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From Copper Price to Project NPV: Metal Prices, Acid Costs, TC/RCs, Freight, CAPEX, OPEX, Taxes, Ramp-Up, and Financial Resilience in Integrated Oxide–Sulfide Copper Projects — A Critical Review

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Abstract

Integrated oxide–sulfide copper projects combine two process routes with distinct technical and commercial exposures, yet project valuation is often communicated through a small set of headline assumptions dominated by copper price and a deterministic net present value. This critical review develops an integrated framework linking ore scheduling, feed grade, metallurgical recovery, ramp-up, product form, realized price, treatment and refining charges, sulfuric acid cost, freight, operating expenditure, capital timing, fiscal architecture, working capital, closure obligations, and uncertainty propagation. The central argument is that project value comes from interactions among these variables and their timing, rather than from any single input. The oxide route is particularly exposed to acid consumption, delivered reagent cost, solution management, and cathode realization, whereas the sulfide route is shaped by comminution intensity, concentrate grade, payability, treatment and refining charges, and smelter logistics. The review distinguishes deterministic sensitivity from coherent scenarios, probabilistic simulation, and real-options reasoning, and proposes a progression toward risk-adjusted project value. Particular emphasis is placed on correlated market variables, stochastic ramp-up, recovery and grade uncertainty, CAPEX overrun, OPEX inflation, fiscal changes, and closure-cost escalation. The resulting framework supports more transparent comparison of integrated copper projects and provides a research agenda for financial models that are technically grounded, time-resolved, and explicit about uncertainty.

Keywords: copper projects; net present value; ramp-up; treatment and refining charges; sulfuric acid; risk analysis

Highlights

- Project NPV depends on interacting technical, market, fiscal, and timing variables, not copper price alone.
- Oxide and sulfide routes create different cost, logistics, and market-risk structures within one integrated project.

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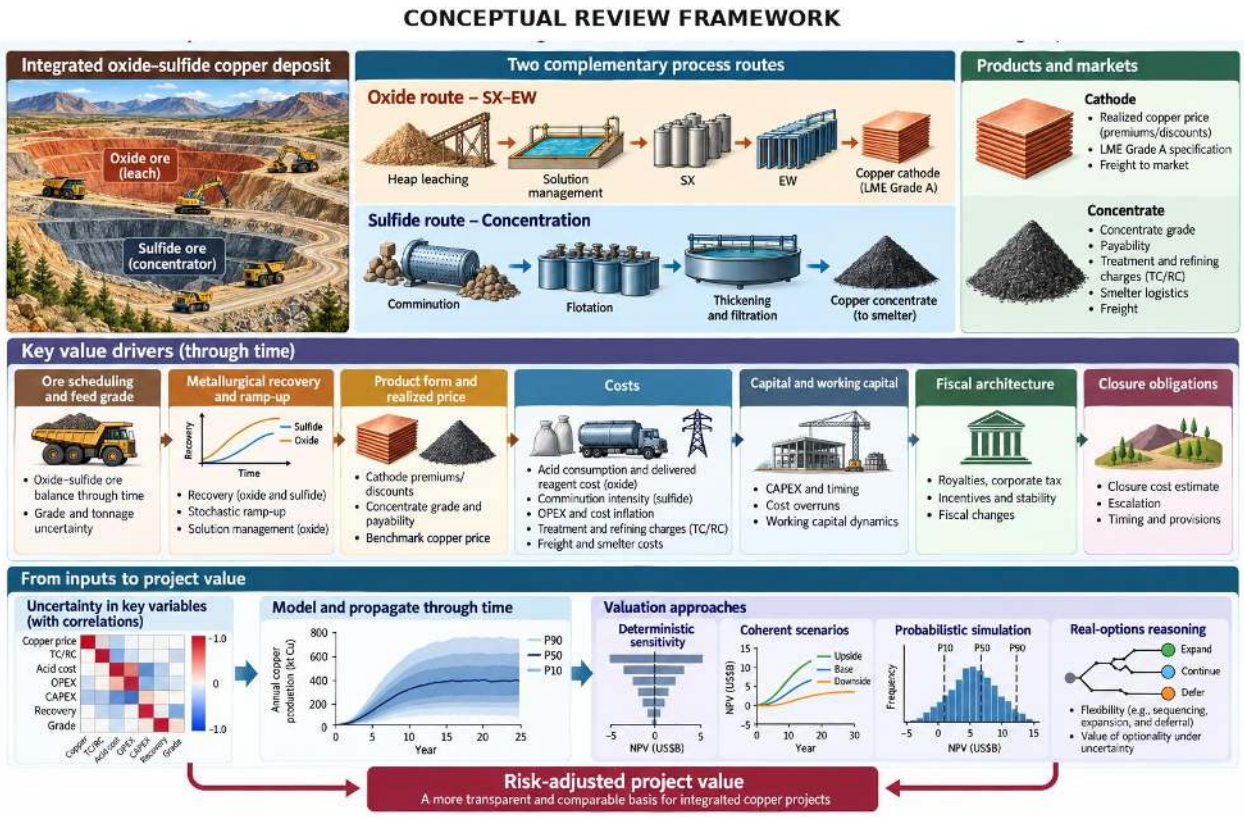
- Ramp-up, CAPEX timing, working capital, and closure shift value because discounted cash flow is strongly time-dependent.
- Risk analysis should progress from one-factor sensitivity to correlated scenarios, Monte Carlo simulation, and real options.

