Structural Divergence of Copper and Palladium Under Global Energy Transition: Fundamental Analysis of an Asymmetric Long-Short Spread Strategy

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Abstract

This study presents a fundamental analysis of the structural divergence between the copper (Cu) and palladium (Pd) markets in the context of the global energy transition and provides a rationale for a long-term asymmetric spread strategy: Long Copper / Short 0.5x Palladium. Drawing on a synthesis of data from more than 80 academic and industry sources, the study demonstrates that the two metals are on opposing demand trajectories: copper faces a structural supply deficit amid four simultaneous demand growth vectors (transport electrification, AI infrastructure, power grid modernization, and defense), while palladium confronts demand destruction resulting from the substitution of internal combustion engines by electric powertrains. Global copper demand is projected to grow from 28 to 42 million tonnes by 2040 (+50%), with a forecasted deficit of approximately 10 million tonnes (S&P Global, 2026). Palladium demand from autocatalysts (84–90% of consumption) is declining at a rate of −1.3% CAGR and will transition to surplus by 2026 (WPIC). The inversion of the Cu/Pd ratio around 2020 has been identified as a marker of technological transition. The 2:1 ratio strategy is justified by the differing volatility of the two assets and the necessity of constraining tail risks on the palladium leg. Stress-testing across five scenarios, accounting for funding rate expenses, confirms a positive expected value (+19% over 2–3 years) and pronounced positive skewness: in the bullish supercycle scenario, returns reach +30–83%, whereas losses in the worst-case scenario are limited by the 0.5x coefficient on the short leg. The strategy enables establishing a position at the origin of a structural megatrend with multiple upside potential under controlled downside risk.

Keywords: *copper, palladium, energy transition, pairs trading, spread strategy, electrification, structural deficit, demand destruction, data centers, electric vehicles.*

Contents

1 Introduction

1.1 Problem Statement and Relevance

The global economy has entered a phase of fundamental transformation of its energy and transportation infrastructure, the scale of which is without precedent since the electrification of the early twentieth century. Three simultaneous megatrends — energy decarbonization, digitalization (including the explosive growth of artificial intelligence infrastructure), and reindustrialization of the defense sector — are creating unprecedented pressure on industrial metals markets, fundamentally restructuring the architecture of global supply and demand.

At the center of this transformation lie two metals whose trajectories are rapidly diverging: **copper** and **palladium**. Copper — the key conductor of electrical energy and heat — is becoming a critical resource for every element of the "green transition": from electric vehicles (which consume approximately 3.6 times more copper than ICE vehicles) to AI data centers (with an intensity of 30–47 tonnes of copper per MW of capacity) and power grid modernization (requiring a doubling of transmission line length by 2040). Palladium, by contrast, is tied to a technology destined for contraction: 84–90% of global palladium consumption is attributable to autocatalysts for internal combustion engines, a market that is steadily shrinking as the vehicle fleet electrifies.

The relevance of this study is determined by several factors:

First, the scale of the projected copper deficit is unprecedented. S&P Global, in its report "Copper in the Age of AI" (January 2026), estimates global demand by 2040 at 42 million tonnes, against a maximum primary production volume of 33 million tonnes (peak in 2030) and a secondary recycling ceiling of approximately 10 million tonnes — yielding a deficit on the order of 10 million tonnes, or 24% of projected demand. Wood Mackenzie (2025) forecasts demand growth of +24% by 2035 to 42.7 million tonnes, requiring the commissioning of more than 8 million tonnes of new capacity that does not yet exist. The University of Michigan (Simon et al., 2025) demonstrates that to incentivize the development of new deposits, the copper price must at least double to 26,000 USD/t, given a mean lead time from discovery to first production of 17.9 years (S&P Global, 2024) [23].

Second, the palladium market is undergoing a structural inflection. After 13 consecutive years of supply deficit (2012–2024, Johnson Matthey), palladium has transitioned to a surplus balance: WPIC forecasts the surplus to grow to 689,000 ounces by 2029. The average palladium price has fallen 61% from the annual average peak of 2021 ($2,398/oz) to the annual average trough of $924/oz in 2024. By March 2026, the price had recovered to 1,366 USD/oz (−43% from peak), yet remains significantly below 2019–2021 levels. The pace of demand destruction is systematically overestimated: palladium consumption in autocatalysts is declining at a rate of only −1.3% CAGR (WPIC), rather than collapsing, as narratives of instantaneous ICE displacement by electric vehicles would suggest.

Third, the inversion of the Cu/Pd ratio, which occurred around 2020 (coinciding with the onset of mass electric vehicle sales), constitutes a market signal reflecting a profound technological shift. The ratio rose from a historical minimum of 2.2x (February 2020, the peak of palladium deficit) to an average of 9.3x (2024–2025), signaling a transition from the "palladium premium of catalytic converters" to the "copper premium of electrification."

This conjuncture creates an opportunity for the construction of an asymmetric spread strategy that exploits the diverging fundamental trends of the two metals. The present study provides a rationale for such a strategy by systematically analyzing every link in the causal chain and subjecting it to stress-testing.

1.2 Research Objectives and Scope

Research objective — to conduct a comprehensive fundamental analysis of the structural divergence between the copper and palladium markets and to justify the parameters of a long-term asymmetric spread strategy: Long Copper / Short 0.5x Palladium.

Research tasks:

1. Decompose copper demand across four key vectors (baseline economic, energy transition, AI/data centers, defense) with quantitative estimates for each vector through 2040.

2. Assess structural supply-side constraints for copper: inelasticity of primary production (17-year lag), the smelting capacity crisis, the ceiling on secondary recycling, and the limits of aluminum substitution.

3. Decompose palladium demand, isolating the automotive segment and analyzing the pace of ICE substitution by electric powertrains.

4. Analyze the historical dynamics of the Cu/Pd spread, identify structural regimes, and assess the degree to which the market has discounted the "electrification scenario."

5. Justify the parameters of the synthetic position (2:1 ratio, implementation instruments, funding rate management).

6. Stress-test the strategy across five scenarios: baseline, copper-bullish, palladium-bearish, geopolitical shock, and recessionary.

7. Systematize risk factors and define conditions for thesis invalidation.

1.3 Methodology and Data Sources

The study is grounded in a multi-level fundamental analysis methodology incorporating elements of scenario modeling and stress-testing. The following analytical approaches are employed:

Physical market balance analysis (supply-demand balance) — aggregation of production, processing, consumption, and inventory forecasts from industry sources (ICSG, S&P Global, Wood Mackenzie, WPIC, Johnson Matthey) with cross-verification.

Econometric elasticity estimates — utilization of findings from academic studies of the price elasticity of copper supply and demand (IMF Working Paper, 2024; Ferdi/CERDI, 2025; Stuermer, 2022) and secondary supply (Fu, Ueland & Olivetti, 2017) [8, 9, 25].

Probabilistic material flow analysis — incorporation of results from dynamic modeling of secondary copper flows (Born & Ciftci, 2024 — 30,000 scenarios; Diersen, Bhuwalka & Olivetti, 2025 — an economic model with price feedback) [1, 5].

Technology audit — assessment of the technology readiness level (TRL) of breakthrough extraction technologies (Nuton/SandLix bioleaching, Jetti catalytic leaching, Florence Copper ISR underground leaching) and their potential contribution to supply.

Engineering substitution analysis — sector-by-sector assessment of the physical limits of copper substitution by aluminum, accounting for conductivity, thermal conductivity, volumetric constraints, and regulatory barriers.

Scenario stress-testing — modeling of spread position behavior under extreme market conditions using historical analogs (2022 nickel squeeze, 1996 Sumitomo manipulation).

Data sources span four categories:

- *Academic publications*: SEG Discovery (University of Michigan), Resources Conservation and Recycling (Born & Ciftci; Fu et al.), AIChE Journal (Diersen et al.), Nature Scientific Reports (Safarzynska et al.), Science Advances (Crane et al.), PLoS ONE (Ni et al.), MDPI Energies (Sheng et al.), World Bank Working Papers.

- *Industry analytical reports*: S&P Global "Copper in the Age of AI" (2026), Johnson Matthey PGM Market Report (2025), Wood Mackenzie, IEA Electricity 2026, ICSG Market Balance Forecasts.

- *Investment bank research*: Goldman Sachs, J.P. Morgan, Bank of America, UBS, Citi, Deutsche Bank, StoneX.

- *Corporate data and reporting*: Rio Tinto (Nuton), Anglo American (SandLix), BHP, Ivanhoe Mines, Codelco, Nornickel, Sibanye-Stillwater.

2 Fundamental Analysis of the Copper Market: The Structural Bull Thesis

2.1 Demand Architecture: Four Growth Vectors

Global copper demand in 2025 is estimated at approximately 28 million tonnes of refined metal. S&P Global, in its report "Copper in the Age of AI" (January 2026), forecasts growth to **42 million tonnes by 2040** — an increase of 50% over 15 years, driven by four structurally independent vectors [35].

Table 1: Decomposition of Global Copper Demand by Growth Vector

Demand vector	2025 (Mt)	2040 (Mt)	CAGR	Share in 2040
Baseline economic (construction, industry, transport)	18.0	23.0	1.6%	53%
Energy transition (EV, renewables, T&D grids)	8.5	15.6	4.1%	36%
AI and data centers	1.1	2.5	5.6%	6%
Defense and robotics	0.4	1.5	9.2%	4%
Total	**28.0**	**42.6***	**2.8%**	**100%**

*Note: S&P Global uses a rounded estimate of ~42 Mt; the sum of subcategories (42.6 Mt) reflects a more granular decomposition with overlap between sectors.
Source: S&P Global, "Copper in the Age of AI," January 2026 [35].

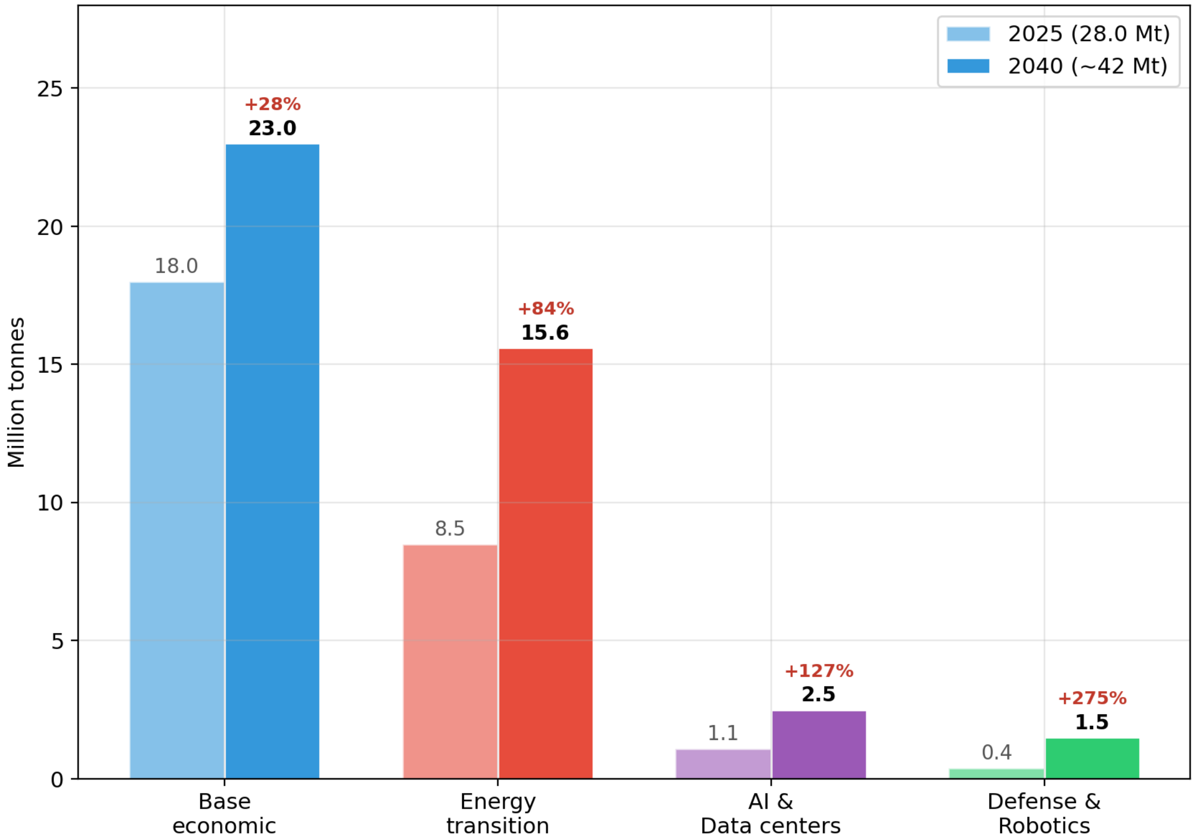

Figure 1: Decomposition of global copper demand by growth vector

Vector 1: Baseline economic demand constitutes the foundation of consumption and is growing at a rate close to global GDP growth (+1.6% CAGR). Construction, household appliances, industrial equipment, and conventional transport remain the largest consumers. By 2040, this segment will reach 23 million tonnes — on its own exceeding the current level of aggregate global demand.

