Market Power versus Geoeconomic Power in Critical Mineral Processing

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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 can also create geoeconomic power. Economists have long realized that a country gains leverage over its trading partners when those partners depend on it and have few alternatives (Hirschman, 1945). A growing literature formalizes and measures this leverage. Kleinman, Liu and Redding (2024) finds that economic dependence can shape political alignment. Clayton, Maggiori and Schreger (2023, 2024) find that a dominant country can threaten to cut off trade to extract concessions from its trading partners. 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. Several papers in the literature have also shown that governments have responded to these issues by increasingly setting trade and industrial policy with these risks in mind (See, Thoenig (2023); Becko, Grossman and Helpman (2025); Mohr and Trebesch (2025)). Generally, this prior work has treated the alternatives available to a country's trading partners as being set by technology, costs, and policy. However, the concentration that creates this geoeconomic leverage also creates market power in the product markets. And, how the dominant country exercises this market power can affect the economic outcomes of firms outside of the dominant country. This, in turn, affects the dominant country's geoeconomic power. This is the classic example of firms inside benefiting those outside of a cartel. A cartel that raises prices also raises the margins of firms outside it (Inderst, Maier-Rigaud and Schwalbe, 2014) and can keep high-cost producers in the market (Asker, Collard-Wexler and De Loecker, 2019). Those producers are the alternatives that limit the dominant country's leverage. Market power and geoeconomic power can therefore work against each other.

These issues are especially important in critical minerals, such as rare earths, gallium, germanium, and graphite, which have recently become geopolitical tools. Critical minerals such as rare earths, gallium, germanium, and graphite have recently become geopolitical tools. Unlike oil, where leverage rests with a cartel of producing countries, leverage in critical minerals rests largely with a single country, China, and at a single stage of the supply chain, processing. Across lithium, nickel, cobalt, graphite, and rare earths, the three largest processing countries accounted for 86% of global output in 2024, and China was the leading refiner in all but nickel. China also refined 44% of the

world's copper (International Energy Agency, 2025). This has led China to use its geoeconomic power in critical minerals, and Western countries to adopt policies to reduce China's power. For example, China has imposed export licensing on gallium, germanium, and graphite and export controls on several rare earth elements (Reuters, 2023*b*,*a*). And the United States has tied tax credits to where minerals are processed, financed processing outside China, taken an equity stake in a domestic rare-earth processor, and imposed tariffs on semi-finished copper.[1]

In critical minerals, concentration in processing gives the dominant country, China, both kinds of power. If the dominant country's processors coordinate, they can raise the fees they charge the firms that supply the raw material, thus exercising market power. The second is geoeconomic power: their dominance gives them the ability to cut off a supplying country's access to processing, which is only valuable if that country has few other places to send its raw material. These two forces are countervailing because higher fees, through the exercise of market power, also benefit processors that do not coordinate, both through higher prices and because some raw material is diverted to them. This in turn attracts greater entry into the processing market. We call this the "umbrella effect." By raising the margins of high-cost processors outside the dominant country, coordination among Chinese processors raises the profits of processors outside of China, and this limits China's geoeconomic power.

This paper asks how does coordination among processors in the dominant country affect that country's geoeconomic power? We build and estimate a model of bargaining between copper mines and copper smelters, and we compare the observed market, in which Chinese smelters coordinate, with counterfactual markets in which they compete.

Understanding these effects for copper is important for several reasons. First, copper is a basic input into several facets of the economy, from construction and power transmission to industrial machinery and electrical equipment (U.S. Geological Survey, 2025). It is also strategically important for national security: The July 2025 U.S. Presidential Proclamation on copper imports identifies copper as essential to defense systems and critical infrastructure (Executive Office of the President, 2025*a*). Second, the demand for copper is expected to grow with electrification, since electric vehicles and renewable generation are more copper-intensive than their legacy counterparts and electricity

[1]See, for example, U.S. Department of the Treasury (2024); U.S. Department of State (2022); Executive Office of the President (2025*b*); MP Materials Corp. (2025); Executive Office of the President (2025*a*); Congressional Research Service (2025).

grids expand (International Energy Agency, 2021, 2025). Third, the raw material supply of copper faces several structural issues: declining ore grades at legacy deposits, long lead times for new mines, and a geographic mismatch between where ore is mined and where it is processed (Dhir, Nishiumi and Kim, 2026).

Copper is also a natural setting for our question, because Chinese processors openly coordinate and control a large share of capacity. Most primary copper is produced through the sulfide processing route with two stages. Mines extract ore and concentrate it into a powder containing roughly 20-35% copper. Processors (smelters) then melt the concentrate into copper anode, which is roughly 99% copper, and then refine it into copper cathode, which is 99.99% copper.[2] Mining is spread throughout the world and is fragmented. In contrast, processing is concentrated in China. In addition, Chinese processors openly coordinate. The largest Chinese processors coordinate through the China Smelters Purchase Team (CSPT), issuing quarterly guidance on a floor for the spot processing fees (treatment and refining charges TC/RC) (Daly and Nguyen, 2019; Liu and Nguyen, 2024).

Our data come from Wood Mackenzie and cover essentially every copper mine and processor (smelter) in the world. For mines, we observe annual copper recovered into intermediate product (concentrate), costs, and ore grade. For processors, we observe capacity, output, operating costs, and the value of the bonus metal. We also observe the contracted flows from each mine to each smelter and the mine-level sales to the spot market, along with the average processing fees (TC/RC) each mine pays in each year. Our estimation sample covers 148 copper mines selling concentrate to 65 processors, 25 of them in China, between 2015 and 2023.

We begin by documenting four facts that guide the model. First, mines sell to a small and persistent set of processors. The average mine ships to 3.3 processors. In addition, a relationship that is active last year remains active this year with probability 78%, and 90% of shipments in a given year go through relationships that were active in the previous year. Second, Chinese processors have a large cost and profitability advantage, yet leave substantial capacity idle. Over 2015-2023, the cash cost of processing a tonne of copper averaged $128 at Chinese processors and $331 elsewhere.[3] Yet, Chinese processors kept an average of 694 thousand tonnes of capacity idle each year, measured

[2] Throughout the paper, we use the terms "processor" and "smelter" interchangeably.

[3] Including treatment charges and the bonus copper, gold, and silver processors keep beyond what they pay for, the average Chinese processors earned $637 per tonne, compared to $277 outside of China.

against an industry benchmark of 88% of nameplate capacity—10% of their available capacity. Third, Chinese processors explicitly coordinate the spot price, setting a public price floor for spot market transactions. Before 2024, the realized spot charge followed the CSPT floor closely. The floor was at or above the spot charge in 16 of the 17 quarters in which both are reported. When we compute a spot charge by reallocating each quarter's spot volume along the merit order of processors' variable costs, the charge lies well below the realized charge until 2025. This corresponds to the year when the CSPT floor was abandoned and also when the two series converged. Fourth, when a mine loses a buyer for a year or less, it sells much of the displaced raw mineral on the spot market and does not cut output. Using the eight longest temporary processor outages between 2017 and 2023, we find that the spot market absorbs about 64% of the volume displaced from independent mines. We also find that existing partners do not take more, and mine output does not fall. When a smelter closes for good, mines instead sign with new processors.

These facts help shape our model. We model the annual routing of raw minerals and bargaining over processing fees on a network of existing mine-processor relationships. Each mine allocates a fixed amount of output across its contracted processors and the spot market. Routing follows a logit specification based on processing fees, pair characteristics, the relative value of selling under contract rather than on the spot market. Each mine-processor pair then engages in Nash-in-Nash bargaining over processing fees. Consistent with the fourth fact, if a negotiation fails, the mine sells the affected volume on the spot market for that year and incurs a disruption cost for placing the cargo at short notice. We model the processor's outside option as zero, reflecting the substantial spare capacity in the industry during our sample. We refer to the resulting equilibrium as Nash-in-Nash with a spot-market threat. Each pair negotiates taking the other negotiations as given, as in Horn and Wolinsky (1988), and the negotiations are linked through the spot price. The model splits the umbrella effect into three components. A higher spot price raises what a processor earns on spot purchases, which, in turn, weakens the mine's position in every contract negotiation, and makes contracts more attractive relative to the spot market. The umbrella effect implies that *all* processors receive these benefits, not just those that are coordinating.

In the empirical baseline, we use the spot fee that is observed, so we do not explicitly model the behavior of the Chinese processors' coordination. However, in our counterfactuals, the spot fee instead clears the market under perfect competition. We calculate counterfactual industry

outcomes in which we hold constant the set of processors, as well as allowing processors to exit once the umbrella effect no longer exists. In our long-run counterfactual, a processor remains active only if its average variable profit covers its fixed cost. The model allows us to split the umbrella effect into three components. The first is direct: the processor earns more on the concentrate it buys on the spot market given the higher coordinated price. The second works through bargaining: because the spot market is the mine's outside option, a higher spot market price weakens the mine's position and raises the contract fee. The third is diversion: contracts become more attractive relative to the spot market, so mines move volume into their contracts. All processors see these benefits. A floor set by Chinese processors raises the profits of processors in Japan, Korea, Europe, India, and Latin America.

Our results suggest that the umbrella effect is large. In the short run, holding relationships fixed and keeping every processor open, replacing the observed spot fee with the perfect-competition fee lowers the spot fee from \$94.5 per tonne to −\$89.2. Contract fees fall from \$110.2 to −\$19.3 at Chinese processors and from \$130.2 to \$0.6 elsewhere. At these fees, 76.3% of processors outside China lose money, against 5.5% in the baseline. Profits fall by \$22.7 billion at Chinese processors and by \$31.4 billion at processors elsewhere, and miners gain \$57.0 billion. The loss to processors outside China is a measure of the implicit subsidy they receive from Chinese coordination.

We then allow for exit. Starting from the short-run equilibrium, we close the most unprofitable processor, reallocate its relationships to the lowest-cost processors with remaining capacity, recompute the equilibrium, and repeat until every remaining processor covers its fixed cost. In the long-run equilibrium, 32.0% of smelting capacity outside China closes, compared with 0.6% in China. The spot fee recovers to −\$43.2, contract fees settle at \$11.5 in China and \$30.5 elsewhere, and China's share of processing rises from 39.7% to 45.2%. Miners still gain \$43.2 billion relative to the baseline. Coordination therefore transfers surplus from miners to processors, and a large share of that transfer goes to processors outside China, enough to keep roughly a third of their capacity open.

Finally, we ask how coordination changes the cost of a trade conflict. We split the world into a US-aligned bloc and China's bloc and prohibit trade in concentrate between them. With coordination in place, the split costs the US-aligned bloc \$2.85 billion per year and strands 10.9% of its mine output, because its own processors cannot process all of it. China's bloc loses \$2.91 billion. In the

long-run equilibrium without coordination, after processors outside China have exited, the same split costs the US-aligned bloc $17.01 billion per year and strands 46.9% of its mine output, while China's bloc loses $1.68 billion. An embargo on Chilean concentrate by China's bloc shows the same pattern. It costs Chile $0.16 billion per year with coordination and $5.89 billion in the long run without it, when 31.7% of Chile's mine output would have nowhere to go. China's bloc loses $1.37 billion in the first case and $1.07 billion in the second. By keeping processors outside China open, coordination makes a full split about one sixth as costly for the US-aligned bloc as it would be in the long run without coordination, and it makes China's bloc pay more for the same split.

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 processors 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 processor coordination is a benefit or a cost.