Graphical abstract



1. Introduction

Copper-project evaluation is frequently reduced to a small number of headline metrics—capital intensity, unit operating cost, long-term copper price, NPV, and IRR. That compression is useful for screening, but it can obscure the economic architecture of integrated oxide–sulfide projects. Such projects combine hydrometallurgical and concentrator/smelter value chains, so the same mine plan feeds two commercial systems with different dependencies on reagents, energy,

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logistics, product specifications, and market deductions. A robust review must therefore connect technical performance to realized revenue and, ultimately, to after-tax free cash flow.

The central question addressed here is: Which technical, market, fiscal, and operating assumptions most strongly control the NPV and IRR of integrated oxide–sulfide copper projects, and how should these uncertainties be propagated through financial models? The working thesis is that project value emerges from the interaction among ore schedule, feed grade, recovery, ramp-up, sulfuric acid cost, concentrate terms, freight, OPEX, CAPEX timing, taxation, working capital, and closure liabilities. In this view, copper price remains pivotal, but it is one node in a coupled system rather than a sufficient explanation of value.

Figure 1 summarizes the review architecture, and Table 1 organizes the main valuation variables. Figure 2 examines ramp-up and payable-copper generation, while Figure 3 illustrates the interaction between copper price and delivered acid cost. Figure 4 links concentrate grade, TC/RCs, and net revenue; Figure 5 illustrates capital timing; Figure 6 maps product-form logistics and netback; and Figure 7 shows the progression from deterministic sensitivity to risk-adjusted valuation. Tables 2–8 compare the principal modeling approaches, covering copper-price assumptions, acid and logistics variables, concentrate commercial terms, capital categories, fiscal effects, uncertainty methods, and research gaps.

A critical perspective is necessary because weak assumptions can produce seemingly precise financial outputs. Using single long-term prices, averages, or static recovery can create false impressions of accuracy. Multiplying scenarios without understanding causal links adds complexity without insight. The goal is to identify variables and interactions that materially affect decision quality.

Table 1 synthesizes the principal variable groups that connect technical performance to project value and provides the vocabulary used throughout the review.

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Table 1. ***Financial variables used in integrated copper-project models***

Variable group	Representative inputs	Primary value pathway
Resource and schedule	ore tonnes, grade, cut-off, stockpiles	Controls timing and quality of plant feed
Metallurgy	Recovery, throughput, acid consumption, concentrate grade	Converts feed into saleable/payable metal
Market	Cu/Au/Ag prices, premiums, TC/RCs	Determines gross and realized product value
Operating cost	Mining, power, acid, grinding media, labor	Determines operating margin and leverage
Capital	initial, deferred, sustaining, replacement	Shapes cash-outflow timing and financing need
Logistics	inland haulage, port, ocean freight, insurance	Converts mine-site value into delivered netback
Fiscal	royalty, income tax, withholding, profit sharing	Transforms pre-tax into post-tax cash flow
Balance-sheet items	working capital, VAT, inventories	Delays cash conversion and affects early cash flow
Closure	provisioning, guarantees, rehabilitation	Creates late-life and sometimes early funding obligations

Note. Variables are grouped by the mechanism through which they affect free cash flow. The framework is adapted from the project-value relationships synthesized from the literature cited in this review.

