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Copper Supply Chain Thermodynamics as a Leading Indicator of Geopolitical Instability

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Abstract:

Every ton of refined copper carries two measurable costs: a financial cost denominated in US dollars on the London Metal Exchange (LME), and a thermodynamic cost measured in gigajoules (GJ) of energy consumed across mining, concentration, smelting, refining, and maritime transit. Under stable conditions, these two costs correlate closely. This paper identifies conditions under which they diverge and argues that persistent divergences between dollar cost and energy cost serve as leading indicators of geopolitical instability in the copper supply chain. Five categories of supply-chain chokepoint are examined: maritime (Hormuz, Malacca, Panama), chemical (sulphuric acid), processing (Chinese smelter concentration), institutional (Codelco, social license in Peru), and hydrological (Atacama desalination). Analysis of the 2026 Hormuz crisis, the concurrent sulphuric acid supply failure, and the structural divergence between Chinese and Western smelting costs demonstrates that the copper supply system is currently experiencing simultaneous stress at multiple nodes. The paper concludes that thermodynamic cost analysis offers a complementary framework to conventional commodity-price analysis for anticipating supply-chain failure and geopolitical realignment.

Keywords: copper, thermodynamics, geopolitical risk, supply chain, chokepoint analysis, energy intensity, critical minerals, smelting concentration

1. Introduction

Copper is the second most electrically conductive metal after silver, at 58.7 MS/m, and orders of magnitude cheaper, making it the primary conductor in global electrical infrastructure [1]. Its price has long been regarded as a leading macroeconomic indicator; the colloquial term 'Doctor Copper' reflects the metal's observed ability to predict turning points in industrial output with greater accuracy than many institutional forecasting models [2]. However, the conventional interpretation of copper price as a demand-side signal overlooks a critical supply-side dimension: the energy cost embedded in every ton of refined metal. The lifecycle energy intensity of copper production ranges from 33 to 102 GJ per ton, depending on ore grade, mining method, and process route [3][4]. As global average ore grades have declined from approximately 1.5% in the 1990s to 0.5% in 2024 [1][5], this energy intensity has risen structurally. Energy accounts for 25–40% of cash operating costs in copper mining [6]. The thermodynamic cost of copper production is therefore not a secondary consideration; it is a primary determinant of the metal's economic viability and geopolitical distribution.

This paper proposes a dual-cost analytical framework in which each ton of copper is evaluated by both its LME dollar price and its cumulative energy input in gigajoules. Persistent divergences between these two measures are hypothesized to function as leading indicators of structural instability in the global copper supply chain. Section 2 reviews existing literature on copper energy intensity, supply-chain vulnerability, and commodity geopolitics. Section 3 outlines the analytical methodology. Sections 4 and 5 present findings across five chokepoint categories and discuss their geopolitical implications. Section 6 provides conclusions and identifies directions for further research.

2. iterature Review

The relationship between ore grade decline and energy intensity in copper mining has been quantified across several studies. Calvo et al. [1] demonstrated that average copper ore grades decreased approximately 25% in a single decade, while total energy consumption at the mines studied increased 46% against a 30% production increase over the same period. Koppelaar and Koppelaar [2] modelled the ore-grade-to-energy relationship and found that below 0.5% grade, energy requirements begin to escalate non-linearly. Northey et al. [3] provided lifecycle energy estimates for copper production ranging from 33 to 102 GJ/t across different ore types and process routes. A 2026 study in the Journal of Industrial Ecology [7] confirmed that, for Chilean operations, ore grade decline at critically low levels eliminates the climate benefits of renewable energy adoption in mining, because the energy demands of processing low-grade ore overwhelm the gains from clean power sources.

Research on maritime chokepoint vulnerability has expanded rapidly. Hall et al. [8], published in Nature Communications in 2025, estimated the expected value of trade disrupted at maritime chokepoints at USD 192 billion annually, with the Taiwan Strait and Suez Canal identified as the highest-risk passages. The UNCTAD Review of Maritime Transport 2024 [9] documented a greater than 50% decline in Suez Canal traffic due to Houthi attacks, with cascading effects on commodity shipping. Wang et al. [10], in a ScienceDirect review, examined the intersection of geopolitics and critical mineral shipping, identifying academic gaps in how maritime transport risk is modelled for mineral supply chains specifically.

