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Coupling geological exploration with anthropogenic cycles: a systematic approach to assess the dynamics of China's long-term copper supply structure

1. Introduction

Copper is widely recognized as a critical strategic metal that underpins the modern industrial system. Its unique combination of electrical and thermal conductivity, ductility, and corrosion resistance renders it indispensable across power grids, transportation, information and communication technologies, and defense-related applications (Elshkaki et al. 2016; Watari et al. 2019). Its strategic role has been formalized in recent policy initiatives; for example, the European Union's Critical Raw Materials Act (CRMA) classified copper among strategic raw materials in 2024, reflecting its importance for the energy transition and digitalization (Kuipers et al. 2018; Yu 2021; European Commission 2023).

China has emerged as the dominant actor in the global copper market. According to recent assessments, China accounted for more than 50% of global refined copper consumption

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in 2023–2024, driving nearly all net demand growth (Dong et al. 2020; International Energy Agency 2021). Global refined copper consumption in 2023 reached approximately 27 million metric tons (Mt), with China's per capita apparent consumption significantly exceeding the global average (Zhang et al. 2015a). Copper is thus a primary target for global geological investment, yet worldwide nonferrous metals exploration expenditures remained constrained, with copper-specific budgets estimated at around 13–15 billion USD in recent years (Witherly 2020; S&P Global 2024).

Despite massive demand, China faces a structural asymmetry in its copper resource endowment. Domestic reserves are limited, and ore grades exhibit a declining trend, which has led to a heavy reliance on imported ores and concentrates (Dong et al. 2019; Li et al. 2023). By 2023–2024, China's refined copper consumption exceeded 15 Mt (approximately 55% of global total), concentrate imports reached over 25 Mt (in gross weight), while domestic mine production was only around 1.8–2.0 Mt (less than 10% of global output) (Mineral commodity summaries 2025, 2025; Yin et al. 2024). This configuration renders the supply chain vulnerable to upstream disruptions originating from a small number of resource-rich exporting countries (Liu et al. 2021).

From an economic perspective, this configuration represents a transition from predominantly geological constraints to geopolitical and market-driven risks (Tilton 1996). China has invested heavily in smelting capacity and downstream fabrication, but the upstream segment remains increasingly dependent on volatile international markets and a concentrated set of suppliers (Li et al. 2023). Understanding how exploration investment, ore depletion, recycling, and trade interact over time is therefore a key question in the economics of mineral resources and national resource security (Northey et al. 2014).

However, both industrial practice and a substantial body of the academic literature remain predominantly "smelting-centric and exploration-neglected". Analyses often focus on midstream bottlenecks in smelting and refining, while upstream exploration is treated as a quasi-infinite boundary condition, implicitly assuming that ore supply can always be expanded when needed (Graedel et al. 2012). In reality, exploration exhibits latency, uncertain outcomes, and declining discovery efficiency, especially in mature districts (Northey et al. 2014; Schodde 2017). Ignoring these features leads to overly optimistic assessments of long-term supply resilience.

Against this backdrop, there is a need for an integrated modeling framework that connects geological exploration decisions with anthropogenic copper cycles and security outcomes (Glöser et al. 2013; Elshkaki et al. 2016).

This paper responds to that need by explicitly endogenizing exploration and linking it to mining, smelting, recycling, and trade within a system dynamics material flow analysis (MFA) model for China.

1.1. Literature review

The STAF (Stocks and Flows) project (Graedel et al. 2012) established a multilevel framework for mapping anthropogenic copper cycles, demonstrating the critical role of in-use stocks in governing future scrap generation (Gerst 2009; Glöser et al. 2013). In China, subsequent studies have applied dynamic MFA to forecast scrap availability based on historical consumption cohorts and sectoral lifetime distributions (Zhang et al. 2015a, b; Dong et al. 2019). These works have greatly improved the understanding of the temporal evolution of the "urban mine". However, these studies typically treat primary mine output as an exogenous input derived from national or international statistics, thereby failing to explain how exploration dynamics and geological constraints shape future supply trajectories (Elshkaki et al. 2016; Dong et al. 2020).

In mineral economics, the relationship between commodity prices, exploration investment, and supply has long been central (Tilton 1996). In theory, higher prices should stimulate exploration, generate new discoveries, and eventually increase production. Yet empirical evidence indicates that the time lag between discovery and production can span one or two decades and that discovery efficiency has declined as easily accessible deposits are exhausted (Guj and Schodde 2025; Northey et al. 2014). Global resource models such as WORLD6 incorporate generic depletion mechanisms (Sverdrup et al. 2017), but rarely quantify the specific impact of country-level policy initiatives on reserve replacement and self-sufficiency.