Read Figure 1 from left to right: technical variables first determine payable production, commercial terms convert payable production into realized revenue, and costs and fiscal obligations then determine the time profile of free cash flow.

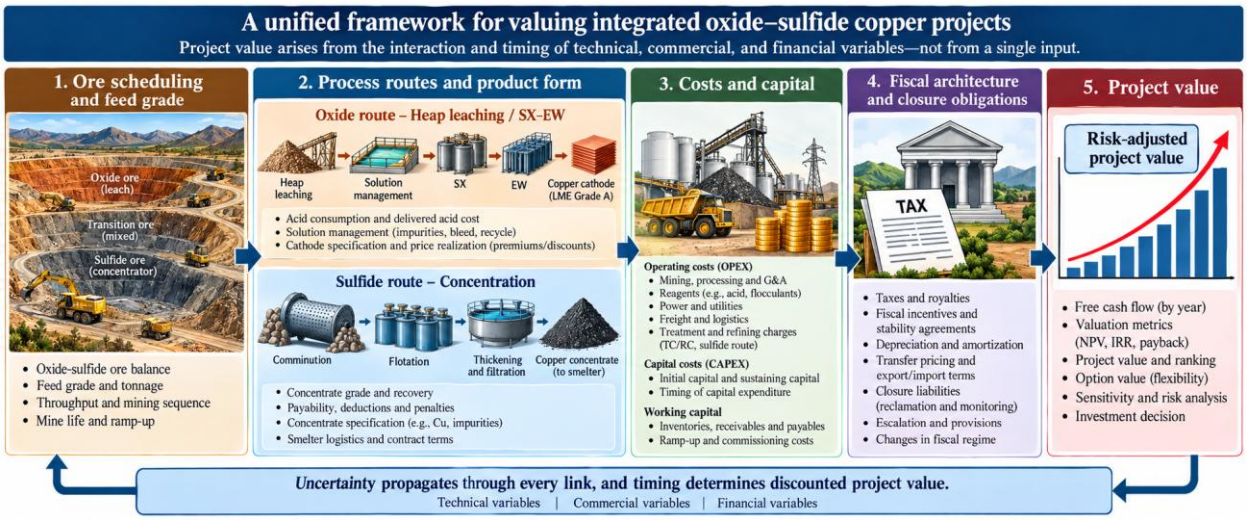

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Figure 1. ***Technical variables → cash flow → NPV/IRR framework.***
Note. Conceptual framework developed for this review and adapted from the project-value relationships synthesized from the cited literature.

This implies that valuation errors can originate upstream. A small bias in grade, recovery, or ramp-up can propagate through production, revenue, working capital, and taxes, producing a much larger change in discounted value than the apparent technical deviation would suggest.

2. Review Methodology and Project-Value Framework

2.1. Scope and evidence architecture

The review uses a structured critical-synthesis approach rather than a systematic review or meta-analysis. Literature discovery was completed through 30 September 2026 using Google Scholar and publisher/indexing pages for bibliographic verification, with complementary consultation of institutional and public technical sources where market, fiscal, or project-practice information was required. Representative search combinations linked the principal value drivers to copper projects, including: (copper AND project valuation AND NPV), (copper AND ramp-up AND recovery), (sulfuric acid AND copper heap leaching AND cost), (copper concentrate AND TC/RC AND payability), (mine planning AND cut-off grade AND uncertainty), (mining CAPEX AND cost estimation), (working capital AND mining project), (mine closure AND financial assurance), and (real options AND mining). The primary emphasis was 2020–2026; older publications were retained only when they provided foundational theory or indispensable methodological context. Sources were included when they clarified a technical, commercial, fiscal, timing, or uncertainty mechanism relevant to the ore-to-cash-flow chain, and excluded when they were preprints, duplicates, non-recoverable records, or insufficiently connected to integrated copper-project valuation. The final bibliography contains 144 sources after the addition of two foundational works. The review does not claim exhaustive retrieval; instead, it documents a reproducible critical-synthesis logic and an explicit search cutoff.