Contributions and related literature This paper relates to several strands of literature. First, we build on empirical models that use Nash-in-Nash bargaining to study hospital–insurer, programmer–distributor, and medical-device markets (Crawford and Yurukoglu, 2012; Grennan, 2013; Gowrisankaran, Nevo and Town, 2015; Ho and Lee, 2017, 2019), and on the theoretical foundations for this approach (Horn and Wolinsky, 1988; Collard-Wexler, Gowrisankaran and Lee, 2019; Ho and Lee, 2023). Most of this work treats the outside option as the payoff from the remaining relationships if the bargained-for option is removed. In our setting, the outside option is selling on the spot market whose price is itself an equilibrium object, which links every negotiation in the market through a single price. This connects our approach to models in which the threat point is a replacement by an excluded firm (Ho and Lee, 2019) and to work on dynamic and repeated contracting (Lee and Fong, 2013; Dorn, 2024). Unlike the previous empirical settings, we study a global commodity market with many-to-many relationships between mines and processors, binding capacity in the counterfactuals, and long-run

exit. Second, we contribute to work on buyer and seller power in vertical markets (Demirer and Rubens, 2025) and on umbrella effects, through which coordination benefits firms outside a cartel (Inderst, Maier-Rigaud and Schwalbe, 2014). We trace how coordination over processing fees affects rival processors' profits and long-run survival.

Third, we contribute to research on geoeconomics and critical-mineral supply chains. Clayton, Maggiori and Schreger (2023) model how a hegemon coordinates threats across economic relationships to secure economic and political concessions. Clayton, Maggiori and Schreger (2024) show how specialization and economies of scale create dependence on a hegemon, and how policies to reduce this dependence can lead to inefficient fragmentation. Within critical minerals, Alfaro et al. (2025) show that China's rare-earth export restrictions induced foreign innovation that economized on rare-earth inputs, while Domínguez-Iino, Elliott and Hsiao (2026) study how mineral concentration and downstream technology choices shape supply-chain vulnerability and policy spillovers. Closely related work by Choi, Pandalai-Nayar and Toma (2026) studies how strategic overproduction can deter entry into rare-earth refining. We identify a countervailing mechanism in copper processing: Coordination raises the profits of processors outside China and preserves alternative capacity, thereby limiting the geoeconomic power associated with China's dominance in processing.

An important caveat to our current results is that we hold mine output fixed, so our counterfactuals do not capture changes in extraction or in mine investment that lower charges might induce. We show empirical evidence for this assumption for small disruptions in processor capacity, but our counterfactuals go beyond this.

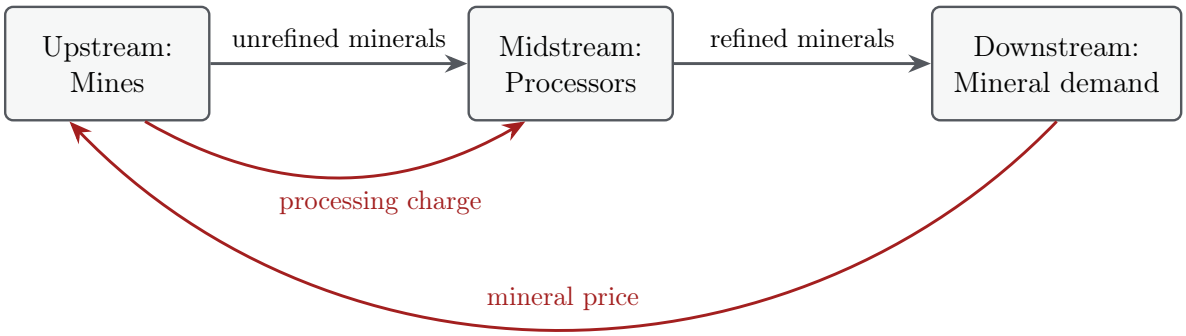
2 Background and Data

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 illustrated using the black arrows. Upstream are miners, which extract ore and are located near copper deposits

Figure 1: The supply chain



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"); we provide more details about this smelting and refining process later in this section. 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.

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. Most unrefined copper is traded under processing charges that are determined through bilateral negotiated contracts.[4]. These contracts are negotiated annually. A smaller share of unrefined copper is processed through prices determined by a spot market. The second price is the global refined copper price which accrues to the upstream miners.

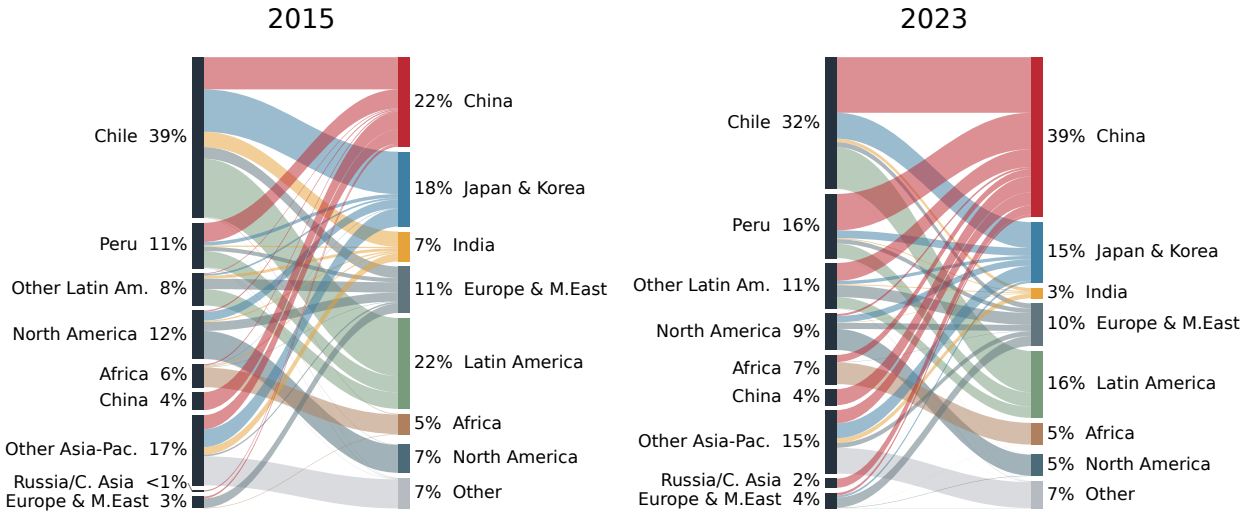
To keep the diagram simple, we omit from Figure 1 some other sources of revenues for processors. We account for these sources in our later analysis. Specifically, a small fraction of the refined copper price accrues to the processor.[5] As well, the smelting process generates by-products which can be

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

[5]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%) is called "free metal" and its value accrues to the smelter.

sold, most notably 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 15.8% of covered output in 2015 and 15.4% in 2023.

Chinese mid-stream coordination Figures 2 shows trade flows from mining countries to processing destinations. Although copper is mined throughout the world, Chinese smelters receive 38.9% of shipments with reported destinations in the 2023 baseline sample and 36.1% in the full Wood Mackenzie allocations. A natural consequence of these flows is that if China could coordinate how its smelters set prices (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' Purchasing 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. The exact workings of the CSPT within each negotiation is somewhat opaque. 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. Given the stated purpose of the CSPT to prevent head-to-head competition between smelters, it is likely that this organization coordinates to dampen competition through exclusion in the negotiation process i.e., it prevents miners from threatening Chinese smelters with replacement with a nearby Chinese smelter.

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.[6] Appendix B provides details on sample construction and coverage, including the smaller sample linked to ownership information. 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.

[6]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 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, and 30.83% involve a Chinese processor.

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

Characteristic	*N*	Mean	SD	Min	Median	Max
Mine-year characteristics						
Copper output (kt Cu)	1,060	96.95	143.66	0.83	46.29	1,190.61
Physical smelter destinations	1,060	3.34	4.04	1.00	2.00	21.00
Spot share of copper output (%)	1,060	16.56	24.18	0.00	0.62	99.49
Average processing fee (USD/t Cu)	1,060	500.82	239.33	22.35	460.17	2,370.62
Smelter-year characteristics						
Net processing cost (USD/t Cu)	507	-133.25	155.13	-775.35	-129.55	446.77
Physical route-year characteristics						
Physical shipment share (%)	3,536	25.01	31.76	0.04	9.97	100.00
Geographic distance (1,000 km)	3,536	10.06	6.77	0.11	10.68	18.86
Domestic route (%)	3,536	18.89	39.15	0.00	0.00	100.00
Chinese processor (%)	3,536	30.83	46.18	0.00	0.00	100.00

SD denotes the sample standard deviation. 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. Monetary values are in 2017 US dollars. Quantities are in kilotonnes of copper.

3 Descriptive Evidence

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

1. Mines sell to a small and persistent set of smelters.
2. Chinese smelters have a large cost and profitability advantage, yet leave substantial capacity idle.
3. Chinese smelters explicitly coordinate price in the spot market.
4. When a mine loses a buyer for a year or less, it sells much of the displaced concentrate on the

spot market and does not cut output; when a buyer closes for good, the mine signs with new smelters.

Observation 1: Mines sell to a small and persistent set of smelters.

Mines sell to a few smelters that can take their concentrate. The data record positive shipments only, so 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. The average mine ships to 3.3 smelters, so 6.0% of possible pairs trade in a given year. To understand which pairs get formed, we estimate linear probability models of the form

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

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 2 reports the estimates. We find that larger smelters are associated with more partners: a 10% increase in capacity raises the probability of a relationship by about 0.3 percentage points. Distance is associated with a lower likelihood of a pair. This remains across all specifications. Conditional on distance, the same-country indicator is positive, but noisy in several of the specifications. When mine-by-year and smelter-by-year effects are included, however, the association is statistically significant. On average, Chinese smelters are more likely to form relationships, but this coefficient is imprecisely estimated.[7]

Generally, these observable pair characteristics explain little of who trades with whom: the within-mine-year R^2 in column 2 is 0.05. In contrast, past trade explains a great deal. A relationship active last year remains active this year with probability 78%, one that lapsed resumes with probability 18%, and a pair that has never traded begins with probability 0.8% (Appendix

[7]The average effect hides significant variation across the mine-country. When we include 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 (Appendix Figure A1).

Table A1). Adding last year's status raises the within R^2 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). In a typical year, 90% of shipments move on relationships that were active the year before (Figure 3). We also find that new relationships are fragile: 46% of relationships begun within the sample end after one year, compared with 18% of those that have lasted four years or more.

Persistence can reflect a cost of switching partners or unobserved match quality between a mine's concentrate and a smelter's furnaces. To account for unobserved match quality, the last column includes mine-by-smelter fixed effects. Here, the coefficient on last year's status falls to 4.4 (s.e. 2.4; column 5). This drop is consistent with persistence that reflects match quality. But switching costs likely also exist. Mines and smelters often sign multi-year contracts where the TCRC charges reset each year, and smelters blend concentrates to meet furnace specifications and impurity limits, so a new source requires testing.

Figure 3: Relationship dynamics. Panel (a): share of shipments on relationships active in the previous year, and share of active relationships that are new, among mines present in both years. Panel (b): probability that an active relationship ends the following year, by consecutive years active; dotted lines are relationships already active in the first sample year, whose length is left-censored.

