Market Power versus Geoeconomic Power in Critical Mineral Processing

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(job market paper)

November 2, 2026

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Abstract

China has become the dominant player in the midstream processing of many critical minerals. This concentration has enabled it to wield geoeconomic power through trade restrictions. We show, however, that concentration can also create an opposing force: market power exercised through national industry coordination. When a country's processors coordinate to raise processing charges, higher charges divert supply to processors elsewhere and increase the charges earned by those competitors. This "umbrella effect" can slow further consolidation, reducing the country's geoeconomic leverage. We quantify this tension in the copper supply chain—an essential input to the energy transition—where the China Smelters Purchase Team coordinates processing charges. We develop a framework for critical-mineral supply chains with coordinated midstream firms. Our results show that, absent coordination, the supply chain would be substantially more concentrated and less resilient to a range of geoeconomic shocks.

Keywords: Copper; critical minerals; trade restrictions; geopolitical risks; energy transition.

JEL Codes: D43, F13, F51, L13, Q31.

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1 Introduction

Trade creates economic gains, but it can also create geoeconomic power. Economists have long recognized that a country gains leverage over its trading partners when those partners depend on it and have few alternatives (Hirschman, 1945; Clayton, Maggiori and Schreger, 2026).[1] This idea is central to recent debates about critical mineral supply chains. Here, low-cost expansion in the middle layer of supply chains has made China the leading refiner of 19 of 20 strategic minerals (International Energy Agency, 2025). China has used this position for geoeconomic leverage through, for example, a ban on processing Australian copper (Thompson, 2021).

However, the same concentration that gives a country geoeconomic power can also give its firms market power. In this paper, we show that these two forms of power can conflict, and we quantify the tradeoff between them. Concentration incentivizes domestic firms to coordinate to exercise buyer power, which raises their own profits. But, this also raises the margins of competitors abroad, helping foreign plants that would otherwise close stay in business. Coordination can therefore slow further consolidation and preserve alternatives that limit the dominant country's geoeconomic leverage.

We study this tension in copper, where China's low-cost smelters dominate the middle of a global supply chain and openly coordinate the processing fees they charge miners through the China Smelters Purchase Team (CSPT). We ask: how does price coordination among a dominant country's firms affect its geoeconomic power? We answer this question in three steps. First, we develop an empirical framework for measuring the extent of price coordination and buyer power at a processing bottleneck under weak restrictions on firms' conduct. Second, we apply the framework to new micro-data on costs, prices, and mine–smelter relationships. Third, we use our estimated model to show that coordination substantially raises Chinese smelters' profits while indirectly

[1] A related literature measures the consequences of such dependence. Kleinman, Liu and Redding (2024) find that economic dependence shapes political alignment. Elliott, Golub and Leduc (2022); Grossman, Helpman and Lhuillier (2023) show that decentralized investment in supply-chain relationships can generate inefficiently fragile supply networks, amplifying small aggregate shocks into large declines in output. Governments increasingly set trade and industrial policy with these risks in mind (Thoenig, 2023; Becko, Grossman and Helpman, 2025; Mohr and Trebesch, 2025).

subsidizing high-cost processing capacity abroad through an "umbrella effect." These implicit subsidies are an order of magnitude larger than total US subsidies for critical mineral processing. By preserving foreign alternatives, coordination substantially weakens China's leverage from restricting access to its smelters.

Although copper is important in its own right as an input into power grids, electric vehicles, and renewable energy technologies (International Energy Agency, 2021), the tradeoff we quantify extends beyond this industry. We document producer coordination across a broad range of Chinese critical-mineral processing industries in Appendix Table F1, including Zinc, Manganese, Chromium, Titanium sponge, and Polysilicon. These issues also extend beyond critical minerals. For example, in antibiotics, China produces over 80% of the world's active ingredients (Coalition for a Prosperous America, 2026).

The copper supply chain is structured as follows. Upstream mines are located throughout the world, and this level of the supply chain is unconcentrated at both the firm and national levels. These mines extract and export "copper concentrate," which we refer to in this paper as the "raw mineral." This raw mineral needs to be processed by a smelter to be turned into "copper cathode," a product that is almost pure copper, through electrolysis. We call this product the "refined mineral." Mines therefore need to sell their raw mineral to a smelter for processing. The smelter market, while unconcentrated at the firm level, is concentrated at the country level, with China processing about half of the raw mineral in 2025. Smelters then sell the relatively homogeneous refined mineral on the global market, where there is a common benchmark price per unit of this commodity.

Trade between mines and smelters takes two forms: negotiated contracts and spot market transactions. There is many-to-many matching between mines and smelters. Mines typically have long-term relationships with a small group of smelters. Mines negotiate a per-unit processing fee separately with each of these smelters each year. Outside this negotiated fee, the allocation of other revenues from the raw mineral is determined by industry norms: mines receive a constant share of the total value of copper, while smelters receive the value of any additional copper above this share

that they recover plus the value of any byproducts (such as silver, gold, and sulfuric acid).

In the spot market, mines sell their raw mineral to intermediaries who then sell to smelters for processing on a one-off basis. Chinese smelters coordinate their spot pricing through the CSPT, which issues public guidance on a floor for spot processing fees. As we show later in the motivating evidence, the mines' outside option in their contract negotiations is the spot market. Therefore, by raising spot fees, the CSPT also indirectly raises fees throughout the processing network, because it weakens mines' outside option.

We construct a novel dataset linking production costs, trading relationships, and processing fees in the global copper supply chain. Our data come from Wood Mackenzie and cover essentially every copper mine and smelter in the world. We observe detailed information at each level of the supply chain, including output, capacity, transfers, and the quantities each mine sells to individual smelters or on the spot market. A key feature of these data is that we observe micro-data on costs throughout the supply chain; this is helpful for our estimation strategy because it allows us to construct a competitive benchmark without inferring costs from assumptions about cartel conduct.

We begin by documenting four facts that guide the model. First, Chinese smelters have a large cost advantage but leave capacity idle. This fact is consistent with the exercise of market power diverting trade away from China toward high-cost processing in the rest of the world.

Our second fact shows direct evidence on how this market power is exercised through the CSPT. Following Borenstein, Bushnell and Wolak (2002), and in the spirit of Asker, Collard-Wexler and De Loecker (2019), we use our cost data to construct a simulated "perfect competition" spot price. We document a large wedge between this price and the realized spot price (which is highly correlated with the CSPT's price floor guidance) up until 2023. We interpret this wedge as arising from the CSPT's price coordination; our data provide an external validation of this interpretation. Concretely, after 2023, spot price coordination collapsed and the CSPT stopped issuing price guidance. After a transition in 2024, we observe the processing fee turning negative in 2025, in line with our simulated price.[2] Moreover, the realized 2025 fee has a similar magnitude

[2] A negative fee arises because there are valuable byproducts in the raw mineral that can also be sold.

to our simulated fee.

Third, mines sell to a small and persistent set of smelters: the average mine supplies 3.3 smelters, and 90% of shipments follow relationships active in the previous year. Fourth, we exploit temporary smelter outages to reveal how mines respond when they lose a buyer. We find that mine output does not fall. Rather, mines reroute their output to the spot market (rather than forming new relationships or rerouting to existing relationships). This motivates our use of the spot market as the mine's (short-run) outside option if annual negotiations break down. By contrast, after permanent closures, mines instead form relationships with new smelters.

Based on these motivating facts, we build a model of annual bargaining, routing, and potential smelter exit. At the start of each period a mine chooses how to route its output across its relationships and the spot market. Each mine–smelter pair bargains over its contract fee; if bargaining fails, the mine sells the affected volume on the spot market and incurs a disruption cost for placing it at short notice. We call this setup "Nash-in-Nash with a spot market threat," similar to Horn and Wolinsky (1988). Concretely, the negotiations are linked to the spot market equilibrium price through the outside option. In turn, the spot market equilibrium price is linked to the contract negotiations through mines' routing decisions. We also allow for smelters to potentially exit if their variable profit over the sample is less than their fixed costs.[3]

We estimate the routing and Nash bargaining model via maximum likelihood. In estimation, we take the empirical spot price as given, and identify the rest of the parameters as equilibrium responses to this price. As a result, we place no assumptions on exactly how the spot price guidance is set by the CSPT, which sidesteps modeling difficulties such as participation constraints or incentive compatibility constraints that sustain coordination which are typical in the theory literature.

We quantify these effects by comparing the observed spot fee with a counterfactual fee that clears the spot market under perfect competition. That is, we repeat the exercise behind our second fact, but embed it within the equilibrium of the model. In the short run, we hold the set of smelters and their relationships fixed. We then allow unprofitable smelters to exit and their raw mineral to

[3]In our sample we observe significant changes in market decisions so this decision rule is arguably a good proxy for the smelter's dynamic decision to exit in the long run, thinking forward to future conditions over the business cycle.

move to surviving plants with spare capacity.[4]

In the short run, competition lowers both spot and contract fees and transfers surplus from smelters to mines. Over our data sample, profits at smelters outside China fall by $31.4 billion, while mines gain $57.0 billion. Chinese smelter profits fall as well. The loss to smelters outside China measures the profit support they receive from the umbrella effect. Under competition, 76.3% of smelter capacity outside China makes losses.

We also consider the longer run, when smelters can exit. Here, 32.0% of smelting capacity outside China closes, compared with 0.6% in China. China's share of processing rises from 39.7% to 45.2%. Exit partly reverses the initial decline in fees, but mines still gain $43.2 billion relative to the baseline. Consolidation also reduces misallocation by lowering total processing costs by 24.0%. Overall, the CSPT's price coordination therefore substantially supports processing capacity outside China.

We next ask how these changes in conduct and capacity affect exposure to geoeconomic shocks. We first consider a China (plus a China-aligned bloc of countries) processing embargo on raw mineral from the largest mining country in our dataset: Chile. This embargo is similar to China's informal ban on Australian concentrate that began in late 2020. We find that in the baseline, if the spot price floor were to hold, Chile's loss would be relatively small. Indeed, it would be outweighed by the China bloc's loss, indicating that in the baseline China has little geoeconomic leverage over Chile. If the spot floor is eliminated, Chile's loss remains small in the short run, at $0.90 billion per year, although it now exceeds the China bloc's loss. What underlies these results is the availability of close smelting substitutes for Chile's processing needs.

In the long run, however, these close substitutes exit, which makes the embargo much more costly for Chile. Approximately one-third of Chile's mine output would be stranded. Overall, the embargo reduces Chilean producers' profits by $5.89 billion per year, compared with $1.07 billion per year for the China bloc.

Next, we consider a global split counterfactual between a US-aligned bloc and a China-aligned

[4]We hold mine output fixed and approximate long-run adjustment through exit and the reallocation of existing relationships. Our fourth fact supports our fixed-output assumption for temporary disruptions.

bloc. With the baseline market structure and price coordination, the split costs the US-aligned bloc $2.85 billion per year, but also costs China's bloc $2.91 billion per year. In other words, neither side has much relative geoeconomic leverage in the baseline. The balance shifts in the short run after price coordination breaks down. Here, the US-aligned bloc's loss rises to $5.40 billion per year, while China's bloc's loss falls to $0.82 billion. In the long run with no coordination and plant exit, the gap is substantially larger. The US-aligned bloc loses $17.01 billion per year, and almost half (46.9%) of its mine output is stranded, compared with 10.9% in the baseline. China's bloc loses only $1.68 billion per year. Without coordination, China would therefore have substantial geoeconomic leverage over the US-aligned bloc.

These results have implications for policy toward critical-mineral supply chains. Much current policy treats concentration in processing as a single problem, to be addressed with subsidies, tariffs, or sourcing rules that support processing capacity outside the dominant country. Our results suggest that the conduct of firms in the dominant country matters for how much support is needed. While Chinese smelters coordinated, they implicitly subsidized smelting capacity open in the rest of the world. This extra capacity gives mining countries additional options to send their concentrate if trade with China is restricted. This points to a tension between competition authorities and national-security agencies with respect to whether Chinese smelter coordination is a benefit or a cost.

Related literature and contributions. We contribute to research on geoeconomics by quantifying how industry conduct shapes the alternatives available to a dominant country's trading partners. Clayton, Maggiori and Schreger (2023, 2024) study the sources of economic coercion and how specialization and economies of scale create dependence. Within critical minerals, Alfaro et al. (2025) study innovation in response to rare-earth trade restrictions, and Domínguez-Iino, Elliott and Hsiao (2026) quantify supply-chain vulnerability and policy spillovers across battery minerals. Closely related work by Choi, Pandalai-Nayar and Toma (2026) studies how strategic overproduction deters entry into rare-earth refining. We quantify a countervailing force: coordination raises rivals'

profits and preserves the processing capacity that limits exposure to trade restrictions.

We also contribute to work on market power and firms outside a cartel. Stigler (1965) and Gaskins (1971) study how a dominant producer's pricing affects the expansion of its rivals, while Inderst, Maier-Rigaud and Schwalbe (2014) analyze umbrella effects. Asker, Collard-Wexler and De Loecker (2019) show how market power shifts oil production toward higher-cost producers outside OPEC. We trace an umbrella effect through spot markets and bilateral contracts, and quantify how the survival of rival plants changes vulnerability to a trade split. The same capacity that raises production costs can provide alternatives during a disruption.

Finally, we build on empirical models of Nash-in-Nash bargaining in vertical markets, including hospital–insurer, programmer–distributor, and medical-device relationships (Crawford and Yurukoglu, 2012; Grennan, 2013; Gowrisankaran, Nevo and Town, 2015; Ho and Lee, 2017, 2019), and on their theoretical foundations (Horn and Wolinsky, 1988; Collard-Wexler, Gowrisankaran and Lee, 2019; Ho and Lee, 2023). In our setting, the spot market supplies a common price that enters every mine's outside option. We use this link to quantify how coordination in one part of the market changes negotiated fees elsewhere. This approach complements models in which a firm can replace a bargaining partner (Ho and Lee, 2019), and work on buyer and seller power in vertical markets (Demirer and Rubens, 2025). We apply it to a global commodity market with many-to-many trading relationships, capacity constraints, and exit.

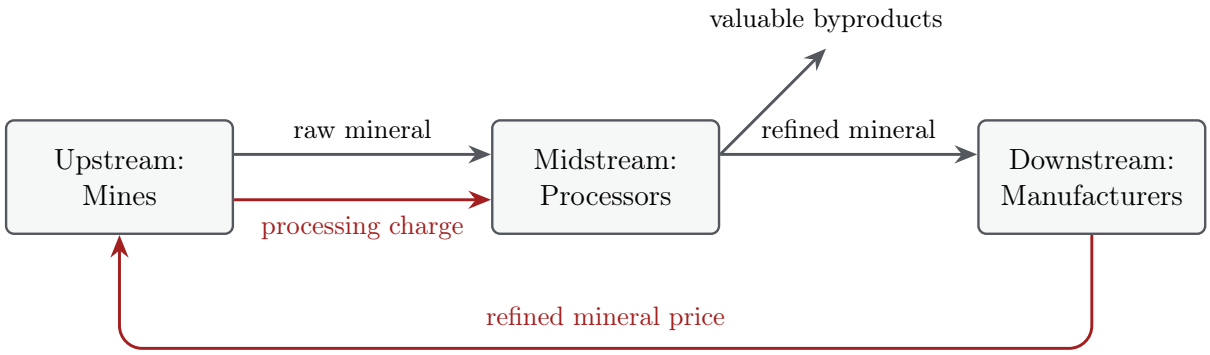
2 Background and Data

2.1 Institutional background

Overview of the supply chain We present a diagram of the copper supply chain in Figure 1. Although our focus is on copper, the structure of the supply chain is relatively similar across other critical minerals, comprising upstream, midstream, and downstream stages. Throughout the paper, we use the terms "processor" and "smelter" interchangeably.