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The financial backbone is conventional discounted cash flow. For period t, free cash flow can be expressed in simplified form as $FCF_t = Revenue_t - OPEX_t - CAPEX_t - Taxes_t - \Delta WC_t - Closure_t$, and NPV as the discounted sum of FCF_t over the project horizon. This deliberately compact representation serves only as an organizing identity: the purpose of the review is to unpack the uncertainty embedded in each term and to show that the variables are neither statistically nor operationally independent.

2.2. Critical-review criteria

Studies were interpreted through five criteria: technical causality, time resolution, treatment of uncertainty, treatment of correlation, and decision relevance. Technical causality asks whether the financial model is linked to grade, recovery, throughput, product quality, or another measurable physical driver. Time resolution asks whether the model distinguishes early and late cash flows. Uncertainty treatment differentiates deterministic assumptions from probability distributions. Correlation treatment asks whether the model jointly models variables such as copper price, TC/RCs, exchange rates, energy prices, and reagent costs. Decision relevance asks whether the method changes a scheduling, staging, financing, or operating decision rather than merely producing a wider range of NPVs. Because the review integrates peer-reviewed and practice-oriented evidence, it weights conclusions toward mechanisms that are transparent, reproducible, and transferable across projects; it treats proprietary benchmark values as examples of market structure rather than universal constants.

For evidence composition, sources were classified by inferential role rather than treated as interchangeable: peer-reviewed research supports mechanisms and analytical methods; public technical reports support project design, engineering, and disclosed feasibility assumptions; institutional market sources support macroeconomic, commodity, and policy context; and proprietary market assessments support contemporary commercial structure such as TC/RC conventions and market tightness. Proprietary values are used only as examples of market structure and are not generalized as universal constants.

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Methodological contributions relevant to this framework span project valuation, project finance, cost of capital, mineral rights, information value, investment flexibility, and market-system modeling (Buchanan, 2025; Chung et al., 2022; Cunningham, 2025; Diaz et al., 2026; Freitas et al., 2015; Gambaro et al., 2025; Generation Mining, 2021, 2025; Kara & Tunc, 2023; Mano et al., 2015; Orion Minerals, 2021, 2025; Samis & Steen, 2020; Valer Dávila et al., 2024; Xiao et al., 2020). Collectively, these studies and technical cases reinforce a central distinction: the mathematics of discounting may be straightforward, but the credibility of NPV and IRR depends on the quality, timing, and internal consistency of the technical, commercial, and fiscal assumptions that generate the cash-flow series.

2.3. From deterministic NPV to decision model

A deterministic base case remains necessary because it provides a transparent reference point. However, it should be treated as one internally consistent state rather than as the expected future. The analytical progression proposed in this review is deterministic base case → one-factor sensitivity → multivariable scenarios → probabilistic simulation → adaptive decision analysis. Each step answers a different question. Sensitivity identifies leverage; scenarios test coherent narratives; Monte Carlo analysis estimates distributions; and real-options or stochastic-optimization methods evaluate the value of changing the plan after uncertainty resolves.

2.4. Valuation perspective, discount rate, inflation, and currency

Unless explicitly stated otherwise, the framework in this review refers to unlevered project valuation based on free cash flow to the firm (FCFF), before financing flows. Debt drawdowns, principal repayments, interest payments, and dividends should therefore not be mixed into project FCFF. A levered equity valuation is a separate exercise based on cash flow to equity (FCFE), in which financing terms and distributions are modeled explicitly. This distinction is essential because the cash-flow definition and discount rate must be internally consistent.