Vector 2: Energy transition — the largest by absolute increment (+7.1 million tonnes). It comprises three sub-segments:

- *Electric vehicles and charging infrastructure*: growth from 2.6 to 6.3 million tonnes per year. An electric vehicle contains approximately 83 kg of copper — 3.6 times more than an ICE vehicle (~23 kg) (ICA / Copper Alliance, average values for a mid-size passenger car). With a projected global EV fleet exceeding 500 million units by 2040, this becomes the dominant sub-segment.

- *Transmission and distribution of electricity (T&D)*: doubling of demand from approximately 3.5 to 7.1 million tonnes per year. According to the IEA, by 2040 the world must add or upgrade 80 million km of electrical grids — equivalent to the entire existing global transmission system. Copper consumption intensity: 19,500 kg/km for trunk lines, 3,700 kg/km for distribution lines. Cumulative T&D investment must reach $7.5 trillion by 2040 (S&P Global).

- *Renewable energy*: solar generation ~1.1 Mt, wind ~0.4 Mt, battery storage systems ~0.5 Mt by 2040.

Vector 3: AI and data centers — the fastest-growing segment by CAGR (+5.6%), with potential for acceleration. S&P Global forecasts data center electricity consumption to grow from 860 TWh (2025) to 1,587 TWh (2030). Copper intensity of data centers is 30–47 tonnes per MW of installed capacity (for AI training clusters) — 7 to 12 times greater than for conventional generation. Morgan Stanley estimates cumulative demand from new data centers at 740,000 tonnes in 2026 alone. Critically, this demand is **price-inelastic**: the cost of copper constitutes 2–4% of a data center's total capex (approximately $115 million against investments of $3–5 billion, S&P Global), and developers "use it without regard to price" (Wood Mackenzie) [37].

Vector 4: Defense and robotics — a new vector not previously identified in industry forecasts. S&P Global projects military consumption to grow approximately 3.8-fold by 2040 (from 0.4 to 1.5 Mt). A potential additional sub-vector is humanoid robots: S&P Global estimates consumption at 1.6 Mt/year upon scaling to 1 billion units; however, this scenario is **speculative** and is not included in the baseline 42 Mt forecast — it represents upside potential beyond the 2040 horizon.

A critical feature of the current demand architecture is the **independence of vectors**. Unlike the 2000s supercycle, where consumption growth was determined by a single factor (Chinese urbanization), the current cycle rests on four structurally distinct drivers, each underpinned by government commitments and long-term infrastructure programs. The loss of one vector (e.g., a slowdown in AI investment) does not eliminate the pressure from the remaining three.

2.2 Copper and AI Infrastructure: The Energy Bottleneck Paradox

The explosive growth of artificial intelligence infrastructure creates a paradoxical situation for the copper market. On the one hand, 30–50% of data centers scheduled for commissioning in 2026 risk being delayed due to power supply constraints (Sightline Climate). On the other hand, every solution to the energy deficit — whether grid modernization, construction of behind-the-meter generating capacity, or expansion of renewables — requires even more copper.

Desynchronization of construction cycles. Data center construction takes 1.5–3 years; however, grid connection can extend to 4–7 years (Bloomberg). In Northern Virginia — the world's largest data center market — Dominion Energy has increased connection timelines for facilities exceeding 100 MW to 7 years. Interconnection queues in PJM (the largest grid operator in the United States) exceed 60 GW, with a mean waiting time of 4+ years (GridLab). In California, the wait reaches 9 years (Introl).

Table 2: Construction Timelines for Generating Capacity

Technology	Construction timeline	Current delays
Solar generation	1.2–2 years	Minimal
Gas generation (BTM)	1.5–3 years	Turbine backlog through 2028–2029
Gas generation (grid-scale)	3–7 years	Wait time >5 years
Onshore wind generation	2–3.5 years	Interconnection queues
SMR (small modular reactors)	5–8 years (optimistic)	First commercial units no earlier than 2030
Large NPP (Gen III+)	10–18 years	Vogtle: $32 billion, 7-year delay

Sources: SEIA, Reuters, SemiAnalysis, Utility Dive, Introl, CSIS.

The paradox of impact on copper demand. The energy bottleneck exerts a bidirectional influence:

Decelerating effect: delayed data center construction reduces direct copper demand (~30–47 t/MW). According to Precedence Research, in the "headwinds" scenario, data center demand is limited to 700 TWh by 2035 instead of the baseline 945 TWh, equivalent to a shortfall of approximately 0.5–1 million tonnes.

Amplifying effect: recognition of the bottleneck accelerates investment in T&D modernization — the largest consumer of copper. Copper demand from T&D doubles to 7.1 Mt/year. The shift to behind-the-meter generation requires additional copper infrastructure.

Table 3: Quantitative Assessment of the Paradox (2040)

Component	Demand at full realization (Mt)	Demand under energy bottleneck	Difference
Data centers (direct)	2.5	1.7–2.0	$-0.5 \ldots -0.8$
T&D modernization	7.1	7.5–8.0 (acceleration)	$+0.4 \ldots +0.9$
Renewables (generation for DCs)	incl. in energy transition	+0.2–0.5 (BTM)	$+0.2 \ldots +0.5$
Gas generation (BTM)	incl. in baseline	+0.1–0.3	$+0.1 \ldots +0.3$
Net effect			$\mathbf{+0.2 \ldots +0.9}$

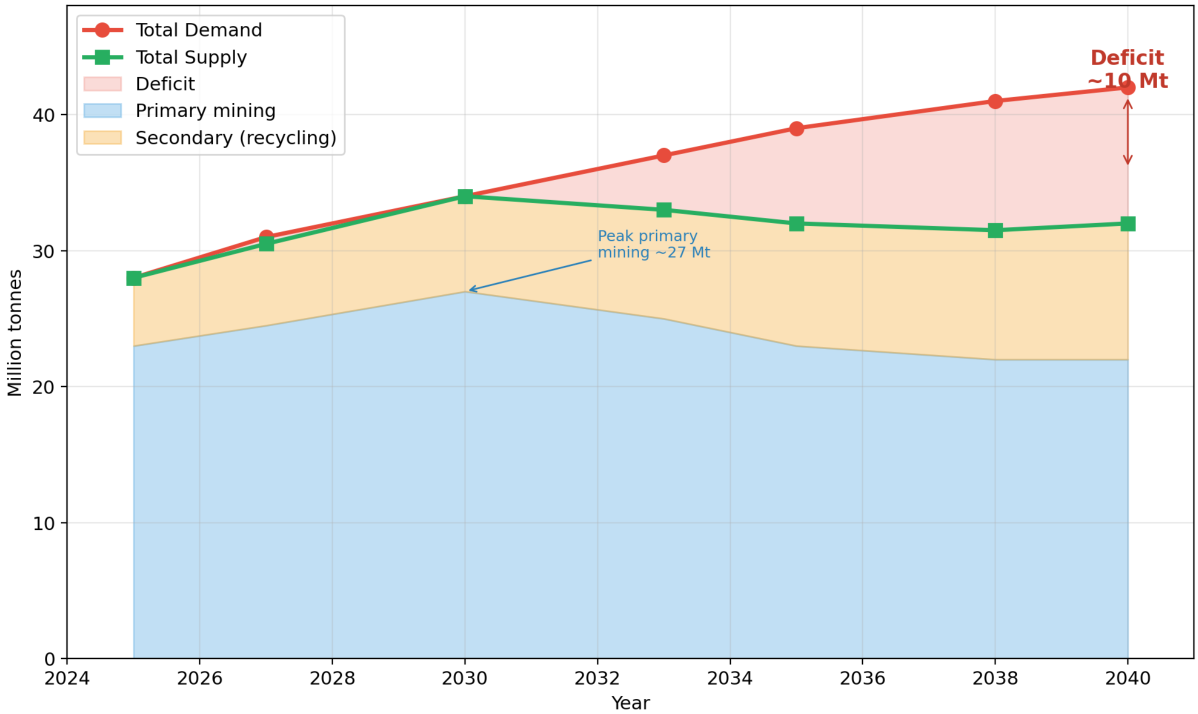

Figure 2: Projected copper supply-demand gap (2025–2040)

The paradoxical conclusion: the energy bottleneck, in all likelihood, **does not reduce but rather increases** aggregate copper demand. As a CRU analyst noted for Reuters: "The power grid is the bottleneck not only for data centers, but also for wind, solar energy, and electric vehicles." Copper is not the "victim" of the energy bottleneck, but its "resolver": every solution to the problem (more grids, more generation, more storage) requires still more copper, creating a self-reinforcing demand cycle.

2.3 Supply Inelasticity: The 17-Year Lag Hypothesis

The central thesis on the supply side is that even a twofold increase in the copper price is incapable of provoking a rapid influx of new physical metal to the market. The mean lead time from deposit discovery to the commencement of commercial production is **17.9 years** globally (S&P Global / MiningVisuals, December 2024), reaching **29 years** in the United States and **34 years** in Zambia [36].

Table 4: Lead Times for New Deposit Commissioning by Jurisdiction

Country/Region	Mean lead time (years)	Key delay factor
Zambia	34	Infrastructure constraints, energy crisis
United States	29	Regulatory environment (NEPA), litigation
Global average	17.9	Combination of factors
Chile	~16	Water scarcity, social protests
DRC	~10	Geopolitical risks, accelerated permitting

Source: S&P Global, World Bank (discovery database 1950–2014).

Price threshold for incentivizing production. A study by the University of Michigan (Simon et al., published in SEG Discovery, May 2025) demonstrates that the current copper price (approximately 13,000 USD/t, March 2026) is insufficient to trigger a new mining megacycle. The price must **at least double to approximately 26,000 USD/t** to ensure the economic viability of new projects. The average construction cost of a new mine is **$22,359 per tonne of annual capacity** (based on 26 projects with planned launch by 2030). To satisfy baseline economic growth (BAU) alone by 2050, it is necessary to commission **78 new large-scale mines** with a capacity of 500,000 t/year each — whereas historically the industry commissions only 2–3 large mines per decade [23].

Ore grade degradation exacerbates the problem. Average copper ore grade has declined by approximately 40% since 1991: from ~1.0% to ~0.52% Cu (S&P Global MI). In Chile (the largest producer), grade has fallen from 1.02% (2000) to 0.66% (2022) — a 35% decrease (Codelco). When grade declines from 1% to 0.65%, approximately **54% more rock mass** must be processed to obtain the same volume of metal, entailing proportional increases in energy consumption, water use, and operating costs [17, 18].

Supply elasticity. Academic studies document substantially higher price elasticity at the individual mine level than aggregate models would suggest. Ferdi/CERDI (2025), employing SVAR + Local Projections on data from 195 mines across 43 countries (2000–2019), found an elasticity of approximately 50% on average and up to 157% at horizon $h = 5$ years [8]. However, this elasticity operates predominantly on the **intensive margin** (existing mines increasing output), not on the **extensive margin** (commissioning new mines). Stuermer (2022), using aggregate data from 1880–2020, estimates elasticity at +5% per +10% price increase — considerably more modest [25].

Aggregate supply assessment (2026–2030). Brownfield expansions (Oyu Tolgoi, Kamoa-Kakula, Quellaveco, Escondida) will deliver approximately 1.2–1.8 million tonnes of incremental growth by peak 2028–2030. Breakthrough technologies (Nuton bioleaching TRL 7, Florence Copper ISR TRL 8, Jetti catalytic leaching TRL 7) — a combined 200–1,150 Kt. AI optimization of existing operations — 150–600 Kt. Including secondary raw material mobilization, the total potential amounts to **1,500–4,050 Kt**, covering only **13–40%** of the cumulative 2026–2030 deficit.

2.4 The Smelting Capacity Crisis: The China Factor and Supply Chain Fragmentation

The prevailing public narrative of the copper crisis focuses on "ore scarcity"; however, a more precise diagnosis points to the **critical concentration of smelting capacity in China** as the key systemic risk.

Scale of concentration. China controls **47.2%** of global smelting capacity (10.05 million tonnes out of 21.3 million tonnes of global production). Since 2005, China has accounted for >**90%** of global growth in smelting capacity (IEA). Total electrolytic refining capacity in China reached 14.22 million tonnes/year (October 2025), 70% of which is controlled by the CSPT group (16 largest companies) [31].