We first describe the flow of physical quantities through the supply chain, which are illus-

Figure 1: The supply chain



Notes: Dark gray arrows show physical flows, and red arrows show payments. Processors earn revenue from processing fees as well as valuable byproducts, such as silver, gold, and sulfuric acid. Processors also retain the value of copper recovered beyond 96.5% of the total copper in the raw mineral (known as "free metal"), which we omit from the diagram for simplicity.

trated using the black arrows. Upstream are miners, which extract ore and are located near copper deposits which are dispersed across the world. These upstream miners send unrefined minerals (called in our setting "copper concentrate") to midstream processors. These midstream processors then turn the inputs into refined minerals (in our setting called "copper cathode"). Refined copper is a relatively homogenous metal that is traded on a global downstream market (in our setting, this is the London Metal Exchange). Although we end Figure 1 at the downstream market, refined copper is then an input into numerous other supply chains, especially those that power the energy transition. Examples include electric vehicles and electricity transmission lines.

Prices and contracts Figure 1 also shows using red arrows the prices through the supply chain. There are two main kinds of prices. First, upstream miners pay mid-stream processors a per-unit processing charge. In effect, processors sell a processing service to mines.[5] Most unrefined copper is traded under processing charges that are determined through bilateral negotiated contracts.[6]. These contracts are negotiated annually. A smaller share of unrefined copper is processed through

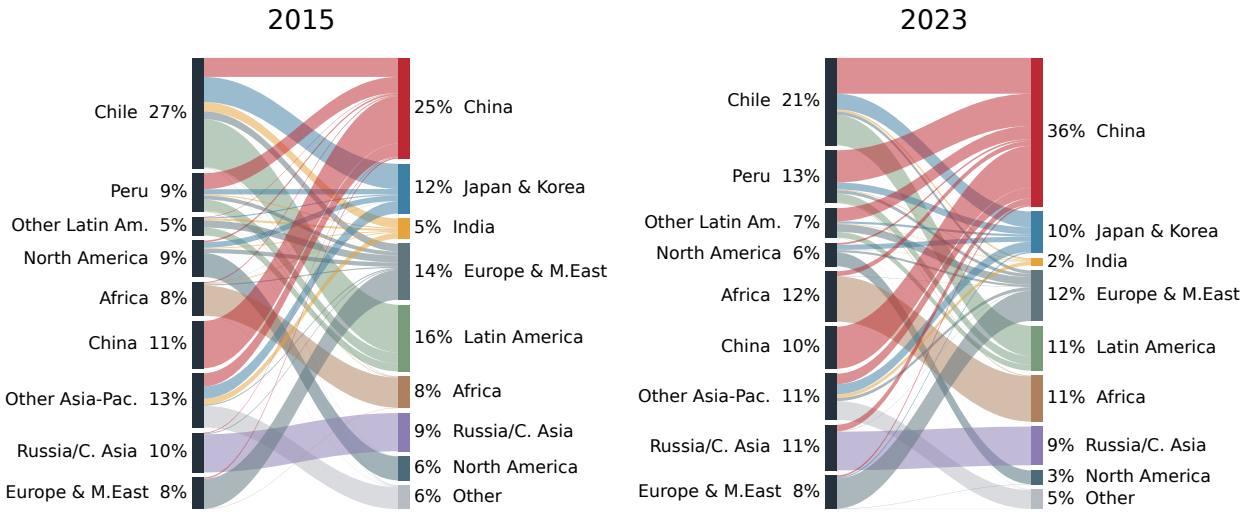
[5]Formally, smelters buy the raw mineral: a smelter pays the mine the refined copper price for the payable copper, minus the processing charge. However, because industry norms are that the miner receives almost all of the downstream value of the refined mineral, this contract effectively works like a fee that the mine pays for processing. So, we describe it this way throughout.

[6]In the copper supply chain these processing charges are called "Treatment Charges and Refining Charges" or "TC/RCs"

prices determined by a spot market. The second price is the global refined copper price, most of which accrues to the upstream miners.

Processors also earn revenue from two other sources, which we account for in our later analysis. Specifically, a small fraction (typically, around 2%) of the refined copper price accrues to the processor; this is a small share of the total revenue of the smelter with around 80% of revenue coming from other sources like the processing fee and so we omit it from Figure 1.[7] As well, the smelting process generates valuable by-products which can be sold, most notably gold, silver, and sulfuric acid.

Figure 2: Trade flows in 2015 and 2023



Notes: Ribbon widths and percentages measure contained copper sent from mining countries (left) to processing destinations (right), including domestic shipments. Spot sales have no observed processing destination and are excluded; they account for 14.9% of reported allocations in 2015 and 15.7% in 2023.

Chinese mid-stream coordination Figure 2 shows trade flows from mining countries to processing destinations. Although copper is mined throughout the world, Chinese smelters receive 36.1% of shipments with reported destinations in 2023 (38.9% in the baseline estimation sample). A natural consequence of these flows is that if China could coordinate how its smelters set prices

[7] An approximate description of how this works is as follows. The amount of copper per unit of unrefined mineral is first estimated using an engineering formula. The processing step will not be able to recover all of the total copper. Instead, the industry norm is that 96.5% of the total copper content will result in refined copper. This is referred to as "payable" copper. Any additional copper that is recovered beyond this amount (typically, around 2%) accrues to the smelter.

(and we describe how they do this later in this section), it could allow for them to potentially exercise market power. Measures of industry concentration show similar potential incentives to exercise market power. Concretely, the industry is unconcentrated at the asset level: the miner and smelter Herfindahl–Hirschman Indices (HHIs) are 135 and 143, respectively. The market is also unconcentrated if we measure concentration at the asset ownership level. Once smelters are aggregated by country, however, the processing side of the market becomes concentrated with an HHI of 1,906, driven primarily by grouping Chinese smelters together.

One may ask: why does China comprise such a large share of global copper processing? The answer is a combination of industrial policy, which expanded processing and manufacturing capacity across numerous Chinese industries in the 2000s, as well as other factors like low electricity prices that make China a good location for processing industries. Our analysis takes place post-2015 when most of these processing capacity investments were built and costs were sunk. Therefore our study does not require us to model or take a stand on the exact motivation for China's capacity expansion.

China coordinates its smelter pricing using an industry-led organization called the "China Smelters Purchase Team" (CSPT). This organization was formed in 2003 to prevent "轮番压价、各个击破," which loosely means the ability of foreign suppliers to pick smelters off one-by-one and push the price down on each in turn. Formally, it sets a price floor in the spot market and takes a lead in the first annual negotiation that occurs between the largest miner and one of the largest smelters. We later find strong evidence that the price floor affects prices. However, in terms of the lead negotiation, we do not find that this affects contracted prices much. Instead, we observe significant dispersion in contracted prices, rather than simply anchoring on this lead negotiation price, indicating that all contracts are actively negotiated.

2.2 Data

We combine three Wood Mackenzie datasets: annual mine costs and production, annual smelter costs and production, and mine-smelter shipment allocations. The mine and smelter panels cover

2000-2023, and shipment allocations cover 2015-2023. We match assets by name and identifier, reconcile shipments with reported mine production, and exclude observations with missing costs. The baseline estimation sample contains 1,060 mine-years from 148 mines and 65 smelters over 2015-2023, of which 25 smelters are in China. This sample includes 3,536 physical shipment observations and 539 spot sales. It covers 56% of world mine production and 64% of output in the full Wood Mackenzie mine panel over 2015-2023. Solvent extraction-electrowinning (SX-EW), which bypasses the concentrate-smelting route modeled here, accounted for 20.5% of global copper mine production in 2023 (International Copper Study Group, 2024). Thus, our baseline sample accounts about 70% of global copper output through the concentrate-smelting route.[8] Appendix C provides details on sample construction, ownership controls, and coverage. A key data feature is that we observe bilateral shipment quantities and mine-year average processing fees, but not bilateral processing fees. Our structural model aims to recover the bilateral contracted processing fees and gains from trade.

Table 1 reports summary statistics for the baseline sample. Mine-year copper output averages 96.95 kilotonnes, more than twice the median of 46.29 kilotonnes. Mines deliver to 3.34 physical smelters on average. A physical shipment accounts for 25.01% of covered mine-year output on average, while the mean mine-year spot share is 16.56%. Average mine-year processing fees are $500.82 per tonne of copper, with a standard deviation of $239.33. Mean mine-smelter distance is 10,060 kilometers; 18.89% of physical shipment observations are domestic, 30.83% involve a Chinese processor, and 10.92% share a common major owner.

3 Motivating Evidence

This section documents four observations that shape the model in Section 4. Additional results are in Appendix A.

[8] This comparison uses recovered copper less reported SX-EW output at the sampled mines (12.38 million tonnes), including output allocated to processors outside the estimation sample. Global non-SX-EW mine production is $22.384 \times (1 - 0.205) = 17.80$ million tonnes, using the ICSG figures.

Table 1: Summary Statistics of the Baseline Sample, 2015-2023

Characteristic	N	Mean	SD	P25	Median	P75
Mine-year characteristics						
Copper output (kt Cu)	1,060	96.95	143.66	18.32	46.29	118.57
Physical smelter destinations	1,060	3.34	4.04	1.00	2.00	4.00
Spot share of copper output (%)	1,060	16.56	24.18	0.00	0.62	26.47
Average processing fee (USD/t Cu)	1,060	500.82	239.33	339.32	460.17	622.83
Smelter-year characteristics						
Net processing cost (USD/t Cu)	507	-133.25	155.13	-223.73	-129.55	-36.33
Physical route-year characteristics						
Physical shipment share (%)	3,536	25.01	31.76	4.18	9.97	31.11
Geographic distance (1,000 km)	3,536	10.06	6.77	2.72	10.68	17.17
Domestic route (%)	3,536	18.89	39.15	0.00	0.00	0.00
Chinese processor (%)	3,536	30.83	46.18	0.00	0.00	100.00
Common major owner (%)	3,536	10.92	31.19	0.00	0.00	0.00

SD denotes the sample standard deviation, and P25 and P75 denote the 25th and 75th percentiles. A physical shipment share is the percentage of total covered mine-year output sent to a particular smelter, including spot in the denominator. Spot shares include zero for mine-years without spot sales. In terms of copper volume, common major owner, domestic route, and Chinese processor account for 27.34%, 34.81%, and 24.57% of total sample output. Monetary values are in 2017 US dollars. Quantities are in kilotonnes of copper.

3.1 Observation 1: Chinese smelters have a large cost and profitability advantage, yet leave substantial capacity idle.

In Figure 3, panel (a), we show the world "merit order" supply curve for copper processing. To construct the curve, we rank each smelter by its net variable cost of production, which we define as per-unit variable costs (like electricity) minus per-unit byproduct benefits (free metals like silver and gold, as well as sulfuric acid). The x-axis is total smelter capacity. We plot the curve for 2023, but the qualitative conclusions are unchanged throughout our sample period. We delineate Chinese smelters (blue) from smelters outside of China (gray).

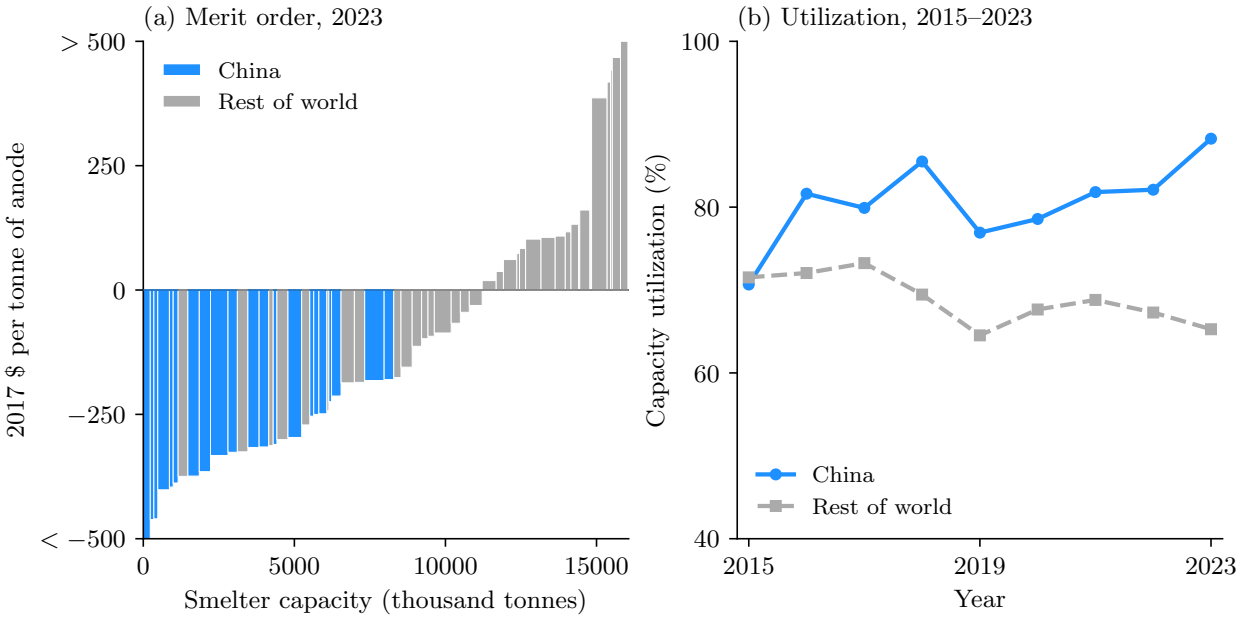
Figure 3(a) illustrates that Chinese smelters hold a significant cost advantage, in the sense that per-unit variable costs are lower than in the rest of the world. Chinese smelters tend to be newer and more efficient, have lower electricity prices, lower labor costs, and less stringent environmental regulations compared to the rest of the world. This cost advantage is amplified when considering

Chinese smelters' ability to extract byproducts from the unrefined mineral. For all smelters in China, and for some smelters in the rest of the world, a negative processing fee would actually cover their variable costs, i.e., they would be willing to pay to process the raw mineral.

Since Chinese smelters have the lowest operating costs, one might expect that they operate at close to capacity (and choose prices to ensure that this happens). However, this is not the case. Instead, Figure 3, panel (b), shows that there is significant excess capacity in Chinese smelters. At the same time, a substantial amount of unrefined mineral is processed by high-cost smelters in the rest of the world.

These patterns are suggestive evidence that price coordination amongst Chinese smelters diverts trade to high-cost smelters elsewhere. To add to this suggestive evidence, we document exactly how Chinese smelters explicitly coordinate prices in the next observation, through the China Smelters Purchase Team (CSPT). However, there are three leading alternative explanations for excess capacity at Chinese smelters. First, it could be that smelters have marginal costs that sharply increase near full utilization. This is not the case: practitioners suggest that it is most profitable to run as close to capacity as possible, and that running below capacity is costly (Brunelli and Moerenhout, 2026). Consistent with this, we find that a smelter's total cost is negatively correlated with utilization, including among the top quartile of utilization when smelters are close to capacity (Appendix Table A4). Although these results show how total costs change with utilization rather than marginal costs, they are inconsistent with sharp "hockey-stick" increasing marginal costs near full capacity utilization. Second, miners may be vertically integrated with smelters, and so choose to deliver unrefined mineral to their integrated smelters. Later, in the model, we allow for this possibility when computing our routing choice model. Third, it may be costly to route to Chinese smelters, and these routing costs may cause miners to prefer smelters close by. We also account for routing preferences later in the model.

Figure 3: Copper smelting costs and capacity utilization



Notes: Panel (a): merit order in 2023. Each column represents a smelter, ordered by net costs (costs minus the value of byproducts), in 2017 dollars. Panel (b): smelter capacity utilization in China versus the rest of the world.

3.2 Observation 2: Chinese smelters explicitly coordinate price in the spot market.

Recall that the CSPT explicitly coordinates to establish a spot market price floor. We compiled its public floor announcements from press reports (Appendix Table A3) and plot them in Figure 4. Prior to 2024, the guidance prices appear to move around with the global business cycle. The CSPT floor fell sharply starting in mid-2023. The CSPT has not issued floor guidance since 2025Q1.