Real cash flows should be discounted at a real rate, whereas nominal cash flows should be discounted at a nominal rate with internally consistent escalation of copper price, acid, freight,

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OPEX, CAPEX, taxes, and closure costs. The currency basis must also be explicit because copper revenues are commonly denominated in US dollars while portions of operating cost, capital expenditure, tax liabilities, and financing may be denominated in local or other currencies. Exchange-rate exposure can therefore alter after-tax value even when physical production is unchanged. For FCFF, a WACC-type rate may be used when its assumptions match the modeled cash flows; for FCFE, the relevant rate is the cost of equity. Country and project-specific risk may affect the required return, but risks already represented explicitly in probabilistic cash-flow distributions should not automatically be duplicated through an additional ad hoc discount-rate premium. The objective is consistency, not mechanical inflation of the discount rate (Brennan & Schwartz, 1985; Buchanan, 2025; Chung et al., 2022; Samis & Steen, 2020).

3. Production Schedule and Ramp-Up as Financial Variables

3.1. Start-up, ramp-up, and discounted value

Start-up and ramp-up are key financial variables because they determine when tonnes, recovery, and payable metal turn into cash. An equivalent production shortfall early in the mine life typically reduces NPV more than a later shortfall because it defers high-weight early cash inflows, can extend working-capital requirements, may delay tax shields, and can postpone debt service. The key modeling question is therefore not only the final throughput, but also the combined path of throughput, grade, recovery, and availability during commissioning.

Figure 2 shows why oxide and sulfide routes should not be assigned a common ramp-up profile: their commissioning constraints differ, and payable copper may lag behind nominal plant completion.

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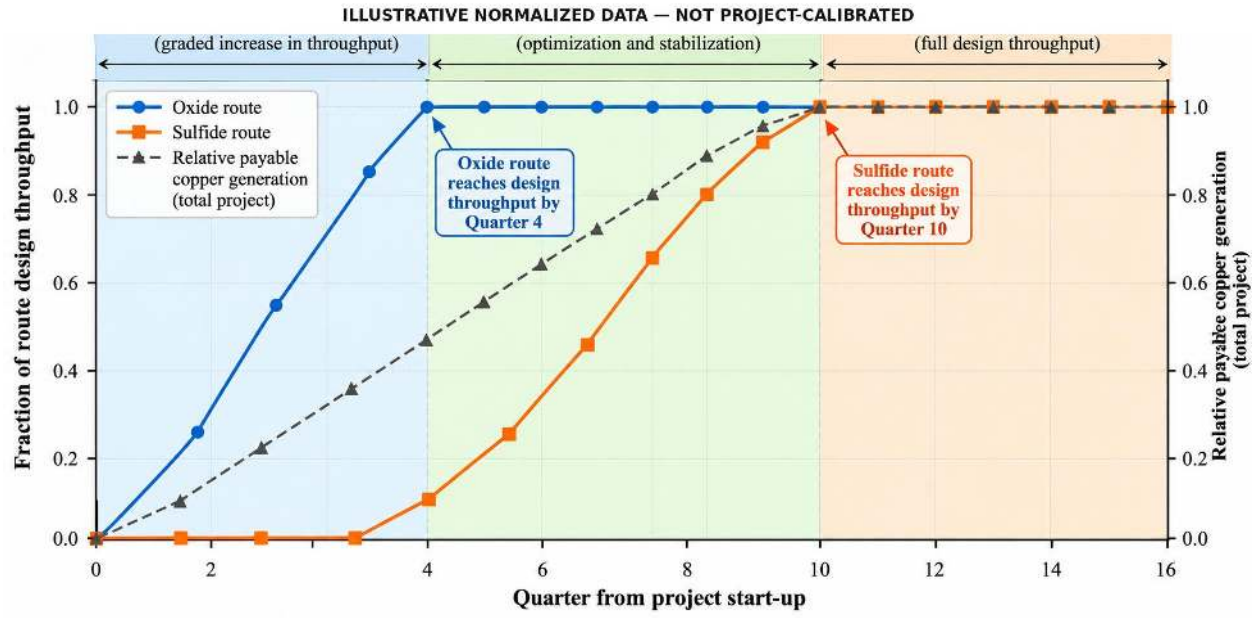

Figure 2. ***Ramp-up → payable copper → revenue → cash-flow generation.***
Note. Author-generated illustrative normalized curves only; not project-calibrated data. The oxide and sulfide trajectories are schematic examples used to demonstrate different commissioning paths and the timing of payable-copper generation.