Parallel research on critical metals has broadened the focus from physical availability to supply chain resilience. Metrics such as import dependence, supplier concentration, and price volatility are increasingly employed to characterize vulnerability (Dong et al. 2020; Galos et al. 2021; Helbig et al. 2018; Yu 2020). For copper, several studies document China's rising dependence on imported concentrates and the geographic concentration of suppliers (Chen et al. 2025) . However, few contributions link exploration, depletion, smelting capacity expansion, recycling, and external dependence within a single dynamic framework, nor do they systematically compare supply-side and demand-side policy strategies (Kuipers et al. 2018; Seck et al. 2020).

The present study contributes to this literature by integrating a price-responsive exploration model into a national-scale copper MFA for China and by evaluating alternative policy pathways in terms of both physical flows and indicators of economic risk, such as the External Dependence Ratio (Dong et al. 2020; Li et al. 2023).

1.2. Research objectives and contributions

The primary objective of this study is to develop and apply a system dynamics MFA model that explicitly couples geological exploration, primary mining, secondary recovery, and trade to assess the evolution of China's copper supply structure under alternative policy scenarios (Glöser et al. 2013; Elshkaki et al. 2016; Dong et al. 2020). Rather than treating mine output as exogenous, the model endogenizes exploration decisions and geological constraints, thus providing a more realistic basis for medium- to long-term security assessment (Northey et al. 2014; Kuipers et al. 2018; Guj and Schodde 2025).

The study makes three specific contributions. First, it constructs an exploration sub-model in which investment responds to lagged copper prices and converts into new reserves through a discovery efficiency parameter that declines over time to capture depletion (Tilton and Lagos 2007; Schodde 2013; Tilton et al. 2018). Second, it links this exploration sub-model to a national copper MFA including mining, smelting, consumption, and recycling, and derives explicit indicators of security and economic risk, such as the External Dependence Ratio and the Secondary Supply Ratio (Dong et al. 2020; Li et al. 2023; Watari et al. 2019). Third, it designs and compares three policy scenarios – Business-as-Usual, Intense Extraction, and Circular Transition – and discusses their implications for the economics of resource security and the design of exploration and recycling policies (Dong et al. 2020; Seck et al. 2020; Watari et al. 2019).

2. Materials and methods

To quantify alternative copper security pathways for China, a discrete-time system dynamics model is developed with annual time steps from 2016 to 2040 (Glöser et al. 2013; Dong et al. 2019). The calibration phase (2016–2024) uses historical data on reserves, mining, smelting, trade and recycling. Unless otherwise noted, reserve data for China are taken from the U.S. Geological Survey (USGS), primarily from Mineral Commodity Summaries and related annual statistical releases (Zhang et al. 2015a; Chen et al. 2025; U.S. Geological Survey 2025). The model is implemented at the national level and tracks copper flows from geological resources to in-use stocks and end-of-life recycling, as well as imports and exports of concentrates and refined copper (Graedel et al. 2004; Gordon et al. 2006; Gerst 2009; Dong et al. 2020).

2.1. System boundaries and framework

Geographically confined to mainland China, the model establishes a closed-loop feedback system coupling two subsystems (Figure 1). Unlike linear “take–make–waste” representations, this framework explicitly endogenizes the Geological Exploration Subsystem (orange panel), where price-responsive investment drives drilling and reserve additions, subject to declining discovery efficiency in mature districts. The Anthropogenic Subsystem (blue/grey panels) traces the full lifecycle from mining, smelting, and manufacturing to end-use stocks and trade flows (Graedel et al. 2004; Glöser et al. 2013; Elshkaki et al. 2016).

Crucially, the Scrap Collection & Separation module (green panel) reflects China’s distinct stock structure. Unlike Western patterns characterized by legacy copper telecom cables, China experienced a technological “leapfrog” to optical fibers, resulting in minimal copper stock in communication lines. Instead, recovery potential is concentrated in power grid assets (>45% of stock) and appliances. Consequently, the model simulates a collection system transitioning from informal networks to standardized industrial parks rather than legacy cable recovery (Li et al. 2023).

A market feedback mechanism (red dashed arrow) closes the loop, linking demand-driven prices to corporate exploration budgets with realistic time lags. This dual-subsystem architecture enables scenario-specific assessment of how intensified exploration (supply-side) versus enhanced recycling (demand-side) alters the External Dependence Ratio (EDR) under geological and policy constraints.