Figure 4 also plots the realized spot price. The realized spot price follows the guidance closely before 2024. That said, it does not always equal it: the guidance was at or above the spot charge in 16 of the 17 quarters in which both are reported, by a median of $6 per dry tonne. In 2024, however, the actual spot and CSPT floor started to deviate. Since 2025, when the CSPT stopped setting a floor, the spot price has turned negative.

Finally, Figure 4 also plots a counterfactual "perfect competition" spot price. To do this, we take all the quantity that is sold on the spot market in each year, reallocate it via the merit order curve using variable costs minus byproduct benefits, and record the marginal cost of the marginal

smelter.[9] We allow reallocation up to 90% of each smelter's capacity (which is around the 75th percentile of utilization); the qualitative findings are unchanged if we allow reallocation up to full capacity. This exercise is inspired by Borenstein, Bushnell and Wolak (2002), which compares observed prices to system marginal cost during the California electricity crisis, and Asker, Collard-Wexler and De Loecker (2019), who use micro-data on costs in the oil and gas industry to quantify the misallocation effects of OPEC.

Our exercise reveals a large wedge between the empirical and the perfect competition spot price for each year pre-2024. Our preferred interpretation of this wedge is that it is the effect of price guidance in the spot market. While we place no assumptions on exactly how the price guidance is set, our results hinge on the assumption that in the absence of the price guidance, the spot market would clear via perfect competition. As a result, there are at least two threats to this assumption which would violate our preferred interpretation, which we now discuss.

First, if processors have market power, the market could re-equilibrate to a price above perfect competition. However, recall that the processor market is very unconcentrated at the firm level, which suggests that market power is not a concern. Second, there may be other constraints like distance or transport costs which prevent the spot market from clearing via the lowest cost processors. However, almost all of the spot market is processed in China, and so our exercise involves reallocating raw mineral across a set of relatively nearby smelters. We also note that in our structural model and counterfactuals we will account for transport costs.

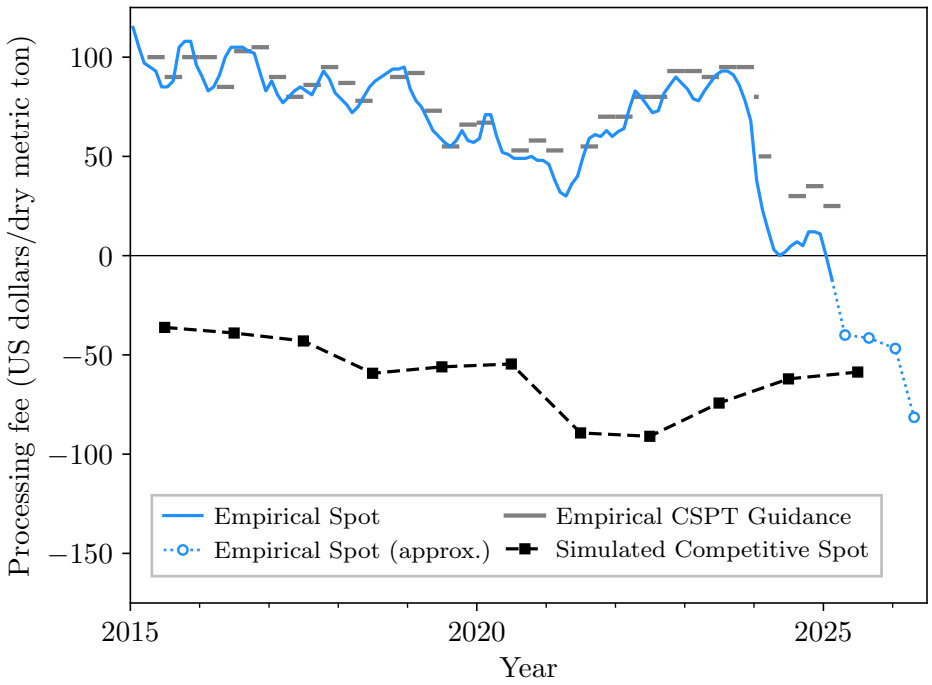
Beyond these institutional details that suggest our approach is reasonable, we also have a direct validation that the market can re-equilibrate to the perfect competition price: the end of the CSPT price floor after 2024. While the year 2024 appears to be a transition year for the market between the cartel and perfect competition, in 2025 the observed processing fee turns negative, consistent with the perfect competition price. Beginning in 2025, the observed processing fees are close to

[9] An alternative way to do this exercise would be to allocate all concentrate to the spot market and compute the price from the merit order curve. However, this exercise would assume that the spot market and the contract market are perfectly substitutable. This is likely not the case in our setting. For example, there is a persistent price premium for contract processing, which is consistent with transaction costs of using the spot market. In our empirical framework later, we flexibly model the relationship between the spot market and the contract market, and let the data discipline the substitution between these two processing options.

our predicted perfectly competitive fees.

The market-clearing exercise in this observation also showcases the value of our micro-data on costs in measuring the effects of cartels. A common challenge in measuring the effects of cartels is that cost data are unobserved (and, indeed, it is typical to make assumptions on conduct to aid in identifying costs). Our approach and data allow us to sidestep this problem. Later in the model, we build on this spot market exercise to quantify the effects of the CSPT on the entire equilibrium of that market.

Figure 4: Spot processing fees versus the perfect competition benchmark



Notes: Quarterly CSPT floor guidance, realized spot treatment charge, and the perfect-competition spot charge. The perfect-competition charge reallocates each year's spot volume across smelters and reports the cost of the marginal smelter.

3.3 Observation 3: Mines sell to a small and persistent set of smelters.

The average mine ships to 3.3 smelters in a year, so 6.0% of possible mine–smelter pairs trade. These relationships are also persistent. A relationship active in year t remains active in year $t + 1$ with probability 78%. An observed relationship that lapses for at least one year has only a 18% of redeveloping. And, a pair that has never traded is established with a probability of

0.8%. Established relationships also take the vast majority of concentrate. In a typical year, 90% of shipments move on relationships that were active the year before. Finally, past trade explains a great deal of who trades with whom. Concretely, the within-mine-year R^2 of a linear probability model of an active relationship rises from 0.05 to 0.58 once last year's status is added (Appendix Tables A1 and A2). In the model, we therefore take each mine's set of smelter relationships as given within a year, and hold it fixed in the short-run counterfactuals.

3.4 Observation 4: When a mine loses a smelter temporarily, it sells much of the displaced raw mineral on the spot market and does not cut output; when a smelter closes for good, the mine signs with new smelters.

Since our model and counterfactuals hinge on how substitutable smelters are, we investigate how exogenous smelter disruptions affect mines' routing choices about where to send their raw minerals. We focus on smelter outages. We consider eleven outages in total. We classify eight outages as "temporary," i.e., the smelter reopens afterwards, and three as "permanent," i.e., the smelter closes for the rest of our sample period.[10] We drop a small number of exposed mines that share an owner with the disrupted smelter, since they may behave differently from mines that do not share an owner with the smelter, but our limited data do not allow us to test for these differences in our motivating evidence.[11]

We estimate the impact of the disruptions on several outcomes. Specifically, for event e with disrupted smelter j, mine i's exposure E_{ie} is its average share of output sold to j in the third and second years before the event, and we estimate:

$$y_{iet} = \theta\, E_{ie}\, \text{Offline}_{jt} + \alpha_{ie} + \tau_{et} + \varepsilon_{iet}, \tag{1}$$

[10] The events are temporary shutdowns at Codelco's Chuquicamata smelter, Nchanga and Mufulira in Zambia, and Dahej in India; the idling of Asarco's Hayden smelter; financial distress at Dongying, Shandong Xiangguang, and Dias d'Ávila; and permanent closures at Tongling's Jinchang smelter, Codelco's Ventanas smelter, and Vedanta's Tuticorin smelter in India.

[11] In the empirical model we do allow for different routing behavior at co-owned smelters.

where Offline_{jt} is the share of year t the smelter was offline and α_{ie} and τ_{et} are event-by-mine and event-by-year effects. Therefore, the estimate of θ can be interpreted as the effect of a full year without the smelter for a mine that sold to that smelter all of its output.

Table 2 reports the estimates. For independent mines, a temporary disruption cuts the share of output sold to the disrupted smelter by 1.18 and raises the share sold on the spot market by 0.76. The spot market thus takes 64% of the displaced volume. While the point estimate is noisy because of our limited disruption data, the change in the share sold to existing or new smelter partners is statistically indistinguishable from zero. Importantly, we do not find evidence that output falls (-0.17, s.e. 0.32).

While the response of miners to temporary disruptions has the greatest implications for our model, since they motivate the choice of the outside option in the model, we also investigate a smaller sample of permanent closures. The response of mines to these closures may differ because they have more time to respond to the disruption. We report the results in column 2. Similarly to the temporary disruption results, the mine's output does not significantly change. However, the mine's behavior in terms of who they contract with does differ. Specifically, mines form new relationships and route their raw mineral to new smelters. This suggests that a mine that permanently loses a smelter replaces the lost relationship with a new one. Interestingly, we also see that the spot share actually falls in column 2. This is consistent with the idea that forming a new relationship is costly, but once that cost is sunk, mines may re-route their raw minerals away from the spot market. We allow for this kind of response in our model.

Table 2: Smelter disruptions: where the displaced volume goes in the year of the disruption

	(1) Temporary disruptions	(2) Permanent closures
Share to disrupted smelter	-1.18***	-0.80***
	(0.24)	(0.10)
Share sold on the spot market	0.76**	-0.51*
	(0.38)	(0.26)
Share to existing smelter partners	0.03	0.43
	(0.46)	(0.39)
Share to new smelter partners	0.40	0.88**
	(0.24)	(0.38)
Log output	-0.17	0.80
	(0.32)	(0.77)
Spot share of displaced volume	0.64	-0.63
Disruptions	8	3
Exposed mine-events	62	32

Notes: Each cell is a separate regression, equation (1), with event-by-mine and event-by-year fixed effects. Exposure is the mine's share of output sold to the disrupted smelter in the third and second years before the event. Shares are of total output. Column 1 uses the eight temporary disruptions and drops exposed mines that share a majority owner with the disrupted smelter. Column 2 uses the three permanent closures. Both columns keep all unexposed mines as controls. Existing smelter partners are the smelters the mine sold to between the start of the window and the year before the event, other than the disrupted smelter. New smelter partners are defined as all other smelters. The spot share of displaced volume is the coefficient on the spot share divided by the fall in the share to the disrupted smelter. Standard errors clustered by mine. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

3.5 What these imply for the empirical model, and why a model

Our goal is to quantify the tradeoff between exercising market power versus geoeconomic power. The motivating evidence cannot answer this question, primarily because it requires us to compute a longer-run equilibrium without Chinese coordination, which we do not observe in the data. However, the motivating evidence does point to several key elements an empirical model requires.

The first (China's cost advantage but excess capacity) and second (Chinese smelters coordinate on the spot price) observations motivate allowing Chinese smelters to act jointly. They also motivate our counterfactual questions. The third observation—that mines sell to a small but persistent set of smelters—motivates modeling trade on a network of persistent relationships. The fourth

observation (mines that lose a buyer for a year or less do not cut output, but sell more on the spot market) supports treating the spot market as the mine's short-run outside option when a negotiation breaks down.

4 Model

4.1 Economic environment and timing

We model decisions over two time horizons. First, at the annual level t, we model routing of the raw mineral from heterogeneous miners, through heterogeneous smelters, and then to the downstream market for the refined mineral. Modeling the market at the annual level is motivated by the fact that contracts are negotiated annually, and mines appear to operate at close to capacity once operating regardless of the copper price.[12] Second, aggregating over all the periods in our data, we consider long-run exit decisions of smelters to remain "active," comparing model-predicted revenue to long-run costs that we observe in our data.

Let i denote an individual mine and j denote an individual smelter. Within each period t, the timing is:

1. Active miners begin the period with a set of smelter relationships A_{it}. The set A_{it} may also potentially include the spot market as an option.
2. Each miner i determines optimal routing across its relationships $j \in A_{it}$ to refine a fixed level of mine output q_{it}. This determines the routing share s_{ijt} of its total production quantity q_{it} of unrefined mineral that the miner delivers to smelter j. The remaining share s_{i0t} is processed on the spot market.
3. Processing fees f_{ijt} are determined by bilateral Nash bargaining for the contracts. Prices in the spot market are also determined either by the industry cartel's price floor (as in the empirical baseline), or by an alternative mode of conduct (e.g., market clearing through

[12] An alternative would be to model the mine's decision as a dynamic extraction problem, linked through the copper ore grade.

perfect competition). Denote the spot price $f_{0,t}$.

4. Miners produce unrefined copper (copper concentrate), ship it to smelters, and the downstream market for the refined mineral clears using the inverse demand curve $p_t = P(z_t, Q_t)$, where p_t is the refined mineral price, $Q_t = \sum_i q_{it}$, and z_t is a demand shifter.

Note that we normalize all prices and quantities so that one (normalized) unit of unrefined mineral converts into one unit of refined mineral.

4.2 Routing choice

A miner i's output q_{it} is made up of a continuum of units of unrefined copper, each indexed by ω. The miner's payoff to shipping one unit ω of unrefined mineral to smelter j (or the spot market $j = 0$) is:

$$v_{ijt}(\omega) = -f_{ijt} + x_{ij}\beta + \sigma_\epsilon \epsilon_{ijt}(\omega) \qquad \text{[Contract payoff]}$$

$$v_{i0t}(\omega) = -f_{0,t} + \sigma_\epsilon \epsilon_{i0t}(\omega) \qquad \text{[Spot market payoff]}$$

In the above, a miner that ships to a contracted smelter pays f_{ijt} and also receives a route-specific payoff of $x_{ij}\beta$, where x_{ij} is a vector of mine-smelter pair covariates. If the miner ships to the spot market, it sells at the spot market price $f_{0,t}$. The above payoffs only include the costs of mineral processing; the benefits to refining copper are common across all options.[13] Therefore, without loss of generality, we exclude these benefits in the routing equation.

Each choice also contains an i.i.d. logit shock. We assume that these logit shocks $\epsilon_{ijt}(\omega)$ represent costs such as scheduling and logistics of each shipment, and that these are paid at the time when routing is decided. This implies they are sunk when prices are determined. These logit shocks are multiplied by a scale parameter σ_ϵ. The scale parameter captures in a stylized way a miner's preference for diversification across its smelter relationships A_{it}. For example, as $\sigma_\epsilon \to 0$, miners route everything towards their highest-payoff smelter.

[13] We also assume that all unrefined copper eventually gets smelted.

Denote μ_{ijt} as the deterministic part of the miner's payoff i.e., $\mu_{ijt} = -f_{ijt} + x_{ij}\beta$ in the case of a contract and $\mu_{i0t} = -f_{0,t}$ in the case of the spot market. Integrating over the optimal j for each ω given these payoffs results in routing shares of total copper production q_{it}:

$$s_{ijt} = \frac{1}{q_{it}} \int_0^{q_{it}} \mathbf{1}\Big\{ j = \arg\max_{k \in A_{it}} v_{ikt}(\omega) \Big\} \, d\omega = \frac{\exp(\mu_{ijt}/\sigma_\epsilon)}{\sum_{k \in A_{it}} \exp(\mu_{ikt}/\sigma_\epsilon)}, \tag{2}$$

and the quantity that smelter j receives from its contracted output is $\sum_i q_{it} s_{ijt}$.