A credible model should capture at least three ramp-up risks: schedule delay before first production, slower-than-planned throughput growth, and delayed metallurgical stabilization. Treating these as a single scalar reduction in annual production hides the asymmetric financial effect of timing. Throughput, availability, and recovery should not be sampled as independent variables by default. During stabilization, pushing throughput can reduce residence time, recovery, or equipment availability, so probabilistic ramp-up should preserve plausible engineering dependence among these components.

3.2. Grade, recovery, stockpiles, and dynamic cut-off

Mine plans translate geological information into an economic sequence, and that sequence should be coupled to process-route constraints. Stockpiles can buffer plant feed but also create optionality: higher-grade material may be brought forward when margins are strong, while marginal material may be deferred. Dynamic cut-off grades, geometallurgical attributes, and

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stochastic scheduling therefore influence value through both average margin and timing. In integrated projects, routing decisions matter most when material can be directed to leach, concentrator, stockpile, or waste depending on mineralogy and market conditions. Routing flexibility must be constrained by a feasible destination set defined by mineralogy, oxidation state, acid-soluble copper, sulfide mineralization, hardness, deleterious-element behavior, stockpile rules, and plant capacities. Dynamic cut-off decisions should therefore be interpreted within the economic lineage established by Lane (1988), while recognizing that modern integrated projects add geometallurgical and stochastic constraints to the classical framework.

The literature on production scheduling, stockpiling, geometallurgy, recovery uncertainty, heap-leach performance, and adaptive mine planning supports treating the production plan as a distribution of possible cash-flow paths rather than as a fixed tonnage table (Biswas et al., 2020; Campos et al., 2022; Cox et al., 2023; Jélvez et al., 2025; Khan & Asad, 2021; Lizama, 2023; Mu & Salas, 2023; Muke et al., 2025; Nancel-Penard et al., 2025; Pereira, 2026a, 2026c, 2026d, 2026f; Robertson & Kotsiopoulos, 2026; Savolainen et al., 2022; Tabesh et al., 2023). The common implication is that geological and metallurgical uncertainty should be propagated through routing, production, and recovery before financial aggregation rather than appended afterward as an arbitrary NPV discount.

3.3. Critical implication

A mine schedule functions as a financial model in physical units, so changes in destination, grade sequence, recovery, or ramp-up affect total copper recovered and timing of value realization. Therefore, annual averages are inadequate for comparing route options or expansion timing.

4. Revenue Formation: More than Copper Price

4.1. Cathode and concentrate revenue

Integrated projects may generate cathode from oxide leaching and copper concentrate from sulfide flotation. These products do not realize the quoted copper price in the same way. Cathode

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revenue depends on grade specification, regional premium or discount, freight, insurance, and sales terms. Concentrate revenue begins with contained metal but is adjusted for payability, treatment and refining charges, deleterious-element penalties, moisture, freight, and sometimes price-participation clauses. Gold and silver credits can materially alter the net smelter return, particularly for lower-grade copper concentrates.

4.2. Gross metal value, NSR, and cash conversion

A useful discipline is to separate gross metal value from realized revenue and from NSR. Gross metal value is a theoretical metal-price product. Realized revenue reflects product-specific commercial terms. NSR further subtracts off-site realization costs. Neither should be confused with operating margin or free cash flow. This hierarchy prevents double counting and makes it possible to compare oxide cathode and sulfide concentrate on a common mine-site value basis.

Evidence on copper-smelting coordination, mineral value chains, product-market dynamics, and copper-production systems supports a clear distinction between contained metal and realized value (Ahmed & Vilkko, 2023a, 2023b; Calzada Olvera, 2022; Dong et al., 2020; Haubner & Strobl, 2023; Namahoro et al., 2022; Sourabh et al., 2023; Stuermer, 2022). These studies also show that operational and commercial decisions at mine, smelter, and value-chain levels can redistribute value through time even when total contained-metal production is unchanged.