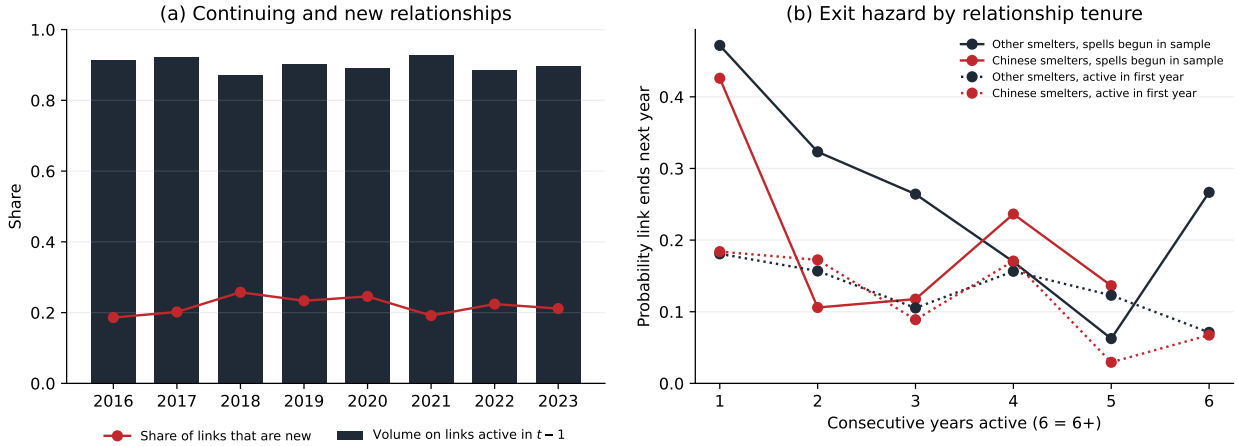


Table 2: Which mine–smelter relationships are active

	(1)	(2)	(3)	(4)	(5)
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***	4.43*
			(1.56)	(1.79)	(2.37)
Active in $t-2$				23.18***	-6.58***
				(1.91)	(2.10)
Active in any year $\leq t-2$				9.79***	
				(1.35)	
Year FE	Yes	No	No	No	No
Mine-country FE	Yes	No	No	No	No
Mine-year FE	No	Yes	Yes	Yes	Yes
Smelter-year FE	No	No	No	Yes	Yes
Pair FE	No	No	No	No	Yes
Mean of dep. var.	6.0	6.0	6.1	6.2	6.2
Observations	56,849	56,849	46,212	37,164	36,476
Mine clusters	145	145	137	127	120
Within R^2	0.056	0.045	0.576	0.619	0.006

Notes: Linear probability models, equation (1). 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. Standard errors clustered by mine. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

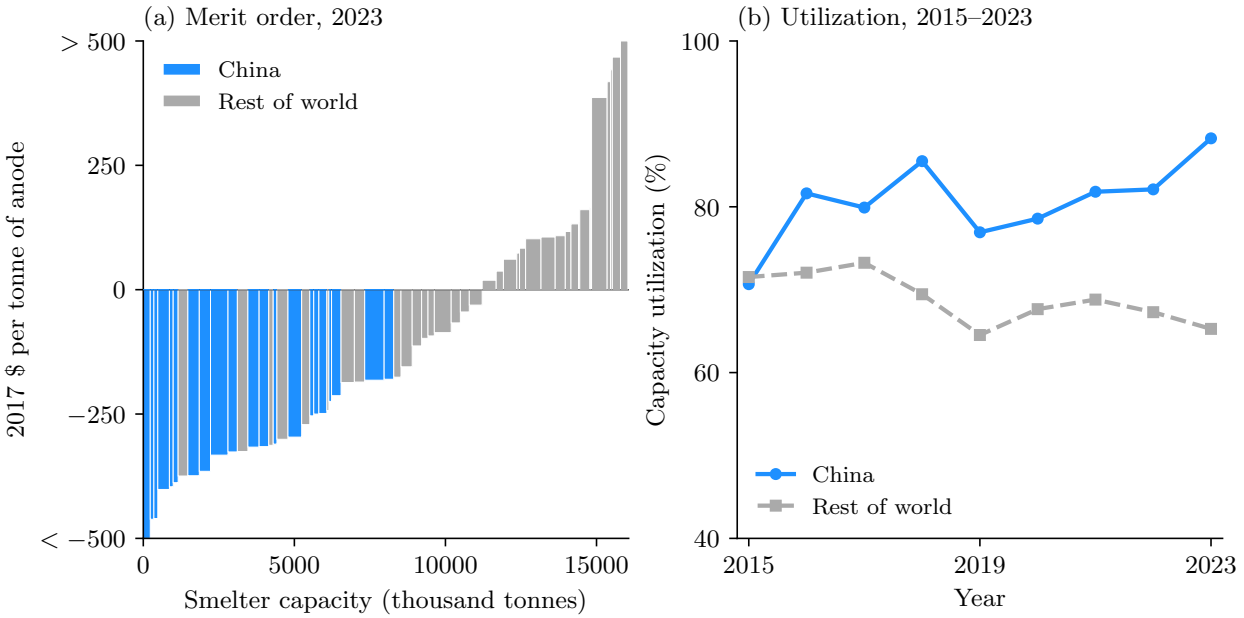
Observation 2: Chinese smelters have a large cost and profitability advantage, yet leave substantial capacity idle.

Chinese smelters have a large cost advantage in Wood Mackenzie's smelter cost data. The net cash cost of smelting a tonne of copper, which nets out by-product credits such as sulfuric acid, averaged \$128 at Chinese smelters and \$331 elsewhere over 2015–2023, weighting smelters by output. Chinese smelters also keep more free metal (Section 2.1). Adding treatment-charge revenue and free copper, gold, and silver, and subtracting net cash cost, the average Chinese smelter earned \$637 per tonne of copper above its cash cost, against \$277 elsewhere.

Figure 4, panel (a), orders smelters in the M18 sample by cash cost less acid and energy credits and the free copper, gold, and silver they retain in 2023. Each column's width is the smelter's sample-adjusted capacity; its height is cost per tonne of anode. Blue identifies China and gray identifies the rest of the world. Negative values mean credits exceed cash costs, before treatment-charge revenue. Chinese smelters account for much of the low-cost capacity.

Panel (b) shows that Chinese smelters ran fuller than smelters elsewhere from 2016 on, but still had spare capacity. Among smelters represented in M18, utilization rose from 70.7% of nameplate capacity in 2015 to 88.3% in 2023, while utilization elsewhere fell from 71.5% to 65.3%. Across Wood Mackenzie's broader cost panel, Chinese smelters left an average of 694 thousand tonnes of capacity idle each year, measured against an industry benchmark of 88% of nameplate. Idle capacity peaked at 1,057 thousand tonnes in 2019 and fell to 371 thousand tonnes in 2023.

Figure 4: Copper smelting costs and capacity utilization



Notes: Panel (a): merit order in 2023. Each column represents a smelter, ordered by cash cost less all credits per tonne of anode, in 2017 dollars. We divide plant-wide costs and credits by total anode production, including copper from scrap. Costs include consumables, power, fuel, labor, maintenance, and onsite services, less acid and energy credits and the value of free copper, gold, and silver retained by the smelter. We exclude treatment charges and downstream margins. Column widths are sample-adjusted capacities from M18. We cap costs outside $[-500, 500]$ for display, as indicated by the endpoint ticks. Panel (b): annual copper production from concentrate divided by nameplate capacity to smelt concentrate, separately for China and the rest of the world. We divide total production by total capacity within each group, using full-plant measures. Both panels include the smelter-years represented in M18, with membership varying by year. Blue identifies China; gray identifies the rest of the world. Source: Wood Mackenzie smelter data.

Observation 3: Chinese smelters explicitly coordinate price in the spot market.

As noted above, the China Smelters Purchase Team (CSPT) explicitly coordinates to establish a spot market price floor. We compiled its public floor announcements from press reports (Appendix Table A2) and plot them in Figure 5. Prior to 2024, the guidance prices appear to move around with the global business cycle. The CSPT has not issued floor guidance since 2025Q1.

Figure 5 also plots the realized spot price. The realized spot price follows the guidance closely before 2024, although 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.

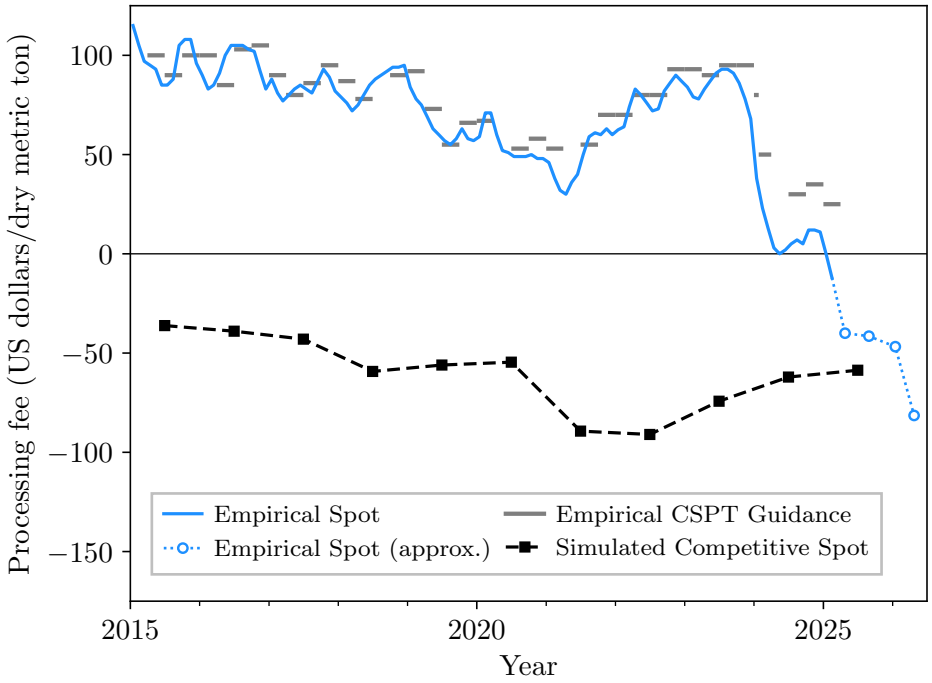
Finally, Figure 5 also plots a counterfactual "perfect competition" spot price. To do this, we take all the quantity that is sold on the spot market in each quarter, reallocate it via the merit order curve using variable costs minus byproduct benefits, and record the marginal cost of the marginal smelter.[8] We allow reallocation up to each smelter's capacity, but the qualitative findings are unchanged if we use alternative assumptions such as reallocations up to 88% of capacity. This exercise reveals a large wedge between the empirical versus the perfect competition spot price. The two series, however, have converged since 2025.

Observation 4: When a mine loses a buyer for a year or less, it sells much of the displaced concentrate on the spot market and does not cut output; when a buyer closes for good, the mine signs with new smelters.

Our model describes bargaining year by year. Each year a mine and a smelter negotiate, and if the negotiation breaks down, the mine sells its concentrate on the spot market in that year. The disagreement payoff is therefore a one-year spot sale, not a new long-term contract. Given the timing and available options after a breakdown, a natural analog is what happens when there is a temporary outage at a smelter. To understand what happens during a smelter outage, we pool the

[8] 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.

Figure 5: 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 quarter's spot volume across smelters in order of variable cost net of by-product credits, up to capacity, and reports the cost of the marginal smelter. Sources: Wood Mackenzie smelter data; press reports listed in Appendix Table A2.

11 longest smelter disruptions between 2017 and 2023, compiled from USGS minerals yearbooks, company reports, and trade press.[9] Eight of these were temporary and three were permanent.

We estimate the impact of the closures 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

$$y_{iet} = \theta\, E_{ie}\, \text{Offline}_{jt} + \alpha_{ie} + \tau_{et} + \varepsilon_{iet}, \tag{2}$$

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. Each coefficient is the effect of a full year without the smelter for a mine that sold all its output to it.

We report results across three sets of closures. First, because some disrupted smelters share

[9]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.

an owner with mines that supplied them, we split the temporary outages across mines that were co-owned with the smelter and those that are independent since an outage at a co-owned smelter may reflect issues with the mine. In addition, we separate the eight temporary disruptions from the three permanent closures, because a permanent closure gives the mine time to sign new long-term contracts, which in the model is a change in the network rather than a failed negotiation.

Table 3 reports the estimates. For independent mines, a temporary disruption cuts the share of output sold to the disrupted smelter by 1.18 per unit of exposure and raises the share sold on the spot market by 0.76 (s.e. 0.38; column 1). The spot market thus takes 64% of the displaced volume ($p = 0.05$ for the spot coefficient). While the point estimate is noisy, existing smelter partners do not appear to increase their offtake (0.03, s.e. 0.46). The point estimate for smelters the mine had not supplied before suggests some of the concentrate may go to new smelters (0.40, s.e. 0.24). Importantly, we do not find evidence that output falls (-0.17, s.e. 0.32).

Mines that share an owner with the disrupted smelter show the same pattern more precisely (column 2): the spot market takes 59% of the displaced volume (0.48, s.e. 0.15). For these mines, their output appears to fall (-0.17, s.e. 0.07), potentially because the problems that took the smelters offline, a strike at Asarco and operating difficulties at Mopani, also hit the mines.