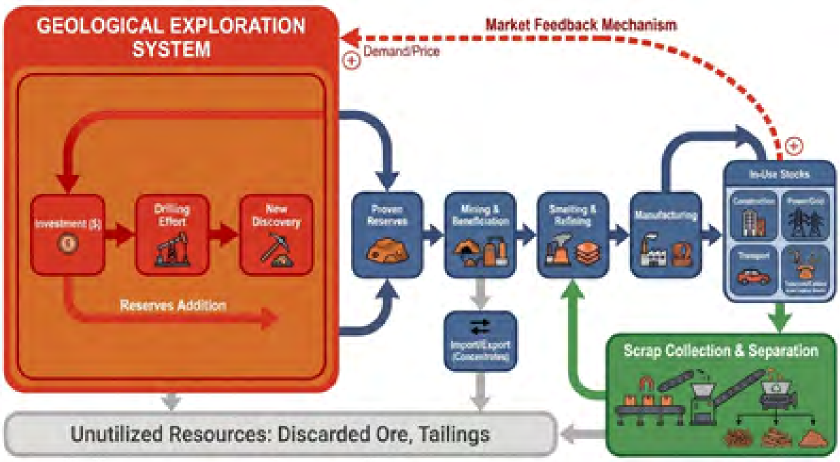

Fig. 1. Integrated system dynamics framework for China's copper supply structure analysis
The geological exploration system (orange) endogenizes reserve replacement via price-responsive investment. The anthropogenic system (blue) encompasses mining, smelting, manufacturing, and in-use stocks. The Scrap Collection & Separation module (green) closes the loop, reflecting a stock structure dominated by power grid assets rather than legacy telecom lines. A market feedback mechanism (red dashed arrow) links prices to exploration, while the grey panel accounts for unutilized resources

Rys. 1. Zintegrowane ramy dynamiki systemowej do analizy struktury podaży miedzi w Chinach

2.2. Geological exploration and reserve dynamics

The geological exploration module quantifies the dual mechanism by which copper prices drive exploration investment and investment is converted into reserve additions, subject to declining discovery efficiency under geological depletion. The theoretical foundation rests on the conservation of mass applied to the reserve stock. Annual reserve additions $R_{add}(t)$ are derived from observed year-end reserve levels $S_{res}(t)$ and mine production $Q_{mine}(t)$ via a stock-balance identity. Observed year-end reserve levels refer to USGS reserve estimates for China, which are used as the baseline reserve series for model calibration.

$$R_{add}(t) = S_{res}(t) - S_{res}(t-1) + Q_{mine}(t) \quad (1)$$

Based on the stock-balance identity (Equation 1) and historical calibration, we further quantify the exploration investment mechanism.

Reflecting the dual drive of market price signals and state-led strategic prospecting mandates, exploration investment $I_{exp}(t)$ is modelled as a power function of the lagged copper price to capture empirically observed budget adjustments:

$$I_{\exp}(t) = I_{base} \cdot \left[\frac{P_{Cu}(t-2)}{P_{ref}} \right]^{\beta} \quad (2)$$

- I_{base} – baseline exploration expenditure ($6.3 \cdot 10^8$ RMB, corresponding to the structural low in 2019),
- P_{ref} – reference price (6,000 USD/t),
- β – price-elasticity coefficient.

Calibration against the 2022–2024 exploration recovery – during which investment increased from 6.57 to 11.69 ($\cdot 10^8$ RMB) in response to a lagged price rise from ~6000 to ~9000 USD/t – yields an estimated elasticity $\beta = 1.5$.

The conversion of investment into new reserves is governed by the discovery efficiency $\eta(t)$:

$$R_{add}(t) = I_{exp}(t) \cdot \eta(t) \quad (3)$$

- $\eta(t)$ – discovery efficiency, calibrated to a 2024 baseline of $\eta(t) = 18.39$ ($\cdot 10^4$ t/10^8 RMB), and assumed to decline exponentially to reflect progressive exhaustion of high-grade deposits:

$$\eta(t) = \eta_0 \cdot \exp[-\lambda(t - t_0)] \quad (4)$$

- η_0 = 18.39 ($\cdot 10^4$ t/10^8 RMB), $t_0 = 2024$,

λ = 0.02 yr^{-1}, representing a 2% annual decline.

Physically, this decay captures the escalating technical difficulty of transitioning from exploring outcropping deposits to targeting deep-seated blind ores in mature districts.

The reserve stock is updated dynamically via the following accumulation equation:

$$S_{res}(t) = S_{res}(t-1) + R_{add}(t) - Q_{mine}(t) \quad (5)$$

ensuring that mining activities remain constrained by the evolving reserve base.

2.3. Primary production and smelting balance

This module quantifies domestic primary production capacity and the smelting feedstock balance, linking mine output, secondary scrap inputs, and concentrate imports to refined copper production. Annual domestic mine production ($Q_{mine}(t)$) is represented as:

$$Q_{mine}(t) = \min[PlanCap(t), S_{res}(t) \cdot \gamma_{extract}] \tag{6}$$

- $PlanCap(t)$ – planned mining capacity (derived from industry projections),
- $\gamma_{extract}$ – maximum sustainable annual extraction rate, calibrated to ~5%, aligning with China's long-term average Reserve-to-Production (R/P) ratio of approximately 20 years, representing an industry-standard equilibrium.

The smelting feedstock balance determines concentrate import requirements. Net concentrate imports (in metal content), $Imp_{conc}(t)$ are computed residually as:

$$Imp_{conc}(t) = \left[Q_{ref\_prod}(t) - Q_{scrap\_feed}(t)\right] / \varepsilon_{smelt} - Q_{mine}(t) \tag{7}$$

- $Q_{ref\_prod}(t)$ – domestic refined production,
- $Q_{scrap\_feed}(t)$ – secondary scrap entering smelting,
- ε_{smelt} – overall smelting and refining recovery efficiency (assumed to be 97.5%).