4.3. By-products and commercial optionality

By-product credits need explicit modeling as they can alter the effective cut-off grade and process route attractiveness. Assumptions should not obscure weak copper economics. The model should show payable percentages, prices, charges, recovery assumptions, and test if credits depend on copper-market conditions or are independent.

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5. Copper Price as the Primary Market Variable

5.1. Long-term price assumptions

Copper price remains the main exogenous revenue variable, but the construction of the price path matters as much as the selected central value. Constant real prices are transparent but suppress cycles. Consensus forecasts aggregate market views but can be procyclical. Forward curves are observable, yet they may reflect hedging, liquidity, and financial conditions rather than long-term equilibrium. Econometric and machine-learning forecasts can identify patterns but are vulnerable to parameter instability, overfitting, and weak causal interpretation. Scenario price paths are most useful when they are linked to explicit supply–demand narratives.

Table 2 compares these approaches and highlights the specific modeling risk each introduces.

Table 2. ***Copper-price modeling approaches***

Approach	Strength	Principal limitation	Best use
Constant real price	Transparent and auditable	Suppresses cycles and regime shifts	Base-case benchmarking
Consensus forecast	Aggregates market expectations	Can inherit common forecast bias	Planning reference
Forward curve	Observable market information	Liquidity and risk premia may distort long horizon	Near-term pricing/hedging
Econometric forecast	Explicit drivers and statistical testing	Parameter instability across regimes	Scenario support
Machine-learning forecast	Captures nonlinear patterns	Overfitting and weak causal interpretability	Short/medium-term stress testing
Scenario path	Internally coherent narrative	Subjective scenario construction	Strategic planning
Stochastic process	Produces a probability distribution	Distribution and correlation assumptions are decisive	Risk-adjusted valuation

Note. The table synthesizes this review; no single pricing method is intrinsically superior across all decision horizons.

Research on copper-price forecasting and commodity volatility indicates that copper prices are regime-dependent and respond to macroeconomic, financial, policy, demand, and supply-chain conditions (Baffes & Kabundi, 2023; Becerra et al., 2022; Chen et al., 2023; Díaz et al., 2020,

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2021; Hu & Gu, 2024; Madziwa et al., 2023a; Oikonomou et al., 2025; Shen & Huang, 2022; Srivastava et al., 2023; Su et al., 2020, 2023; Zhao et al., 2023). Long-horizon studies and institutional outlooks further show that structural demand, resource development, and policy assumptions vary materially across scenarios (Atakhanova et al., 2026; Castillo et al., 2024; International Energy Agency, 2021, 2023, 2024, 2025, 2026; Li et al., 2024; Olofsson, 2022; Renner & Wellmer, 2020; Soares et al., 2025; U.S. Geological Survey, 2024, 2025, 2026; World Bank, 2020, 2021, 2022, 2023, 2024, 2025, 2026). Accordingly, a single long-term copper price is best treated as a transparent scenario anchor rather than as a probability statement.

5.2. Price risk and decision asymmetry

Price uncertainty is asymmetric when staging options are available: adverse price conditions may support delay, contraction, or rerouting, whereas favorable conditions may support acceleration or expansion. Static NPV does not capture this flexibility, and upside should be recognized only when the operating plan can respond. The value of volatility therefore depends on the decision rules embedded in the model.

6. Sulfuric Acid as a Revenue-Independent Economic Risk

6.1. Delivered acid cost and oxide-route margin

In oxide leaching, delivered sulfuric acid cost depends on sulfur markets, by-product acid availability, regional supply and demand, port capacity, ocean and inland freight, storage, and handling. This creates a market exposure that is partly independent of copper price. Copper prices may rise while acid costs also increase, compressing oxide-route margins when acid consumption is high or supply is constrained. The sign and magnitude of copper-price–acid-cost dependence are not universal: they can change with sulfur markets, smelter-acid output, fertilizer demand, regional shortages, transport constraints, and industrial cycles. Correlated scenarios should therefore be justified causally or empirically for the relevant geography and market regime rather than imposed through a fixed generic coefficient.