4.3 Processing fees

We model annual negotiations of processing fees through Nash bargaining. Since the routing choices and shares s_{ijt} are fixed by the time bargaining occurs, we can consider each negotiation separately. Furthermore, the Nash product is multiplied by s_{ijt}, but since this is a fixed constant at the time negotiations take place, we can exclude it from the Nash bargaining problem. Overall, the Nash bargaining problem is:

$$f_{ijt} = \arg\max_f \left[-f + x_{ij}\beta - (-d - f_{0,t}) \right]^\delta \left[a_j p_t + f - c_j \right]^{1-\delta}. \tag{3}$$

Here, the miner's agreement point is $-f + x_{ij}\beta$. The miner's outside option is $-d - f_{0,t}$. That is, if bargaining breaks down, miners route all copper tied to this negotiation to the spot market. We also include an additional disruption parameter d that captures additional costs to routing to the spot market at potentially short notice in the case of disagreement.

The assumption that miners face an outside option in negotiations of the spot market—as opposed to routing to a smelter within the existing relationships or forming a new relationship—is arguably the right one in this setting. Negotiations are typically conducted in parallel annually, and most unrefined mineral is processed under these contracts. Therefore, it is not trivial to simply switch negotiation partners if bargaining breaks down since many smelters have already signed their contracts. Furthermore, our descriptive evidence shows that, when bargaining breaks down, mines do not route more concentrate to their remaining smelters.

We assume that the smelter gains $a_j p_t + f - c_j$ from agreement, where a_j is the smelter's "free metal" share, p_t are the prices for that metal, and c_j is the smelter's other net costs (variable costs of running the smelter minus credits from byproducts). We assume that each smelter's outside option is zero, i.e., they will not be able to fill their capacity with alternative unrefined mineral. This is a reasonable assumption for the empirical baseline equilibrium because the industry is significantly over-capacity, even for low-cost Chinese smelters. To compute counterfactuals, we introduce an alternative algorithm where smelters may be capacity constrained. In this case, smelters have a non-zero outside option where they can replace capacity from a lost contract with unrefined minerals from the spot market.

In terms of the spot market, we use the observed spot price $f_{0,t}$ from the data in the empirical baseline and hence place no assumptions on conduct. We compare this to a simulated perfect competition market clearing in our counterfactuals.

4.4 Long-run decisions

We assume that smelters will exit if they are unprofitable over the sample period. Since there is overcapacity in the empirical baseline, and our counterfactuals typically involve cases where smelter profits decrease, exit is likely the relevant margin for processing firms in this industry. Smelter j's variable profit in year t is:

$$\pi_{jt} = \sum_i q_{it} s_{ijt} \left(a_j p_t + f_{ijt} - c_j \right) + q_{0jt} \left(a_j p_t + f_{0,t} - c_j \right), \tag{4}$$

where q_{0jt} is the spot volume that smelter j processes. Then, smelter j remains active if its average variable profit over the T years of the sample covers the annual fixed cost F_j: $\bar{\pi}_j \equiv \frac{1}{T} \sum_{t=1}^{T} \pi_{jt} \geq F_j$.

4.5 Equilibrium

We define an equilibrium as a set of processing fees f_{ijt}, spot fees $f_{0,t}$, routing shares s_{ijt}, spot volumes q_{0jt}, refined prices p_t, and a set of active smelters, that satisfy:

1. Optimal routing shares s_{ijt} (Equation (2)).
2. Processing fees f_{ijt} determined by Nash bargaining (Equation (3)).
3. The spot fee $f_{0,t}$ is determined by either the empirical fee or a perfect competition allocation algorithm.
4. Downstream prices p_t determined by market clearing.
5. The set of active smelters determined by the condition $\bar{\pi}_j \geq F_j$.

We refer to this equilibrium concept as "Nash-in-Nash with a spot-market threat." Concretely, consider the case when the spot market clears via perfect competition. Here, each mine-smelter pair uses Nash bargaining to determine the fee in their contract, taking the outcomes of other negotiations as given, as in Horn and Wolinsky (1988). The negotiations are linked through the spot market equilibrium price, which enters as the mine's outside option in every negotiation. In turn, the spot market equilibrium price is linked to the contract negotiations through mines' routing decisions, which depend on the negotiated fees and determine both the supply of unrefined mineral to the spot market and residual smelter processing capacity. The concept is also related to the "Nash-in-Nash with threat of replacement" equilibrium concept (Ho and Lee, 2019). In our paper, the threat point is to sell the unrefined mineral on the spot market, whereas in their setting the threat is replacement by an excluded firm.

4.6 The tradeoff between exercising market power versus geoeconomic power

To illustrate the key forces that underpin our later results, consider a simplified version of the framework, where a hegemon (in our setting, China) with a set of mid-stream smelters S_{hegemon} wishes to potentially exert geoeconomic power over a country with a single upstream firm i. Denote by W the objective function of the hegemon, who values both the profits of its own firms, as

well as its geoeconomic power:

$$W = \lambda \underbrace{\Pi_{\text{hegemon}}}_{\text{Hegemon's firms' profits}} + (1-\lambda) \underbrace{\Big(V_i(A_i) - V_i(A_i \backslash S_{\text{hegemon}})\Big)}_{\text{Geoeconomic power } G_i} \quad \text{where} \quad A_i = \{j : \bar{\pi}_j \geq F_j\} \tag{5}$$

Here, λ is the hegemon's preference weight on its own smelters' profits: $\Pi_{\text{hegemon}} = \sum_{j \in S_{\text{hegemon}}} \pi_j$, relative to its ability to exert geoeconomic power. The term $V_i(A)$ is mine i's expected payoff from routing its output across a set of smelters A. We define geoeconomic power as the value of lost welfare to i if the hegemon were to remove all of its mid-stream firms from i's choice set i.e., an embargo on processing through these firms. If there were several upstream firms, then the geoeconomic power term G_i could be summed over i to deliver the hegemon's total geoeconomic power.

Suppose this hegemon faces a choice over two regimes: allow national price coordination within the mid-stream of a supply chain, or, enforce competition policy which would create a competitive spot market. Then, the hegemon will allow price coordination if and only if:

$$\lambda \geq \frac{\Delta G_i}{\Delta G_i + \Delta \Pi_{\text{hegemon}}} \tag{6}$$

The component $\Delta\Pi_{\text{hegemon}}$ is the change in the hegemon's profits comparing price coordination to competitive pricing. The term ΔG_i is the change in geoeconomic power of the hegemon after moving to competitive pricing and can be written as a function of two diversion ratios: $D_{\text{hegemon}\to \textit{exit}}$, which is the share of the hegemon's volume that the exiting smelters — if they were operating — would process if the hegemon was removed, and $D_{\textit{exit}\to\text{hegemon}}$, which is the share of the exiting smelters' volume that the hegemon would process if the exiting smelters were removed:

$$\Delta G_i = -q_i \sigma_\epsilon \log\big(1 - D_{\text{hegemon}\to \textit{exit}}\, D_{\textit{exit}\to\text{hegemon}}\big) \tag{7}$$

Equation 7 illustrates that, in this simplified version, the gain in geoeconomic power comes from

how substitutable the hegemon's smelters are with the exiting smelters. If they are close substitutes (the diversion ratios D are high), the exiting smelters are the mine's main alternative to the hegemon, so ΔG_i is large and the threshold λ for price coordination will be high. On the other hand, if they are not close substitutes (either diversion ratio ≈ 0), then ΔG_i will be small. Not in the above formula, but possible in our later counterfactuals, is that so many smelters may exit that, if the hegemon used an embargo, some unrefined mineral may not find a smelter at all and could therefore be "stranded." This raises the hegemon's geoeconomic power further.

5 Estimation and Identification

Our empirical strategy combines the structural vertical-bargaining framework (Crawford and Yurukoglu, 2012; Grennan, 2013; Gowrisankaran, Nevo and Town, 2015; Ho and Lee, 2017, 2019) with the direct cost-measurement approach used in studies of commodity and energy markets (Borenstein, Bushnell and Wolak, 2002; Asker, Collard-Wexler and De Loecker, 2019). A central advantage of our setting is that we read each processor's variable operating costs, byproduct credits, and fixed operating expenses directly off the facility-level data, rather than inferring marginal and fixed costs from pricing or exit decisions. Because these cost categories directly measure the heterogeneity in the gains from processing, our estimation only needs to recover seven behavioral parameters describing how mines allocate shipments and how those gains are divided.

5.1 Observed and Estimated Primitives

Table 3 distinguishes primitives read directly from the data, calibrations, and estimated parameters. Matching production, cost accounts, and shipment allocations at the facility level preserves differences in operating costs and byproduct revenue across the processors within each mine's network.

Table 3: Overview of Parameters

Name	Parameter	Source
Net variable cost	c_{jt}	Observed in data
Gross variable costs (consumables, power, fuel)		Observed in data
Non-copper benefits (sulfuric-acid credits, gold and silver bonuses)		Observed in data
Fixed operating cost (labor, maintenance, onsite services)	F_j	Observed in data
Free-copper rate	a_j	Calibrated
Route payoff parameters	β	Estimated
Routing shock scale	σ_ϵ	Estimated
Mine bargaining weight	δ	Estimated
Disagreement cost	d	Estimated

Operating costs and byproduct revenues The facility cost accounts provide two decompositions that we read directly off the data. First, they split net variable processing cost into gross variable operating expenses—consumables, power, and fuel—less byproduct benefits from sulfuric acid, energy, gold, and silver. We write this annual input as c_{jt}, corresponding to c_j in Section 4.[14] Second, the accounts separate these variable inputs from labour, maintenance, and onsite services, which we treat as fixed operating costs F_j over the annual bargaining horizon. These two decompositions play distinct roles in the model: variable costs c_{jt} determine the short-run surplus from processing a contract and the competitive spot benchmark, while fixed operating expenses F_j determine whether a smelter covers its costs to remain active in the longer run.

Free copper is recorded separately. We calibrate a_j as the smelter's mean annual free-copper rate during 2015–2023, using bonus-copper revenue, production, and observed copper prices. Its contribution to surplus, $a_j p_t$, then varies with copper prices. Appendix Table D1 reports these rates by processing country, withholding individual facility rates for confidentiality.

5.2 Estimation

We jointly estimate seven parameters: four route-utility coefficients β (on $\log(1 + \text{distance})$ and indicators for a common major owner, a domestic smelter, and a Chinese smelter), the routing

[14] Energy and sulfur credits retain their reported signs; gold and silver bonuses are subtracted. Net variable cost can be negative when byproduct benefits exceed operating expenses, explaining why competitive processing fees can fall below zero.

shock scale σ_ϵ, the mine bargaining weight δ, and the disagreement cost d. Common major ownership requires a named owner holding at least 50% in both assets, with missing ownership coded as zero; Appendix E.2 compares alternative ownership definitions on the same sample.

For each candidate parameter vector, we solve for bilateral contract fees and routing shares at observed mine output, copper prices, and spot processing fees. Solving the Nash bargaining problem in Equation (3) yields the bilateral fee:

$$f_{ijt} = (1-\delta)\big(x_{ij}\beta + f_{0,t} + d\big) + \delta\big(c_{jt} - a_j p_t\big). \tag{8}$$

Intuitively, the negotiated fee is a weighted average of the maximum fee the mine is willing to pay to avoid diverting concentrate to the spot market and the minimum fee the smelter requires to cover its net variable cost after free-copper revenue. Because facility costs, byproduct credits, free-copper revenues, and the spot fee are all measured in dollars, both reservation values enter directly from the data. Given the resulting bilateral fees, mines allocate shipments across their contracted partners and the spot market according to the logit routing rule in Equation (2).

From bilateral fees to the observed average A key data constraint is that contract fees f_{ijt} are not observed at the individual mine–smelter pair level; instead, we observe each mine's annual realization-cost rate, which serves as a proxy for the average processing fee across its contracted deliveries. To match this mine-level observation, we aggregate the model-predicted bilateral fees across the mine's contracted smelters using its predicted conditional contract shipment shares as weights. In 365 of the 1,060 mine-years, the mine ships to a single contracted processor and makes no spot sales, so the observed mine-level fee directly measures that relationship's bilateral fee. When a mine uses multiple processors, the model must simultaneously match the mine's overall average fee and the division of tonnage across partners with different observed costs and byproduct revenues.

The estimation criterion combines two normalized components with equal weight: an output-weighted fractional-share log-likelihood that matches observed bilateral and spot shipment shares,

and the mean squared error between observed and predicted mine-average fees (scaled by the sample standard deviation of observed fees). We report 95% bootstrap percentile confidence intervals from 100 valid, converged draws that resample entire mine histories and reestimate the model. Appendix D provides the formal criterion and bootstrap details.

5.3 Identification

Shipment patterns reveal how mines value different routes, observed mine-level fees anchor the overall level of processing charges, and facility cost accounts measure the cost and byproduct differences that generate bargaining surplus across partners.

Recovering bilateral processing fees Even though processing fees are observed only as mine-year averages rather than by individual contract, combining bilateral shipment shares with facility-level cost data pins down the underlying bilateral fees. First, for the 365 mine-years with a single contracted smelter and no spot sales, the observed mine-average fee equals the bilateral fee directly. Second, when a mine splits its output across multiple smelters, its shipment shares reveal how attractive each partner is: holding route characteristics such as distance and ownership fixed, a smelter receiving a larger share of the mine's concentrate must be charging a lower processing fee. Observed bilateral shipment shares therefore pin down the fee differences across a mine's partners, while the observed mine-year average fee pins down their overall level. Third, Nash bargaining ties each smelter's fee to its own observed operating costs and byproduct credits, so observing which specific smelters a mine uses—together with their facility cost accounts—further disciplines how fees vary across partners within the mine's portfolio.

Routing coefficients β The route-payoff coefficients β are identified from how a mine divides shipments among connected smelters that differ in distance, ownership ties, or location. In network data without cost records, a mine might ship more to a commonly owned or Chinese smelter either because it values that relationship directly or because that smelter has lower operating costs and

offers a lower fee. Our facility-level cost and byproduct data separate these two channels: by observing each smelter's net processing cost and free-copper revenue directly, we account for cost-driven fee advantages and attribute the remaining systematic tilt in shipment shares to the route preferences β.

Bargaining weight δ and routing scale σ_ϵ The mine's bargaining weight δ and the routing scale σ_ϵ are separated by combining how shipment shares and processing fees respond to observed cost and price variation. When a smelter has lower operating costs or higher byproduct and free-copper revenues, there is a larger bilateral surplus to divide. If mines have strong bargaining power (δ is high), smelters pass more of their cost and byproduct advantages through into lower contract fees, and mines shift shipments more strongly toward lower-cost partners. How aggressively a mine reallocates tonnage toward lower-cost smelters within its network reflects the ratio of cost pass-through to routing dispersion (σ_ϵ), which is anchored in dollar terms because costs and byproduct credits are observed in dollars. Data on processing fees then separate the two parameters: the extent to which mine-average fees move with partners' net processing costs versus with the external spot fee directly reveals how bargaining power δ splits the surplus between mines and smelters, leaving σ_ϵ to explain the remaining dispersion in shipment shares.

Disagreement cost d The disagreement cost d is identified jointly from the level of negotiated contract fees relative to the spot fee and from how mines split output between long-term contracts and the spot market. A higher cost of scrambling to place concentrate on the spot market upon disagreement weakens the mine's bargaining position, pushing negotiated contract fees above the prevailing spot fee, while simultaneously making contracted delivery more attractive relative to planned spot sales. Because smelter operating costs and byproduct credits are measured directly in the data rather than absorbed into an unobserved cost intercept, the fee premium that mines pay relative to the spot benchmark isolates the disagreement friction d.

Maintained assumptions Identification treats mine production, processor cost accounts, and the set of active contract relationships as predetermined within each year. Treating the network as fixed in the short run reflects annual parallel contracting: in our descriptive evidence, temporary smelter disruptions lead mines to divert volume to the spot market rather than to other existing partners, supporting the spot market as the relevant short-run disagreement outlet. Longer-run survival additionally depends on whether variable profits cover measured fixed operating expenses; we do not model relationship formation.