Permanent closures appear different (column 3). After a permanent closure, the spot share falls (-0.51, s.e. 0.26), and mines sign with new smelters, which take about all of the displaced volume (0.88, s.e. 0.38). This suggests that a mine that permanently loses a smelter replaces the amount with a new contract perhaps because the closure is more predictable. The largest of these closures, Tuticorin, shows this most clearly.[10]

[10] Tuticorin, a 400 thousand tonne smelter in Tamil Nadu, India, was ordered closed in May 2018 after protests over pollution, a decision driven by local politics and environmental regulation rather than by the copper market. In an event study of the 30 exposed mines (Appendix Table A3), exposed mines did not cut output and replaced the lost buyer within the year, mostly with smelters they had not sold to in the previous year: the share of their shipments to identified smelters going to such smelters rose by 1.66 per unit of exposure in 2018, and the share going to Chinese smelters by 1.31. For each percentage point of output a mine had sold to Tuticorin, about 1.18 percentage points of its later output went to smelters it had not supplied in 2016–2017 (Appendix Table A4).

Table 3: Smelter disruptions: where the displaced volume goes in the year of the disruption

	(1) Temporary, independent pairs	(2) Temporary, co-owned pairs	(3) Permanent closures
Share to disrupted smelter	-1.18***	-0.81***	-0.80***
	(0.24)	(0.15)	(0.10)
Share sold on the spot market	0.76**	0.48***	-0.51*
	(0.38)	(0.15)	(0.26)
Share to existing smelter partners	0.03	0.07***	0.43
	(0.46)	(0.02)	(0.39)
Share to new smelter partners	0.40	0.27**	0.88**
	(0.24)	(0.12)	(0.38)
Log output	-0.17	-0.17**	0.80
	(0.32)	(0.07)	(0.77)
Spot share of displaced volume	0.64	0.59	-0.63
Disruptions	8	8	3
Exposed mine-events	62	7	32

Notes: Each cell is a separate regression, equation (2), 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; the treatment is exposure times the share of each year the smelter was offline. Shares are of total output. Columns 1 and 2 use the eight temporary disruptions and column 3 the three permanent closures (Tuticorin, Tongling's Jinchang smelter, and Codelco's Ventanas smelter). Column 1 drops exposed mines that share a majority owner with the disrupted smelter; column 2 keeps only those exposed mines. Both 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 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. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

3.1 What these imply for the structural model, and why a structural model

Our goal is to answer three questions. How much of the gap in charges between Chinese and non-Chinese smelters reflects China's cost advantage, and how much reflects coordination among Chinese buyers? How would charges and trade flows change if Chinese smelters bargained independently instead of coordinating? And how would mines and smelters outside China be affected by new smelting capacity outside China, or by trade restrictions and smelter disruptions? The reduced-form evidence cannot answer these questions, but points to key elements a structural model requires.

The first observation that mines sell to a small, but persistent, set of smelters motivates modeling trade on a network of persistent relationships, with route utilities that vary by source country and distance. The second (China's cost advantage but excess capacity) and third (Chinese smelters coordinate on the spot price) observations motivate allowing Chinese smelters to act jointly, and

motivate our counterfactual questions. The fourth observation (mines that lose a smelter do not reduce output, but increase sales on the spot market) supports treating a one-year spot sale as a mine's payoff when a negotiation breaks down.

4 Model

4.1 Economic environment and timing

Overall, 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.[11] 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 perfect competition). Denote the spot price $f_{0,t}$.
4. Miners produce unrefined copper, 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

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

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. The vector x_{ij} also includes a constant which captures the spot-contract wedge (for example, the inconvenience to the miner of negotiating with a trader outside its typical long-term contracts). 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.[12] 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.

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

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

ω given these payoffs results in routing shares of total copper production q_{it}:

$$s_{ijt} = \frac{1}{q_{it}} \int_0^{q_{it}} \mathbf{1}\Big\{ j = \arg\max_{k \in A_{it}} v_{ikt}(\omega) \Big\} \, d\omega = \frac{\exp(\mu_{ijt}/\sigma_\epsilon)}{\sum_{k \in A_{it}} \exp(\mu_{ikt}/\sigma_\epsilon)}, \tag{3}$$

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 in the Nash bargaining problem. Overall, the Nash bargaining problem is:

$$f_{ijt} = \arg\max_f \left[-f + x_{ij}\beta - (-d - f_{0,t}) \right]^\delta \left[a_j p_t + f - c_j \right]^{1-\delta}. \tag{4}$$

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 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:

$$\pi_{jt} = \sum_i q_{it} s_{ijt} \left(a_j p_t + f_{ijt} - c_j \right) + q_{0jt} \left(a_j p_t + f_{0,t} - c_j \right), \tag{5}$$

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 (3)).
2. Processing fees f_{ijt} determined by Nash bargaining (Equation (4)).
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:

$$W = \lambda \underbrace{\Pi_{\text{hegemon}}}_{\text{Hegemon's firms' profits}} + (1-\lambda) \underbrace{\Big(V_i(A_i) - V_i(A_i \backslash S_{\text{hegemon}})\Big)}_{\text{Geoeconomic power } G_i} \qquad \text{where} \qquad A_i = \{j : \bar{\pi}_j \geq F_j\} \tag{6}$$

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:

$$\lambda \geq \frac{\Delta G_i}{\Delta G_i + \Delta \Pi_{\text{hegemon}}} \tag{7}$$

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: $D_{\text{hegemon} \to exit}$, 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 $D_{exit \to \text{hegemon}}$, which is the share of the exiting smelters' volume that the hegemon would process if the exiting smelters were removed:

$$\Delta G_i = -q_i \sigma_\epsilon \log\left(1 - D_{\text{hegemon} \to exit} \, D_{exit \to \text{hegemon}}\right) \tag{8}$$

Equation 8 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

5.1 Estimation

We estimate the routing and bargaining parameters by matching simulated shipment shares and mine-average processing fees with observed values. The seven parameters are four route-utility coefficients β, the routing shock scale σ_ϵ, the bargaining weight δ, and the disagreement wedge d. The routing-utility covariate x_{ij} includes constant, $\log(1 + \text{distance})$, and indicators for a domestic

smelter and a Chinese smelter. We calibrate the smelter-specific free-copper rate a_j at the observed mean level during the period 2015-2023.[13] Table C1 in Appendix C presents the specific values of the smelters' free-copper rates by processing country.[14]

For each candidate parameter vector, we solve the bargaining problems and compute routing shares at observed refined copper prices and spot processing fees. We minimize a criterion combining a log-likelihood of routing share with squared errors in mine-average professing fees. The share component includes the spot shipments and is weighted by mine-year output. The processing-fee errors are scaled by the sample standard deviation of the observed fees; see further details in Appendix C.

5.2 Identification

We discuss how we identify the parameters using variation in shipment quantity and mine-year processing fees.

Routing parameters β The routing parameters are informed by the variation in shipment from a mine to different processors. For example, a mine sending relatively more raw minerals to a nearby processor, after accounting for processing fees and country indicators, provides information to identify the distance coefficient. The domestic coefficient is informed by mines shipping to both domestic and foreign processors. The Chinese-smelter indicator is identified by mines shipping to Chinese and non-Chinese processors.

Bargaining weight δ and routing scale σ_ϵ Variation in the shipment shares alone does not separate δ from σ_ϵ. The large shipments concentrated on attractive routes can be due to either a high mine bargaining weight or a small routing shock scale. Observed mine-year processing fees and observed processors' costs add restrictions needed to distinguish the mechanism. A dollar increase in processing costs raises the negotiated fee by δ and a dollar increase in the spot price raises the negotiated fee by $1-\delta$. The fact that we observe the costs, free-metal revenue, and spot fees (thus the gain from trade) and the cross-sectional variation in these surplus help identify the bargaining weight. With bargaining weight and the gain from trade disciplined by processing charges, the

[13] On average, the free-metal share is 0.0316 for Chinese smelters and 0.0170 elsewhere.
[14] Specific values at smelter level are withheld due to data confidentiality.

sensitivity of allocation shares to the routing payoffs identifies σ_ϵ.

Routing constant payoff β_0 and disagreement cost d Increasing β_0 and reducing d by the same amount leaves the contracted processing fees and shares unchanged. However, the routing constant payoff raises the utility of contracted processors relative to the spot-market option, increasing the share of raw copper sent to these contracted processors. Observed spot shipments help separate β_0 from d.

Exogenous network assumption A central assumption is that the mine-processor network A_{it} is fixed. We currently assume the network is exogenous. We interpret network exogeneity as a short-run restriction. Over horizons shorter than one year, we assume that the raw mineral displaced by a contract disagreement is all sold at the spot market. Our evidence that temporary smelter disruptions increase spot sales, with little additional shipments from the mines to other existing processing partners, supports this interpretation. For longer horizons, mines can renegotiate with threat of establishing new relationships. Explicitly modeling relationship formation is our immediate future research extension.

6 Results and Model Fit

Table 4 reports results. The sample contains 1,060 mine-years during 2015-2023, covering 148 mines and 65 smelters. Appendix D reports additional results when common ownership is controlled in the routing utility.

Table 4: Parameter Estimates

Parameter	Estimate
Contract constant, β_0	4.47
$\log(1 + \text{distance})$	-66.72
Domestic smelter	-45.09
Chinese smelter	51.36
Routing shock scale, σ_ϵ	1,332.57
Mine bargaining weight, δ	0.280
Disagreement cost, d	934.02

Notes: The table reports results for the main specification. Payoff coefficients, the disagreement cost, and the routing shock scale are in 2017 US dollars per tonne of copper. Distance enters as $\log(1 + \text{distance})$. Standard errors have not yet been computed.

Bargaining and the spot-market threat The estimated mine bargaining weight is $\delta = 0.277$, implying that mines receive 28% of the incremental gain from agreement and smelters receive 72%. 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 just the additional payoffs through the additional bilateral contract from the mine when operating under the capacity.

The estimated disagreement cost is \$946 per tonne. This parameter measures the additional loss from moving contracted concentrate to the spot market as 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 \$684 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 \$6.25 per tonne, holding the processing fee and other route characteristics fixed. The Chinese-smelter coefficient is positive, at \$24.83, conditional on observed costs, smelter-specific free-copper revenue, and distance. The domestic coefficient is negative, at \$30.00 in magnitude. Note that this is a conditional comparison within observed relationships. It does not imply that mines generally prefer foreign processors, because domestic routes are also closer than others and the model conditions on the existing relationship network.

Model fit The model fits the allocation shares very well. The correlation between observed and fitted shipment shares is 0.864. For processing fees, both the data and the model produce the same average level \$501 per tonne. The correlation between observed and fitted annual values is 0.866. Appendix Figure D1 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.

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

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%

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

8 Conclusion and Next Steps

We provide a structural model linking dynamic extraction, negotiated TC/RCs, and downstream competition in the global copper supply chain. Results show persistent differences in processing conditions between China and other smelters, and broad heterogeneity in bargaining weights. These results imply why shocks to trade or capacity need not transmit uniformly across mines, processors, and countries.

The next step is to use these estimates in counterfactual exercises. The scenarios currently at the top of the agenda include export restrictions by major mining countries, coordinated bargaining by Chinese smelters or by groups of mines, large smelter outages, and subsidized smelting-capacity expansion outside China.