TC/RC collapse as a systemic indicator. Treatment/Refining Charges (TC/RC) represent the fee that a mining company pays to a smelter for processing copper concentrate (~25–35% Cu) into refined cathode copper (99.99% Cu). This is the industry's standard model: the miner produces a semi-finished product (concentrate) that has no direct market, and pays for the service of transforming it into an exchange-tradable commodity. In a healthy market, TC/RC are positive and provide the smelter's margin. When TC/RC are negative, the economics invert: the smelter **pays the miner** for the right to receive feedstock, in order to utilize idle capacity and earn revenue from by-products (sulfuric acid, gold, silver).

TC/RC have exhibited an unprecedented decline:

Period	TC/RC ($/t)	Commentary
2023	~$80	Stable market
Early 2024	~$45	Onset of deficit following Cobre Panama closure
January 2025	−$49	Historic record — smelters paying miners
2026 benchmark	$0	Unprecedented: Antofagasta-CSPT agreement — zero processing fee

Negative TC/RC signify an inversion of processing economics: smelters **pay mining companies** for the right to process concentrate. This paradox is explained not by an absolute scarcity of ore, but by the fact that **too much smelting capacity has been constructed**: capacity grew by 30–40% over five years, while concentrate supply increased by only 15–20%.

Stratification by enterprise size (SMM, September 2025) exposes the depth of the crisis: large plants operate at 88% utilization, medium-sized plants at 79%, and small plants at 60%. Small enterprises operating at 60% utilization are generators of excess concentrate demand — they are willing to purchase feedstock at negative TC/RC, creating "price noise" in the spot market.

Survival mechanism: by-products. Despite negative TC/RC, no mass plant closures have occurred. The reason lies in an unprecedented rise in by-product revenues: sulfuric acid prices surged by approximately 500% over 2.5 years, reaching 1,045 yuan ($145)/t in January 2025. The cumulative effect for Chinese smelters is estimated at $1.5 billion in additional profit in 2024. Sulfuric acid came to provide more than 64% of by-product revenue (against a historical average of 27%).

Supply chain fragmentation. In parallel with the smelting crisis, fragmentation of global trade flows is unfolding:

- *Resource nationalism*: Indonesia imposed a complete ban on copper concentrate exports (from 2023); the DRC — a ban on cobalt exports plus a requirement for 40–60% local processing; Armenia — export duties.
- *Tariff war*: the 50% US tariff on copper products (Section 232, July 2025) created a record COMEX premium over LME of $2,520/t (30%), forming a de facto dual-circuit pricing system.
- *Concentrate as a contested asset*: Chilean and Peruvian concentrate (collectively ~67% of Chinese imports) is becoming the subject of competition between the United States and China.

Crisis scenarios (5-year horizon):

Scenario	Probability	Price impact
Cascading resource nationalism	80–90% (underway)	+20–40%
Fragmentation into two markets (West/East)	70–80% (underway)	+15–30% Western premium
Mass closure of unprofitable plants	60–70%	Volatility +/−20%
China restricts refined copper exports	20–30%	+50–100% (shock)
New capacity closes the deficit	15–25% within 5 years	Neutralization (>10 years)

Note on divergence of 2026 balance forecasts. Key sources diverge radically in their assessments of the 2026 refined copper market balance: J.P. Morgan forecasts a deficit of −330 Kt, ICSG a deficit of −150 Kt, and Goldman Sachs a surplus of +160 Kt. The difference between the extreme estimates is approximately 490 Kt. The divergence is explained by differing assumptions regarding Chinese demand (GS estimates it at −8% y/y in Q4 2025, JPM as resilient) and the treatment of the Section 232 tariff effect (GS includes reverse inventory flows from the US, JPM does not). This study adopts the **consensus mean forecast** — a moderate deficit of approximately 100–200 Kt in 2026, transitioning to a growing deficit from 2027 onward — as most consistent with ICSG data and the trend of declining surplus forecasts (ICSG revised its 2025 estimate from +289 to +178 Kt). The long-term deficit forecast of approximately 10 Mt by 2040 (S&P Global) is not contested by any source [32, 33, 30, 35].

2.5 The Ceiling on Secondary Recycling and the "Urban Mining" Trap

The hypothesis that "urban mining" can compensate for the primary production deficit is **quantitatively refuted** by multiple independent models.

Current balance. The global copper scrap market in 2024 totaled 10.56 million tonnes, of which End-of-Life (EoL) scrap (from decommissioned products) provides only **23%** of global demand (Born & Ciftci, 2024) [1]. The overall recycling rate (including manufacturing scrap) is approximately 35% (ICSG).

Ceiling on secondary supply. Three independent models yield a consistent estimate:

Table 5: Secondary supply ceiling for copper

Source	**Horizon**	**EoL scrap share ceiling**	**Conditions**
Born & Ciftci (2024), 30,000 scenarios	2050	33.4% (mean STEPS); 49.6% (95th pctl. NZE)	Collection rate rising to 90%
S&P Global (2026)	2040	~34% of supply	EoL CR rising from 50% to 66%
Diersen & Olivetti (2025)	2040	36–53% of demand	4 scenarios, incl. maximum

Even in the most optimistic scenario (95th percentile of 30,000 simulations by Born & Ciftci), the EoL scrap share **does not exceed 50%** — and this under conditions that the authors classify as "the most optimistic of those modeled" [1, 5].

"Locked-in" copper. Global in-use copper stocks exceed **460 million tonnes** (2020) and are projected at approximately 650 million tonnes by 2040. More than 60% is concentrated in buildings and infrastructure with service lives of 40–100 years. Copper wiring in buildings lasts 70–100+ years and in 90–100% of cases remains "entombed" until the building is demolished. Underground cables are rated for 20–30 years but frequently serve 40–50+ years. Copper invested in infrastructure today will return as scrap in **23–100 years** depending on the sector [27].

The price trap paradox. Rising copper prices stimulate scrap collection, but simultaneously create a self-reinforcing cycle that intensifies the future deficit:

1. Growth in secondary supply depresses prices (Ryter & Olivetti, 2022: each additional tonne of scrap displaces only approximately 0.5 tonnes of primary production) [19].
2. Price declines kill investment in new mines.
3. After 10–15 years (the lag of investment decisions plus construction), an even more acute deficit emerges.

Safarzynska et al. (2023, Nature Scientific Reports) demonstrated that under a global circular economy with evolving consumer budgets, primary copper production **increases by 21%** by 2050–2100 — the classic Jevons paradox: recycling reduces the cost of the secondary product, which stimulates consumption, which in turn increases total demand [20].

Price elasticity of EoL scrap is extremely low: Fu, Ueland & Olivetti (2017) estimate it at **0.10–0.21** (ARDL model). This means that a doubling of the copper price would increase the scrap flow by only approximately 20%, rather than doubling it [9].

2.6 The Limits of Aluminum Substitution: The "Hard Core" of Non-Substitutable Demand

At the current Cu/Al ratio of approximately 4.2x (January 2026), copper-to-aluminum substitution has moved from the phase of "gradual trend" into the phase of "structural shift." However, the physical limitations of aluminum define a clear substitution ceiling.

Current state of substitution:

- HVAC (heating, ventilation, air conditioning): aluminum is already present in **40%** of global installations (Norsk Hydro); Daikin Industries has halved its copper usage.
- EV wiring harnesses: copper has been reduced by **30%** from 2015 to 2024 (from 30 to ~21 kg/vehicle); Xiaomi has introduced aluminum high-voltage harnesses.
- Transformers: aluminum windings deliver equivalent efficiency per DOE standards at a cost **13.8%** lower (Eaton).

The "hard core" of non-substitutable demand (substitution $<15\%$):

Application	Reason for non-substitutability	Share of demand
Busbars and data center power distribution	Aluminum requires 60% greater cross-section; at rack densities of 120+ kW, space is critical	~5%
EV motor windings	Copper conductivity is 40% higher; thermal conductivity ~400 vs. ~237 W/m·K; hairpin windings are optimized for copper	~4%
Subsea HV cables	Corrosion resistance to seawater; span lengths of 50+ km; repair costs	~3%
Data center liquid cooling	Cu thermal conductivity is 69% higher than Al; at rack densities of 100–600 kW, only copper suffices	~2%
Semiconductors/connectors	Sub-micron dimensions; specific properties	~8%

Collectively, the "hard core" constitutes **40–50%** of global demand and is **virtually non-substitutable at any price**.

Maximum substitution ceiling by sector, assuming Cu/Al > 7x ($10/lb at current aluminum prices):

Sector	Share of demand	Substitution potential	Substitutable volume (Mt)
HVAC/air conditioning	~8%	70–85%	1.6–1.9
Overhead power lines	~12%	Already substituted	0
Transformers	~6%	50–70%	0.8–1.2
EV wiring harnesses	~5%	40–60%	0.6–0.8
Onshore wind generation	~4%	30–50%	0.3–0.6
Building wiring	~15%	15–30%	0.6–1.3
Underground cables	~10%	15–30%	0.4–0.8
EV motors	~4%	10–20%	0.1–0.2
AI data centers	~5%	5–10%	0.1
Subsea cables	~3%	0–5%	0.0
Semiconductors/connectors	~8%	0–5%	0.0
Other	~20%	10–20%	0.6–1.1
Total	**100%**		**5.1–8.0**

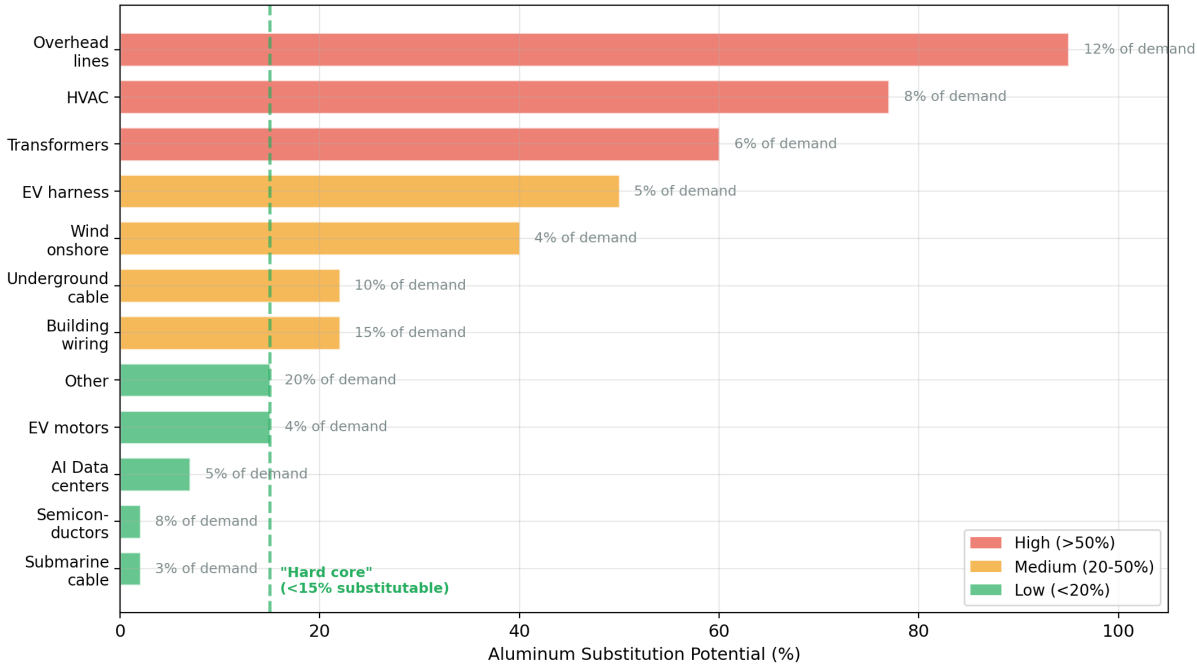

Figure 3: Copper-to-aluminum substitution ceiling by sector

The theoretical substitution ceiling is 5–8 Mt; however, it includes substitution already realized (HVAC 40%, overhead power lines), substitution requiring 5–10 years of engineering transition, and substitution in sectors with building code barriers. **The realistic volume of new substitution at $10–15/lb: 3–5 million tonnes (10–18% of demand).** This covers only a portion of the projected 10 million tonne deficit by 2040.

A critical constraint: substitution exhibits the property of **hysteresis** (Sprott ETFs): "Switching from copper to aluminum is not merely a metal swap, but a restructuring of the industrial complex requiring investment in new equipment." This means: the transition begins slowly, but the **reverse transition is equally slow**, even if copper prices decline [54].

2.7 Price Elasticity of Demand and Destruction Thresholds

The price elasticity of demand for copper exhibits a critical **temporal asymmetry**: in the short term, demand is virtually unresponsive to price, but over a 3–5 year horizon, adaptation becomes complete.

Table 6: Price Elasticity of Copper Demand and Supply (IMF, 2024)

Horizon	Demand elasticity	Supply elasticity	Interpretation
$h = 0$ (instantaneous)	-0.08 (≈ 0)	-0.006 (≈ 0)	Market is completely inelastic
$h = 1$ (1 year)	-0.48	0.58	Adaptation begins
$h = 2$ (2 years)	-0.56	0.82	Substitution gains momentum
$h = 3$ (3 years)	-0.71	0.84	Project reassessment
$h = 5$ (5 years)	-1.01	0.94	Full adaptation

Source: IMF Working Paper, 2024 [3].