6 Results and Model Fit

Table 4 reports the parameter estimates for the baseline specification, which includes the common-major-owner indicator. These seven parameters describe routing and surplus division across facilities whose operating costs, byproduct benefits, and free-copper rates are measured separately (Table 3). The sample contains 1,060 mine-years during 2015–2023, covering 148 mines and 65 smelters. Appendix E compares the baseline with specifications that omit the ownership indicator or use an indicator for any common owner on the same sample.

Table 4: Parameter Estimates

Parameter	Estimate	95% bootstrap CI
$\log(1 + \text{distance})$	-65.22	[-142.41, -3.90]
Common major owner	79.17	[-87.65, 389.62]
Domestic smelter	-75.67	[-323.11, 277.71]
Chinese smelter	26.91	[-99.01, 144.37]
Routing shock scale, σ_ϵ	1,259.94	[198.55, 3,436.60]
Mine bargaining weight, δ	0.269	[0.085, 0.636]
Disagreement cost, d	939.03	[356.51, 2,257.75]

Notes: Brackets report 95% percentile confidence intervals that are bootstrapped on 100 draws.

Bargaining and the spot-market threat The estimated mine bargaining weight is $\delta = 0.269$, which assigns 26.9% of the incremental gain from agreement to mines and 73.1% to smelters. This weight describes the division of the gain relative to disagreement payoffs. A mine can sell on the

spot market if negotiations fail, whereas a smelter's gain from agreement is the additional payoff from the bilateral contract when operating below capacity.

The estimated disagreement cost is \$939 per tonne. This parameter measures the additional loss from moving contracted concentrate to the spot market when a negotiation fails, relative to a planned spot sale. It captures short-notice logistical and commercial costs. This loss weakens the mine's threat point and raises the bilateral contracted fee by $(1-\delta)d$, about \$687 per tonne, holding routing utility and processing costs fixed.

Routing payoffs and diversification The distance coefficient is negative: a $1,000$ km increase in geographic distance, from $10,000$ to $11,000$ km, reduces the routing payoff by \$6.22 per tonne, holding the processing fee and other route characteristics fixed. The common-major-owner coefficient is positive, at \$79.17 per tonne. The Chinese-smelter coefficient is \$26.91 and the domestic coefficient is $-\$75.67$, conditional on processing fees, observed costs, smelter-specific free-copper revenue, distance, and ownership. These are conditional comparisons within observed relationships. The domestic coefficient does not imply that mines generally prefer foreign processors, because domestic routes are also closer and the model conditions on the existing relationship network. The estimated routing shock scale is \$1,260 per tonne.

Model fit The correlation between observed and fitted shipment shares, including spot, is 0.864. Mean processing fees are \$500.82 per tonne in the data and \$500.68 in the model. The correlation between observed and fitted annual mean fees is 0.861, while the correlation across mine-years is 0.374. The model therefore captures the mean level and broad annual movements in processing fees more closely than their variation across mine-years. Appendix Table E1 reports fit statistics, and Appendix Figure E1 shows annual fitted routing shares and processing fees.

7 Counterfactuals

7.1 Eliminating Chinese coordination

Short-run effects and implied rest-of-world subsidies We begin by analyzing the effects of Chinese coordination in the short-run i.e., holding existing smelter-miner relationships A_{it} fixed, and assuming all smelters remain open. To do so we move from the empirical spot price (which is potentially elevated due to the price floor), to a price that is determined by a competitive spot market counterfactual. We present the results in the "Short run" column of Table 5.

The initial effect is to dramatically reduce the spot price from \$94.5 on average across the sample period, to $-$\$89.2. Since the spot price enters into the outside option of the contracts, this also causes contract prices to fall. Recall that negative fees (the smelter pays the miner to process the copper) are possible, because the smelting process also releases valuable byproducts that the smelter can sell. Indeed, our predicted short-run competitive fee is close to the empirical fee in 2025, after the CSPT lost control of the market. As a result of the changes in prices, we find that China's share of total processing increases. This is primarily through increased spot market processing, which fills Chinese smelters that are under-utilized in the baseline.

These price increases and trade diversion to non-Chinese smelters are the "umbrella effects" of Chinese coordination. In aggregate, these effects are very large. For example, we find that without Chinese coordination, 76.3% of the rest of world smelters would be unprofitable in the short run, due to their relatively high costs. Another way of benchmarking the magnitude of the umbrella effect is as an implied subsidy: how much would the rest of world have to subsidize its smelters to make them as profitable as they are moving from competition to Chinese coordination? We find these implied subsidies are around \$31.4 billion in total over the sample period. This is an order of magnitude higher than the "Historic Investments" in the Inflation Reduction Act which has allocated to date \$2.3 billion across *all* critical mineral supply chains.

Long-run market structure We begin from the short run equilibrium, which holds relationships A_{it} fixed. In that equilibrium, a large number of smelters outside China are unprofitable. In the longer-run this will lead to some smelters exiting. It will also result in the reallocation of unrefined mineral to existing smelters, raising their profitability and dampening further exit.

We simulate this long-run equilibrium iteratively using what we call an "efficient exit" algorithm. We start with the most unprofitable smelter in the data and allow it to exit from the market. We then reallocate its miner relationships starting from the lowest net-cost smelter with remaining capacity. We also reallocate any spot market mineral that smelter processed to the spot market. Given this new set of relationships, we recompute the short-run equilibrium for every year in our data. If there are still smelters that are unprofitable, we continue the algorithm, removing the next most unprofitable smelter.

Our "efficient exit" algorithm is likely a good approximation for how the industry consolidation process would work in reality. For example, since 2024 when coordination broke down in the spot market and prices collapsed, smelters such as PASAR in the Phillipines have shut down, with the stated reason the collapse in processing fees. Our algorithm identifies PASAR as one of the first smelters to close. Furthermore, our algorithm preserves existing relationships at smelters that do not close, consistent with Observation 1.

In total, we find that 32.0% of rest of world processing capacity would close outside China. China would be relatively unaffected. Smelter exit raises the spot price to $-$\$43.2 in the long-run, which causes contracted fees to also rise. Since most smelters exit outside China, long-run consolidation causes further increases in supply chain concentration as more raw mineral is diverted to Chinese smelters. From an efficiency perspective, smelter consolidation reduces misallocation by 24.0%, measured in terms of the reduction in smelters' total costs. The reduction in misallocation is primarily driven by eliminating fixed costs of low-utilization smelters outside China.

Table 5: Short-run and long-run outcomes after eliminating Chinese coordination

	Baseline	Short run	Long run with plant exit
Processing fees ($/tonne)			
Spot	94.5	−89.2	−43.2
Contracts, China	110.2	−19.3	11.5
Contracts, rest of world	130.2	0.6	30.5
China share of processing	39.7%	41.2%	45.2%
Loss-making smelters			
China	0%	6.5%	0%
Rest of world	5.5%	76.3%	0%
Capacity closed			
China	–	–	0.6%
Rest of world	–	–	32.0%
Change in smelter finances ($bn)			
China			
Revenue	–	−23.9	−16.6
Costs	–	−1.2	−2.6
Profits	–	−22.7	−14.0
Rest of world			
Revenue	–	−33.1	−26.6
Costs	–	−1.6	−10.0
Profits	–	−31.4	−16.7
Change in miner profit ($bn)	–	+57.0	+43.2
Misallocation	–	−0.9%	−24.0%

7.2 Implications for China's exercise of geoeconomic power

We next simulate scenarios where China exercises geoeconomic power, and compute the consequences for the supply chain under different market structures. We present the results in Table 6. We first split the world into two blocs, one with China and China-aligned countries (like Russia), and one with US-aligned countries that includes the US, Europe, Japan, and South America. We assume that miners can only process their raw minerals at smelters within their bloc. This exercise mirrors groupings used by policymakers who study geoeconomic fragmentation.

In the baseline the US-aligned bloc would face a moderate geoeconomic cost. In total the cost

would be $2.85 billion per year and 10.9% of miners' output would be stranded. However, the embargo would also be costly for China at $2.91 billion per year. Note that in the exercise we hold the smelter spot price floor fixed. It is possible that the embargo could also affect the CSPT's ability to hold its firms to the price floor. In this case, the effects of this scenario would be bounded by the competitive short-run scenario, in the second column.

In the long-run market structure, where the supply chain has consolidated, China's embargo has significantly worse consequences for the US-aligned bloc. The US-aligned bloc would lose $17.01 billion per year, and $153.1 billion over the sample period. Almost half (46.9%) of the US-aligned bloc's output would not be processed and therefore stranded. China, on the other hand, would face an order of magnitude lower costs, and thus have significant geoeconomic leverage.

We also measure China's geoeconomic leverage over specific countries, using Chile as an example, which is the largest copper mining country in the world. In the baseline and short-run, where processing capacity is held fixed, China does have some geoeconomic leverage over Chile. Specifically, an embargo would force Chilean miners to process their raw mineral at high-cost smelters outside of China, which command higher processing fees. However, Chile's geoeconomic position would be much more fragile without long-run Chinese spot market coordination. Here, a Chinese embargo would cost Chile $5.89 billion on average per year, and 31.7% of its mine output would be stranded.

Overall, these scenarios showcase the key tension of Chinese concentration in the mid-stream of a supply chain. Although price coordination increases the profits of domestic Chinese firms, it undermines China's long-run geoeconomic power.

Table 6: Trade restrictions between a US-aligned bloc and China's bloc

	Baseline	Short run	Long run with plant exit
Full split			
US-aligned bloc's loss ($bn per year)			
Miners	4.15	8.04	17.53
Smelters	−1.30	−2.64	−0.52
Total	2.85	5.40	17.01
US-aligned mine output stranded	10.9%	11.8%	46.9%
China's bloc's loss ($bn per year)			
Miners	0.14	−0.16	−0.57
Smelters	2.77	0.98	2.25
Total	2.91	0.82	1.68
Embargo on Chile			
Chile's loss ($bn per year)	0.16	0.90	5.89
Chile's mine output stranded	0%	0%	31.7%
China's bloc's loss ($bn per year)	1.37	0.43	1.07

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APPENDICES

A Additional descriptive results

A.1 Relationships

To study which relationships form, we pair every mine with every smelter that buys from at least one sample mine in the same year. This gives 56,849 mine–smelter–year pairs, of which 6.0% trade. We estimate linear probability models of the form

$$100 \cdot \mathbf{1}\{q_{ijt} > 0\} = \beta' X_{ijt} + \rho_1 \mathbf{1}\{q_{ij,t-1} > 0\} + \rho_2 \mathbf{1}\{q_{ij,t-2} > 0\} + \alpha_{it} + \gamma_{jt} + \varepsilon_{ijt}, \quad (9)$$

where X_{ijt} contains an indicator for a Chinese smelter, log great-circle distance, an indicator for a smelter in the mine's own country, and log smelter capacity. In some specifications, we include mine-by-year effects, α_{it}, to absorb the mine's output, its number of partners, and market conditions, so the coefficients describe which smelters a given mine chooses among. In some specifications, we also include smelter-by-year effects, γ_{jt}, to absorb the smelter's capacity and costs.

Table A1 reports the estimates. Larger smelters have more partners: a 10% increase in capacity raises the probability of a relationship by about 0.3 percentage points. Distance lowers the probability of a relationship in every specification. Conditional on distance, the same-country indicator is positive but imprecise, and on average Chinese smelters are no more likely to be partners. Past trade explains far more: adding last year's status raises the within R^2 from 0.05 to 0.58 (column 3), and activity one year, two years, and further back all survive mine-year and smelter-year fixed effects (column 4). New relationships are also fragile: 46% of relationships begun within the sample end after one year, compared with 18% of those that have lasted four years or more.

The average Chinese-smelter coefficient hides variation across mine countries. With mine-by-year effects, a Chinese smelter is 15 percentage points more likely to be a partner of a mine in Peru,

and the premium is -6 percentage points for a mine in Australia (Figure A1). Mines in Kazakhstan, Chile, and Mexico also lean toward Chinese buyers. Mines in Brazil, Canada, Sweden, and the United States lean away from them; many of these mines sell to domestic smelters or have long-standing offtake agreements with smelters in Europe, Japan, and Korea. Across the remaining smaller producing countries, pooled, there is no premium on average (-2.0 percentage points, s.e. 1.9).

Table A1: Which mine–smelter relationships are active

	(1)	(2)	(3)	(4)
Chinese smelter	-0.60	-0.57	-0.08	
	(0.80)	(0.80)	(0.24)	
Log distance	-3.65***	-3.76***	-1.07***	-0.67***
	(0.68)	(0.69)	(0.19)	(0.17)
Same country	3.49	3.16	0.49	0.93*
	(2.44)	(2.47)	(0.68)	(0.55)
Log smelter capacity	3.05***	3.05***	0.81***	
	(0.40)	(0.40)	(0.13)	
Log mine shipments	2.48***			
	(0.46)			
Active in $t-1$			74.34***	49.08***
			(1.56)	(1.79)
Active in $t-2$				23.18***
				(1.91)
Active in any year $\leq t-2$				9.79***
				(1.35)
Year FE	Yes	No	No	No
Mine-country FE	Yes	No	No	No
Mine-year FE	No	Yes	Yes	Yes
Smelter-year FE	No	No	No	Yes
Mean of dep. var.	6.0	6.0	6.1	6.2
Observations	56,849	56,849	46,212	37,164
Mine clusters	145	145	137	127
Within R^2	0.056	0.045	0.576	0.619

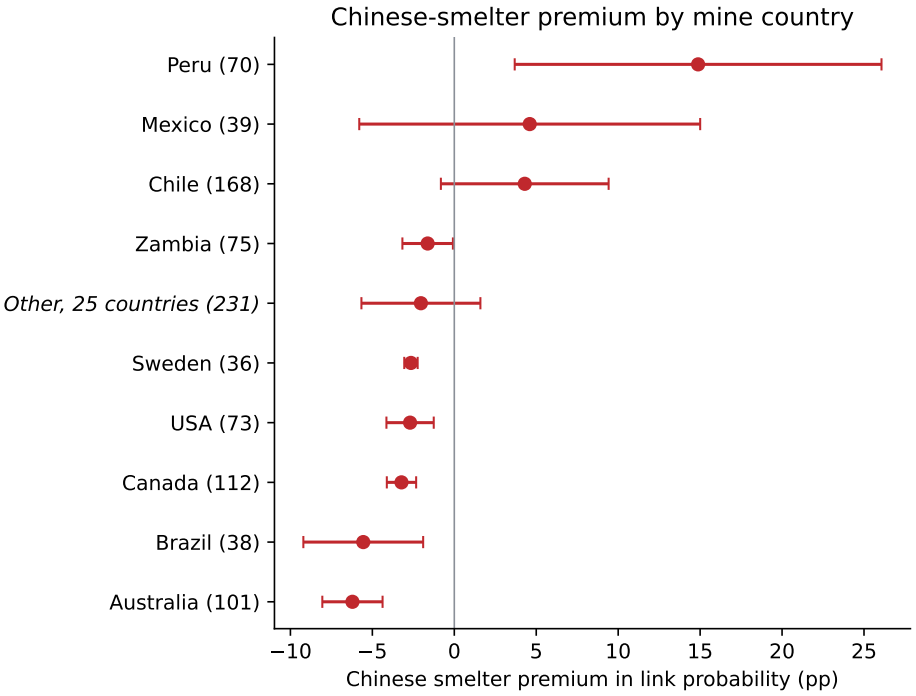
Notes: Linear probability models, equation (9). The dependent variable is 100 times an indicator for positive shipments from mine i to smelter j in year t. The sample pairs every mine with every smelter that buys from at least one sample mine in year t. Distance is great-circle distance in kilometers. Columns with lags drop pairs not observed in the lagged years. We do not report a specification with mine-by-smelter fixed effects: with about nine years per pair, such effects bias the coefficients on lagged status toward zero. Standard errors clustered by mine. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A2: Persistence of mine–smelter relationships

	Probability link is active in t			
	Active in $t-1$	Inactive in $t-1$, active earlier	Never active before	Unconditional
All smelters	0.783	0.183	0.008	0.061
Chinese smelters	0.799	0.141	0.008	0.058
Other smelters	0.776	0.200	0.008	0.063
Pair-years, active in $t-1$	2,852			
Pair-years, inactive in $t-1$	43,360			

Notes: Share of mine–smelter pairs with positive shipments in year t, by status in earlier years. Pairs enter if both mine and smelter are in the sample in t and $t-1$. "Active earlier" means active in some year $\leq t-2$ within the sample.