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APPENDICES

A Additional descriptive results

A.1 Relationships

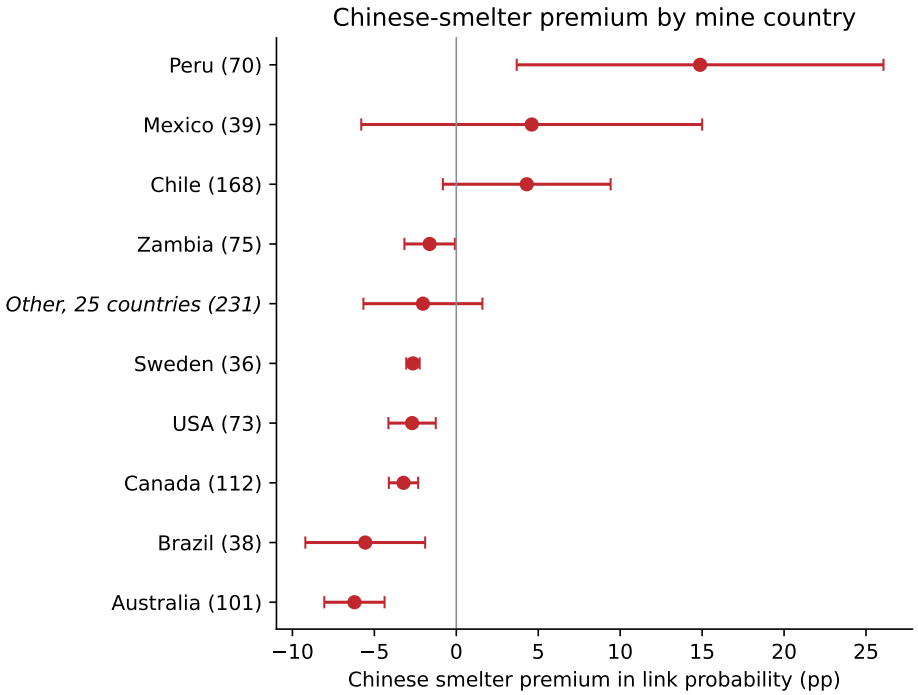
Table A1: Persistence of mine–smelter relationships

	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.

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).

Figure A1: Chinese-smelter premium in the probability of an active relationship, by mine country. 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 A2: 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)
2026Q1	none issued	–	SMM
2026Q2	none issued	-78.5	Reuters (Kitco)
2026Q3	none issued	-132	Reuters (Kitco)
2026Q4	none issued	-226.2	SMM

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.

A.3 The Tuticorin closure

Vedanta's Tuticorin smelter in Tamil Nadu, India, had about 400 thousand tonnes of annual capacity and ran on imported concentrate. It stopped operating in late March 2018 for maintenance and was not allowed to restart. In April the state pollution control board declined to renew its operating consent, and in May, after protests over pollution in which police killed thirteen people, the state government ordered it permanently closed.

We measure each mine's exposure E_i as the share of its 2015–2017 output, including spot sales, sold to Tuticorin. 30 mines were exposed; the median exposed mine sold 5% of its concentrate to Tuticorin and the mean 10%. For each outcome we estimate

$$y_{it} = \sum_{k \neq 2017} \theta_k \, E_i \mathbf{1}\{t = k\} + \alpha_i + \tau_t + \varepsilon_{it}, \tag{9}$$

so that θ_k is the change in y for a mine that sold all its output to Tuticorin, relative to 2017 and to unexposed mines.

Exposed mines did not cut output (Table A3). They replaced the lost buyer quickly, mostly with smelters they had not supplied before rather than with the spot market. In 2018 the share of an exposed mine's shipments going to such smelters rose by 1.66 per unit of exposure (s.e. 0.39), and the share going to Chinese smelters, measured in levels, by 1.31 (s.e. 0.32), about 13 percentage points for a mine with average exposure. Of the volume exposed mines sold to new partners after the closure, 74% went to Chinese smelters, compared with 32% for unexposed mines (Table A5). The pre-trend tests do not reject for output ($p = 0.25$) or the share sold to new partners ($p = 0.38$). They reject for the number of partners ($p < 0.01$), which was already falling, and for the share sold to Chinese smelters ($p = 0.01$), part of which is mechanical because exposure is measured from the same years. The average effect of a full year without Tuticorin on the charge exposed mines paid is -332 dollars per tonne per unit of exposure (s.e. 161), but charges were already falling between 2016 and 2017 by about as much as in 2018, so the decline cannot be separated from a trend.

Table A4 asks, mine by mine, whether the lost volume went to the mine's existing options in proportion to their shares. For each of the 109 mines observed in both 2016–2017 and 2019–2020, we regress the change in the share of output sold to each group of destinations on the mine's pre-closure

Tuticorin share s_{iT}. Proportional reallocation implies a coefficient of one for all pre-closure options taken together. The estimate is -0.18 (s.e. 0.39; $p = 0.003$ for equality with one), and the coefficient for new smelter partners is 1.18 (s.e. 0.39) against a prediction of zero.

Trade data show the same reallocation at higher frequency. In quarterly importer-reported flows of copper concentrate, exporting countries that had sent more of their concentrate to India shifted it to China after the second quarter of 2018, by 0.37 per unit of their 2016 India share (s.e. 0.08).

Table A3: Mine outcomes after the Tuticorin closure

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Effect by period			Average effect of a full year closed		Pre-trend test	Mean, exposed mines
Outcome	2018	2019–2020	2021–2023	Estimate	Randomization p	p-value	2015–2017
Share to closed smelter	-1.068***	-1.536***	-1.460***	-1.437***	0.00	0.09	0.121
	(0.060)	(0.136)	(0.167)	(0.120)			
TC/RC (2017 $/t)	-163.296*	-396.182*	-472.579***	-331.723**	0.03	0.26	579.672
	(85.548)	(217.328)	(180.098)	(161.019)			
Log output	0.707***	0.511	-0.212	0.464	0.24	0.25	4.849
	(0.203)	(0.808)	(1.015)	(0.608)			
Number of smelter partners	0.604	-6.795**	-7.479**	-3.303*	0.06	0.00	7.951
	(1.510)	(3.032)	(3.395)	(1.721)			
Effective partners (1/HHI)	0.523	-2.290	-2.937	-1.051	0.17	0.00	4.766
	(1.200)	(1.974)	(2.119)	(1.033)			
Share of volume to new partners	1.662***	0.272	0.473**	0.687***	0.01	0.38	0.120
	(0.392)	(0.540)	(0.197)	(0.257)			
Number of new partners	10.270**	4.101*	1.062	4.135**	0.00	0.20	1.460
	(5.105)	(2.464)	(2.515)	(1.948)			
Share to Chinese smelters	1.315***	1.146***	0.757	1.289***	0.00	0.01	0.136
	(0.315)	(0.429)	(0.539)	(0.307)			
Share to other Indian smelters	-0.011	-0.000	-0.133	-0.052	0.19	0.79	0.075
	(0.102)	(0.255)	(0.486)	(0.229)			
Share to Japan & Korea	0.041	0.335	0.346	0.201	0.15	0.30	0.288
	(0.059)	(0.306)	(0.453)	(0.239)			
Spot share of output	0.165	-0.047	-0.257	0.010	0.94	0.78	0.240
	(0.403)	(0.459)	(0.523)	(0.449)			
Shipment-weighted distance (1,000 km)	4.448***	2.472	-0.630	3.039	0.07	0.01	9.907
	(0.854)	(2.945)	(4.284)	(2.474)			

Notes: Each row is a separate regression with mine and year fixed effects. Coefficients are per unit of exposure, the mine's 2015–2017 share of output sold to Tuticorin. Shares of destinations are of shipments to identified smelters; the spot share is of total output. Columns 1–3 come from one regression with exposure interacted with indicators for 2018, 2019–2020, and 2021–2023; 2015–2017 is the comparison period. Column 4 interacts exposure with the share of each year Tuticorin was offline (0.77 in 2018 and one thereafter). Column 5 is a randomization-inference p-value for column 4 from 500 random reassignments of exposure across mines. Column 6 is the p-value of a joint Wald test that the 2015 and 2016 event-study coefficients, relative to 2017, are zero. Column 7 is the 2015–2017 mean among exposed mines. New partners are smelters the mine did not sell to in the previous year. Standard errors clustered by mine. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A4: Where the volume sold to Tuticorin went: tests of the routing model

	(1)	(2)	(3)	(4)
		of which		
	All pre-closure options	Pre-closure smelter partners	Spot market	New smelter partners
Pre-closure Tuticorin share s_{iT}	-0.18	0.17	-0.35	1.18***
	(0.39)	(0.47)	(0.68)	(0.39)
Logit prediction	1.00	0.58	0.42	0.00
p-value, estimate = prediction	0.003	0.452	0.310	0.003
Mean of dep. var.	-0.081	-0.090	0.009	0.095
Mines		109		
Exposed mines		25		

Notes: One observation per mine observed in both 2016–2017 and 2019–2020; Al Masane, which sold all its output to Tuticorin, is excluded. The dependent variable is the change between the 2016–2017 and 2019–2020 averages in the share of the mine's output sold to the destinations named in the column heading. Shares are of total output, including spot sales. Pre-closure smelter partners are smelters other than Tuticorin that the mine sold to in 2016–2017; new smelter partners are all others. Column 1 is the sum of columns 2 and 3. Each regression includes a constant. The row labeled logit prediction reports the coefficient under proportional reallocation, from the same regression with the predicted change, $S_{ig}\, s_{iT}/(1 - s_{iT})$, as the dependent variable, and the p-value tests whether the difference between the actual and predicted changes is unrelated to s_{iT}. Robust standard errors. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A5: Destination of Tuticorin's former supply

	Exposed mines		Control mines	Exposed − control	Model
Destination	Before	After	change	change	change
Closed smelter	0.056	0.000	+0.000	-0.056	-0.056
Other India	0.042	0.032	-0.010	-0.001	+0.004
China	0.166	0.280	+0.023	+0.092	+0.011
Japan & Korea	0.215	0.224	+0.005	+0.005	+0.012
Other	0.323	0.270	-0.013	-0.041	+0.015
Spot	0.197	0.193	-0.005	+0.001	+0.013
Volume to partners new since before		0.131	0.094 (level)	+0.038	0
Mines	27	27	82		

Notes: Volume-weighted destination shares of total output, with spot sales as a destination, for mines present in both 2016–2017 and 2019–2020. Exposed mines sold to Tuticorin in 2015–2017. "Model change" removes Tuticorin from each exposed mine's 2016–2017 shipments and rescales the remaining destinations proportionally. Because shares are volume-weighted, a few large mines dominate the aggregate changes.

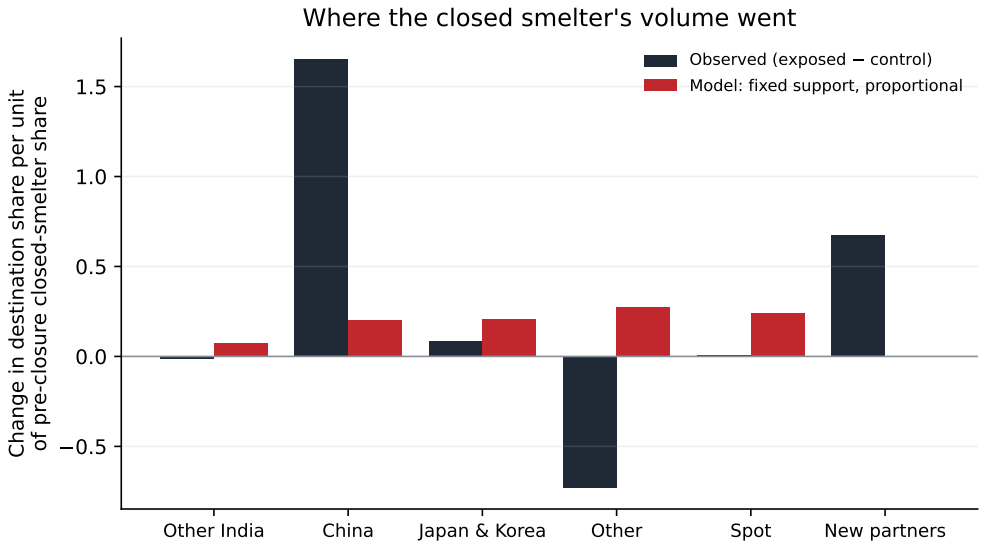


Figure A2: Change in exposed mines' destination shares after the Tuticorin closure, net of the change for unexposed mines, per unit of pre-closure Tuticorin share, compared with proportional reallocation on a fixed set of relationships.

A.4 China's ban on Australian concentrate

In late 2020, during a broader trade dispute, Chinese buyers were told to stop purchasing a range of Australian products, including copper ore and concentrate, and Chinese imports of Australian concentrate fell to zero in 2021. The episode removed every Chinese smelter from the options of one country's mines, and it is the closest historical counterpart to counterfactuals in which China uses its position in processing as leverage.