2.4. Refined copper demand and secondary supply

Refined copper demand $Dcons(t)$ is projected using a logistic saturation function, reflecting the empirical trajectory of per capita in-use stock accumulation in China's late-stage industrialization:

$$Dcons(t) = \frac{K_{peak}}{\left[1 + \exp\left(-r(t - t_{mid})\right)\right]} \tag{8}$$

- K_{peak} – asymptotic demand ceiling,
- r – logistic growth rate,
- t_{mid} – inflection year. Parameters are calibrated to historical consumption data (2016–2024) and reconciled with independent projections.

Secondary supply ($Q_{sec}(t)$) is calculated as:

$$Q_{sec}(t) = D_{cons}(t) \cdot SSR(t) \tag{9}$$

↳ $SSR(t)$ – Secondary Supply Ratio, defined as the share of demand met by secondary copper. System resilience and economic risk are evaluated using the External Dependence Ratio:

$$EDR(t) = \frac{Imp_{conc}(t)}{Q_{ref\_prod}(t)} \tag{10}$$

↳ $Imp_{conc}(t)$ – net concentrate imports (in metal content) and
$Q_{ref\_prod}(t)$ – domestic refined copper production. EDR thus measures the share of domestic smelting feedstock sourced from imports; lower values indicate reduced upstream vulnerability.

2.5. Model validation

Model validity is assessed through retrospective comparison of simulated trajectories against observed historical data (2016–2024), focusing on mine production, refined output, consumption, and imports. Validation results indicate that the Mean Absolute Percentage Error (MAPE) for these key variables remains below 8%, aligning with established benchmarks for dynamic MFA models (Elshkaki et al. 2016; Dong et al. 2020). Overall, the model accurately replicates both absolute levels and temporal trends, and all scenario runs satisfy mass balance within ±0.1% tolerance.

3. Scenario design and parameterization

3.1. Model enhancements and key assumptions

The framework integrates stock-driven dynamic MFA with a price-responsive geological module. Refined demand follows per capita stock saturation curves (Dong et al. 2020), with outflows determined by sector-specific lifetimes (Construction: 40–50 yr; Power grid: 30–40 yr; Transport: 10–15 yr; Electronics: 5–10 yr). Crucially, the model endogenizes primary production: unlike conventional exogenous MFA, it incorporates an exploration feedback mechanism where discovery efficiency declines by 5–8% to simulate mature-district exhaustion (Northey et al. 2014; Schodde 2017). Secondary supply follows a three-stage cascade (collection–separation–recycling). Parameter uncertainties (lifetimes ±15%, recycling rates ±10%) are quantified via Monte Carlo simulation (10,000 iterations) to generate 90% confidence intervals. To isolate policy impacts, all scenarios share identical demand and geological baselines, diverging solely in exploration investment intensity and secondary supply targets, as summarized in Table 1.

3.2. Business-as-Usual (BAU) scenario

The BAU scenario projects a continuation of 2016–2024 structural trends, absent major new policy interventions (Dong et al. 2019; Elshkaki et al. 2016). Domestic mine production grows moderately at ~1.5% annually, constrained by declining ore grades (average Cu content falling from ~0.58% to ~0.52% by 2040; (Northey et al. 2014)), tightening environmental regulations, and exploration investment that responds passively to price signals without additional fiscal stimulus (Schodde 2017; Tilton et al. 2018). The secondary supply ratio (SSR) is held constant at 12.5% throughout the projection period, reflecting the absence of policy-driven improvements in recycling infrastructure, collection logistics, or end-of-life product recovery systems (Li et al. 2023).

This scenario represents a counterfactual baseline for evaluating alternative interventions. It perpetuates the current "smelting-centric" paradigm, characterized by large midstream capacity but persistent upstream vulnerability, in which import dependence remains structurally unresolved (Dong et al. 2020).

3.3. Intense Extraction scenario (Supply-Side Strategy)

The Intense Extraction scenario simulates a supply-side policy response prioritizing domestic geological security through intensified exploration and accelerated extraction. Motivated by analogous resource nationalism policies in major producing countries, this scenario assumes a sustained 20% increase in annual exploration investment relative to the BAU price-response baseline (Equation 2), alongside a relaxation of maximum extraction rate constraints from $\gamma_{extract} = 0.05$ (BAU) to 0.06 yr^{-1}, representing a reduction in reserve-to-production ratio from 20 to ~17 years – within geologically plausible bounds but accelerating depletion (Mudd 2010; Guj and Schodde 2025).

Recycling performance improves only marginally (SSR rising from 12.5% in 2024 to 13.5% by 2040), reflecting limited policy attention to demand-side measures. Consequently, the primary policy lever is intensified geological exploration and extraction (Elshkaki et al. 2016; Seck et al. 2020).