Figure A1: Chinese-smelter premium in the probability of an active relationship, by mine country



Notes: Coefficients on a Chinese-smelter indicator interacted with mine-country indicators, from a linear probability model with mine-year fixed effects and controls for log distance, same country, and log smelter capacity. Each coefficient compares Chinese and non-Chinese smelters as partners of mines in that country. Countries with at least 20 mine-years are shown separately, and the remaining countries are pooled; the number of mine-years is in parentheses. Chinese mines are excluded because for them a Chinese smelter is always a domestic smelter. 95% confidence intervals clustered by mine.

A.2 CSPT guidance for spot treatment charges

Table A3: CSPT quarterly guidance for spot treatment charges

Quarter	Guidance TC ($/dmt)	Spot TC near announcement ($/dmt)	Source
2016Q1	100	100	Kupfermail
2016Q2	85	–	Kupfermail
2016Q3	103	–	Kupfermail
2016Q4	105	102	Kupfermail
2017Q2	80	–	Kupfermail
2017Q3	86	–	SMM
2017Q4	95	–	Kupfermail
2018Q1	87	–	Fastmarkets
2018Q2	78	66	Fastmarkets
2018Q3	none issued	77	Fastmarkets
2018Q4	disputed	88	SMM
2019Q1	92	92	Reuters (Mining.com)
2019Q2	73	–	Fastmarkets
2019Q3	55	52.5	Fastmarkets
2019Q4	66	60	Kupfermail
2020Q1	67	57.26	SMM
2020Q2	none issued	–	Reuters (Mining.com)
2020Q3	53	51.71	SMM
2020Q4	58	48.56	SMM
2021Q1	53	–	SMM
2021Q2	none issued	33.5	Reuters (Mining.com)
2021Q3	55	38.5	Reuters (Mining.com)
2021Q4	70	65.29	SMM
2022Q1	70	61.4	Reuters (Mining.com)
2022Q2	80	84.5	Reuters (Mining.com)
2022Q3	80	73	S&P Platts
2022Q4	93	85.1	Reuters (Mining.com)
2023Q1	93	84.5	Reuters (Business Recorder)
2023Q2	90	80.1	Mysteel
2023Q3	95	90.7	Mysteel
2023Q4	95	92.4	Mysteel
2024Q1	80	56.8	S&P Platts
2024Q1 (Jan.)	50 (revised)	27.94	Reuters (Kitco)
2024Q2	none issued	11.2	Reuters (Mining.com)
2024Q3	30	3.24	SMM
2024Q4	35	-0.8	Reuters (Kitco)
2025Q1	25	6.91	SMM
2025Q2	none issued	-24.14	Press report
2025Q3	none issued	-43.79	SMM
2025Q4	none issued	-41.3	Reuters (Energy News)

Notes: Guidance set by the China Smelters Purchase Team for its members' spot purchases of copper concentrate in the quarter, nominal dollars per dry metric tonne; the refining charge is one tenth of the treatment charge in cents per pound. "None issued" marks quarters in which the group met but did not set guidance. For 2018Q4, reports conflict on whether guidance of $90 was set. The 2024Q1 guidance of $80 was revised to $50 in January 2024. The spot charge is the assessment reported in the same or a contemporaneous article; publishers' indices differ. Quarters before 2016 and 2017Q1 are missing because we found no report. Compiled from press reports by the outlets listed.

Table A4: Smelter cost and capacity utilization

	All years	Top quarter of utilization (89%+)
	(1)	(2)
Utilization (10 percentage points)	−16.1***	−18.7***
	(5.9)	(6.0)
Smelter and year FE	Yes	Yes
Smelter-years	548	125
Smelters	72	29

Notes: Each column regresses a smelter's cost per tonne of raw mineral on its utilization, with smelter and year fixed effects. The coefficient is the change in cost for a 10 percentage point increase in utilization. Both columns keep smelters observed in at least two years of the data. Column 2 keeps smelter-years in the top quartile of utilization (89% of capacity or more), for smelters with at least two such years. Standard errors clustered by smelter. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

B Misallocation

This appendix measures the cost of the observed allocation of concentrate across smelters. We follow Asker, Collard-Wexler and De Loecker (2019), who measure misallocation in global oil extraction as the gap between what it costs to produce the observed output and the cost if the same output came from the lowest-cost producers. Transport costs matter more in our setting, so we measure misallocation route by route and include them.

Measuring misallocation. In each year, we observe the tonnes of copper in concentrate that mine i ships to smelter j, x^0_{ijt}, smelter j's cost per tonne, c_{jt}, and the cost per tonne of shipping concentrate from mine i to smelter j, τ_{ij}. The cost-minimizing allocation holds each mine's total shipments fixed and solves

$$C^*_t = \min_{\{x_{ijt}\geq 0\}} \sum_{i,j} (c_{jt} + \tau_{ij})\, x_{ijt} \quad \text{subject to} \quad \sum_j x_{ijt} = \sum_j x^0_{ijt} \;\; \forall i, \qquad \sum_i x_{ijt} \leq A_{jt} \;\; \forall j. \tag{10}$$

Misallocation is the difference between the cost of the observed allocation and this minimum, $M_t = \sum_{i,j}(c_{jt} + \tau_{ij})x^0_{ijt} - C^*_t$. We solve the problem by linear programming.

We take transport costs from the structural model. The routing model's coefficient on log distance implies that a mine values a route at \$63.5 less per tonne of copper for each log point of distance, so the transport cost of route ij is $\tau_{ij} = 63.5 \times \log(1 + \text{distance}_{ij})$.[15] Capacity is 88% of the smelter's nameplate capacity to smelt concentrate, the industry benchmark used in Observation 1, or its output that year if higher. Concentrate that a smelter takes from the spot market and from traders, whose source we do not observe, is held at its observed level, and A_{jt} is the capacity that remains.

Our main cost measure is Wood Mackenzie's net cash cost: consumables, power, fuel, labor, maintenance, and onsite services, net of credits for sulfuric acid and energy. The merit-order figures additionally subtract free copper, gold, and silver retained by smelters; the misallocation calculations use net cash cost before these free-metal receipts. Net cash cost includes some costs that are likely fixed in the short run, so as a robustness check we also use variable cost, which drops labor, maintenance, and onsite services.[16] The observed allocation covers shipments to the 73 smelters in Wood Mackenzie's cost database, about 10.9 million tonnes of copper a year. It excludes concentrate sold on the spot market or to traders, whose destination is not identified, and concentrate sent to smelters outside the cost database, mainly in Russia, Kazakhstan, Iran, and the Democratic Republic of Congo.

How large is misallocation? We report the totals for 2015–2023 in Table B1. Smelters spent \$23.6 billion on cash costs to smelt this concentrate. Reassigning it to the cheapest available smelters would have lowered smelting costs by \$7.2 billion. Because some of the concentrate would travel further, transport costs would rise by \$1.0 billion, so the net saving is \$6.2 billion,

[15] This is the coefficient in the main specification of the routing model. We use only the distance term, not the model's indicators for a domestic route or a Chinese smelter, which we take to measure preferences rather than costs. Distance is the country-pair distance used in estimation. For mine and smelter countries that never trade in the estimation sample, we predict it from the great-circle distance between mine and smelter, using the relation between the two among observed routes. Because this transport cost is identified only up to a constant per tonne, we report misallocation relative to smelting cost rather than to smelting plus transport cost.

[16] Wood Mackenzie's per-tonne cost fields divide each smelter's costs by its total anode production. In 23 smelter-years between 2015 and 2023, the copper from flux ore included in that figure is a thousand times too large, which pushes production above capacity by as much as a factor of 111 and makes the per-tonne cost far too low. We recompute per-tonne costs from the dollar totals after dividing copper from flux ore by 1,000 in those smelter-years. A smelter that is idle in a year is assigned its average cost in the years it operated.

26% of smelting costs or $63 per tonne of copper. The cost-minimizing allocation would raise China's share of this concentrate from 31% to 36%. It takes output away mainly from KGHM's two Glogow smelters, Chuquicamata, Horne, Garfield, Caletones, and Potrerillos, all of which are captive, and from Onahama in Japan and Pasar in the Philippines. The concentrate goes mainly to Mufulira and Nchanga in Zambia and to Chinese smelters such as Dongying, Jinchuan, Tongling's Jinguan smelter, and Chifeng Jinjian. Misallocation fell over the sample, from $80 per tonne in 2015 to $52 per tonne in 2023, as Chinese smelters ran closer to capacity (Figure B1).

Where the misallocation is. We split misallocation into three parts, computed in sequence. Allowing concentrate to move only among smelters outside China, holding fixed how much each mine sends to China, saves $5.1 billion, 83% of the total: cheap capacity outside China, mainly in Zambia, Germany, and India, could replace much of the output of expensive smelters outside China. Allowing concentrate to move only among Chinese smelters saves $0.47 billion, 8% of the total, since Chinese smelters have similar costs. Allowing concentrate to move between the two groups, once each is efficient on its own, saves the remaining $0.61 billion, 10%. This last part is small because of the order of the steps: by the time concentrate may move to China, cheap capacity outside China has already replaced the most expensive smelters outside China.

The "idle Chinese capacity" counterfactual reverses the order. It starts from the observed allocation and allows only one change: mines can send concentrate to idle Chinese capacity in place of the most expensive smelters elsewhere, so shipments to Chinese smelters can only rise and shipments to other smelters can only fall. Mines would then send an average of 663 thousand tonnes of copper a year to Chinese smelters, mainly to Dongying, Jinchuan, Tongling's Jinguan smelter, Baiyin, and Chifeng Jinjian, and mostly away from Chuquicamata, Horne, Potrerillos, Onahama, and Tsumeb. Costs would have been $2.9 billion lower, 47% of total misallocation. The two orders therefore credit idle Chinese capacity with between 10% and 47% of misallocation. Unlike total misallocation, the idle Chinese capacity counterfactual does not trend down: it ranges from $16 to $41 per tonne of copper and moves with the amount of idle capacity in China, which

was largest in 2019 and smallest in 2023.

Vertical integration. The high-cost smelters outside China are mostly captive, taking at least a quarter of their concentrate from mines with the same majority owner. There are 33 such smelters, and they produce 42% of the copper smelted, but 78% of the output that the cost-minimizing allocation moves away from smelters is at captive smelters. Weighting by output, captive smelters outside China had a net cash cost of $352 per tonne, against $224 at independent smelters outside China and $108 in China; most of the gap is in labor, maintenance, and onsite services (Figure B2). Rerouting only the shipments between co-owned mines and smelters, 35% of the volume, would have saved $4.1 billion, 65% of total misallocation, and about 33% of the concentrate that moves would go to Chinese smelters. Holding co-owned shipments fixed instead reduces misallocation to $4.1 billion, 65% of the baseline.

The idle Chinese capacity and integration counterfactuals overlap and should not be added: 75% of the output that idle Chinese capacity displaces comes from captive smelters. Both largely describe the same reallocation, from captive smelters outside China to idle capacity in China, and the accounting cannot tell us whether coordination among Chinese smelters or integration outside China keeps this output where it is. Holding co-owned shipments fixed, the idle Chinese capacity counterfactual still saves $2.0 billion, because idle Chinese capacity can also displace output at high-cost smelters that are not captive and concentrate that captive smelters buy from independent mines.

Robustness. The results are similar for the mines in our estimation sample, which ship about 9.2 million tonnes of copper a year to smelters in the cost database: misallocation is $4.9 billion, 26% of smelting costs, and the idle Chinese capacity counterfactual accounts for 50% of it. With variable cost alone, misallocation is $4.5 billion, but the idle Chinese capacity counterfactual is much smaller, $0.7 billion or 15% of the total, while the integration counterfactual is $2.2 billion, 48%. This is because the cost advantage of Chinese smelters is mostly in labor, maintenance, and onsite services. Variable costs are small once acid credits are subtracted, and negative in total in

2021 and 2022 when acid prices were high, so misallocation is large relative to actual variable costs in this case. Which estimate is closer depends on how much of their labor, maintenance, and onsite service costs smelters would save by running less, or by closing.

The 88% benchmark may also misstate the capacity smelters can use. The median Chinese smelter reached 0.98 of nameplate capacity in its best year over 2015–2024, and 79% of Chinese smelters reached 88% at some point; outside China, the median smelter reached 0.86, and only 47% reached 88% (Figure B3). The benchmark therefore likely understates the capacity Chinese smelters can use and overstates it elsewhere. With capacity set to each smelter's highest observed utilization, or the larger of that and 88%, misallocation ranges from $5.9 billion to $7.8 billion, and the idle Chinese capacity counterfactual from 47% to 57% of the total (Table B2).

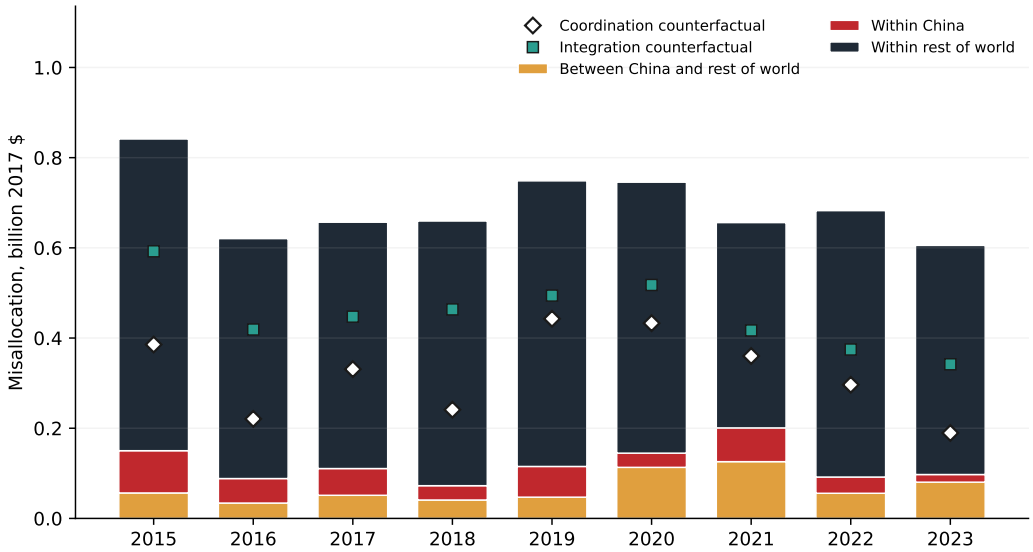
Caveats. The exercise holds each mine's output fixed and reallocates only the concentrate that is smelted, so it does not measure the effect of coordination on the charges mines pay, which could change mine output. Our cost measure is an average cost: for a smelter running well below capacity, the cost of an extra tonne is likely lower than its average cost, because labor, maintenance, and onsite services likely do not rise one-for-one with output. The variable-cost results bound this concern. Smelters also differ in the concentrates they can treat and in how much copper and precious metal they recover, which the accounting does not count as costs. Finally, the split treats misallocation within the rest of the world as independent of Chinese conduct. The model in Section 4 suggests otherwise: when Chinese smelters coordinate to raise processing charges, smelters elsewhere earn higher charges too, and high-cost smelters that would otherwise close may stay open. In the long-run counterfactual without coordination in Section 7, 32.0% of smelting capacity outside China closes, so part of the misallocation within the rest of the world may itself be a consequence of coordination.