The near-zero short-term elasticity ($\varepsilon \approx -0.08$) creates the foundation for speculative squeezes: a 10% price increase destroys only 0.8% of consumption. Fifty to sixty percent of demand growth is attributable to structural (policy-driven) sectors — grids, EV, data centers — where forgoing copper means forgoing the project.

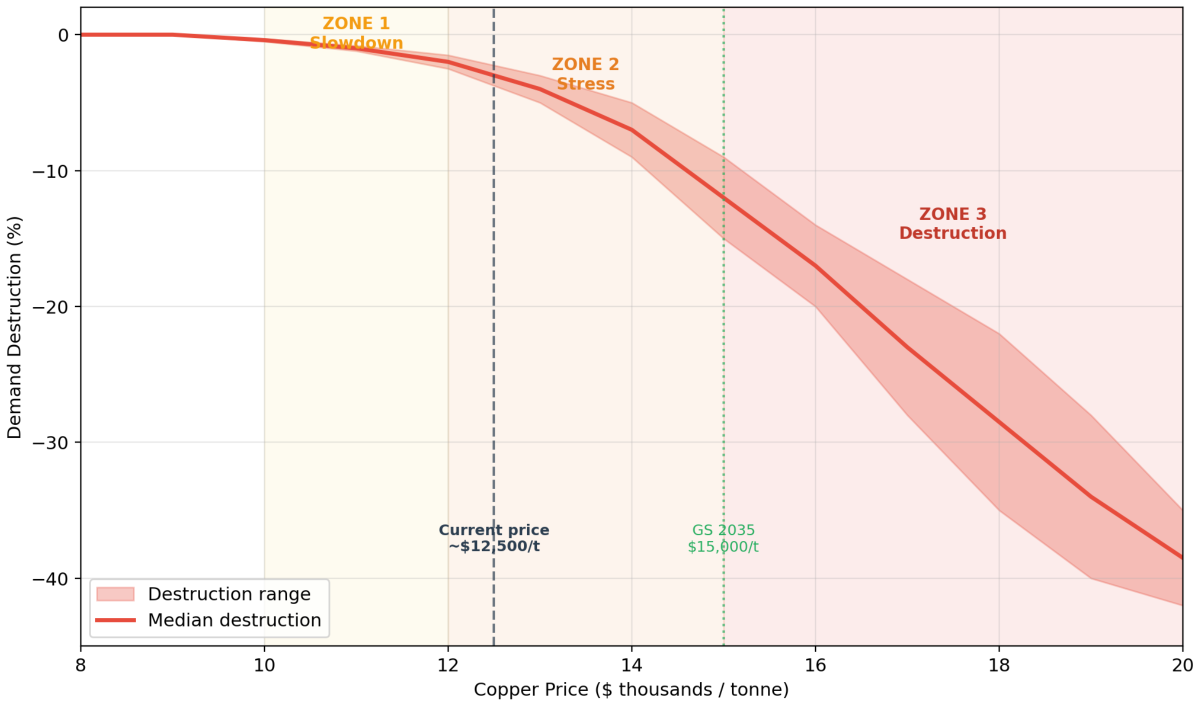

Figure 4: Copper demand destruction curve: three zones

Three zones of the destruction curve:

Zone 1: Slowdown ($10,000–12,000/t | $4.50–5.45/lb). Activation of Cu-to-Al substitution in HVAC; consumers defer purchases; marginal construction projects lose profitability. Demand destruction: -0.5% ... -1.5%.

Zone 2: Stress ($12,000–15,000/t | $5.45–6.80/lb). The market was situated in this zone in early 2026. Cu/Al > 4.2x triggers the "Great Metal Migration." Grid modernization projects become 15–25% more expensive; some are deferred. Demand destruction: -3% ... -9% in the short term, up to -20% in the long term.

Zone 3: Breakdown (>$15,000/t | >$6.80/lb). Irreversible destruction of infrastructure demand. The cost of electrical wiring in a home ($6,000–30,000) becomes prohibitive for mass construction. EV manufacturers incur additional costs of $400–600 per vehicle. Utilities defer grid modernization. Destruction: −12% **...** −20% in the short term, −28% **...** −42% over a 5-year horizon.

Precise thresholds of infrastructure destruction:

Indicator	Price level
Onset of project delays	$12,000–13,000/t ($5.45–5.90/lb)
Mass Cu-to-Al substitution	$13,000–14,000/t at Cu/Al > 4.0x
Cancellation of grid modernization projects	$14,000–15,000/t ($6.35–6.80/lb)
Destruction of baseline macroeconomic demand	>$16,000/t (>$7.25/lb)

Importantly: even Goldman Sachs — the most "bullish" among major banks over the long term — views its $15,000/t forecast for 2035 not as an equilibrium price, but as an **incentive price**, at which the market begins to self-correct through accelerated substitution and new supply [30].

Self-regulating mechanism (feedback loop). The destruction curve is not static — it describes a dynamic feedback cycle that constrains price upside:

1. Copper price rises above $12,000–13,000/t → activation of Al substitution and project delays.
2. Substitution reduces demand by 3–9% → reduction of the deficit.
3. Reduction of the deficit → downward price pressure.
4. Price decline → slowdown of investment in new mines (reverse lag of 10–15 years).
5. After 10–15 years → a new deficit, even more acute.

This cycle implies that the **copper price will most likely oscillate within the "destruction corridor" of $10,000–15,000/t** for a substantial portion of the 2026–2035 period, with brief excursions beyond its bounds during squeezes. Sustained residence above $15,000/t is unlikely (>5 years), as it triggers irreversible substitution and new supply processes. For the spread strategy, this means: the primary source of returns is the **slow structural widening of the Cu/Pd spread**, not a sharp copper price spike.

3 Fundamental Analysis of the Palladium Market: A Structural Bearish Thesis

3.1 Demand Structure: Dominance of Autocatalysts

Palladium occupies a unique position among industrial metals: unlike copper, which is diversified across dozens of sectors, demand for palladium is **concentrated in a single application** — three-way catalytic converters (TWC) for gasoline internal combustion engines.

Structure of Global Palladium Demand (2024–2026):

Sector	Share of Demand	Volume (Moz, ~2024)	Trend
Autocatalysts (gasoline + hybrids)	84–90%	~7.7	Declining from peak of 8.4 Moz (2019)
Electronics and MLCC	~8–9%	~0.8	Growing (semiconductors for AI)
Chemical/petrochemical industry	~8–9%	~0.8	Stable
Jewelry and investment	~2–3%	~0.2	Minimal

Sources: Johnson Matthey PGM Market Report 2025, Fortune Business Insights, Nornickel [34, 42].

Automotive palladium consumption peaked at ~8.4 Moz in 2019 and declined to ~7.7 Moz by 2024, with a further forecast of ~7.1 Moz in 2025 (Johnson Matthey). The drivers of this decline are a combination of two factors: (a) the growing share of pure BEVs (which do not require catalysts) and (b) partial substitution of palladium by platinum in tri-metallic catalysts.

The contrast with non-automotive demand is critically important: **Nornickel forecasts a +2% increase in industrial palladium consumption in 2025**, supported by demand from AI semiconductors (MLCC — multilayer ceramic capacitors), as well as the aerospace and defense industries. Emerging vectors — hydrogen fuel cells, OLED displays, defense applications — may add **0.9–1.0 Moz annually** by the 2030s (Palladium Technology Center, Nornickel). However, this growth is insufficient to offset the erosion of the automotive segment [42].

The concentration of demand in a single sector subject to technological displacement renders palladium **structurally vulnerable** — in contrast to copper, whose demand is growing along four independent vectors simultaneously.

3.2 Impact of Vehicle Fleet Electrification on Demand

Vehicle fleet electrification is the central factor underpinning the bearish thesis on palladium. However, the pace of this transition is systematically overestimated in popular narratives.

Actual Electrification Dynamics:

- Global EV sales reached **17.8 million** in 2024 (~19.9% of new sales, +25% y/y).
- EV Volumes forecasts: 23.7 million in 2025 (25.5%), 43.2% by 2030, 83% by 2040.
- However, **new sales represent only a small fraction of the active fleet**: even at a 40%+ EV share of new sales by 2030, ICE vehicles requiring palladium will dominate roads until 2040.

Deceleration of Electrification (2025–2026):

- Consumer sentiment: **50%** of global car buyers intend to purchase an ICE vehicle within the next 24 months (+13 p.p. in 2025 vs. 2024); preference for BEVs fell to **14%** (−10 p.p.) (EY).
- In the US, EV sales growth slowed to **+10% in 2024 vs. +40% in 2023.**
- BloombergNEF (2025 EV Outlook) reduced its cumulative US EV sales forecast through 2030 **by 14 million units** relative to the previous estimate, reflecting the Trump administration's policies (elimination of federal incentives) [29].

Production Dynamics for ICE/Hybrid Vehicles:

Indicator	2024	2025 (forecast)	2030 (forecast)	Change 2024–2030
ICE + hybrids requiring PGM (million units)	~79	~76	~67	−15% over 6 years
Annual rate of decline	—	−3.8%	−1.3% CAGR	Gradual erosion

Sources: Nornickel, WPIC [42, 38].

WPIC states: "Despite the continued growth of BEV share to 28% by 2030, ICE vehicles and hybrids will dominate automotive production until 2040." The aggregate decline in automotive palladium demand represents a **gradual erosion at** −1.3% **CAGR**, not a structural collapse.

An additional factor: **tightening environmental standards** (the transition from Euro 6 to Euro 7 in Europe, China 6 to China 7, and US EPA Tier 4 from 2027) mandate **increased palladium loading per ICE vehicle** — the "loading offset" effect, which partially neutralizes the reduction in volumes.

3.3 The PHEV/HEV Paradox: A Countercyclical Demand Buffer

The most underappreciated factor in palladium market analysis is the paradoxical impact of hybrid vehicles (PHEV, MHEV, EREV) on demand. Hybrids not only retain the need for a catalytic converter but also **require 10–20% more palladium** per vehicle compared to a standard ICE.

The Paradox Mechanism. Hybrid engines cyclically start and stop, causing the catalytic converter to spend a significant portion of its operating time in "cold start" mode (below the activation temperature of 250–400°C). In this mode, untreated hydrocarbons and nitrogen oxides pass through the catalyst without being cleaned. The engineering response is **increased palladium loading** to compensate:

Vehicle Type	Pd Loading (relative)	Cold Start Susceptibility
Standard gasoline ICE	1.0x (baseline)	Low
Mild hybrid (MHEV)	1.05–1.10x	Moderate
Plug-in hybrid (PHEV)	1.10–1.20x	High
EREV (extended-range electric vehicle)	1.15–1.25x	Very high
Pure BEV	0x	N/A

PHEV/EREV Market Dynamics:

- PHEV sales grew by **62% in Europe** (September 2025).
- PHEVs and hybrids accounted for **22% of all light vehicle sales in the US** (Q1 2025).
- EREVs (extended-range electric vehicles) captured **25% of electric SUV sales in China** (2024).

The paradox is that **the fastest-growing segment of the automotive market (PHEV/EREV) is not an enemy but an ally of palladium**. As long as hybrids remain the dominant transitional vehicle (rather than pure BEVs), palladium demand has a structural buffer. This fundamentally limits the pace of automotive demand destruction and explains why the decline proceeds at −1.3% CAGR rather than precipitously.

3.4 Supply Dynamics: Collapse in North America and Geopolitical Risks

The bearish thesis on palladium rests on the assumption of excess supply against the backdrop of declining demand. However, **palladium supply is contracting faster than demand**, creating a significant tail risk for the short position.

North America — Supply Collapse:

- **Sibanye-Stillwater** (the sole primary palladium producer in the US): announced a reduction in mining output at the Stillwater and East Boulder mines of **~45%**. The reason is unprofitability at current prices [44].
- **Lac des Iles** (Canada): cessation of commercial production by mid-2027.
- In aggregate: a loss of **200,000–400,000 ounces** of primary supply from North America over the 2025–2027 horizon.

South Africa — Chronic Atrophy:

- Impala Platinum placed the Two Rivers mine on care and maintenance (2024).
- Chronic power supply disruptions (load shedding) constrain production volumes.
- A number of PGM mines in the Bushveld Complex are operating below the profitability threshold.

Russia — Geopolitical Risk:

- **Nornickel** provides **~40% of global palladium supply** [42].
- Any escalation of sanctions pressure could instantaneously remove a substantial volume of supply.
- At present, Russian palladium is not subject to direct sanctions; however, logistical and payment restrictions are already impeding deliveries.