From a resource economics perspective, this scenario embodies an intertemporal trade-off: higher upfront exploration capital and accelerated depletion of domestic reserves in exchange for a near-term reduction in external dependence, at the cost of diminished future supply flexibility. It tests whether intensified primary production can materially alter China's supply structure, given geological constraints.

3.4. Circular Transition scenario (Demand-Side Strategy)

The Circular Transition scenario shifts strategic emphasis from “breaking new ground” (geological exploration) to “urban mining” (end-of-life product recovery), building upon the foundation laid by China’s 14th Five-Year Plan (2021–2025). Taking the 14th FYP’s target of 4 million tons of secondary copper as the 2025 baseline (implying a secondary supply ratio of ~22–25%), our scenario projects this intensified recycling trajectory through 2040, aligning with the strategic priorities of the emerging 15th Five-Year Plan (2026–2030).

The secondary supply ratio follows a sigmoid trajectory, rising from 12.5% (2024) to 32% (2035) and 35% (2040). This pathway assumes:

- Collection rate improvements: from 65% (2024) to 85% (2040) for major product categories (construction, power grid).
- Sorting efficiency gains: enhanced mechanical separation and hydrometallurgical preprocessing to address the extreme difficulty of liberating copper from complex WEEE matrices, thereby reducing contamination losses.
- Regulatory enforcement: stricter waste electrical and electronic equipment (WEEE) collection mandates.

Table 1. Scenario parameter summary (2025–2040)

Tabela 1. Podsumowanie parametrów scenariusza (2025–2040)

Parameter	BAU	Intense extraction	Circular transition
Supply-Side			
Exploration investment multiplier	1.0 (baseline)	1.2 (sustained +20%)	1.0 (baseline)
Maximum extraction rate ($\gamma_{extract}$)	0.05 yr^{-1}	0.06 yr^{-1}	0.05 yr^{-1}
Discovery efficiency decline (λ)	0.02 yr^{-1}	0.02 yr^{-1} (baseline)	
+ 5–8% cumulative penalty	0.02 yr^{-1}		
Demand-Side			
Secondary Supply Ratio (SSR) 2024	12.50%	12.50%	12.50%
SSR 2035	12.50%	13.00%	32%
SSR 2040	12.50%	13.50%	35%
Collection rate (end-of-life products)	65% (constant)	66% (2040)	85% (2040)
Product lifetime adjustment	Baseline	Baseline	+15–20% (selected sectors)
Policy emphasis	No intervention	Geological security	Circular economy

All scenarios share the identical demand projection (Equation 8) and baseline geological depletion dynamics (Equation 4). The “exploration investment multiplier” applies to Equation (2); the “cumulative penalty” in the Intense Extraction scenario reflects the additional decline in discovery efficiency (affecting λ) resulting from targeting lower-grade deposits.

These assumptions are feasible and realistic; the 35% target for 2040 remains below the current recycling levels in the EU (~38%), confirming its achievability for China as it matures.

This SSR trajectory is complemented by moderate product lifetime extensions in selected sectors: +15% for building wire (from 45 to 52 years), +20% for power grid infrastructure (from 35 to 42 years), reflecting improved maintenance practices and design-for-longevity standards. Consumer electronics and transport sectors maintain baseline lifetimes due to rapid technological obsolescence.

Exploration investment and primary extraction parameters remain at BAU levels (no additional fiscal stimulus for geological prospecting; extraction rate $\gamma = 0.05\ \text{yr}^{-1}$), thereby isolating the impact of demand-side circularity interventions. This design emphasizes that external dependence reduction in this scenario is achieved exclusively through enhanced urban mining, not through intensified greenfield exploration – a critical policy distinction.

4. Results and discussion

4.1. Demand trajectory and peak consumption

Under the calibrated logistic saturation function, China's refined copper demand follows a classic S-curve trajectory. After a phase of rapid expansion, the growth momentum dampens, projecting a stabilization at a "Peak Plateau" of approximately 17.8 million metric tons between 2030 and 2032 (see Figure 2). This saturation reflects the maturation of infrastructure and manufacturing stocks.

1. Urbanization saturation: the projected peak stems primarily from the deceleration of infrastructure growth as China's urbanization reaches a saturation threshold, marking the completion of major buildouts in tier-1/tier-2 cities (Dong et al. 2020).
2. Structural shift: while demand from traditional construction sectors declines, the surging copper intensity in electric vehicles and grid modernization partially counterbalances this drop, consistent with the transition toward service-oriented sectors (Zhang et al. 2015a).
3. Technological efficiency: adoption of copper-saving technologies in power transmission and electronics (Elshkaki et al. 2016).

