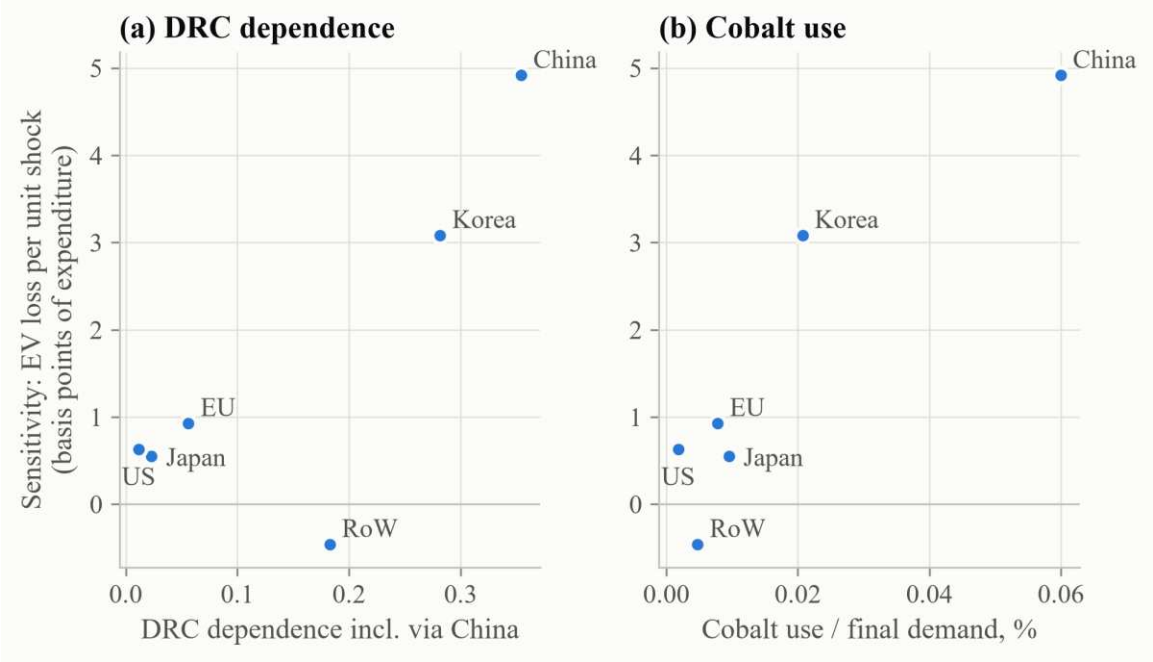


Fig. 4 Stage 2: welfare sensitivity against (a) DRC dependence including cobalt embodied in imports from China and (b) cobalt use relative to final demand

4.6 Is a cobalt stockpile worth it?

A stockpile of refined cobalt equal to 60 days of use is worth USD 59 mn in Japan, 20 mn in Korea, 74 mn in the US and 166 mn in the EU (Appendix Table A6, Fig. 5). In S1, releasing it lowers the rise in refined-cobalt prices by about 6 percentage points (in the US, from 40% to 34%). Net of the cost of refilling the stock, the payout is USD 135 mn in the US, 78 mn in the EU, 36 mn in Japan and 25 mn in Korea. At a holding cost of 5% per year, the stockpile therefore pays off if an S1-size disruption occurs with an annual probability above 2.7% in the US, 4.1% in

Korea, 8.2% in Japan and 10.7% in the EU; with holding costs of 3–7%, the threshold ranges from 1.6–3.8% (US) to 6.4–14.9% (EU).

In the MC, the stock is released in years when DRC output falls by more than one standard deviation. This improves the 5% VaR in every region, from −30 to −17 USD mn in Japan, −57 to −43 in Korea, −303 to −229 in the US and −210 to −174 in the EU. The expected annual payout exceeds the premium at 5% in Japan (3.6 against 2.9), Korea (2.3 against 1.0) and the US (11.7 against 3.7), but not in the EU (5.5 against 8.3), whose stock is large relative to its exposure. These figures use the 986 draws that solve both with and without the stockpile. The 13 draws that fail only with the release all have large negative shocks (e between −0.32 and −0.15); leaving them out shrinks the 5% VaR without the stockpile by 2–5% and, because the payout grows with the shock, makes the expected payout slightly conservative.