Reverse Substitution Pd→Pt. In 2023–2024, a number of automakers switched to platinum in catalytic converters (when Pt < Pd). However, in 2025 **platinum appreciated above palladium**, eliminating the economic incentive for substitution. WPIC estimates that peak substitution of palladium by platinum in 2025 reached **877,000 ounces**, with a subsequent reversal potentially adding **366,000 ounces of additional demand** for palladium by 2027 [38].

3.5 Production Costs and the Palladium Price Floor

Understanding the cost structure is critical for assessing the lower bound of palladium prices — the level below which supply begins to self-liquidate through mine closures.

AISC (All-In Sustaining Cost) by Key Producers (2024–2025 Estimates):

Producer	Region	AISC ($/oz)	Source	Status
Nornickel	Russia	First quartile*	Wood Mackenzie, Metals Focus	Profitable; low cost
Anglo American Platinum	South Africa	~$986/3E oz	Annual Report 2024	Marginally profitable
Impala Platinum	South Africa	~$950–1,050/PGM oz	Integrated Report 2023	Under pressure
Sibanye-Stillwater (US)	USA	~$1,343/2E oz	SENS H1 2024	Loss-making; cutting 45%
Smaller SA producers	South Africa	>$1,200/oz (est.)	Analyst reviews	Closure/care & maintenance

*Note: Nornickel does not publish a standardized AISC per PGM ounce; it focuses on cash costs per tonne of Ni/Cu. External estimates (Wood Mackenzie, Metals Focus) place the company in the first quartile of the global PGM cost curve.

Palladium Price Floor. At 900–1,000 USD/oz, approximately 30–40% of global capacity (predominantly in South Africa and North America) becomes unprofitable. Nornickel, as the largest producer, remains profitable down to 600–750 USD/oz owing to low energy costs and by-product metals (nickel, copper, platinum). This establishes a **hard price floor of 600–700 USD/oz** — the level at which supply contracts to such an extent that the balance reverts to deficit.

For the strategy, this implies: the maximum downside potential for palladium from the current 1,366 USD/oz to 700–800 USD/oz (−42–49%), but not to zero. The "industrial demand floor" (150–250 USD/oz) is a theoretical level for a world without autocatalysts, but at such prices supply would collapse well before that point is reached.

3.6 Palladium Inventories and Investment Demand

Exchange Inventories and ETF Positions:

- Palladium inventories on NYMEX/COMEX: extremely low — approximately **210,000 ounces** (of which 141,000 registered and 69,000 eligible) as of early 2026. This is significantly below the 2015–2019 levels and creates a thin buffer for absorbing supply shocks.

- ETF positions (Aberdeen Standard Physical Palladium Shares, Sprott): sustained outflows during 2023–2025 amid the bearish narrative. Liquidation of ETF holdings adds physical metal to the market, amplifying the surplus.
- Russian state reserves (Gokhran): the volume is classified. According to Moscow Times (2010), citing Nornickel senior executive Viktor Sprogis, the large Soviet palladium stockpile had been "virtually exhausted." Johnson Matthey (2013) estimated annual Gokhran sales at approximately 250,000 ounces with a declining trend. Residual reserves are estimated by industry analysts as insignificant relative to the scale of the market.

Implications for the Strategy: low and declining palladium ETF inventories mean that the "cushion" for absorbing supply shocks is thin. A geopolitical shock (Russian sanctions) amid low inventories could trigger a disproportionately sharp price spike — which confirms the necessity of a half-sized short leg.

3.7 Cu/Pd Correlation under Crisis Conditions

To assess the hedging properties of the spread position, the behavioral correlation of the two metals under stress conditions is critically important.

Historical Cu/Pd Correlation (Monthly Logarithmic Returns). The calculation was performed using COMEX (HG) and NYMEX (PA) monthly closing prices for the period January 2005 – January 2026 (212 common observation points). Pearson correlation coefficient:

Period	Cu/Pd Correlation	n (months)	Market Context
2005–2026 (full)	+**0.50**	211	Moderate positive (both are industrial metals)
2007–2009 (GFC)	+**0.61**	17	Elevated in crisis: both fell 50–65%
2019–2020 (COVID)	+**0.26**	7	Weak: short shock with rapid divergence in recovery
2022 (Fed tightening)	+**0.18**	11	Low: copper −25%, palladium −40%, different drivers
2023–2025 (divergence)	+**0.04**	31	Near zero: structural divergence; copper rises, palladium falls

Data source: COMEX HG=F, NYMEX PA=F (Yahoo Finance). Method: monthly log-returns, Pearson coefficient.

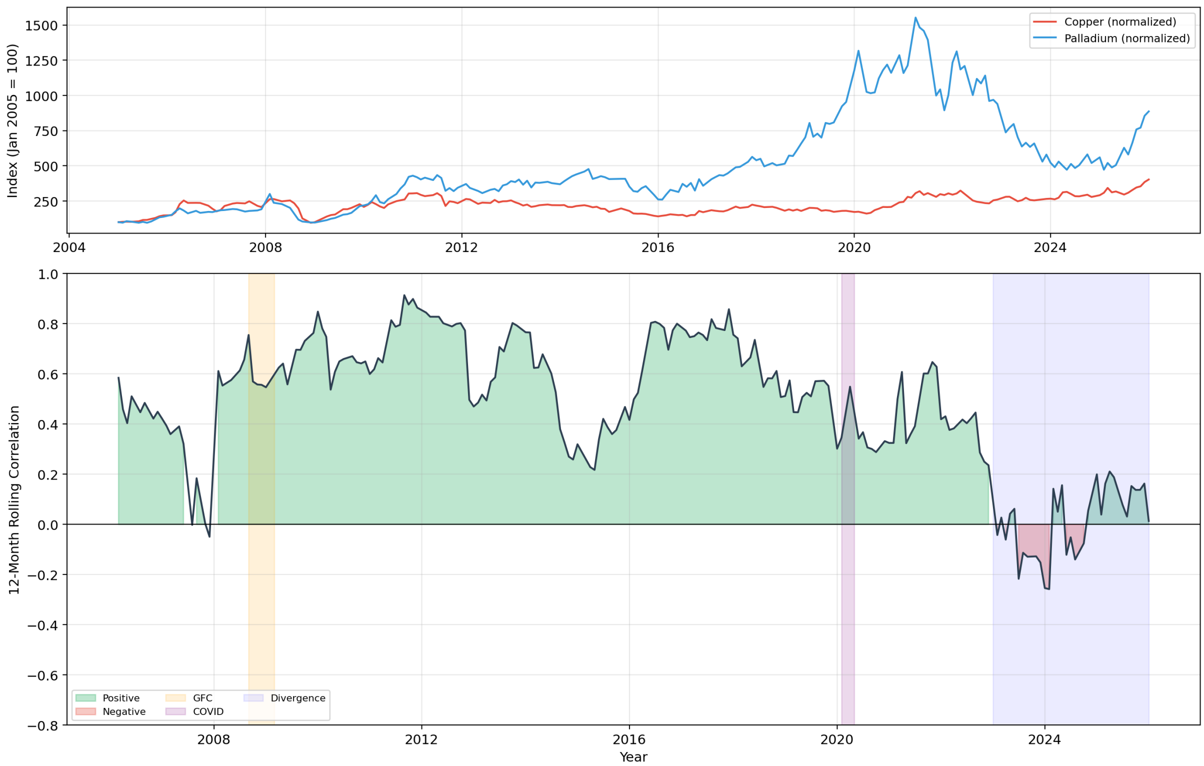

Figure 5: Cu/Pd Correlation Analysis: Normalized Prices and 12-Month Rolling Correlation

Conclusions for the Strategy:

1. In the divergence phase (2023–2025), the correlation is virtually zero ($r = +0.04$) — **ideal conditions** for a spread position: the metals' movements are independent, each leg generates returns from its own fundamental driver.

2. In crises, correlation increases but **not to extreme values**: GFC +0.61 (not +0.85, as is often assumed for industrial metals); COVID +0.26 (short shock with rapid divergence). This means that the Pd leg provides **partial** but not complete hedging under stress.

3. The 12-month rolling correlation (Fig. 8) demonstrates a clear structural reversal: from persistently positive $+0.4 \ldots + 0.7$ in 2005–2019 to near-zero and periodically negative values since 2020. This **quantitatively confirms** the thesis of structural divergence rather than cyclical oscillation.

4. Key implication: the spread position Long Cu / Short Pd **is not market-neutral** and does not protect against systemic risk-off events. It is a **directional bet on the continuation of divergence**, supported by data showing declining correlation since 2020.

3.8 Palladium Market Balance Forecast through 2030

Table 7: Palladium Market Balance Forecast

Indicator	2024	2025	2026	2029
Total demand (Moz)	~10.1	~9.8	~9.6	~9.0
Automotive demand (Moz)	~7.7	~7.1	~6.9	~6.3
Total supply (Moz)	~10.0	~10.0	~10.1	~9.7
Balance (Moz)	~0	+0.2	+0.5	+0.7
Average price ($/oz)	924	~1,000	~1,000–1,100	~900–1,100

Sources: WPIC, Johnson Matthey, SFA Oxford. Forecasts for 2026–2029 represent consensus estimates [38, 34].

Figure 6: Palladium Market Balance and Price Forecast (2019–2029)

Key conclusions:

1. The market is transitioning from equilibrium to a **growing surplus**: from ~0 in 2024 to ~689,000 ounces by 2029.
2. The surplus accumulates **gradually** rather than abruptly — consistent with the gradual decline in automotive demand.

3. The average price stabilizes in the range of 900–1,100 USD/oz — significantly below the peak of 2,398 USD/oz (2021) but above the "floor" of industrial demand (150–250 USD/oz under full electrification).

4. The market has already discounted approximately 60% of the maximum downside potential (from 2,398 to 924 USD/oz in annual average terms).

Tail Risks to the Forecast:

- *Upside for palladium*: sanctions against Russian palladium (+40% of supply at risk); sharp acceleration of PHEV vs. BEV adoption; reverse substitution Pt→Pd.

- *Downside for palladium*: accelerated BEV adoption; absence of supply disruptions; technological breakthroughs in catalysts (reduction in PGM loading).

4 Historical Dynamics of the Cu/Pd Spread

4.1 Four Structural Regimes of the Cu/Pd Ratio (2012–2026)

The Cu/Pd ratio (copper price in \$/t divided by the palladium price in \$/oz) exhibits a clear succession of structural regimes, each reflecting the dominant market force. The calculation was performed on monthly data from COMEX (HG, \$/lb × 2,204.62 = \$/t) and NYMEX (PA, \$/oz) for the period 2005–2026, comprising 212 observations.

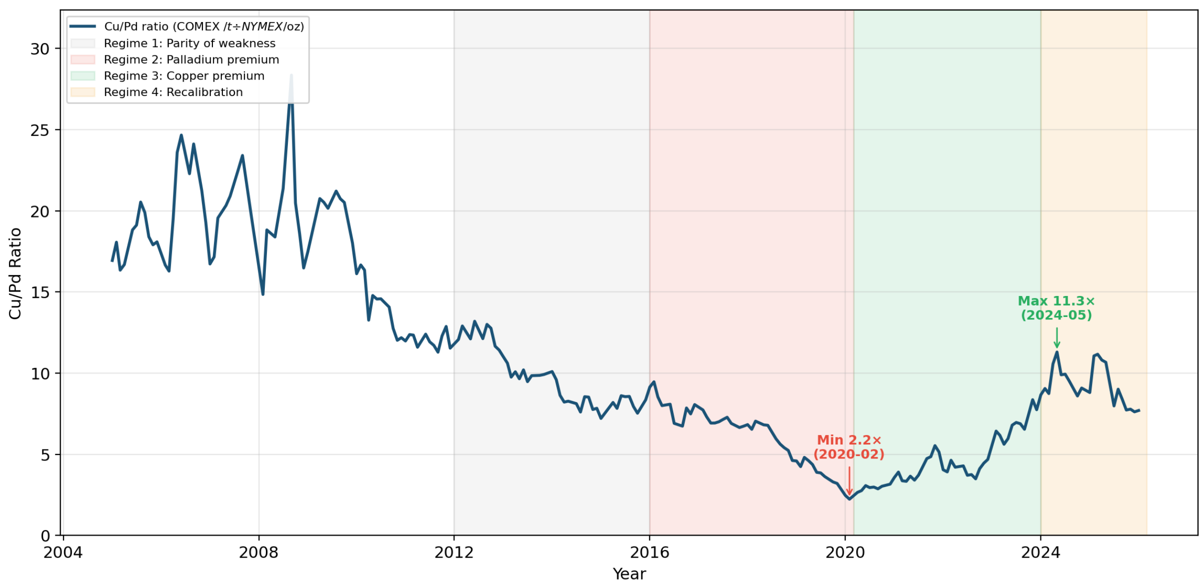

Figure 7: Cu/Pd Ratio: Four Structural Regimes (2005–2026)

Table 8: Structural Regimes of the Cu/Pd Ratio (COMEX/NYMEX)

Period	Range	Mean	Dominant Force
2012–2015	7.2–13.2x	9.7x	Weakness in both metals; Dieselgate (2015)
2016 – Feb. 2020	2.2–9.5x	6.1x	"Palladium premium": 13 years of Pd deficit
March 2020 – 2023	2.7–8.4x	4.5x	Inversion: BEV boom, Pd demand destruction
2024 – Jan. 2026	7.6–11.3x	9.3x	Recalibration: BEV slowdown, PHEV boom

Regime 1 (2012–2015): Parity of Weakness. Both metals under pressure: copper — due to the deceleration of Chinese construction; palladium — due to the dominance of diesel engines in Europe (prior to the Dieselgate scandal in September 2015). Average ratio ~9.7x.