Table B1: Misallocation in copper smelting, 2015–2023

	Volume	Smelting	Misallocation		Of which			Counterfactual ($bn)		China share (%)	
	(Mt per year)	cost ($bn)	$bn	$ per tonne	Within China	Within rest of world	Between groups	Idle China	Inte-gration	Actual	Cost-minimizing
All shipments, cash cost	10.9	23.6	6.22	63	0.47	5.14	0.61	2.90	4.07	31	36
Variable cost	10.9	3.9	4.52	46	0.39	3.87	0.25	0.67	2.19	31	28
Co-owned shipments held fixed	10.9	23.6	4.06	41	0.44	3.35	0.26	2.03	–	31	33
Estimation-sample mines, cash cost	9.2	18.6	4.89	59	0.42	3.98	0.49	2.43	3.42	28	34

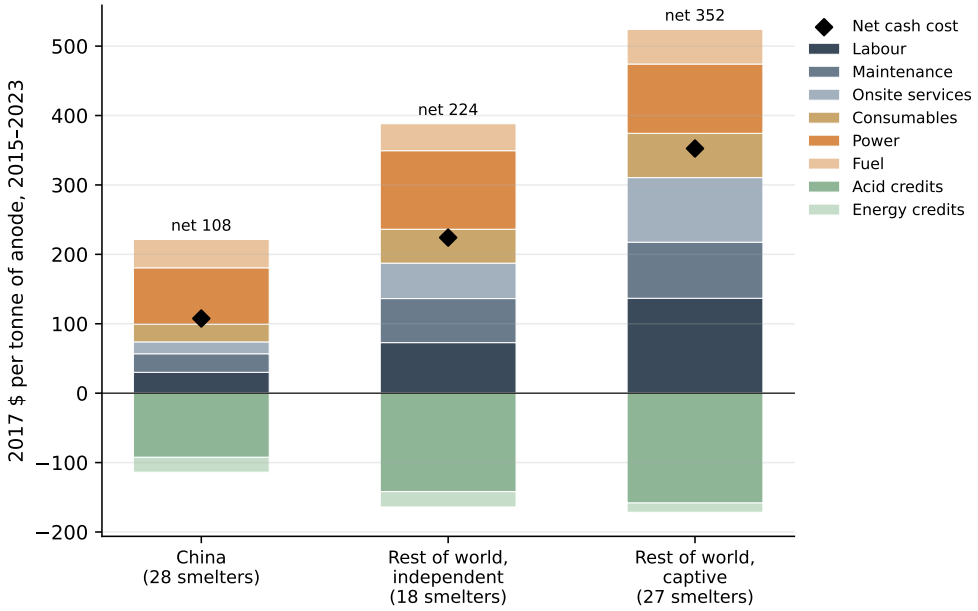
Notes: Billions of 2017 dollars summed over 2015–2023, except volume (million tonnes of copper a year), misallocation per tonne (2017 dollars), and China shares. Misallocation is the cost of the observed allocation of concentrate minus the cost of the cheapest allocation, equation (10), where cost is smelting cost plus a transport cost from the routing model's distance coefficient. Each mine's total shipments are held fixed. Capacity is 88% of nameplate capacity or observed output if higher, after subtracting the concentrate from the spot market and traders. Smelting cost is cash cost excluding transport. Within China and within the rest of the world are the savings from rerouting concentrate among smelters in each group, holding fixed how much each mine sends to the group; between groups is the remainder. The idle Chinese capacity counterfactual lets shipments to Chinese smelters rise, and shipments to other smelters fall, starting from the observed allocation. The integration counterfactual reroutes only shipments between a mine and a smelter with the same majority owner (co-owned shipments). The first panel covers all shipments to smelters in Wood Mackenzie's cost database, and the second covers shipments from mines in the estimation sample. China share is the share of volume smelted in China.

Figure B1: Misallocation by year



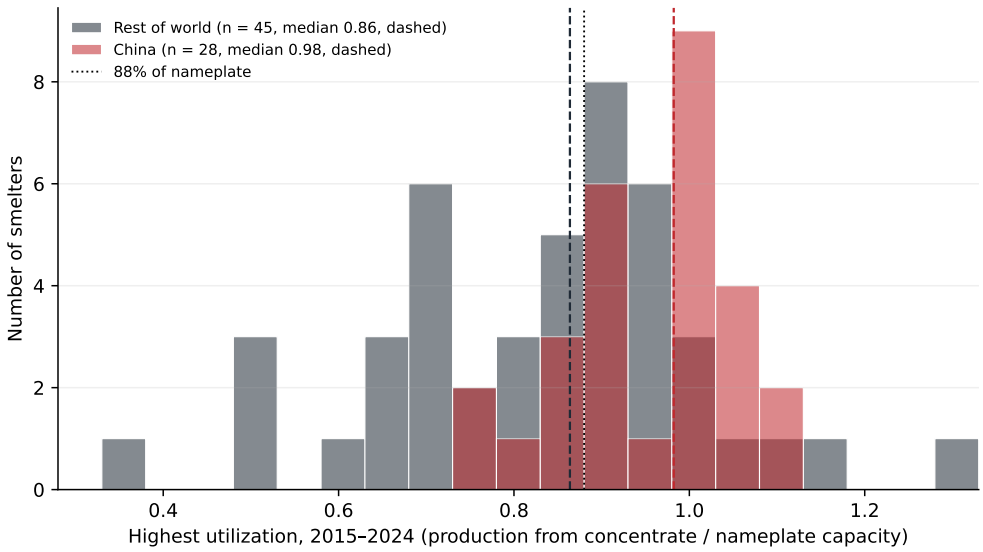
Notes: All shipments to smelters in Wood Mackenzie's cost database. Bars split misallocation into the parts within China, within the rest of the world, and between the two groups. Diamonds mark the idle Chinese capacity counterfactual (labeled "coordination counterfactual" in the figure), and squares the integration counterfactual. Smelting cost plus transport cost, billions of 2017 dollars.

Figure B2: Smelter cash cost by component, 2015–2023



Notes: Chinese smelters, independent smelters outside China, and captive smelters outside China, which took at least 25% of their concentrate from mines with the same majority owner. Components are weighted by anode smelted from concentrate. Acid and energy credits are shown below zero, and diamonds mark net cash cost. 2017 dollars per tonne of anode. Source: Wood Mackenzie smelter cost data.

Figure B3: Highest observed utilization, 2015–2024



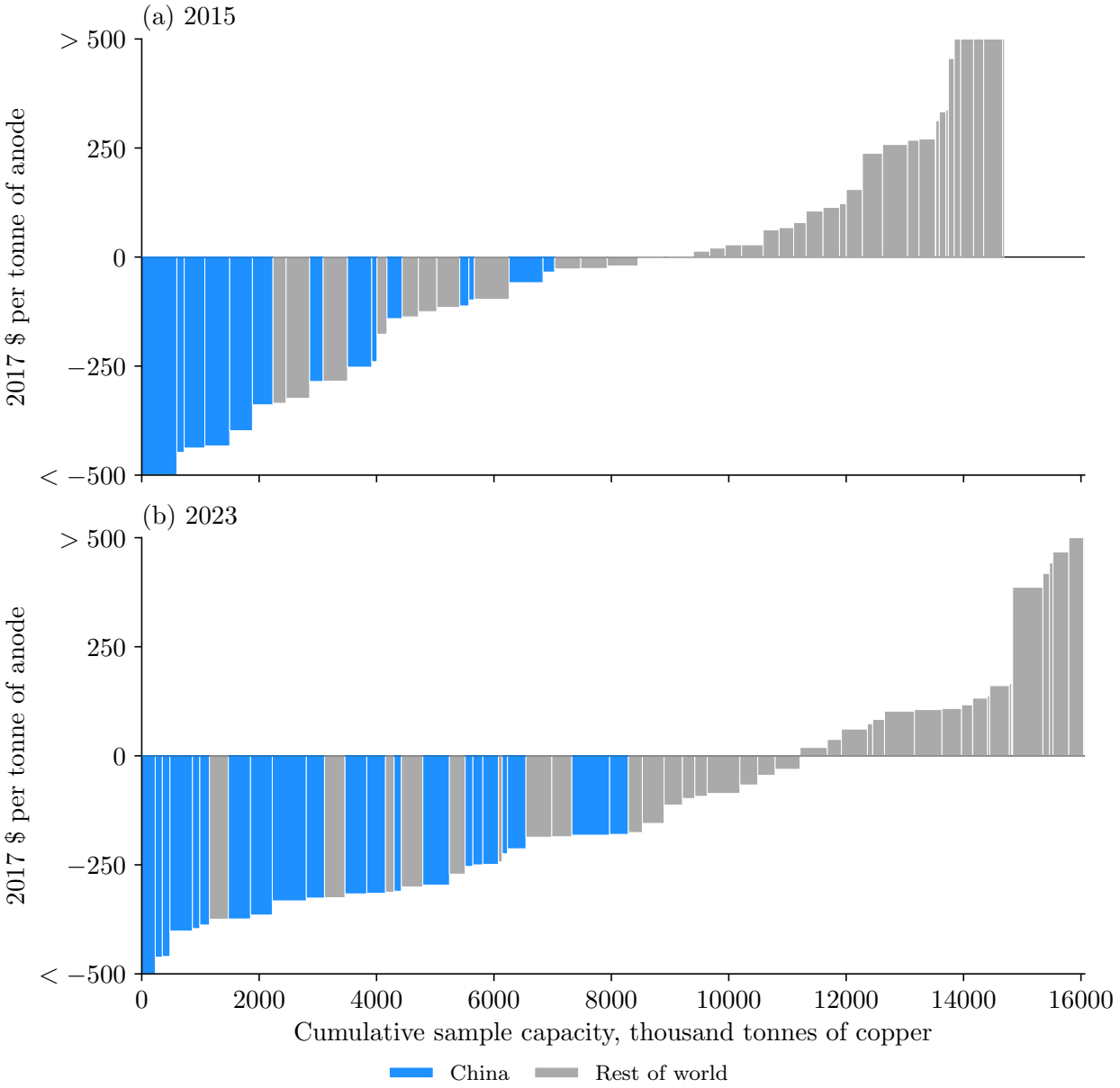
Notes: Each smelter's highest ratio of anode production from concentrate to nameplate capacity to smelt concentrate, China (28 smelters) and the rest of the world (45 smelters). Dashed lines mark medians and the dotted line marks 88% of nameplate capacity, which is a bin edge. Ratios above one likely reflect understated nameplate capacity. Source: Wood Mackenzie smelter data.

Table B2: Misallocation under alternative measures of capacity, 2015–2023

Capacity measure	All shipments, with transport cost ($bn)				Chinese idle capacity (kt per year)	Sample mines with freight ($bn)
	Misallocation (% of smelting cost)	Between groups	Idle China counterfactual	Integration counterfactual		
88% of nameplate (baseline)	6.2 (26)	0.6	2.9 (47)	4.1 (65)	694	4.9
Highest observed utilization, 2015–2024	5.9 (25)	0.9	3.4 (57)	3.7 (63)	888	4.6
Larger of 88% and highest utilization, 2015–2024	6.9 (29)	0.7	3.6 (52)	4.5 (65)	989	5.5
Larger of 88% and highest utilization, 2005–2024	7.8 (33)	0.6	3.7 (48)	5.0 (65)	1,082	6.2

Notes: Billions of 2017 dollars summed over 2015–2023, net cash cost. Percentages in parentheses are shares of actual cost for misallocation and shares of misallocation for the two counterfactuals. Highest observed utilization is each smelter's highest ratio of anode production from concentrate to nameplate capacity over the stated years, applied to nameplate capacity in each year. Smelters without a year of positive production in the window are assigned 88%. In every row, capacity is at least observed output. Chinese idle capacity is the average over years of Chinese capacity minus Chinese output. The last column is route-level misallocation for mines in the estimation sample, with transport costs. See Table B1 for definitions.

Figure B4: Merit order of copper smelting capacity, 2015 and 2023



Notes: Each column is a smelter, ordered by gross cash cost less acid and energy credits and free copper, gold, and silver retained by the smelter, per tonne of anode in 2017 dollars. Treatment charges and downstream margins are excluded. Columns and horizontal zero-line segments: blue for China; gray for the rest of the world. Column width is sample-adjusted capacity from the M18 structural-estimation sample. The figure includes the physical smelter-years represented in that sample in each year. Costs outside $[-500, 500]$ are capped for display and indicated by the endpoint ticks, < -500 and > 500. Source: Wood Mackenzie smelter cost data.

C Data Sources and Coverage

C.1 Data Sources and Sample Construction

We combine three main Wood Mackenzie datasets: annual mine costs and production, annual smelter costs and production, and shipments from mines to smelters. The mine and smelter panels cover 2000-2023 and shipment allocation data cover 2015-2023. Over these periods, the mine panel covers 338 mines in 42 countries, and the smelter panel covers 90 smelters in 26 countries. The allocation data covers 424 named mines and 146 smelters, together with spot sales.

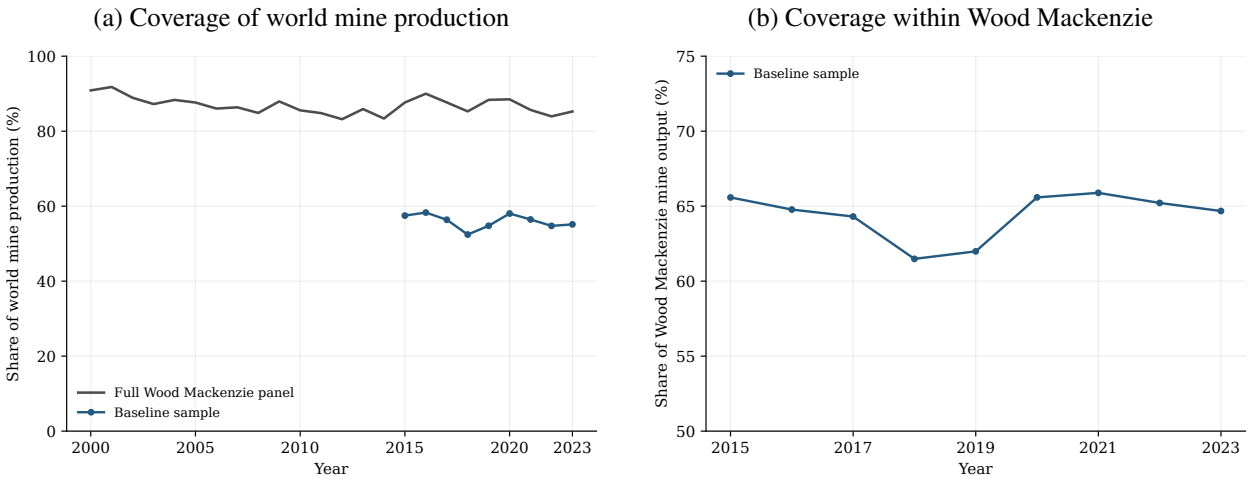
We match the three datasets using asset names and identifiers. We reconcile shipment allocations with reported mine production and express quantities in refined copper. We exclude observations with missing cost information. The estimation sample contains 3,536 shipments from a mine to a smelter and 539 spot sales, covering 1,060 mine-year clusters, 148 mines and 65 smelters during 2015-2023. We link ownership records to this sample and control for a common major owner, defined as a named owner holding at least 49.99% in both the mine and smelter. Missing ownership information is coded as zero. Ownership controls do not impose an additional sample restriction, and the alternative ownership specifications use the same observations.

Table 1 in Section 2.2 reports summary statistics for this estimation sample.

C.2 Data Coverage

Figure C1 compares the Wood Mackenzie mine panel and the estimation sample with world mine production reported by the USGS (U.S. Geological Survey, 2024). The full Wood Mackenzie panel accounts for 86.7% of world mine production over 2000–2023 and 86.8% over 2015–2023. Over the estimation period, the estimation sample covers 55.9% of world production and 64.4% of output in the full Wood Mackenzie mine panel.