Before the ban, Australian smelters took about 40% of all Australian concentrate, smelters in Japan and Korea 13%, and Chinese smelters 5% directly; another 34% was sold to traders, much of it likely bound for China (Figure A3). After the ban, Chinese smelters took nothing, the share sold to traders fell to 26%, and the share going to Japan and Korea rose to 20%.

We estimate equation (9) on the estimation sample with exposure an indicator for the 16 Australian mines and 2019 as the reference year (Table A6). The share of Australian mines' output going to China changed by -0.05 (s.e. 0.03), essentially all of its pre-ban level of 0.04, and the share sold to traders by -0.21 (s.e. 0.06). The volume went to smelters in Japan and Korea, whose share rose by 0.11 (s.e. 0.05), and elsewhere, mainly the Philippines and Europe, whose share rose by 0.12 (s.e. 0.06). Output did not change significantly (-0.17, s.e. 0.12), and neither did the charges Australian mines paid relative to other mines (5 dollars per tonne, s.e. 27). The pre-trend test rejects for the spot share ($p = 0.03$) and for charges ($p = 0.01$). The ban put at risk about 33% of the output of the average Australian mine, but Australia supplies only about 5% of the world's concentrate, and smelters outside China had room to take it. Prominent Hill is a typical case (Table A7): it replaced its Chinese and trader volume with sales to the Pasar smelter in the Philippines and to Mount Isa in Australia.

Figure A3: Destination of Australian copper concentrate, 2015–2023. Shares of all Australian concentrate in the Wood Mackenzie allocation data, by destination. "Traders and spot" is concentrate sold to traders or on the spot market, whose smelter is not identified. The shaded area marks the period after China stopped buying Australian concentrate in late 2020.

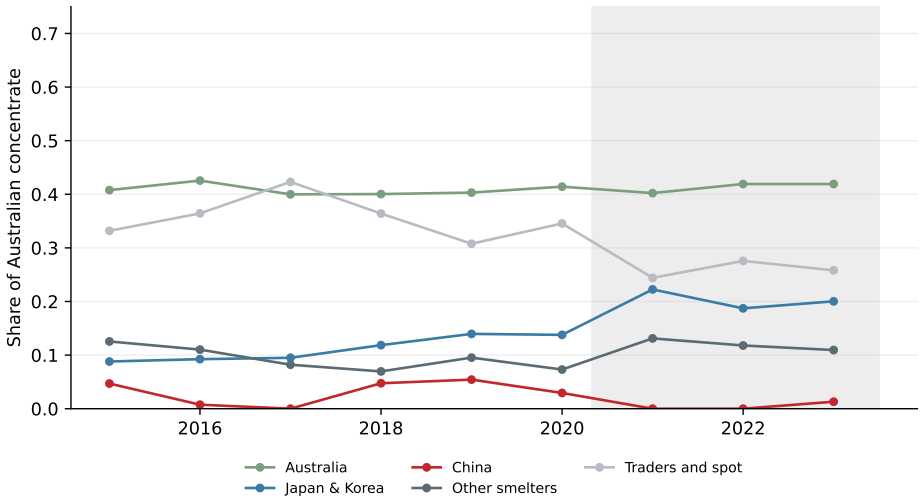


Table A6: Australian mines after China stopped buying Australian concentrate

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Effect by period			Average effect of a full year of the ban		Pre-trend test	Mean, Australian mines
Outcome	2020	2021–2022	2023	Estimate	Randomization p	p-value	2018–2019
Share to Chinese smelters	0.006	-0.047**	-0.062	-0.054*	0.10	0.88	0.039
	(0.027)	(0.024)	(0.040)	(0.028)			
Spot share of output	-0.037	-0.226***	-0.172**	-0.207***	0.00	0.03	0.280
	(0.039)	(0.060)	(0.083)	(0.065)			
Share to Japan & Korea	-0.014	0.123**	0.088*	0.115**	0.00	0.25	0.181
	(0.026)	(0.051)	(0.049)	(0.050)			
Share to Australian smelters	0.028	0.036*	0.017	0.027	0.47	0.88	0.293
	(0.024)	(0.021)	(0.019)	(0.020)			
Share to other smelters	0.016	0.113*	0.129	0.119*	0.01	0.10	0.207
	(0.040)	(0.059)	(0.087)	(0.062)			
Share of volume to new partners	-0.204***	-0.033	-0.042	-0.002	0.96	0.37	0.225
	(0.065)	(0.036)	(0.061)	(0.034)			
Number of new partners	-0.225	0.276	0.278	0.323	0.29	0.38	0.700
	(0.225)	(0.218)	(0.212)	(0.202)			
Number of smelter partners	0.154	0.623**	0.611*	0.613**	0.21	0.61	1.905
	(0.236)	(0.298)	(0.362)	(0.305)			
Log output	-0.065	-0.095	-0.330	-0.173	0.15	0.72	3.979
	(0.102)	(0.102)	(0.222)	(0.118)			
TC/RC (2017 $/t)	10	15	-13	5	0.90	0.01	431
	(34)	(30)	(30)	(27)			

Notes: Each row is a separate regression of equation (9) with mine and year fixed effects, in which exposure is an indicator for Australian mines and 2019 is the reference year. Columns 1–3 come from one regression with the Australia indicator interacted with indicators for 2020, 2021–2022, and 2023; 2015–2019 is the comparison period. Column 4 interacts the indicator with the share of each year under the ban (two months in 2020 and all of 2021–2023). Column 5 is a randomization-inference p-value for column 4 that reassigns the Australia indicator across mines 500 times. Column 6 is the p-value of a joint Wald test that the 2015–2018 event-study coefficients are zero. Column 7 is the 2018–2019 mean for Australian mines. Destination shares are of total output, including spot sales. New partners are smelters the mine did not sell to in the previous year. Standard errors clustered by mine. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A7: Australian mines before and after China stopped buying Australian concentrate

	Output	2018–2019 share of output					2021–2022 share of output				
Mine	(kt/yr)	China	Spot	Japan, Korea	Australia	Other	China	Spot	Japan, Korea	Australia	Other
Olympic Dam	155	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00
Mount Isa Copper	107	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00
Prominent Hill	106	0.41	0.22	0.00	0.08	0.29	0.00	0.00	0.00	0.28	0.72
Cadia Hill	84	0.00	0.06	0.94	0.00	0.00	0.00	0.11	0.89	0.00	0.00
Ernest Henry	72	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00
DeGrussa	69	0.00	0.84	0.11	0.00	0.05	0.00	0.51	0.24	0.00	0.26
Northparkes	39	0.00	0.22	0.65	0.00	0.13	0.00	0.00	1.00	0.00	0.00
Boddington Expansion	32	0.00	0.80	0.03	0.00	0.17	0.00	0.27	0.12	0.00	0.61
Cobar - CSA	22	0.00	0.59	0.00	0.00	0.41	0.00	0.59	0.00	0.00	0.41
Telfer	15	0.00	0.52	0.17	0.00	0.30	0.00	0.00	0.71	0.00	0.29

Notes: Australian mines in the estimation sample observed in both periods. Output is average annual copper in concentrate in 2018–2019, in thousand tonnes. Shares are of each period's total output; "Spot" is sales to traders or on the spot market. "Other" is smelters outside China, Japan, Korea, and Australia.

B Data Sources and Coverage

B.1 Data Sources and Summary Statistics

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 baseline 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. To control for vertical integration, we also link the sample with ownership information and identify pairs of mine-smelter that share at least one named owner. Restricting attention to the mine-year cluster with complete ownership information for receiving processors leaves 1,029 mine-year clusters, 145 mines, and 64 smelters.

Table B1 reports summary statistics for both samples. Average covered mine-year output is 96.95 kilotonnes in the baseline and 97.06 kilotonnes in the sample with ownership control. Mines deliver to 3.34 and 3.29 physical smelters on average, respectively. Average mine-year processing fees are \$500.82 and \$500.20 per tonne. The two samples have similar production, fee, and geographic characteristics. Common ownership is observed in 18.3% of physical shipment observations and 37.0% of total copper in the sample that includes this control.

Table B1: Summary Statistics of the Estimation Samples, 2015–2023

Characteristic	*N*	Mean	SD	Min	Median	Max
Panel A: Baseline sample						
Mine-year characteristics						
Copper output (kt Cu)	1,060	96.95	143.66	0.83	46.29	1,190.61
Physical smelter destinations	1,060	3.34	4.04	1.00	2.00	21.00
Spot share of copper output (%)	1,060	16.56	24.18	0.00	0.62	99.49
Average processing fee (USD/t Cu)	1,060	500.82	239.33	22.35	460.17	2,370.62
Smelter-year characteristics						
Net processing cost (USD/t Cu)	507	-133.25	155.13	-775.35	-129.55	446.77
Physical route-year characteristics						
Physical shipment share (%)	3,536	25.01	31.76	0.04	9.97	100.00
Geographic distance (1,000 km)	3,536	10.06	6.77	0.11	10.68	18.86
Domestic route (%)	3,536	18.89	39.15	0.00	0.00	100.00
Chinese processor (%)	3,536	30.83	46.18	0.00	0.00	100.00
Common owner (%)	—	—	—	—	—	—
Panel B: Sample with ownership control						
Mine-year characteristics						
Copper output (kt Cu)	1,029	97.06	143.94	0.98	46.48	1,190.61
Physical smelter destinations	1,029	3.29	3.97	1.00	1.00	21.00
Spot share of copper output (%)	1,029	16.67	24.25	0.00	0.84	99.49
Average processing fee (USD/t Cu)	1,029	500.20	239.37	22.35	458.55	2,370.62
Smelter-year characteristics						
Net processing cost (USD/t Cu)	497	-131.43	154.51	-775.35	-128.10	446.77
Physical route-year characteristics						
Physical shipment share (%)	3,385	25.33	31.91	0.04	10.14	100.00
Geographic distance (1,000 km)	3,385	10.01	6.77	0.11	10.68	18.86
Domestic route (%)	3,385	19.23	39.42	0.00	0.00	100.00
Chinese processor (%)	3,385	29.19	45.47	0.00	0.00	100.00
Common owner (%)	3,385	18.35	—	0.00	0.00	100.00
Common-owner shares of copper volumes (%)						
Among shipments to smelters				44.74		
Out of all shipments, including spot				37.04		

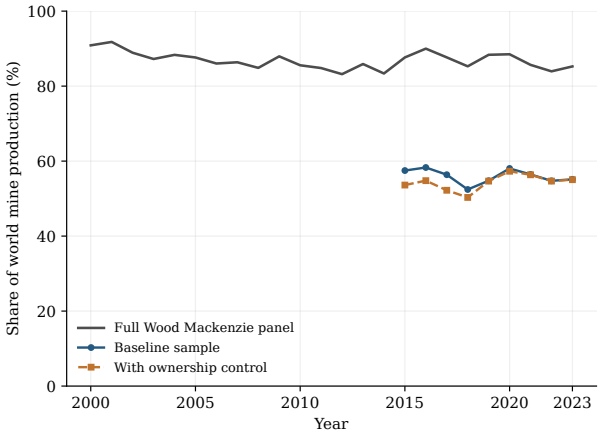
Distributional statistics are unweighted; SD denotes the sample standard deviation. A physical shipment share is the percentage of total covered mine-year output sent to a particular smelter, including spot in the denominator. Spot shares include zero for mine-years without spot sales. Monetary values are in 2017 US dollars. Quantities are in kilotonnes of copper. Common ownership is reported for the sample that includes this control. The final two rows pool copper shipped along common-owner links over 2015-2023, using total physical shipments and total covered output including spot as denominators, respectively.