Regime 2 (2016 – February 2020): Palladium Premium. Following Dieselgate, Europe pivots from diesel to gasoline, sharply increasing palladium demand. Simultaneously, supply stagnates. Palladium enters a streak of 13 consecutive years of deficit (2012–2024). The palladium price rises from 500 USD/oz (2016) to 2,500 USD/oz (February 2020). The Cu/Pd ratio collapses to a historical low of **2.2x** (February 2020).

Regime 3 (March 2020 – 2023): Inversion — The Copper Premium. The onset of mass BEV sales triggers the narrative of "ICE death." Palladium loses 61% from its annual average peak ($2,398 to $924). Copper receives an impulse from electrification and the energy transition. Cu/Pd rises from 2.7x to 8.4x — an increase of 3.1 times in less than 4 years.

Regime 4 (2024 – January 2026): Recalibration. The market reassesses the pace of electrification: the PHEV boom, deceleration of BEV sales, and reduction in federal incentives. Palladium receives support from the supply collapse (Sibanye-Stillwater −45%) and reverse substitution Pt→Pd. The average ratio returns to ~9.3x (range 7.6–11.3x). As of January 2026, Cu/Pd = 7.7x with copper at $5.90/lb and palladium at $1,688/oz.

4.2 The 2020 Spread Inversion as a Marker of Technological Transition

The inversion of the Cu/Pd ratio that occurred in 2020 is neither accidental nor a cyclical fluctuation — it precisely coincides with a **qualitative shift** in the global automotive industry:

- 2020 — global BEV sales exceeded **3 million units** for the first time (growth of 43% y/y).
- 2020 — the EU introduces penalties of EUR 95 per g/km of CO_2 above the limit, compelling automakers to mass-launch EV models.
- 2020 — China announces a carbon neutrality target by 2060.
- 2020–2021 — capital investments in EV infrastructure exceed $100 billion globally.

The chronological coincidence of the Cu/Pd reversal with the mass launch of electrification confirms that the market correctly prices the redistribution of industrial demand: from palladium (ICE catalysts) to copper (electrical wiring, motors, charging stations, grids). The increase in Cu/Pd from its minimum of 2.2x (February 2020) to an average of 9.3x (2024–2025) is a structural, not cyclical, signal.

4.3 Degree of "ICE Death" Discounting in Current Palladium Prices

To what extent does the current palladium price already reflect the scenario of full electrification?

What Has Already Been Discounted:

- Palladium fell 61% from its 2021 annual average peak (2,398 to 924 USD/oz in 2024), subsequently recovering to 1,688 USD/oz by January 2026 (−30% from peak).
- In a hypothetical "100% BEV" world (zero automotive demand), the fundamental "floor" for palladium is determined by residual industrial demand (approximately 15% of current levels): 150–250 USD/oz.
- The current price (1,688 USD/oz, January 2026) implies that the market values "not-yet-discounted" automotive demand at 1,400–1,500 USD/oz, i.e., it expects the preservation of a significant automotive segment over a 5–10+ year horizon.

What Has NOT Been Discounted (Upside Risks for Palladium):

1. Reverse substitution Pd→Pt: potentially +366,000 oz by 2027.
2. Supply collapse in North America: Sibanye-Stillwater −45%, Lac des Iles closure.
3. Geopolitical shock: sanctions against Nornickel (40% of global Pd).
4. PHEV/EREV boom: increased palladium loading per vehicle.
5. New industrial applications: hydrogen, OLED, defense (+0.9–1.0 Moz by the 2030s).

4.4 Retrospective Simulation of the Strategy (2012–2026)

To assess the historical behavior of the strategy, a stylized retrospective simulation was conducted: Long Cu (1.0x) / Short Pd (0.5x), excluding funding costs, with monthly rebalancing.

Results by Period (Cumulative P&L):

Period	Cu (%)	Pd (%)	Long Cu 1.0x	Short Pd 0.5x	**Total**	Characterization
2012–2015	−30%	−15%	−30%	+7.5%	−22.5%	Both decline; Cu underperforms
2016–2020	+15%	+320%	+15%	−160%	−145%	Catastrophe: Pd rally destroys
2020–2024	+80%	−65%	+80%	+32.5%	+112.5%	Triumph of divergence
2024–Mar 2026	+45%	+48%	+45%	−24%	+21%	Both rise; Cu dominates

Key Conclusions from the Retrospective Analysis:

1. **The 2016–2020 period would have been catastrophic** (−145% cumulative). The palladium rally of +320% with a half-sized short position generated a loss of −160%, not offset by the modest rise in copper. This confirms that the strategy **critically depends on the correctness of the divergence thesis** and is not a statistical arbitrage.

2. **The 2020–2024 period validates the thesis** (+112.5%). The Cu/Pd inversion precisely coincided with mass electrification. If the energy transition thesis is correct, then 2020–2024 is not an anomaly but the beginning of a new structural regime.

3. **The current period (2024–2026) is mixed**: both metals are rising (copper — on fundamental demand, palladium — on recovery from oversold conditions + supply collapse). The short Pd leg generates a loss. This is a period of **recalibration** that may persist for 6–18 months.

4. **Critical lesson:** the strategy cannot be evaluated over an arbitrary historical window. It is profitable **only** in the divergence regime (2020–2024). In the "parity of weakness" (2012–2015) or "palladium premium" (2016–2020) regimes, it is loss-making. The investor must hold a well-founded conviction that the current divergence regime will persist.

Conclusion: the palladium market has already **absorbed the greater part** of the bearish narrative. The remaining downside potential (from 1,000–1,400 to 700–800 USD/oz in an extreme accelerated-BEV scenario) is limited and is offset by non-trivial tail risks to the upside. This justifies a **half-sized rather than full-sized** short position in the proposed strategy.

5 Construction of the Synthetic Spread Position

5.1 Strategy Mechanics: Long Cu / Short 0.5x Pd

The proposed strategy constitutes an **asymmetric pair trade (spread trade)** in which:

- **Long leg**: a position on rising copper prices (full size, 1.0x).
- **Short leg**: a position on declining palladium prices (half size, 0.5x).
- **Horizon**: 2–5 years (structural position, not tactical).
- **Instruments**: perpetual futures contracts on decentralized and centralized exchanges.

The strategy is predicated on the **structural divergence** of two markets rather than on statistical mean-reversion characteristic of classical pair trading strategies. Unlike a standard pair trade, where the spread is expected to revert to its mean, this strategy assumes **further widening of the Cu/Pd spread**, driven by fundamental factors.

Return Profile:

Scenario	Cu	Pd	Position Outcome	Prob.
Base case: gradual electrification	+15–30%	−10–20%	**Profit** (both legs)	40–50%
Bullish on Cu (squeeze/supercycle)	+40–80%	−5–15%	**Significant profit**	20–25%
Bearish on Pd (accelerated BEV)	+5–15%	−25–40%	**Profit** (Pd leg dominates)	10–15%
Geopolitical shock (Russian sanctions on Pd)	+0–10%	+30–80%	**Loss** (Pd leg; limited by 0.5x)	5–10%
Recession (both decline)	−20–30%	−15–25%	**Loss** (Cu leg dominates)	10–15%

5.2 Rationale for the Asymmetric Ratio (2:1)

The choice of a 2:1 ratio (full position in Cu, half position in Pd) is driven by three factors:

Factor 1: Differential Conviction. The bullish thesis on copper is supported by four independent demand vectors and multiple supply constraints — the level of conviction is high. The bearish thesis on palladium, while directionally correct in general, is complicated by non-trivial tail risks (Russian geopolitics, reverse substitution Pt→Pd, PHEV boom) — the level of conviction is moderate.

Factor 2: Volatility. Palladium historically exhibits significantly higher volatility than copper: the daily ATR of palladium is 2–4% vs. 1–2% for copper. At full position size (1:1), the volatility of the Pd leg could dominate the P&L, transforming the strategy from "long copper with a hedge" into "de facto short palladium" — which does not correspond to the investment thesis.

Factor 3: Tail Risk Management. The maximum adverse scenario for the short position is a geopolitical shock removing 40% of global palladium supply (sanctions against Nornickel). In such a scenario, palladium could rise by +50–100% over a short period. A half-sized position limits the loss to 25–50% of the short leg's notional, which is manageable within the context of a 2–5-year horizon.

The alternative (aggressive) 1:1 ratio is permissible for investors with high risk tolerance and conviction in the absence of geopolitical shocks. In this case, the return profile becomes more convex: returns are higher if the base scenario materializes, but losses under adverse scenarios are also more substantial.

5.3 The Role of Funding Rates and the Practice of Hedging through DeFi Derivatives

The key practical challenge of long-term holding of perpetual futures contracts is the **funding rate**. Perpetual futures employ a mechanism of periodic payments (every 4–8 hours) to keep the contract price close to the spot index:

- When the market is in contango (long positions dominate): **longs pay shorts**.
- When the market is in backwardation (short positions dominate): **shorts pay longs**.

For the copper market, which is in a sustained bullish trend, funding is predominantly **negative for long positions** (longs pay). Over a 1–3 year horizon, cumulative funding costs can amount to **10–30%** of the position's notional, significantly reducing returns.

Mechanism for Hedging Funding through the Pd Leg:
The short palladium position serves a dual function:

1. **Fundamental hedge**: generating profit from palladium's decline, compensating for temporary drawdowns on the copper side.

2. **Funding hedge**: in conditions of a bullish palladium market (or neutral), short positions **receive** funding, partially or fully offsetting funding costs on the long copper leg.

The effectiveness of this mechanism depends on the specific platform and prevailing market conditions. In practice, the correlation of funding rates between copper and palladium is low, which implies incomplete offset — however, even partial mitigation of costs substantially improves the economics of the long-term position.

5.4 Implementation Instruments: CME, LME, HyperLiquid

Traditional Exchanges (CME, LME):

- *Advantages*: regulated, high liquidity, physical delivery, institutional infrastructure.
- *Disadvantages*: high entry threshold (standard CME copper contract = 25,000 lbs ~ $147,500); brokerage account required; margin requirements; limited trading hours.
- *Suitable for*: institutional and qualified investors with capital starting from 500,000 USD.

HyperLiquid (DEX):

- *Advantages*: no KYC; minimal entry threshold (from $50); 24/7 trading; USDC margin.
- *Disadvantages*: synthetic contracts without physical delivery; dependence on price oracles (Chainlink, Pyth); counterparty risk (smart contract risk); limited liquidity in copper ($75 million/day at peak vs. $92 billion/day on CME+LME+SHFE).
- *Suitable for*: retail investors with capital of $1,000–$500,000 seeking access to macro markets without barriers.
- *Palladium on HyperLiquid*: the platform provides perpetual futures contracts on palladium alongside copper, silver, and gold. Palladium liquidity is lower than copper, which is taken into account when choosing the position-building tactic (in tranches, not all at once).

Alternative Instruments (for completeness):

- *ETFs*: CPER (United States Copper Index Fund) for the Cu leg; PALL (Aberdeen Standard Physical Palladium) for the Pd leg. Advantage: no funding costs or rolling; disadvantage: inability to short without a margin account; ETF fees (expense ratio ~0.6–0.8% per annum).
- *Classical CME futures*: HG (copper, 25,000 lbs) and PA (palladium, 100 oz). Advantage: maximum liquidity; disadvantage: high threshold (147,500 USD per HG contract; 136,600 USD per PA contract), rolling every 1–3 months (contango/backwardation costs).

- *CFDs at regulated brokers*: Interactive Brokers, Saxo Bank. Allow trading both metals with moderate leverage and without rolling; overnight charges (~3–5% per annum) are lower than perpetual futures funding.

Impact of DeFi Platforms on Price Formation. The volume of DeFi derivatives on copper (approximately 75 million USD/day) constitutes 0.08% of classical exchanges — the impact on price formation is mathematically negligible (Kyle, 1985: the significance threshold begins at 3–5% market share). Price formation on DeFi platforms follows CME/LME through price oracles (Chainlink, Pyth), not the reverse. DeFi platforms serve the function of an **access instrument** to commodity markets, without exerting an independent influence on fundamental price levels [12].