On the concentration of copper processing capacity, Columbia University's Centre on Global Energy Policy (CGEP) [11] reported that China produced 48% of global smelting output in 2024 despite accounting for only 8% of copper concentrate production. Wood Mackenzie [12] found that China has contributed 75% of all global smelter capacity growth since 2000 and described complete replacement of China in the copper supply chain as 'unfeasible.' Toro et al. [13] examined the water-energy nexus in Chilean copper leaching and identified that desalination transfers the problem of water scarcity into a problem of energy cost. Benavides et al. [14] analyzed barriers and opportunities for desalination investment in Chilean mining, finding that while desalination enables continued operation independent of freshwater, it embeds a permanent energy premium into production costs. Existing literature has examined these factorsenergy intensity, maritime vulnerability, processing concentration, and hydrological stresslargely in isolation. This paper contributes by integrating them within a single thermodynamic framework and examining the conditions under which they compound.

3. Methodology

The analytical framework employed in this paper evaluates each node in the copper supply chain along two parallel dimensions: (a) the financial cost, defined as the cash operating cost per ton of copper at that node, denominated in US dollars; and (b) the energy cost, defined as the cumulative gigajoule input per ton at that node, derived from published lifecycle energy analyses [1][2][3][4].

Five categories of supply-chain chokepoint are identified and examined: maritime transit (Strait of Hormuz, Strait of Malacca, Panama Canal), chemical inputs (sulphuric acid supply), processing concentration (Chinese smelter dominance and TC/RC pricing), institutional nodes (state producers and social-license constraints), and hydrological constraints (desalination dependency in Chile and watershed conflicts in Peru). For each chokepoint, the analysis identifies: (i) the mechanism by which the chokepoint adds energy cost to the supply chain; (ii) the degree to which the resulting energy cost is reflected in the LME dollar price; and (iii) the geopolitical implications of any persistent divergence between the two.

Where the dollar cost and energy cost move in parallel, the system is considered stable at that node. Where the energy cost rises without a corresponding dollar-price adjustment (as in Chilean desalination), or where the dollar cost is artificially suppressed below the energy cost (as in Chinese state-subsidized smelting), the divergence is classified as a structural distortion with geopolitical implications. The paper also applies scenario analysis to five plausible stress events, evaluating the direction and magnitude of dollar-joule divergence under each scenario.

4. Results and Discussion

4.1 Energy Cost Profile of Copper Production

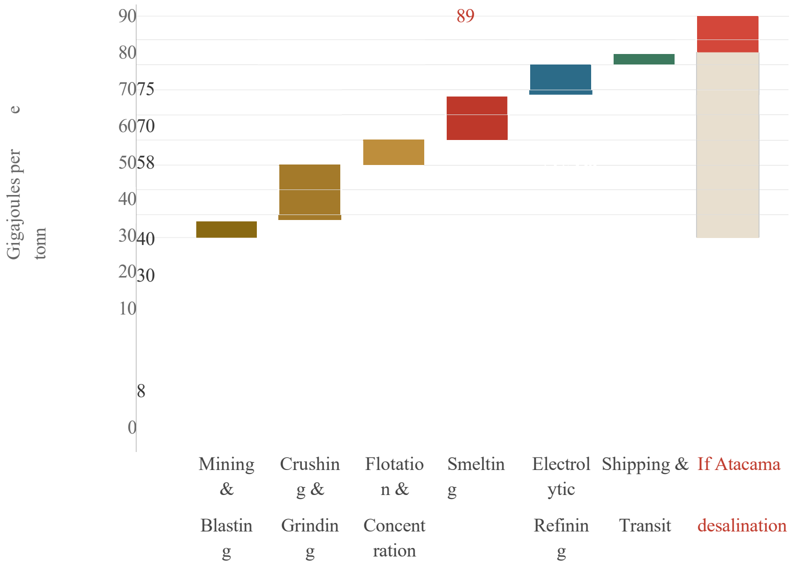
Fig. 1 presents the cumulative energy cost of producing one ton of refined copper across six production stages. The total ranges from approximately 60 GJ/t for high-grade operations with conventional water supply to over 89 GJ/t for low-grade Chilean operations requiring desalination. Crushing and grinding account for the largest single energy input (approximately 22 GJ/t), followed by smelting (18 GJ/t) and electrolytic refining (12 GJ/t).