B.2 Data Coverage

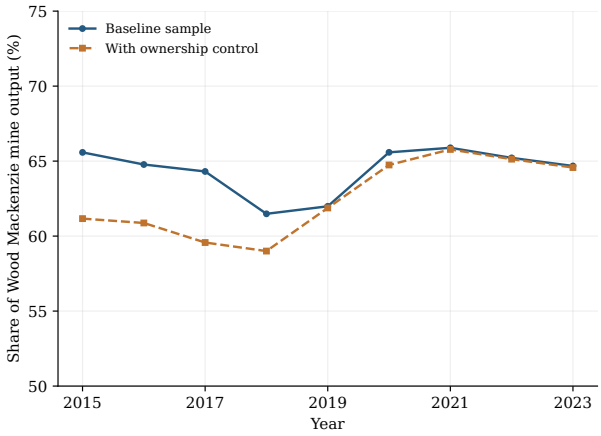
Figure B1 compares the Wood Mackenzie mine panel and the two estimation samples with world mine production reported by the USGS (U.S. Geological Survey, 2024). The full Wood Mackenzie panel accounts for 86.7% of world mine production over 2000–2023 and 86.8% over 2015–2023. Over the estimation period, the baseline sample covers 55.9% of world production and the sample with ownership control covers 54.3%. These correspond to 64.4% and 62.6% of output in the full Wood Mackenzie mine panel, respectively.

Figure B1: World Mine Production and Coverage within Wood Mackenzie

(a) Coverage of world mine production



(b) Coverage within Wood Mackenzie



Panel (a) divides reported copper output in the full Wood Mackenzie mine panel and covered output in each estimation sample by USGS world mine production. Panel (b) divides covered sample output by total output in the Wood Mackenzie mine panel. Both samples include physical deliveries and spot allocations. The full source-panel series spans 2000-2023. The estimation samples span 2015-2023.

C Estimation

This appendix describes the free-copper calibration and estimation criterion used in Section 5.1.

C.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 C1 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 C1 withholds processor identities and individual rates for data confidentiality.

Table C1: 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

C.2 Estimation Criterion

Let $\vartheta = (\beta, \sigma_\epsilon, \delta, d)$ denote the seven estimated parameters. 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

$$\bar{f}_{it}(\vartheta) = \sum_{j \in A_{it} \setminus \{0\}} \frac{s_{ijt}(\vartheta)}{1 - s_{i0t}(\vartheta)} f_{ijt}(\vartheta). \tag{C1}$$

The weights are fitted shares conditional on contracted delivery.

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

$$\begin{aligned} J(\vartheta) = & -\frac{1}{\sum_{(i,t)\in\mathcal{S}} q_{it}} \sum_{(i,t)\in\mathcal{S}} q_{it} \sum_{j \in A_{it}} s_{ijt}^{\text{obs}} \log s_{ijt}(\vartheta) \\ & + \frac{1}{|\mathcal{T}|} \sum_{(i,t)\in\mathcal{T}} \left[\frac{\bar{f}_{it}^{\text{obs}} - \bar{f}_{it}(\vartheta)}{\widehat{\sigma}_f} \right]^2, \end{aligned} \tag{C2}$$

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 a 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. In the baseline, the sample contains 1,060 mine-years, with 3,536 physical smelter-mine-year observations and 539 spot observations.

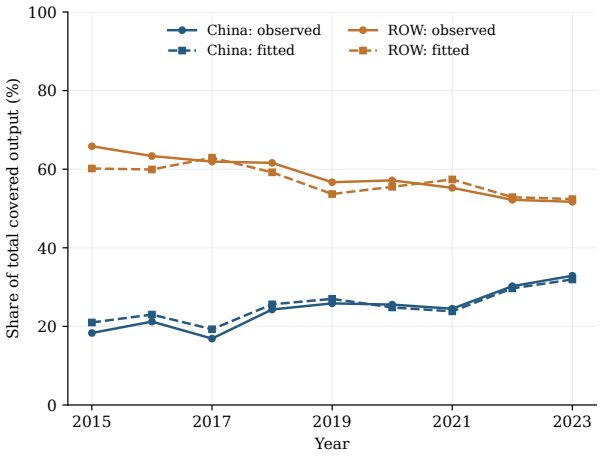
D Additional Estimate Results

D.1 Model Fit

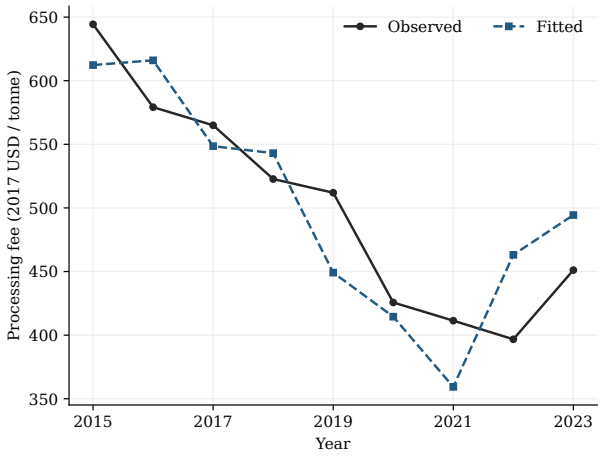
Figure D1 shows the fitted shipment shares and processing fees for the main specification. Overall, the model fits the data very well and captures the main patterns in the data. China's share rises from 18.3% to 32.9% in the data, compared with 21.0% to 31.9% in the fitted series. Observed average processing 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.

Figure D1: Annual Routing Shares and Processing Fees: Main Specification

(a) China and ROW shipment shares



(b) Annual mean processing fees



Notes: Observed series are solid and fitted series are dashed. Panel (a) plots fitted routing shares by China vs. Rest of the world. Panel (b) plots fitted annual mean processing fees (in 2017 US dollars per tonne).

D.2 Estimate Results with Ownership Control

We control for vertical integration by augmenting the contract payoff with an indicator for whether the mine and smelter is owned by the same owner. Table D1 reports the parameter estimates for this specification. The same-ownership coefficient is positive, at $50.58 per tonne, implying a higher payoff from routes to smelters with the same owner, holding processing fees and other route characteristics fixed. The estimated mine bargaining weight is 0.285, compared with 0.277 in the baseline, while the disagreement cost increases from $946 to $1,078 per tonne. These small changes indicate that vertical integration is not major driver of the estimated routing preferences and bargaining parameters. Smelters still receive most of the incremental gains from negotiation.

E Misallocation of Smelting Output

Observation 2 shows that Chinese smelters are the cheapest in the world to run, yet they left capacity idle in every year of our sample while smelters with much higher costs kept operating elsewhere. In this section, we measure the cost of this misallocation. To do this, we follow Asker, Collard-Wexler and De Loecker (2019), who measure misallocation in global oil extraction as the gap between what it costs the oil industry to produce the observed output and the cost if the same output came from its lowest-cost producers. In our setting, however, transportation costs are more important.

Table D1: Parameter Estimates with a Common-Ownership Indicator

Parameter / statistic	Baseline	Ownership control
Contract constant, β_0	8.87	13.43
Log one plus distance	-65.59	-79.74
Domestic smelter	-30.00	-106.51
Chinese smelter	24.83	34.11
Common owner	—	50.58
Routing shock scale, σ_ϵ	1,263.35	1,526.47
Mine bargaining weight, δ	0.277	0.285
Disagreement cost, d	946.22	1,078.14
Mines	148	145
Smelters	65	64
Mine-years	1,060	1,029
Contracted route-years	3,536	3,385
Spot choices	539	526
Share correlation	0.864	0.863
Processing fee correlation	0.866	0.868

Therefore, we measure misallocation route by route and account for transportation costs. We find three things.

1. Misallocation is large. Even after accounting for transportation costs, sending each mine's concentrate to the cheapest available smelters would have saved $6.2 billion over 2015–2023, or 26% of what smelters spent.
2. Idle capacity at Chinese smelters accounts for between 10% and 47% of this misallocation, depending on how we measure idle capacity.
3. Most of the high-cost output outside China comes from smelters that are vertically integrated with mines. These smelters produce 42% of the copper smelted, but 78% of the output that the cost-minimizing allocation moves away from smelters is at these smelters.

E.1 Measuring misallocation

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

$$C^*_t = \min_{\{x_{ijt}\geq 0\}} \sum_{i,j} (c_{jt} + \tau_{ij})\, x_{ijt} \quad \text{subject to} \quad \sum_j x_{ijt} = \sum_j x^0_{ijt} \;\; \forall i, \qquad \sum_i x_{ijt} \leq A_{jt} \;\; \forall j. \quad \text{(E1)}$$

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 the transportation 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] Reallocating concentrate to the lowest cost smelters requires a measure of capacity at each smelter. In our data, we observe nameplate capacity. We set the practical capacity limit to 90% of the smelter's nameplate capacity to smelt concentrate, the industry benchmark used in Observation 2, or to its maximum observed output over our sample, if that is 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 practical capacity that remains.

We also require a measure of smelting costs. Our main measure is Wood Mackenzie's net cash cost: consumables, power, fuel, labor, maintenance, and onsite services, net of credits for sulfuric acid and energy. Cash cost includes some costs that are likely fixed in the short run, so as a robustness check we also use a measure of variable cost, dropping labor, maintenance, and onsite service costs.[16]

The observed allocation covers shipments to the 73 smelters in Wood Mackenzie's cost database and about 10.9 million tonnes of copper per 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.

We split misallocation into three parts. The first is the saving from rerouting concentrate among Chinese smelters, holding fixed how much each mine sends to China. The second is the saving from optimizing shipments within the rest of the world. The third is the remainder, which represents the saving from moving concentrate between the two groups once each group is efficient on its own.

[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 transportation 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.

If Chinese coordination that leads to Chinese smelters withholding capacity would show up in this remainder.

We bound the impact of China's coordination by considering two reallocation methods. In the first, we allow Chinese smelters to increase output only after the rest of the world has already moved its own concentrate to its cheapest smelters. Therefore, we first minimize the costs wihtin all non-Chinese smelters and, separately, within all Chinese smelters, holding fixed their respective quantities. After this, we allow smelting quantities to shift from the rest of the world to Chinese smelters. This will lead to a conservative amount of misallocation due to Chinese withholding. In our second approach, we compute a "coordination counterfactual" that starts from the observed allocation and shifts smelting output first to Chinese smelters. Here, shipments to Chinese smelters can only rise, and shipments to other smelters can only fall, so the only change allowed is moving concentrate into idle Chinese capacity.

We analyze a second source of misallocation. Many smelters outside China also belong to mining companies and take much of their concentrate from their owners' mines. We measure misallocations that arise from these vertically integrated mine-smelter pairs. We call a smelter vertically integrated, or captive, if it took at least a quarter of its concentrate from mines with the same majority owner. There are 33 such smelters, and they produce 42% of the copper smelted. In this case, only shipments between a mine and a smelter with the same majority owner can be rerouted. These shipments make up 35% of the volume. As a robustness check, we also do the reverse and hold these shipments fixed.