6 Stress Testing and Scenario Analysis

6.1 Base Case Scenario: Gradual Electrification (Probability: 40–50%)

Assumptions: electrification continues at current rates; BEV share in new vehicle sales reaches ~43% by 2030 (EV Volumes); hybrids remain a transitional solution; the structural copper deficit builds gradually; no major geopolitical shocks.

Copper: the investment bank consensus defines a range of $10,000–13,000/t for 2026–2027, rising to $12,000–15,000/t by 2030. Goldman Sachs forecasts $15,000/t by 2035 as the incentive price. The supply deficit builds gradually: ~330 Kt in 2026 (J.P. Morgan), widening to 1–2 Mt/year by 2030.

Bank	2026 Forecast ($/t)	2027 Forecast	Long-Term
Goldman Sachs	10,710 (H1) – 11,200 (Q4)	10,800	15,000 by 2035
J.P. Morgan	12,075 (average)	12,500	12,000 (10-year LT)
Bank of America	12,000	13,501	Peak up to 15,000 possible
UBS	12,000 (end of Q1)	13,000 (end of 2027)	"Structural bull case"
StoneX	11,490 (average)	—	"Price is unsustainable"

Palladium: the surplus builds to 689 thousand ounces by 2029 (WPIC). Price range: $900–1,400/oz, with an average of $1,000–1,100/oz. Gradual erosion of automotive demand (−1.3% CAGR) is partially offset by growth in industrial consumption (+2%).

Cu/Pd ratio: in the base case scenario, the ratio widens to **9–13**× (copper dominance zone), confirming the directional thesis of the strategy.

Position outcome for Long Cu / Short 0.5× Pd:

- Long leg: +15–30% over 2–3 years.
- Short leg: +5–15% (from a 10–20% decline in Pd, at 0.5× sizing).
- Combined return: **+17–38%** over 2–3 years (before funding costs).
- Net of funding (~5–15% cumulative): **+5–30%** net return.

6.2 Bull Case Scenario for Copper: Squeeze + Supercycle (Probability: 20–25%)

Assumptions: the J.P. Morgan structural deficit (330 Kt in 2026) materializes; capital rotation from equities into commodities intensifies; LME inventories fall below 100,000 t; one or more triggers are activated — force majeure at a major mine, tariff shock, or Chinese export restrictions.

Historical rally analogues:

Asset	Period	Gain (trough to peak)
Copper	2001–2006 (China boom)	+462%
Copper	2020 (COVID) – 2021	+128%
Copper	2025–2026 (to ATH)	+63%
Silver	2025 (annual)	+240%
Uranium	2001–2007	+1,380%
Rhodium	2016–2021	+2,900%
Nickel	2022 (squeeze)	+305% (2 days)

Banks systematically underestimate peaks: Goldman Sachs expected $10,000–11,000 for 2026; the market delivered $14,500. In the 2001–2011 supercycle, copper rose cumulatively by +588% ($1,600 → $11,000). The current cycle has produced +215% so far ($4,600 → $14,500).

Extreme squeeze scenario ($16,000–18,000/t):

Requires simultaneous convergence of 4+ triggers: force majeure + large short position + tariff-driven stockpiling + geopolitical shock. Probability: 5–10%. Peak duration: 1–2 weeks.

Physical rejection mechanisms at $16,000–18,000/t:

1. Physical buyers refuse to purchase (analogy with the 2022 nickel squeeze: no consumer bought nickel at $100,000/t).
2. Massive scrap release: +0.5–1.0 Mt of additional scrap per quarter.
3. Accelerated substitution: at Cu/Al > 5×, aluminum becomes 2.5–3× cheaper.
4. Exchange intervention: following 2022, the LME introduced a 15% daily price move limit.
5. Political intervention: strategic reserves of China, the US, and the EU.

Weekly model of an extreme squeeze:

Week	Price ($/t)	Event
0	12,500	Base price
1–3	13,000–14,500	Trigger: force majeure + margin calls on shorts
4–6	15,000–17,000	Liquidation cascade, stop-loss triggers breached
7–8	17,000–18,000	Peak. Physical buyers exit
9–10	15,000–16,000	LME limits + emergency scrap
11–13	13,000–14,000	Correction, profit-taking
14–20	11,500–12,500	Return to fundamental levels
21–26	10,500–11,000	Overshoot to the downside due to substitution "scars"

Position outcome: with copper rising +40–80% and a moderate palladium decline of −5–15%, the combined return amounts to **+42–87%** (before funding). This scenario is maximally favorable for the strategy.

6.3 Bear Case Scenario for Palladium: Accelerated BEV Adoption (Probability: 10–15%)

Assumptions: a technological breakthrough in batteries (solid-state) sharply reduces BEV costs; governments tighten ICE bans; PHEV/EREV lose their appeal; no supply disruptions in Pd.

Palladium: large surpluses; price falls to **$700–800/oz** (Statista, SFA Oxford — bear case scenario). Automotive demand declines at an accelerated pace (−3–5% CAGR instead of −1.3%).

Copper: moderate growth (+5–15%), as accelerated electrification increases demand.

Cu/Pd ratio: widens to **13–17×** — historically unprecedented levels.

Position outcome: profit is generated predominantly by the Pd leg: palladium decline of −25–40% (×0.5 = +12–20%), plus moderate Cu leg appreciation (+5–15%). Combined return: **+17–35%**.

6.4 Risk Scenario: Geopolitical Shock to Palladium (Probability: 5–10%)

Assumptions: escalation of sanctions against Russia includes palladium; Nornickel (40% of global supply) is effectively cut off from Western markets; simultaneously, Sibanye-Stillwater fails to restore production volumes.

Palladium: a sharp rally of **+30–80%** over 1–3 months. The price may briefly return to $1,800–2,200/oz. However, unlike 2020 (when the deficit was organic), a sanctions-driven shock tends to dissipate: trade flows are redirected through third countries, strategic stockpiles are activated, and Pt/Pd substitution accelerates.

Copper: neutral or mildly positive (+0–10%), provided the geopolitical shock does not escalate into a global recession.

Position outcome: loss on the Pd leg: Pd rally of +50% × 0.5 = −25%. The Cu leg provides partial compensation: +0–10%. Net loss: −15–25%.

This is the **worst-case scenario** for the strategy, which justifies two defensive mechanisms:

1. Half-sizing of the Pd leg (0.5× coefficient) limits losses.

2. Sanctions-driven shocks to palladium are historically short-lived: supply flows are redirected within 3–6 months, after which the price corrects.

6.5 Risk Scenario: Recession and Speculative Capital Reversal (Probability: 10–15%)

Assumptions: global recession (world PMI below 48); sharp US dollar strengthening (DXY above 110); reversal of over $30 billion in speculative capital from base metals; repeal/relaxation of Section 232 tariffs; Chinese demand falls below −5% y/y.

Copper: crash to $9,000–10,000/t (author's model based on five simultaneous triggers). The speculative premium of approximately $2,500/t (Sucden Financial) evaporates entirely. Structural "floor": the 90th percentile C1 cash cost of global production is approximately $6,700/t (S&P Global MI); including AISC and sustaining capital expenditures — $8,000–9,000/t.

Palladium: decline of −15–25%, but less severe than copper, since palladium is already near production cost and contains less speculative premium.

Position outcome: loss, dominated by the Cu leg. Copper −20–30% (full size) vs. palladium −15–25% (half size, i.e., +7–12% on the Pd leg). Net loss: −8–18%.

The Pd leg partially offsets the loss on the Cu leg — a property absent from a pure long copper position.

Summary matrix of scenarios (before and after funding):

Estimated cumulative funding costs over 2–3 years: Long Cu pays ~8–20%; Short Pd receives ~3–8%. Net funding: −5–12% of the notional position value.

Scenario	Prob.	Cu	Pd	Long Cu 1.0×	Short Pd 0.5×	Total (pre)	Funding	**Total (post)**
Base case	40–50%	+15–30%	−10–20%	+15–30%	+5–10%	+20–40%	−5–12%	**+8–35%**
Bull Cu	20–25%	+40–80%	−5–15%	+40–80%	+2.5–7.5%	+42–88%	−5–12%	**+30–83%**
Bear Pd	10–15%	+5–15%	−25–40%	+5–15%	+12.5–20%	+17–35%	−5–12%	**+5–30%**
Geopol. Pd	5–10%	+0–10%	+30–80%	+0–10%	−15–40%	−5–40%	−5–12%	**−10–52%**
Recession	10–15%	−20–30%	−15–25%	−20–30%	+7.5–12.5%	−8–18%	−5–12%	**−13–30%**

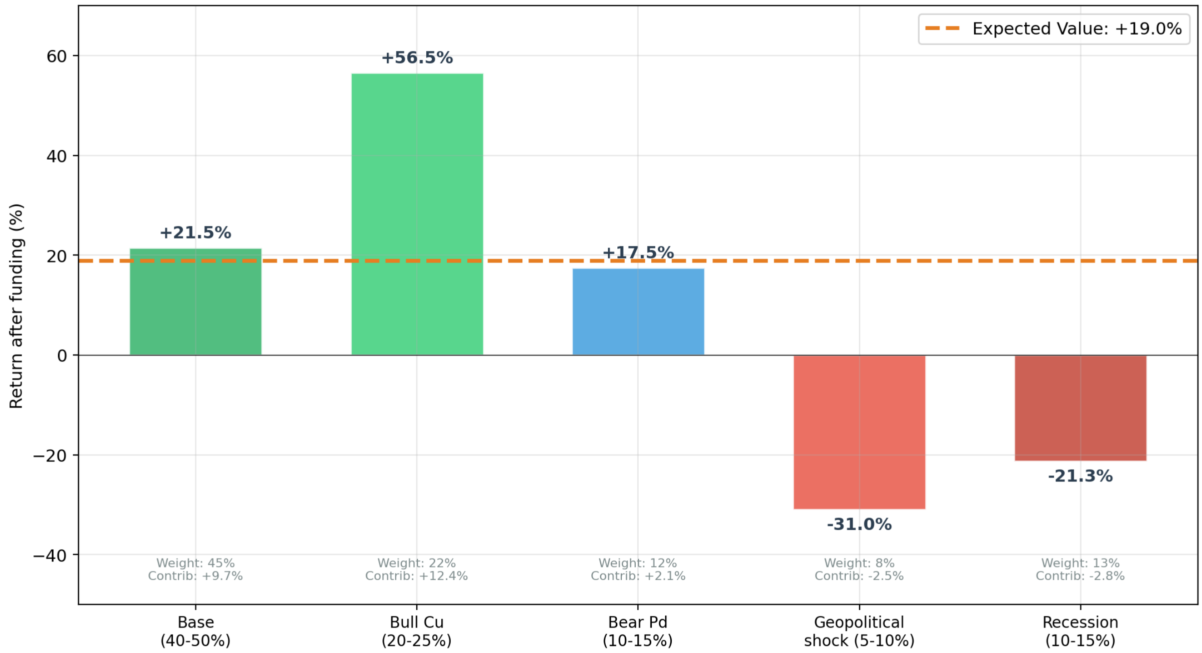

Figure 8: Scenario analysis: Long Cu / Short 0.5× Pd (post-funding)

Expected value (adjusted for funding). Calculation using median outcomes for each scenario and median probability weights:

Scenario	Weight	Median outcome (post-funding)	Contribution
Base case	45%	+21.5%	+9.7%
Bull Cu	22%	+56.5%	+12.4%
Bear Pd	12%	+17.5%	+2.1%
Geopolitical Pd shock	8%	−31.0%	−2.5%
Recession	13%	−21.3%	−2.8%
Total expected value	**100%**		**+18.9%**

The expected value of +**18.9% over 2–3 years** (6.3–9.5% annualized). This moderately exceeds the USD risk-free rate (~4.5% on T-bills as of March 2026), but **does not constitute an extraordinary return** — the risk premium amounts to approximately 2–5% annualized. The strategy is attractive not so much for its absolute return as for its **positive asymmetry**: the median loss in adverse scenarios (−21% to −31%) carries a combined probability weight of ~21%, whereas the median profit in favorable scenarios (+17% to +57%) carries a weight of ~79%.

Sensitivity analysis of the expected value to scenario weights:

Weight shift	Expected value
Base calculation (above)	+18.9%
Recession 25% (vs. 13%), base case 30% (vs. 45%)	+6.2%
Geopolitical shock 15% (vs. 8%), base case 35% (vs. 45%)	+8.7%
All adverse scenarios 35% (vs. 21%)	+2.1%
All favorable scenarios combined 85%	+26.4%

Under an aggressively pessimistic shift in scenario weights (adverse scenarios at 35%), the expected value remains **weakly positive** (+2.1%) but does not justify the risk. The strategy requires the investor's conviction that the combined probability of recession plus geopolitical shock **does not exceed approximately 30%**.

