SUSTAINABILITY OF THE GLOBAL BALANCE BETWEEN SUPPLY AND DEMAND FOR METALS IN THE LONG TERM – AN APPLICATION TO COPPER

Maylis PEYRET, Université Paris-Dauphine–PSL, maylis.peyret@dauphine.psl.eu
Frédéric GONAND, Université Paris-Dauphine–PSL, frederic.gonand@dauphine.psl.eu

Overview

The energy transition and digital transformation drive rising demand for copper, raising concerns about the long-term sustainability of supply-demand balance. This paper presents a model of long-run equilibrium prices and quantities, with a supply side relying on a cumulative availability curve (CAC) (as in Tilton, 2018), a demand-side relyng on simulations from the International Energy Agency (IEA). This setting allows for modelling different alternative, possible dynamics of metal markets until 2050 depending on different conditions of technological progress and resource constraints on the copper market. Our results highlight that sustainable, long-run equilibrium on the copper market up to 2050 may depend critically on the interplay between demand elasticity, technological progress, and cumulative resource extraction. Our modelling also show how shifts in energy mixes and industrial demand may affect the sustainability of copper supply.

Methods

We model demand using a CES function, calibrated with empirical data on copper usage in sectors driving energy transition and economic growth (International Energy Agency, 2021). The demand for metal $Q_{d,t}$ at time t is expressed as $Q_{d,t} = BP_t^{\sigma-1}$, where B is a scaling parameter representing baseline demand, P_t is the price of copper at time t, and σ is the demand price elasticity.

The supply side is modeled using a logistic depletion function derived from the cumulative availability curve (CAC) (as in Tilton, 2018). The inverse CAC function, denoted $c_{max}(P)$ provides the total recoverable quantity of copper at different price levels $c_{max}(P) = \frac{L}{1 + e^{-\alpha(P-P_m)}}$, where L is the asymptotic maximum level of cumulative availability, α controls the steepness of the sigmoid curve, and P_m is the midpoint price at which availability increases most rapidly.

The annual supply $Q_{s,t}$ is then given by a logistic depletion function $Q_{s,t} = \frac{c_{max}(P_t)}{1 + \exp\left[\gamma\left(\frac{c_t}{c_{max}(P_t)} - \theta\right)\right]}$ where γ is the steepness parameter, θ is the inflection point of the logistic curve, and c_t represents cumulative extraction at time t.

We define sustainable equilibrium in a metal market as a state where:

1) **Long-term equilibrium prices remain finite and bounded**: Price levels stabilize or grow at a manageable rate without explosive dynamics.
2) **Supply can meet demand without reaching resource exhaustion**: Cumulative extraction remains below a critical threshold of total available resources, ensuring that future generations are not deprived of essential materials.
3) **Demand remains elastic enough to prevent chronic shortages**: Sufficient price elasticity of demand is crucial to allow substitution and innovation in response to high prices, thereby stabilizing the market.

In a numerical application on copper data, we simulate market dynamics under four distinct scenarios: the Sustainable Development Scenario (SDS), the Stated Policies Scenario (STEPS), the Net Zero by 2050 Scenario (NZE2050), and a Business-as-Usual Scenario (BAU). Each scenario reflects varying assumptions regarding technological progress, recycling rates, and the pace of energy transition, allowing us to assess the impact of different trajectories on long-term market sustainability.

Results

Theoretical Conditions for Sustainable Market Equilibrium

Our analysis shows how a sustainable equilibrium relies on a balance between demand elasticity, technological progress, and resource depletion. Specifically, we show that:

1) **Price elasticity of demand has to remain relatively high**: When substitutes are unavailable or costly, low elasticity can lead to chronic shortages and runaway price increases. In scenarios where elasticity exceeds a critical threshold, prices stabilize more readily, preventing large demand-supply mismatches.
2) **Technological progress on both supply and demand sides is essential**: Without ongoing improvements in material efficiency and recycling, cumulative extraction accelerates, pushing the system toward unsustainability. In scenarios where technological progress is significant, demand growth slows, and available resources last longer.
3) **Moderate initial demand growth**: Demand should not grow too rapidly relative to initial resource availability, as defined by the slope of the CAC at early price levels.

Numerical Application to Copper

Applying our theoretical model to copper with four demand scenarios designed by the International Energy Agency (IEA) highlights the risks of unsustainable equilibrium in high-demand scenarios:

- **In the BAU scenario**, where recycling rates remain low and demand grows steadily, cumulative extraction reaches nearly 95% of identified resources by 2050, with prices rising sharply.
- **In the SDS scenario**, where technological progress is faster and recycling rates are higher, cumulative extraction remains well below critical levels, and price increases remain manageable.
- **In the NZE2050 scenario**, despite aggressive demand growth, higher substitution elasticity and strong recycling efforts stabilize the market.

These results illustrate that without sufficient investment in secondary supply and technological innovation, copper markets risk unsustainable dynamics, with potential long-term supply crises.

1. **Price Trajectories**: Under BAU, prices increase non-linearly as demand surpasses supply growth for copper. In scenarios with higher technological progress and recycling, price increases remain moderate.
2. **Resource Depletion**: Cumulative extraction in high-demand scenarios approaches the upper limit of the CAC for copper, highlighting risks of supply shortages.
3. **Recycling Impact**: Enhanced recycling rates in SDS and STEPS scenarios alleviate pressure on primary supply of copper, reducing equilibrium price volatility.
4. **Equilibrium Stability**: Price elasticity plays a critical role in market stability, with insufficient elasticity leading to supply-demand mismatches and potential market instability on the copper market.

Conclusions

We develop a theoretical framework to assess the sustainability of metal markets, defining clear conditions under which long-term equilibrium can be maintained. Sustainable equilibrium depends critically on the interplay between demand elasticity, technological progress, and cumulative resource extraction. Our results suggest that policy measures promoting recycling and substitution are crucial to preventing supply shortages and ensuring market stability.

Future research will extend this work by incorporating stochastic elements to capture uncertainties in technological progress and recycling infrastructure development, as well as exploring policy instruments that can encourage sustainable market behavior.

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