The peak timing and magnitude align closely with independent stock-driven projections for China under moderate circularity assumptions, providing confidence in the baseline demand pathway. Importantly, demand saturation does not automatically resolve supply-side vulnerabilities. Under the Business-as-Usual scenario, concentrate import requirements increase by approximately 20% by 2040 relative to 2024 levels (from ~9.0 to ~10.8 million tons in metal content), placing additional pressure on global concentrate supply chains and exacerbating upstream exposure.

This "saturated growth" phase (2025–2035) constitutes a critical strategic window during which structural reforms – particularly investments in recycling infrastructure – can yield long-lasting reductions in external dependence without the urgency of managing rapid demand expansion.

4.2. Geological constraints on supply-side interventions: the Intense Extraction scenario

Under the Intense Extraction scenario, domestic mine production increases from 1.80 million tons (2024) to a peak of 2.35 million tons around 2032–2035, representing a 30% increase driven by sustained 20% higher exploration investment (relative to BAU) and accelerated extraction ($\gamma = 0.06$ vs. 0.05 yr^{-1}; Table 1). This trajectory reflects the maximum plausible output expansion under realistic geological and capital constraints. However, even at this production peak, domestic mine output satisfies less than 13.2% of concurrent refined demand (2.35 Mt mine production/17.8 Mt demand in 2032). The structural imbalance persists: demand is 13.5× greater than the economically viable domestic primary supply. Beyond 2035, mine production plateaus and then declines as two mechanisms compound:

- discovery efficiency decay (η declining at 2% yr^{-1} plus 5–8% cumulative penalty from targeting lower-grade deposits; Equation 4),
- reserve exhaustion under accelerated extraction (R/P ratio falling from 20 to 17 years).

By 2040, output regresses to 2.15 million tons, only marginally above BAU levels (2.00 Mt), despite sustained higher investment. These findings demonstrate that, under China's geological endowment, primary mining expansion can deliver only marginal, transient relief rather than structural solutions to import dependence. From a resource economics perspective, the supply response exhibits sharply diminishing marginal returns: sustaining 20% higher exploration investment yields only a 7.5% output advantage by 2040 (2.15 vs. 2.00 Mt), while accelerating reserve depletion by 15% (R/P ratio 17 vs. 20 years). This intertemporal trade-off – short-term output gains at the cost of long-term supply flexibility – limits the strategic value of intensified extraction as a standalone policy lever.

4.3. The "Smelting trap": structural upstream vulnerability

Both Business-as-Usual (BAU, red circles) and Intense Extraction (orange squares) scenarios remain trapped in high dependency, with the External Dependence Ratio (EDR) staying above 61% through 2040 (Figure 2). The Intense Extraction scenario yields diminishing returns: despite 20% higher investment, EDR falls by only 2.5 percentage points (61.6% vs. 64.5% in BAU) as accelerated reserve depletion offsets production gains. This reveals a "smelting trap": a path-dependent mismatch where abundant downstream capacity is locked into chronic upstream deficits, necessitating >60% reliance on imported concentrates. This configuration exposes China to supply disruptions, price volatility, and geopolitical coercion. Historical over-investment in processing capacity, ignoring geological constraints, has severely limited strategic flexibility.

4.4. Urban mining as strategic solution: the Circular Transition

In contrast, the Circular Transition scenario (green crosses) achieves structural decoupling. By elevating the Secondary Supply Ratio (SSR) to 35% by 2040, secondary production reaches 6.2 million tons, directly displacing 3.5 million tons of imports relative to BAU. Consequently, EDR drops to 42.0% by 2040 – a 22.5 percentage point reduction vs. BAU and a 19.6 pp advantage over Intense Extraction. Crucially, this pathway is more cost-effective and sustainable: it reduces import risk without accelerating geological depletion (reserves remain ~4,100 · 10^4 tons in 2040), essentially treating the "urban mine" as a renewable, scalable reserve base that outperforms domestic extraction in both security and environmental efficiency.

4.5. Quantitative scenario comparison and policy trade-offs

Figure 2 quantifies the divergent outcomes of the three scenarios. The Intense Extraction scenario (S2) proves to be a "high-cost, low-gain" strategy: despite sustained 20% higher

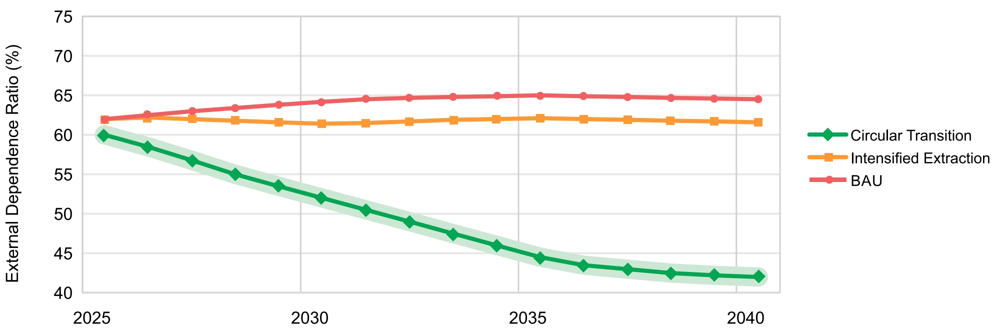

Fig. 2. Long-term evolution of China's copper External Dependence Ratio (EDR) under three scenarios (2025–2040)
The BAU (red circles) and Intensified Extraction (orange squares) scenarios exhibit a "lock-in" effect, maintaining the EDR persistently above 60% despite upstream interventions. In contrast, the Circular Transition scenario (green crosses) achieves a structural decoupling, driving the EDR down to approximately 42% by 2040. The green shaded band represents the ±1 standard deviation uncertainty interval derived from Monte Carlo simulations of recycling rate variability (±10%)