7 Risk Factors and Strategy Limitations

7.1 Risks to the Bullish Copper Thesis

Speculative overheating and correction. As of early 2026, net-long positions on the LME are at the 80th percentile of historical values; Chinese traders on the SHFE hold their maximum net-short position since 2021. Over $30 billion in speculative capital entered base metals in 2025 — an all-time record (Goldman Sachs). Sucden Financial estimates a "speculative gap" of approximately $2,500/t between the current price and the fundamentally justified level ($10,500–11,500/t). Historically, positions above the 75th percentile have resulted in an average three-month return of −4.2% [56].

Tariff premium ≠ demand. A significant portion of the 2025–2026 rally has been driven by inventory accumulation in anticipation of Section 232 tariffs (450,000–830,000 tonnes "stranded" in US warehouses), rather than by growth in real consumption. The 50% Section 232 duty (July 31, 2025) was imposed on semi-finished and copper-derived products, while refined copper **was not included** in the immediate application (15% scheduled for 2027 and 30% for 2028). Any change in the tariff regime (expansion, relaxation, or repeal) is capable of triggering sharp movements in the COMEX-LME spread, creating a significant binary risk for long positions [51].

Weakening Chinese demand. Goldman Sachs estimates Chinese demand in Q4 2025 at −8% y/y. Capital Economics notes a "disconnect between price and actual physical demand." The Yangshan premium (an indicator of Chinese physical demand) fell to $20–27/t — its lowest level since July 2024.

Short-term surplus. Goldman Sachs forecasts a surplus of +160 Kt in 2026 and +300 Kt in H2 2026. The ICSG revised the 2025 balance toward a surplus of +178 Kt. A short-term surplus creates downward pressure on the price [30, 32].

7.2 Risks to the Bearish Palladium Thesis

Geopolitical shock (key risk). Nornickel accounts for ~40% of global palladium supply. An escalation of sanctions could remove 3–4 Moz from supply instantaneously. Historical precedent: palladium reached its ATH of $3,440/oz in March 2022 amid threats of disruption to Russian supplies.

Reverse substitution Pd→Pt. The rise in platinum prices above palladium (2025) has eliminated the incentive for substitution. WPIC forecasts the return of up to 366,000 oz of palladium demand by 2027 [38].

PHEV/EREV as a "hidden bull." The fastest-growing segment (PHEV +62% in Europe) requires 10–20% more palladium per vehicle than a standard ICE. If hybrids displace pure BEVs as the dominant transitional format, demand destruction will decelerate significantly.

Supply collapse exceeds demand destruction. Sibanye-Stillwater −45%, Lac des Iles closure, South African attrition — supply may contract faster than demand, keeping the market in deficit [44].

7.3 Correlation and Macroeconomic Risks

Simultaneous movement in the same direction. Under risk-off conditions (global recession), both metals decline. Analysis based on COMEX/NYMEX data shows that the Cu/Pd correlation increases during crises (up to +0.61 during the GFC), although it remains lower than for the Ag/Cu pair (+0.90 on a 30-day window, Sucden Financial) or Au/Cu (˜+0.60). The Pd leg partially, but not fully, compensates for Cu losses in the recessionary scenario.

US dollar strengthening. A DXY above 110 creates pressure on all dollar-denominated commodity markets. Copper and palladium decline simultaneously, but copper — carrying a larger speculative component — may suffer more severely.

DeFi platform liquidity. Trading volume for copper on HyperLiquid (approximately $75 million/day) and Open Interest ($38 million) determine the position management tactics: accumulation and unwinding of large positions are executed in tranches to minimize market impact.

7.4 Regulatory and Infrastructure Risks

Tariff uncertainty. The Section 232 decision (deadline — June 30, 2026) represents a binary catalyst: imposition of tariffs ≥ 25% on cathodes "locks in" 500+ Kt within the US and amplifies the deficit on LME/SHFE (bullish); repeal/postponement — releases 500+ Kt and collapses the COMEX-LME arbitrage (bearish).

Resource nationalism. The cascading increase in export restrictions (Indonesia, DR Congo, Armenia, and potentially Chile and Peru) may fragment the market, creating local deficits and surpluses of unpredictable configuration.

DeFi regulatory risk. Tightening regulation of crypto derivatives (MiCA in the EU, potential SEC/CFTC measures in the US) may restrict access to instruments for implementing the strategy on platforms such as HyperLiquid.

8 Limitations of the Study

The present study has a number of methodological and practical limitations that should be taken into account when interpreting the results:

1. **Reliance on third-party forecasts.** The study synthesizes forecasts from S&P Global, J.P. Morgan, Goldman Sachs, WPIC, Johnson Matthey, and other sources, but does not construct an independent econometric model of market balances. Investment bank forecasts are systematically revised (the ICSG revised its 2025 forecast from +289 to +178 Kt within a single quarter) and may contain institutional biases.

2. **Subjectivity of probability estimates.** The scenario weights (40–50% base case, 20–25% bull case, etc.) represent expert assessments rather than the output of a statistical model. Sensitivity analysis demonstrates that under an aggressively pessimistic shift (adverse scenarios >35%), the expected value approaches zero.

3. **Absence of a full backtest.** The Long Cu / Short 0.5× Pd strategy has not been backtested on historical data. Retrospective analysis of Cu/Pd regimes (Section 4) indicates that during the 2016–2020 period (palladium premium regime), the

strategy would have been unprofitable. Profitability depends on the correctness of the structural divergence thesis rather than on statistical properties of the time series.

4. **Approximate funding cost estimates.** The range of 5–12% cumulative costs over 2–3 years is based on current funding rates (March 2026), which are volatile and dependent on market conditions. During periods of extreme contango (squeeze), Long Cu funding costs may briefly reach 0.5–1% per day.

5. **DeFi instrument liquidity dictates entry tactics.** HyperLiquid offers perpetual futures contracts on both copper and palladium, enabling implementation of both legs of the strategy on a single platform. Trading volumes amount to $10–75 million/day, which is sufficient for retail-sized positions; however, large positions (exceeding $100,000) are recommended to be accumulated in tranches to minimize slippage.

6. **Data horizon.** All forecasts and price data are current as of March 2026. Industrial metals markets are subject to rapid revisions. The study describes an analytical framework, not a point-in-time trading recommendation.

7. **Currency risk is not addressed.** The strategy is denominated in USD. For investors with a non-dollar base currency, exchange rate fluctuations may materially affect returns in their domestic currency.

9 Conclusion

The present study demonstrates that the copper and palladium markets are in a state of **structural divergence**, driven by the global energy transition — a process whose scale, irreversibility, and multidirectional nature are without precedent in modern economic history.

Regarding copper, the following has been established:

1. Global demand will grow from 28 to 42 million tonnes by 2040 (+50%), driven by four structurally independent vectors: baseline economic growth (+28%), the energy transition (+83%), AI infrastructure (growth from 1.1 to 2.5 Mt), and defense/robotics (growth from 0.4 to 1.5 Mt).

2. Supply is structurally constrained: a 17.9-year lag from discovery to production; ore grade degradation (−40% since 1991); a smelting concentration crisis in China (47% of global capacity, TC/RC = $0); a secondary recycling ceiling of 25–35% of demand. The cumulative deficit by 2040 amounts to approximately 10 million tonnes (24% of demand).

3. Aluminum substitution is limited by a "hard core" of non-substitutable demand (40–50%): data centers, submarine cables, EV motors, and liquid cooling. The maximum substitution ceiling: 15–25% (4–7 Mt), covering only a fraction of the deficit.

4. The energy bottleneck paradox: every solution to the energy supply problem for AI infrastructure requires even more copper, creating a self-reinforcing demand cycle.

Regarding palladium, the following has been established:

1. 84–90% of demand is concentrated in autocatalysts — the only sector subject to technological displacement by electrification.
2. Demand destruction proceeds at a rate of −1.3% CAGR (WPIC), rather than precipitously: the PHEV/EREV boom (elevated Pd loading), the slowdown in BEV sales, and tightening environmental standards create buffers.
3. Supply is collapsing: Sibanye-Stillwater −45%, Lac des Iles closure, South African attrition. Russia (Nornickel, 40% of global Pd) constitutes a permanent geopolitical risk.
4. The market has already discounted approximately 60% of the maximum potential decline (from the peak of \$2,398 to \$924/oz in 2024), limiting the remaining downside potential.

The inversion of the Cu/Pd ratio (from a minimum of 2.2× in February 2020 to an average of 9.3× in 2024–2025, calculated on COMEX/NYMEX data) has been identified as a market marker of the technological transition, chronologically coinciding with the mass launch of fleet electrification.

The proposed Long Cu / Short 0.5× Pd strategy is justified by:

- A positive expected value (+18.9% over 2–3 years at median scenario weights, adjusted for funding).
- Positive asymmetry: the profit potential in favorable scenarios (+42–87%) substantially exceeds the loss potential (−5–30%).
- Built-in hedging: the Pd leg partially offsets Cu losses in the recessionary scenario and mitigates funding costs.
- The 2:1 ratio reflects the differing degree of conviction and manages the tail risk of a geopolitical palladium shock.

Thesis invalidation conditions:

1. *For copper*: a global recession with PMI falling below 48 + tariff repeal + Chinese demand collapse exceeding −10% y/y → price below \$9,000/t.
2. *For palladium*: full-scale sanctions against Nornickel + suspension of BEV programs + reverse substitution Pt→Pd → price above \$2,000/oz.
3. *For the spread*: Cu/Pd sustainably below 5.0× (for more than 3 months) = a return to the "palladium premium," invalidating the electrification thesis.

The present study confirms that the structural divergence of copper and palladium is not a cyclical phenomenon but reflects a fundamental restructuring of industrial demand driven by the irreversible energy transition. The asymmetric spread strategy enables the exploitation of this divergence with controlled risk and a positive expected value over a 2–5 year horizon.

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A Copper-to-Aluminum Substitution Matrix by Sector

Sector	Share of global demand	Substitution potential	Substitutable volume (Mt)	Time lag
HVAC/air conditioning	~8%	70–85%	1.6–1.9	2–3 years
Transmission lines (overhead)	~12%	Already realized	0	—
Transformers	~6%	50–70%	0.8–1.2	3–5 years
EV wiring harnesses	~5%	40–60%	0.6–0.8	2–4 years
Onshore wind generation	~4%	30–50%	0.3–0.6	3–5 years
Building wiring	~15%	15–30%	0.6–1.3	5–10 years
Underground cables	~10%	15–30%	0.4–0.8	5–7 years
EV motors	~4%	10–20%	0.1–0.2	5–8 years
AI data centers	~5%	5–10%	0.1	>10 years
Submarine cables	~3%	0–5%	0.0	—
Semiconductors/connectors	~8%	0–5%	0.0	—
Other	~20%	10–20%	0.6–1.1	Varies
Total	**100%**	—	**5.1–8.0**	—

Note: the theoretical ceiling of 5–8 Mt includes substitution already realized and processes requiring 5–10 years of engineering transition. The realistic volume of new substitution at $10–15/lb: 3–5 million tonnes.

B Consensus Copper Price Forecasts (2026–2035)

Source	2026 ($/t)	2027	2030	2035	Deficit/Surplus 2026
Goldman Sachs	10,710–11,200	10,800	~12,000	15,000	+160 Kt surplus
J.P. Morgan	12,075	12,500	~12,000	12,000 (LT)	−330 Kt deficit
Bank of America	12,000	13,501	—	Peak 15,000	—
UBS	12,000	13,000	—	—	—
Citi (bull case)	Up to 15,000 (Q2)	—	—	—	—

Source	2026 ($/t)	2027	2030	2035	Deficit/Surplus 2026
StoneX	11,490	—	—	—	—
Industry consensus	—	—	—	~10,900	—
Forwards	—	—	—	~10,390	—

C Key Palladium Market Parameters

Parameter	Value	Source
Global production (2024)	~10.0 Moz	Johnson Matthey
Automotive demand (2024)	~7.7 Moz (84–90%)	Johnson Matthey
Peak automotive demand	8.4 Moz (2019)	Johnson Matthey
Projected surplus (2029)	689 thousand oz	WPIC
Russia's share of supply	~40% (Nornickel)	Nornickel
ATH price	$3,440/oz (March 2022, intraday)	LBMA
Annual average peak	$2,398/oz (2021)	Statista
Price (March 2026)	~$1,366/oz	TradingEconomics
Decline from annual average peak	−43% (from $2,398)	Calculated
CAGR of automotive demand	−1.3% through 2029	WPIC
Pd loading on PHEV vs. ICE	+10–20% higher	Johnson Matthey

Study completion date: April 2026.
All forward-looking estimates are based on data available as of March 2026 and are subject to revision as market conditions change.