The desalination premium for Atacama operations adds approximately 14 GJ/tan energy input that did not exist in Chilean copper production costs before 2015 [13][14]. Cochilco

[17] projects that by 2034, seawater pumping and desalination alone will consume 6.5 terawatt-hours per year, or one-fifth of all energy consumed by Chilean mining.

Fig. 1: Cumulative Energy Cost of Producing One Ton of Refined Copper (GJ/t)

Mid-range estimates. Sources: Calvo et al. [1], Koppelaar & Koppelaar [2], Cochilco [17]



Maritime Chokepoints as Energy Barriers

The closure of the Strait of Hormuz in February 2026 added approximately 30% in fuel costs to bulk carriers rerouting via the Cape of Good Hope, translating to additional embodied energy in every ton of copper cathode and chemical inputs transiting the affected routes [15][16]. COMEX copper futures reached

$6.51/lb by May 2026 [15]. The Strait of Malacca, at 1.7 miles wide at its narrowest point, carries over 60% of China's seaborne imports, including most copper concentrate bound for Chinese smelters [8][10]. Hall et al. [8] estimate that a Taiwan Strait disruption would rank among the highest-impact maritime chokepoint events globally. The Panama Canal's 2023–24 drought reduced transit capacity by 40%, affecting copper and metal concentrate shipments from Latin America to Atlantic markets [9][18]. Each of these chokepoint's function as an energy barrier: when activated, it raises the joule cost of copper without necessarily producing an immediate corresponding movement in the dollar price.

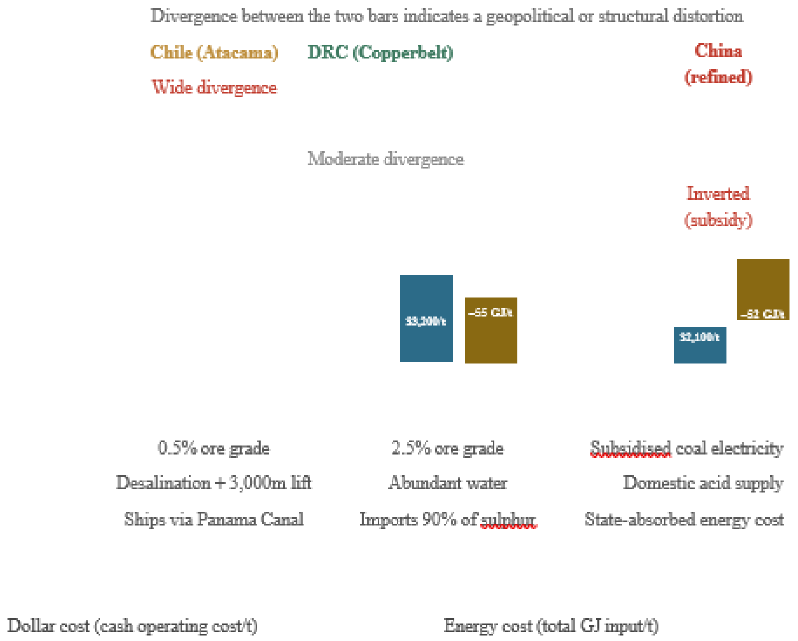
4.2 The Sulphuric Acid Chokepoint

Sulphuric acid is required at approximately 2.5 ton per ton of copper produced via the SX-EW process, which accounts for roughly 16% of global copper output [19]. In 2026, three concurrent disruptions affected global acid supply: the Hormuz closure blocked approximately 45% of globally traded Sulphur [15]; Russia extended its Sulphur export ban [20]; and China suspended acid exports to protect domestic fertilizer production [21]. Spot acid prices in Chile doubled between February and May 2026 [22]. The thermodynamic significance of this disruption lies in the dual function of sulphuric acid: it serves as a chemical energy carrier in both copper leaching and phosphate fertilizer production [21][22]. A sustained acid shortage therefore generates simultaneous pressure on metals and agricultural supply chains through a single molecular bottleneck.

4.3 Processing Concentration and the Subsidy Divergence

China's 48% share of global smelting output [11] has produced a structural inversion in processing economics. The 2026 benchmark TC/RC between Antofagasta and Jiangxi Copper was set at $0/the first zero-fee benchmark in industry history [23]. Spot TC/RCs reached negative $78.50/t [24]. Chinese state-backed smelters absorb these losses through energy subsidies, byproduct acid revenue, and precious-metal credits [11][12]. The energy input required for smelting is approximately equivalent across geographies; the dollar cost is not. Chinese smelters operate at less than half the cash cost of Western equivalents [11]. This dollar-joule divergence is the clearest structural distortion in the current copper supply chain (Fig. 2). Its consequence is the progressive closure of non-Chinese smelting capacity, concentrating the refining stage of the supply chain in a single jurisdiction.