Rys. 2. Długoterminowa ewolucja wskaźnika zależności zewnętrznej Chin w zakresie miedzi (EDR) w trzech scenariuszach (2025–2040) exploration investment, it yields only a marginal 2.5 percentage point EDR reduction (staying >60% through 2040). This limited efficacy aligns with global empirical patterns of diminishing discovery rates in mature regions. China's geological reality – characterized by declining ore grades (0.87% to 0.58%) and the "low-hanging fruit" effect – imposes physical hard limits that investment alone cannot overcome without escalating energy and waste intensity.

In stark contrast, the Circular Transition scenario (S3) achieves a structural breakthrough, reducing EDR to 42.0% by 2040 – a level comparable to developed circular economies like the EU. By decoupling supply growth from primary depletion, S3 offers a triple strategic advantage:

- physical efficiency, utilizing high-purity anthropogenic stocks (>120 Mt) rather than low-grade ores;
- economic resilience, mitigating exposure to global treatment charge volatility;
- strategic flexibility, preserving domestic reserves as a "reserve option" for future crises rather than exhausting them prematurely.

Consequently, demand-side circularity constitutes a significantly more efficient and sustainable instrument for China's copper security than supply-side intensification.

4.6. Model limitations and future research

Four limitations constrain this study. While the model captures long-term structural evolution, it does not capture acute, short-term supply shocks (e.g., strikes, sudden trade wars), which would require discrete event modeling. First, data uncertainties and statistical discontinuities were mitigated via mass balance reconciliation and Monte Carlo uncertainty propagation (Figure 2), yet measurement errors remain inherent to official statistics. Second, spatial aggregation: the national-scale design abstracts from regional heterogeneities in geological endowments and industrial capacity, potentially smoothing localized bottlenecks. Third, market exogeneity: global prices are treated as fixed inputs, ignoring the feedback effects of China's dominant market power (~50% of global consumption) on international trade dynamics. Fourth, physical focus: the model assesses physical feasibility rather than economic efficiency, lacking explicit accounting for implementation costs or subsidies.

Future research should prioritize:

- integrating economic cost modules (e.g., levelized cost of supply) to enable welfare-based policy ranking;
- developing spatially disaggregated models to capture provincial supply chain nuances;
- endogenizing global market feedbacks via coupled partial equilibrium frameworks;
- incorporating emerging technologies (e.g., biohydrometallurgy) to assess sustainability beyond 2040 under deep decarbonization scenarios.

Conclusions and policy implications

This study developed an integrated geological-industrial system dynamics model (calibrated MAPE <8%) to evaluate China's copper security under geological constraints. The analysis yields three critical findings. First, demand stabilization is insufficient: although consumption peaks at ~17.8 Mt (2030–2032), the External Dependence Ratio (EDR) under Business-as-Usual remains >64% through 2040, debunking the assumption that peak demand naturally alleviates import risks. Second, supply-side intensification hits geological hard limits: the Intense Extraction scenario is a "high-cost, low-gain" strategy, achieving only a 2.5 percentage point (pp) EDR reduction despite 20% higher investment. The marginal investment efficiency is prohibitively low (~0.8% EDR reduction per 10% spending increase) due to declining ore grades (0.87% to 0.58%) and mature-basin exhaustion. Third, circularity is the dominant solution: the Circular Transition scenario reduces EDR by 22 pp (to 42% by 2040), proving 8.8 times more effective than intensification. By mobilizing 6.2 Mt of secondary supply, this pathway preserves ~300 $\cdot$ 10^4 tons of domestic reserves and avoids the embodied energy costs of primary production.

Policy Implications:

China must pivot from a "smelting-centric" expansion to an "urban mining" strategy. We recommend three priority actions:

- Prioritize circular infrastructure: achieving a 35% Secondary Supply Ratio by 2040 requires ~50–80 billion RMB investment in collection and sorting networks, but displaces 3–4 Mt of imports. Key levers include mandating Extended Producer Responsibility (target >85% collection), harmonizing waste standards, and tax incentives for formal recyclers.
- Rationalize midstream capacity: To break the "smelting trap", policymakers should phase out 10–15% of inefficient smelters dependent on single-source imports, preventing excess capacity from locking in upstream vulnerability.
- Optimize geological strategy: rather than pursuing unrealistic volume targets, domestic mining should stabilize at 2.0–2.2 Mt/year, focusing on high-grade deposits to preserve strategic options.