Figure C1: World Mine Production and Coverage within Wood Mackenzie



Panel (a) divides reported copper output in the full Wood Mackenzie mine panel and covered output in the estimation sample by USGS world mine production. Panel (b) divides covered sample output by total output in the Wood Mackenzie mine panel. The estimation sample includes physical deliveries and spot allocations and uses the common-major-owner control. The full source-panel series spans 2000-2023; the estimation sample spans 2015-2023.

D Estimation

This appendix describes the free-copper calibration and estimation criterion used in Section 5.2.

D.1 Calibrated Free-Copper Rates

Each annual free-copper rate is bonus-copper revenue divided by the value of refined copper at the annual copper price. We calibrate a_j as the mean over years during 2015-2023. Table D1 summarizes these rates by processing country, weighting each smelter's mean by its anode production over the same usable years. Estimation uses the smelter-specific rates. Table D1 withholds processor identities and individual rates for data confidentiality.

Table D1: Calibrated Free-Copper Rates by Processing Country

Processing country	Mean free-copper rate (%)
Australia	2.034
Brazil	1.868
Bulgaria	0.724
Canada	2.828
Chile	0.996
China	3.161
Finland	1.267
Germany	2.161
India	2.633
Indonesia	2.505
Japan	2.197
Mexico	1.346
Namibia	0.000
Peru	0.915
Philippines	0.000
Poland	1.821
Serbia	2.156
South Africa	0.671
South Korea	2.373
Spain	1.882
Sweden	2.376
United States	1.731
Zambia	1.323

D.2 Estimation Criterion

Let $\vartheta = (\beta, \sigma_\epsilon, \delta, d)$ denote the seven baseline parameters. The vector β contains coefficients on log one plus distance and indicators for a common major owner, a domestic smelter, and a Chinese smelter. The alternative with any common owner also has seven parameters, while the alternative without an ownership indicator has six. For each candidate, we compute fitted routing shares $s_{ijt}(\vartheta)$ and bilateral processing fees $f_{ijt}(\vartheta)$ at observed copper prices and spot processing fees. The model counterpart of the observed mine-average contracted processing fee is

$$\bar{f}_{it}(\vartheta) = \sum_{j \in A_{it} \setminus \{0\}} \frac{s_{ijt}(\vartheta)}{1 - s_{i0t}(\vartheta)} f_{ijt}(\vartheta). \tag{D1}$$

The weights are fitted shares conditional on contracted delivery. The observed target is the reported mine-level realization-cost rate, used as a proxy for the average fee on retained contracted deliveries. This assumes that the reported rate is representative of those deliveries; bilateral fees themselves are unobserved. Section 5.3 explains how shipment shares and the bargaining restrictions jointly discipline their recovery.

Let $\mathcal{S}$ denote the routing sample and $\mathcal{T}$ the mine-years with observed average fees. We minimize

$$J(\vartheta) = -\frac{1}{\sum_{(i,t)\in\mathcal{S}} q_{it}} \sum_{(i,t)\in\mathcal{S}} q_{it} \sum_{j\in A_{it}} s_{ijt}^{\text{obs}} \log s_{ijt}(\vartheta) + \frac{1}{|\mathcal{T}|} \sum_{(i,t)\in\mathcal{T}} \left[\frac{\bar{f}_{it}^{\text{obs}} - \bar{f}_{it}(\vartheta)}{\widehat{\sigma}_f} \right]^2, \tag{D2}$$

where $\widehat{\sigma}_f = 239.33$ is the sample standard deviation of observed fees, in 2017 US dollars per tonne of copper. The first component is an output-weighted fractional-share log-likelihood that includes observed spot allocations. The second gives equal weight to each mine-year fee observation. Both normalized components receive unit weight, and Euler-equation moments receive zero weight. All three specifications use 1,060 mine-years, with 3,536 physical smelter-mine-year observations and 539 spot observations. The choice sets and fee scale remain fixed throughout optimization of each sample.

D.3 Bootstrap Inference

For each ownership specification, we draw 100 bootstrap samples by resampling the 148 mines with replacement, retaining each selected mine's entire observed history and its shipment relationships. We reestimate all model parameters in every draw. The observed refined copper price path, the zero own-output price derivative, spot processing fees, processing costs, and calibrated revenue inputs are held fixed. Exposure weights and covariate scaling divisors are recalculated in each draw.

Reported 95% confidence intervals are the 2.5th and 97.5th percentiles of the estimates across draws that are both valid and optimizer-converged, using linear interpolation between adjacent ordered estimates. All 100 draws meet these conditions for each specification. We compute the percentiles in original covariate units and report them directly, allowing the intervals to be asymmetric around the point estimates. With 100 draws, the tail percentiles depend on relatively few draws, so their endpoints remain subject to simulation uncertainty.

E Additional Estimate Results

E.1 Model Fit

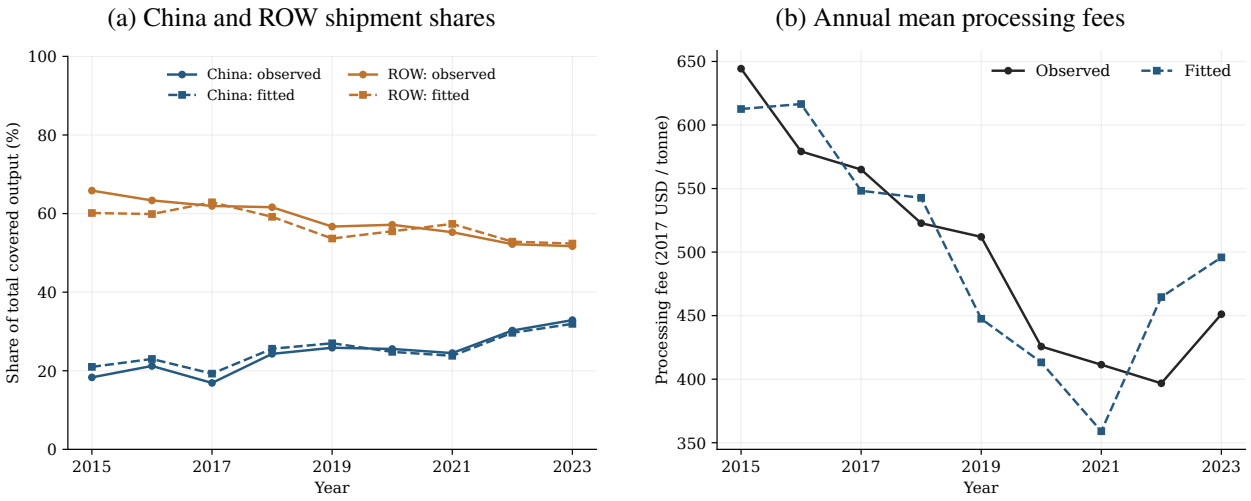
Table E1 and Figure E1 report fit for the baseline specification with the common-major-owner indicator. The correlation between observed and fitted shares is 0.864 across all observed choices, including spot. The processing-fee correlation is 0.374 across mine-years and 0.861 across annual means. China's share rises from 18.3% to 32.9% in the data, compared with 21.0% to 31.9% in the fitted series. Observed average processing fees fall from $644 per tonne in 2015 to $397 in 2022 before recovering to $451 in 2023. The fitted series captures the broad decline and recovery, although it reaches its trough one year earlier, in 2021.

Table E1: Baseline Model Fit

Outcome	N	Correlation	RMSE
Contracted shares	3,536	0.900	13.90
More than one available destination	3,171	0.691	14.68
All observed choice shares	4,075	0.864	15.65
Spot shares, when available	539	0.472	24.18
Mine-year processing fees	1,060	0.374	222.55
Annual mean processing fees	9	0.861	43.11

Notes: The baseline specification includes the common-major-owner indicator. Correlations and RMSE give equal weight to observations within each row. Share RMSE is in percentage points; processing-fee RMSE is in 2017 US dollars per tonne of copper. Annual mean processing fees give equal weight to mines within each year. All observed choice shares combine contracted and available spot choices.

Figure E1: Annual Routing Shares and Processing Fees: Main Specification



Notes: Observed series are solid and fitted series are dashed. Panel (a) divides deliveries to China and the rest of the world (ROW) by total covered output, including spot quantity. For fitted routing shares, the denominator includes $\exp(-f_{0,t}/\sigma_\epsilon)$ when the observed active choice set has positive spot quantity. Annual shares aggregate the resulting fitted physical and spot quantities; observed shares use observed quantities. China and ROW shares sum to one minus the spot share. Spot shipments have no assigned processing country. Panel (b) averages contracted processing-fee rates across mines in each year with equal mine-year weights, pooling all mine countries. Fees are in 2017 US dollars per tonne. Destination sets and mine-year output are held at observed values.

E.2 Alternative Ownership Specifications

Table E2 compares three specifications on the same sample of 1,060 mine-years, 148 mines, and 65 smelters. The baseline includes `same_major_owner`, which equals one when a named owner holds at least 50% in both assets. The first alternative omits ownership from the routing utility. The second replaces the major-owner indicator with `same_owner`, which equals one when the mine and smelter share any named owner with a positive stake. Missing ownership information is coded as zero for both indicators; ownership does not screen the sample.

The baseline common-major-owner coefficient is \$79.17 per tonne, with a 95% bootstrap confidence interval of $[-87.65, 389.62]$. The any-common-owner coefficient is \$34.62, with an interval of $[-165.14, 355.59]$. Both ownership intervals include zero, whereas the distance intervals lie below zero in all three specifications. The estimated mine bargaining weight is 0.269 in the baseline, 0.283 without an ownership indicator, and 0.279 with any common owner. The disagreement costs are \$939, \$925, and \$965 per tonne, respectively, and the routing shock scales range

from \$1,200 to \$1,279. These point estimates assign most of the incremental bargaining gains to smelters under each specification. The domestic coefficient is more sensitive to the ownership control, changing from $-\$75.67$ in the baseline to $-\$13.68$ without ownership and $-\$53.16$ with any common owner. All three columns report 95% mine-history bootstrap percentile confidence intervals in brackets.

Table E2: Parameter Estimates under Alternative Ownership Specifications

Parameter / statistic	Baseline	No ownership indicator	Any common owner
$\log(1 + \text{distance})$	-65.22	-61.69	-66.68
	[-142.41, -3.90]	[-147.12, -3.63]	[-145.79, -4.81]
Common major owner	79.17	—	—
	[-87.65, 389.62]		
Any common owner	—	—	34.62
			[-165.14, 355.59]
Domestic smelter	-75.67	-13.68	-53.16
	[-323.11, 277.71]	[-236.98, 356.74]	[-286.59, 340.87]
Chinese smelter	26.91	31.55	26.63
	[-99.01, 144.37]	[-98.90, 135.65]	[-97.27, 144.71]
Routing shock scale, σ_ϵ	1,259.94	1,199.86	1,279.39
	[198.55, 3,436.60]	[200.33, 3,538.28]	[172.68, 3,454.88]
Mine bargaining weight, δ	0.269	0.283	0.279
	[0.085, 0.636]	[0.086, 0.462]	[0.087, 0.608]
Disagreement cost, d	939.03	925.50	965.06
	[356.51, 2,257.75]	[371.56, 1,846.20]	[359.49, 2,103.24]
Mines	148	148	148
Smelters	65	65	65
Mine-years	1,060	1,060	1,060
Contracted route-years	3,536	3,536	3,536
Spot choices	539	539	539
Share correlation	0.864	0.864	0.864
Mine-year fee correlation	0.374	0.366	0.367
Annual mean fee correlation	0.861	0.867	0.865
Objective	2.555570	2.561626	2.560265
Share component	1.690866	1.690822	1.690800
Processing-fee component	0.864704	0.870804	0.869465

Notes: The baseline includes a common-major-owner indicator. The alternatives omit the ownership indicator or replace it with an indicator for any common named positive-stake owner. All columns use the same M18 narrow-v2 sample. Monetary parameters are in 2017 US dollars per tonne of copper. Brackets report 95% percentile confidence intervals: the 2.5th and 97.5th percentiles, with linear interpolation, of 100 valid, optimizer-converged draws per specification that resample entire mine histories. Dashes indicate excluded covariates. Share correlation includes contracted and available spot choices. Annual mean fee correlation uses nine annual observations. The objective gives unit weight to the share and processing-fee components and zero weight to Euler-equation moments.

F Coordination in Other Chinese Processing Industries

Table F1 summarizes public evidence on producer coordination in Chinese critical-mineral processing from January 2024 to October 2026. Panel A lists specific agreements on prices, output or capacity, and Panel B lists general industry initiatives and proposals.

Table F1: Evidence on coordination in Chinese critical-mineral processing, 2024–2026

Mineral and product	Coordinating institution	Announced or reported measures
Panel A: Specific agreements		
Zinc: concentrate smelting	China Zinc Smelters Purchasing Team (CZSPT)	Treatment-charge guidance; coordinated maintenance; output cuts. Reuters (2024); Antaike (2026).
Manganese: electrolytic metal	EMM industry committee and producer alliance	Output limits; joint purchasing; shared warehousing. Association minutes; Mysteel (2025).
Manganese: silicomanganese	Manganese alloy association and participating producers	Output cuts. SMM (2026).
Magnesium: primary metal	CNIA Magnesium Branch and major smelters	Output cuts; joint stockpiling; proposed guidance price. Association release; CNIA (2025).
Chromium: ferrochrome	Ulanqab ferroalloy association and alliance	Price floor at cost; coordinated maintenance; joint negotiation with steel buyers. Declaration (2025); Minutes (2026).
Titanium: sponge	Leading sponge-titanium producers	Price coordination; output cuts. CNIA branch authors (2025).
Silicon: polysilicon refining	Eight leading producers and industry associations	Price floor at cost; proposed capacity limits. Daqo (2026); OPIS (2026).
Metallurgical coal: coke	China Coking Industry Association market committee	Price coordination; recommended output cuts. Futures Daily (2025).
Panel B: General initiatives and proposals		
Lead: smelting	CNIA and lead/zinc smelters	Coordinated maintenance; delayed new capacity. CNIA account.
Phosphate: yellow phosphorus	Producers following an industry meeting	Price coordination. Longzhong (2026).
Lithium: carbonate and hydroxide	CNIA Lithium Branch	Capacity restraint; long-term supply contracts. Futures Daily (2025).

Continued on the next page.

Table F1 (continued)

Mineral and product	Coordinating institution	Announced or reported measures
Graphite industry	China Non-metallic Minerals Industry Association	Pricing pledge. BTR (2025).
Tin: smelting	CNIA Tin Branch and 18 participating firms	Self-discipline pledge. CNIA (2026).
Antimony: smelting and oxide	CNIA Antimony Branch and industry participants	Capacity restraint; proposed seasonal output cuts and cost-based pricing. CNIA (2025); SMM (2026).
Nickel and cobalt industry	CNIA Nickel-Cobalt Branch	Self-discipline pledge. CNIA (2025).
Tungsten industry	Tungsten–molybdenum industry forum	Supply-chain cooperation. CNIA (2025).
Vanadium industry	CISA vanadium branch and industry alliance	Self-discipline pledge; investment restraint. Panzhihua Steel (2025).
Tantalum and niobium	CNIA Tantalum-Niobium Branch	Self-discipline discussions. CNIA (2024).
Rare dispersed metals (six)	CNIA Rare Dispersed Metals Branch	Self-discipline pledge. CNIA (2025).
Fluorspar: fluorite industry	China Mining Association	Self-discipline initiative. Association index (2026).

Notes: Panel A lists specific agreements on prices, output or capacity. Panel B lists general industry initiatives and proposals. We report measures as announced or reported. In January 2026, the national regulator opposed direct agreements on polysilicon prices, output and capacity. CNIA is the China Nonferrous Metals Industry Association, CISA is the China Iron and Steel Association, and EMM is electrolytic manganese metal.