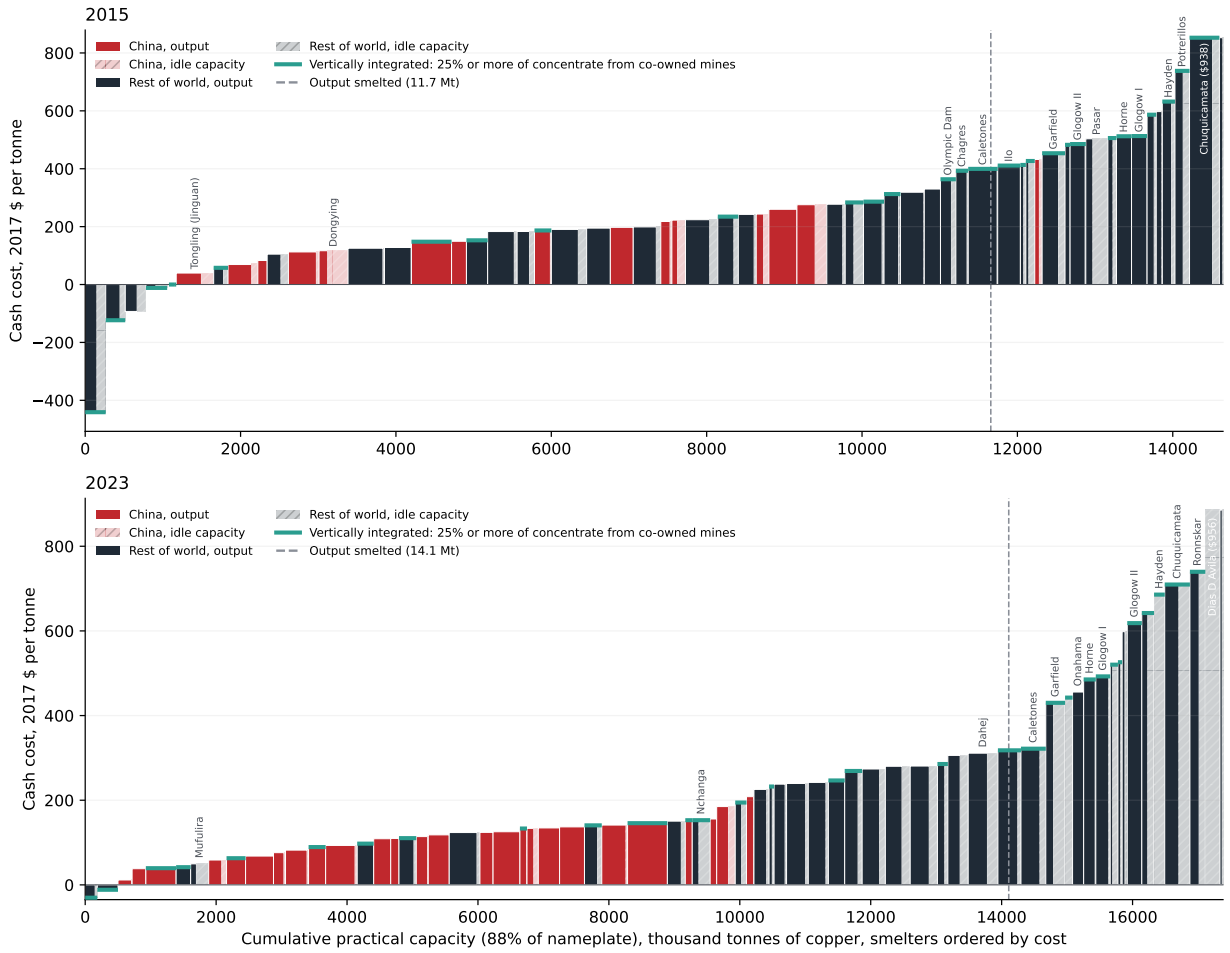
E.2 How large is misallocation?

We start by showing the merit orders in our first and last year of complete data in Figure E2. Each bar is a smelter, and the smelters are ordered from cheapest to most expensive. The width of a bar is the smelter's capacity, and its height is its cash cost per tonne. The solid part of each bar is the copper the smelter actually smelted, and the hatched part is capacity it left idle. A teal line along the top of a bar identifies a vertically integrated smelter. The dashed vertical line marks how much copper was smelted in total.

If concentrate was allocated efficiently, smelter capacity would be used from left to right: the cheapest smelters would run full, and the most expensive smelters, to the right of the dashed line,

would be the ones left idle (ignoring transportation costs for now). The figure shows something different. In 2015, several Chinese smelters with idle capacity, including Tongling's Jinguan smelter and Dongying, had costs below $150 per tonne. At the same time, Codelco's Chuquicamata and Potrerillos smelters, KGHM's Glogow smelters, Hayden, Horne, and Garfield operated at costs between about $450 and $950 per tonne. Over this time period, China's idle capacity fell from 923 thousand tonnes in 2015 to 371 thousand tonnes in 2023, but the high-cost smelters outside China kept operating.

Figure E2: Merit order of copper smelting capacity, 2015 and 2023. Each bar is a smelter, ordered by net cash cost. Bar width is practical capacity, 88% of nameplate capacity to smelt concentrate or observed output if higher. The solid part is output smelted from concentrate and the hatched part is idle capacity. A teal line along the top of a bar marks a vertically integrated smelter, one that took at least 25% of its concentrate from mines with the same majority owner. The dashed line marks total output. Bars above the axis limit are cut off and labeled with their cost. 2017 dollars per tonne of anode. Source: Wood Mackenzie smelter cost data.



The merit order ignores where concentrate comes from. A cheap smelter in China is only a good substitute for an expensive smelter in Chile if the extra cost of shipping Chilean concentrate to China is smaller than the difference in smelting costs. Equation (E1) accounts for this. It reassigns each mine's concentrate across smelters to minimize smelting plus transport costs, with each mine's output fixed and each smelter limited to its capacity.

The cost-minimizing allocation takes output away mainly from the high-cost smelters on the right of Figure E2. The largest reductions are at KGHM's two Glogow smelters, Chuquicamata, Horne, Garfield, Caletones, and Potrerillos, all of which are vertically integrated, and at Onahama in Japan and Pasar in the Philippines. The concentrate goes mainly to two groups of smelters with low costs and idle capacity: Mufulira and Nchanga in Zambia, and Chinese smelters such as Dongying, Jinchuan, Tongling's Jinguan smelter, and Chifeng Jinjian. Smaller amounts go to low-cost smelters elsewhere, such as Aurubis's Hamburg smelter and Dahej in India.

Table E2 reports the totals for 2015–2023. 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. This is 26% of smelting costs, or $63 per tonne of copper. Transport costs therefore matter, but they offset only a small part of the difference in smelting costs. The cost-minimizing allocation would also raise China's share of this concentrate from 31% to 36%.

Misallocation has fallen over our sample (Figure E3), as Chinese smelters ran closer to capacity. It was $80 per tonne in 2015 and $52 per tonne in 2023.

Where the misallocation is. To understand how much of this misallocation involves China, we split it into three parts. We compute the parts in sequence, as each step answers a narrower question.

1. *Within the rest of the world.* We first allow concentrate to move only among smelters outside China, holding fixed how much each mine sends to China. This saves $5.1 billion, 83% of the total. Most of the misallocation is therefore among smelters outside China: cheap capacity outside China, mainly in Zambia, Germany, and India, could replace much of the output of the expensive smelters outside China without any concentrate moving to China.

Table E2: 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	Coordi-nation	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 (E1), 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 coordination 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.

2. *Within China.* We next allow concentrate to move only among Chinese smelters, holding fixed how much each mine sends to China. This saves $0.47 billion, 8% of the total. Chinese smelters have similar costs, so there is little to gain from rearranging output among them.
3. *Between the two groups.* Finally, starting from the allocation in which each group is already efficient on its own, we allow concentrate to move between China and the rest of the world. This saves the remaining $0.61 billion, 10% of the total.

If Chinese smelters hold back capacity, the third part is where it would appear. The third part is small, however, because of the order of the steps. By the time concentrate is allowed to move to China, the most expensive smelters outside China have already been replaced by cheap capacity outside China, so there is little high-cost output left for idle Chinese capacity to displace.

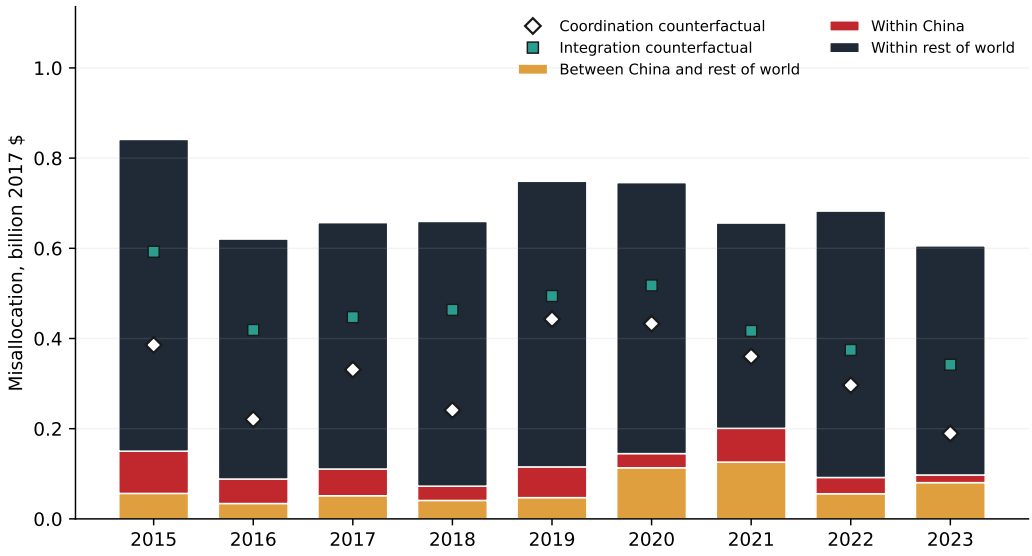
The "coordination counterfactual" reverses the order. It starts from the observed allocation and allows only one change: mines can send concentrate to idle Chinese capacity in place of the most expensive smelters elsewhere. Shipments to Chinese smelters can only rise, and shipments to other smelters can only fall. In this case, mines would 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. Under this counterfactual, costs would have been $2.9 billion lower, 47% of total misallocation.

These two exercises bound the costs associated with Chinese smelter coordination. At the low

end, eliminating Chinese withholding reduces costs by 10%, while at the high end, it reduces costs by 47%. For comparison, Asker, Collard-Wexler and De Loecker (2019) attribute between 14.1% and 21.9% of misallocation in oil extraction to market power.

Unlike total misallocation, the coordination 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 (Figure E3).

Figure E3: Misallocation by year, 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 coordination counterfactual, in which mines send concentrate to idle Chinese capacity in place of the most expensive smelters elsewhere, and squares mark the integration counterfactual, in which only shipments between co-owned mines and smelters are rerouted. Smelting cost plus transport cost, billions of 2017 dollars.



E.3 Vertical integration

The high-cost smelters outside China are mostly vertically integrated with mines. Weighting by output, captive smelters outside China had a net cash cost of $352 per tonne, compared with $224 at independent smelters outside China and $108 in China. Most of the gap is in labor, maintenance, and onsite services rather than in consumables, power, and fuel (Appendix Figure **??**). Captive smelters produce 42% of the copper smelted. However, of the output that the cost-minimizing allocation moves away from smelters, 78% is at captive smelters.

The integration counterfactual is correspondingly large. Rerouting only the shipments between

co-owned mines and smelters would have saved $4.1 billion, 65% of total misallocation. 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, and removes 35% of the misallocation within the rest of the world.

Importantly, the coordination and integration counterfactuals overlap and should not be added. Of the output that idle Chinese capacity displaces in the coordination counterfactual, 75% comes from captive smelters. Both counterfactuals therefore largely describe the same reallocation, from captive smelters outside China to idle capacity in China. 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 coordination 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.

E.4 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. For these mines, misallocation is $4.9 billion, 26% of smelting costs, and the coordination counterfactual accounts for 50% of it (Table E2).

Using variable cost alone, misallocation is $4.5 billion. Here, however, the coordination 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. Whether the coordination counterfactual is closer to the cash-cost or the variable-cost estimate depends on how much of labor, maintenance, and onsite services a smelter would save by running less, or closing.

Finally, the 88% benchmark may misstate the capacity smelters can actually use. To check this, we compute each smelter's highest observed utilization over 2015–2024 (Appendix Figure **??**). The median Chinese smelter reached 0.98 of nameplate capacity in its best year, and 79% of Chinese smelters reached 88% at some point. Outside China, the median smelter reached 0.86, and only 47% reached 88%. The benchmark therefore likely understates the capacity Chinese smelters can use

and overstates it elsewhere. Appendix Table **??** reports the results when capacity is 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 coordination counterfactual from 47% to 57% of the total.

E.5 Interpretation

Three caveats are worth noting for this exercise. First, it holds each mine's output fixed and only adjusts its concentrate that is smelted. It does not measure the effect of coordination on the processing charge, itself, which would potentially change production at the mine level. Second, 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. And, finally, not all of the gap reflects market power. Smelters differ in the concentrates they can treat, in their ability to recover copper and precious metals, which we do not count as a cost.

The split between the two measures of coordination also has an economic interpretation. The between-group measure 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 remain in business. In the long-run counterfactual without coordination in Section 7, 32% of smelting capacity outside China closes. Part of the misallocation within the rest of the world may therefore itself be a consequence of coordination.