These insights extend to other industrializing economies (e.g., Chile, Peru), suggesting that early investment in circularity yields significantly higher returns than reactive measures post-saturation. Concurrently, China should leverage its massive recycling scale to lead the setting of global standards for secondary resource flows, shifting from a market participant to a governance leader.

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COUPLING GEOLOGICAL EXPLORATION WITH ANTHROPOGENIC CYCLES: A SYSTEMATIC APPROACH TO ASSESS THE DYNAMICS OF CHINA'S LONG-TERM COPPER SUPPLY STRUCTURE

Keywords

copper supply structure, circular economy, urban mining, scenario analysis, critical minerals

Abstract

China accounts for over 50% of global refined copper consumption yet contributes less than 10% of mine production, creating structural upstream vulnerabilities despite its massive midstream refining capacity. To address this imbalance, we developed an integrated system dynamics framework coupling a price-responsive geological exploration module with dynamic material flow analysis (MFA). Uniquely, this model endogenizes reserve replacement dynamics and accounts for discovery efficiency decay, enabling a realistic assessment of supply security under geological constraints (2025–2040). We evaluate three pathways: Business-as-Usual (BAU), Intense Extraction, and Circular Transition. Projections indicate refined demand peaks at ~17.8 million tons between 2030 and 2032. However, demand saturation fails to alleviate import pressure. Under BAU and Intense Extraction, the External Dependence Ratio (EDR) remains persistently above 60%, confirming a "smelting trap" where excess processing capacity necessitates chronic import reliance. Supply-side intensification proves inefficient due to diminishing returns from declining ore grades. Conversely, the Circular Transition scenario – leveraging China's specific power-grid-dominated anthropogenic stock – elevates the secondary supply ratio to 35%, reducing the EDR to ~42% by 2040 without accelerating reserve depletion. We conclude that prioritizing "urban mining" infrastructure over greenfield exploration yields superior, sustainable risk reduction, highlighting the strategic imperative of shifting from a smelting-centric to a circular-centric paradigm.

POWIĄZANIE BADAŃ GEOLOGICZNYCH Z CYKLAMI ANTROPOGENICZNYMI: SYSTEMATYCZNE PODEJŚCIE DO OCENY DYNAMIKI DŁUGOTERMINOWEJ STRUKTURY PODAŻY MIEDZI W CHINACH

Słowa kluczowe

struktura podaży miedzi, gospodarka o obiegu zamkniętym,
wydobycie surowców z odpadów, analiza scenariuszy, surowce krytyczne

Streszczenie

Chiny odpowiadają za ponad 50% światowego zużycia miedzi rafinowanej, a jednocześnie generują mniej niż 10% światowej produkcji kopalnianej, co powoduje strukturalną wrażliwość sektora wydobywczego pomimo ogromnych mocy przerobowych w sektorze rafinacji. Aby zaradzić tej nierównowadze, opracowaliśmy zintegrowany model dynamiki systemowej łączący moduł poszukiwań geologicznych reagujący na zmiany cen z dynamiczną analizą przepływu materiałów (MFA).

Model ten w unikalny sposób uwzględnia dynamikę odnawiania zasobów oraz spadek wydajności poszukiwań, umożliwiając realistyczną ocenę bezpieczeństwa dostaw w warunkach ograniczeń geologicznych (2025–2040). Oceniamy trzy ścieżki: Business-as-Usual (BAU), Intense Extraction oraz Circular Transition. Prognozy wskazują, że popyt na produkty rafinowane osiągnie szczyt na poziomie około 17,8 mln ton w latach 2030–2032. Jednak nasycenie popytu nie zmniejsza presji importowej. W scenariuszach BAU i intensywnej eksploatacji wskaźnik zależności zewnętrznej (EDR) utrzymuje się na poziomie powyżej 60%, co potwierdza istnienie „pułapki hutniczej”, w której nadwyżka mocy przerobowych powoduje chroniczną zależność od importu. Intensyfikacja podaży okazuje się nieefektywna ze względu na malejące zyski wynikające z obniżającej się jakości rudy. Natomiast scenariusz „Circular Transition” – wykorzystujący specyficzne zasoby antropogeniczne Chin zdominowane przez sieć energetyczną – podnosi udział podaży wtórnej do 35%, zmniejszając wskaźnik EDR do około 42% do 2040 r. bez przyspieszania wyczerpywania się zasobów. Dochodzimy do wniosku, że priorytetowe traktowanie infrastruktury „wydobycia miejskiego” w stosunku do poszukiwań na nowych terenach zapewnia skuteczniejsze i bardziej zrównoważone ograniczenie ryzyka, co podkreśla strategiczną konieczność przejścia od paradygmatu skoncentrowanego na hutnictwie do paradygmatu opartego na obiegu zamkniętym.