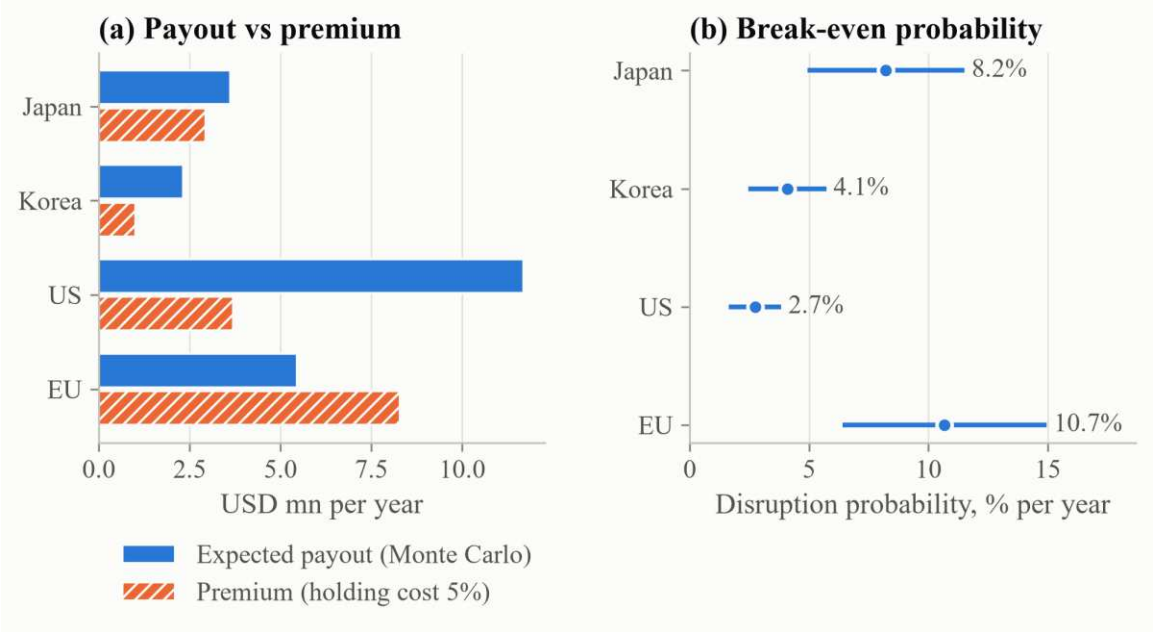


Fig. 5 Stockpile of 60 days: (a) expected annual payout in the MC against the premium at a 5% holding cost; (b) annual probability of an S1-size disruption at which the stockpile breaks even (dot: 5% holding cost; line: 3–7%)

4.7 Robustness

We check five assumptions. First, Korea's battery production has no official figure and is proxied by exports, which implies no domestic sales. If half of Korean output is instead sold at home, Korea's S2 result changes sign, from −3.8 bn to +1.9 bn, as Korea replaces Chinese exports, and its battery price rise falls from 134% to 41%. Other regions barely change (US −15.7 bn to −14.8 bn; EU unchanged), so H1 is unaffected. Second, estimating the ARIMA with d = 0

(ARMA(0,1) with a trend) gives a residual SD of 0.135 rather than 0.147; since results are nearly linear, VaRs shrink by about 8%. Third, without the Indonesian supply response ($\eta = 0$), VaRs change by less than 10% in most regions (China −954, US −341, EU −224, Korea −58 USD mn), the exception being Japan (Section 4.4). Fourth, we do not reassign the hydroxide exports of Zambia and South Africa to the DRC, although USGS production data suggest that 93% and 87% of them are re-exported DRC material; doing so would raise DRC exports of intermediates by about 3.5%, so DRC dependence is slightly understated. Finally, on the solution method, the export-tax method used for S3 reproduces the S2 quota solution exactly, and 2 of the 1,000 MC draws ($e = -0.31$ and -0.26) do not solve even with finer homotopy steps.

5 Policy implications

The results have three implications for policy, one for each group of countries in the value chain.

The first concerns the importing economies. Most policies to secure cobalt supply aim at the mining stage, through new mines outside the DRC and investment in mining abroad. Our results suggest that this addresses the smaller part of the exposure. A restriction on mined cobalt raises cobalt prices sharply, but because cobalt is a small part of battery costs, the effect on users is diluted along the chain. A restriction on batteries, by contrast, hits users directly and costs Japan, Korea, the US and the EU seven times as much. Diversifying the supply of cathodes and batteries therefore offers more protection than diversifying mines alone. Domestic battery production is one way to do so: Japan, with its own battery industry, gains when Chinese batteries become scarce, while Korea, which in our data relies on imports from China for most of its batteries, loses, although this result depends on how much of Korea's battery output is sold at home (Section 4.7).

The second concerns the restricting countries. The DRC's quota achieves part of its aim. It raises the DRC's income through quota rents and encourages refining at home, because only unrefined cobalt is restricted. Its cost, however, falls first on China, the main buyer of DRC hydroxide, and reaches battery users only in diluted form, which limits the leverage it gives the DRC over final users. It also creates an opening for Indonesia, whose cobalt exports from nickel processing gain market share. When China restricts batteries at the same time, the DRC's gains shrink, because lower battery output reduces the demand for cobalt. A restriction at one stage of a value chain can thus be weakened by a restriction at another.

The third concerns stockpiles. A 60-day stockpile of refined cobalt is reasonable insurance for the US, Korea and Japan. Its break-even disruption probabilities are 2.7–8.2% per year, and in the MC its expected payout exceeds its holding cost. Two restrictions in a single year, 2025, suggest that the risk is not remote. For the EU, the expected payout falls short of the holding cost, and the break-even probability is higher, at 10.7%. A shorter holding period, or a stock targeted at the users most exposed, may be more cost-effective there. More generally, a stockpile of refined metal protects against restrictions on mined or refined cobalt, but not against restrictions on batteries, the larger risk identified here.

6 Conclusions

This paper compared disruptions at the mining and the processing stage of the cobalt value chain in a global CGE model, combining Monte Carlo draws of supply shocks and elasticities with stress tests of the export restrictions introduced in 2025. Four conclusions follow. (i) Processing is the chokepoint because it controls far more value, although per dollar of restricted trade the mining stage is the more damaging. (ii) The cost of an upstream restriction falls on the processing country rather than on final users. (iii) Losses from ordinary supply shocks are small and grow in proportion to the shock, and easier substitution shifts them among importers rather than reducing them. (iv) A 60-day cobalt stockpile breaks even at annual disruption probabilities of 2.7–10.7%.

The analysis has limitations. Producers cannot replace cobalt with other materials, Korea's battery production is proxied by its exports, and the 58% cut in all battery exports is an assumption for comparability that goes beyond the announced controls. The model is also static and covers one mineral. Extending it to material substitution, recycling and the dynamics of new refining capacity, and to nickel, lithium and graphite, would show whether the pattern found here holds for other battery minerals.

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