Fig. 2: Dollar Cost vs. Energy Cost of Copper by Source Region



4.4 Hydrological Constraints and the Water-Energy Recursion

Chile's Atacama region has experienced fourteen consecutive years of drought [14][17]. BHP's Escondida mine now operates entirely on desalinated seawater pumped 3,000 meters uphill [13]. This introduces a thermodynamic recursion: the energy required to produce copper rises because the water required to produce copper now demands its own energy input. Each year the drought persists, the energy cost of Chilean copper increases structurally, while the energy cost of copper from water-abundant regions under Chinese control (DRC, Zambia) remains stable [12][14]. The divergence widens the competitive gap between Chilean and Chinese-controlled supply in both dollar and joule terms.

5. Scenario Analysis

Five stress scenarios were evaluated for their effect on dollar-joule divergence across the supply chain. In all five cases, the directional outcome is consistent: copper becomes structurally more expensive in energy terms, and the distribution of that energy cost becomes more geographically concentrated.

Taiwan contingency: Interdiction of the Malacca Strait severs concentrate supply to Chinese smelters, fracturing the LME into competing dollar- and renminbi-denominated pricing systems. Dollar-joule divergence widens on both sides of the fracture as subsidized and unsubsidized systems decouple permanently [8][11]. **Extended Hormuz closure:** Prolonged Sulphur blockade curtails SX-EW operations in Chile and the DRC; acid prices remain elevated; the food-metals nexus compounds inflationary pressure [15][21][22]. **Southeast Asian conflict:** Disruption to Indonesian concentrate exports (Grasberg alone produced approximately 680,000 tons in 2023) forces substitution from thermodynamically costlier Australian sources via contested sea lanes [8][10]. **Indian subcontinent recession:** India imports over 91% of its copper inputs; a demand collapse in the system's most energy-vulnerable participant would generate a deflationary price signal that obscures the underlying energy-cost trajectory [11][16]. **AI infrastructure bust:** A capex freeze across hyperscale data-center construction would reduce demand for the most energy-intensive new copper application, creating oversupply against committed mine expansions [25].

Across all five scenarios, the invariant finding is directional: the energy cost of copper rises or redistributes in ways that favor jurisdictions willing to subsidize thermodynamic work at the state level. The variance across scenarios lies in severity and timing, not direction.

6. Conclusion and Future Scope

This paper has presented a thermodynamic framework for analyzing the copper supply chain and identifying geopolitical faultlines. The central finding is that persistent divergences between the dollar cost and the energy cost of copper production function as structural indicators of instability. Five categories of chokepoint maritime, chemical, processing, institutional, and hydrological were examined, and in each case the divergence between financial and thermodynamic cost was found to correlate with observable geopolitical tension or supply-chain fragility. The most significant divergence identified is the structural gap between Chinese and Western smelting costs, which reflects a state-level energy subsidy that the current LME pricing mechanism does not capture. The progressive closure of Western smelting capacity is a direct consequence of this divergence. Sadi Carnot demonstrated in 1824 that the efficiency of any heat engine is bounded by absolute physical limits [26]. The copper supply chain is approaching analogous ceilings: hard limits on the energy efficiency of extraction from depleting ore bodies, of desalination and water transport, and of smelting from increasingly scarce concentrate. The nations that control the next phase of industrialization will be those willing to commit the greatest thermodynamic work measured in joules, not dollars to the production of ordered metal from disordered rock.

Several limitations should be noted. The energy-cost estimates used are derived from published mid-range values and vary by operation. The dollar-cost comparisons reflect industry averages rather than mine-specific data. Future work should develop a quantitative index of dollar-joule divergence, calibrated against historical supply disruptions, to enable real-time monitoring. Integration of satellite-derived water availability data with energy-cost modelling for the Atacama and Andean mining regions represents a further research opportunity. The framework may also be extended to other critical minerals lithium, cobalt, nickel, rare earths where similar thermodynamic chokepoints and processing concentrations exist.

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