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Figure 3 visualizes this two-dimensional exposure. The same copper price can yield different oxide-route margins based on acid cost, and the same acid cost can be tolerable or destructive depending on copper price and metallurgical response. The plotted surface is hypothetical: it uses author-generated values solely to show directional interaction and does not estimate the margin of any named project.

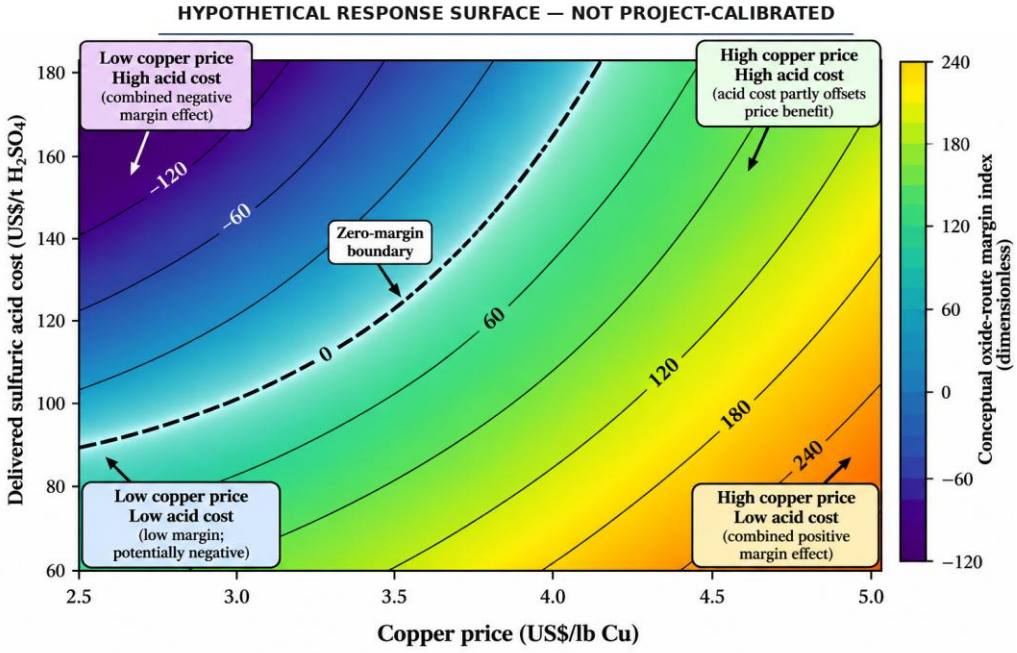

Figure 3. ***Copper price versus delivered acid cost and oxide-route margin.***
Note. Author-generated hypothetical response surface only; not project-calibrated data. Axes and contour values are illustrative and demonstrate the direction of interaction between copper price and delivered acid cost; they must not be interpreted as transferable project margins.

6.2. Consumption, mineralogy, and supply risk

Acid consumption should be separated into acid used for copper dissolution, acid consumed by gangue, and acid retained or neutralized in solution-management circuits. Mineralogy therefore links technical variability directly to market exposure. A project with high nominal copper recovery can still have weak economics if it underestimates gangue-acid consumption. Supply

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disruption adds a different risk: insufficient acid can reduce throughput even when the project is willing to pay a high spot price.

Hydrometallurgical studies on leaching, free acidity, heap performance, mineralogical deportment, and copper-ore response reinforce the need to model reagent demand as a function of mineralogy, hydrodynamics, and operating strategy rather than as a constant unit cost (Pereira & Barbosa, 2017; Pereira, 2026b, 2026e, 2026g, 2026h). This coupling is especially important during ramp-up, when irrigation strategy, solution inventory, and acid efficiency may not yet be stable.

Table 3 summarizes the acid-price and logistics variables that economic models should represent separately.

Table 3. ***Acid-price and logistics variables***

Variable	Physical/economic meaning	Risk mechanism
Acid consumption (kg/t)	Metallurgical demand	Mineralogy and operating control
Supplier price	Ex-works acid value	Regional sulfur/acid balance
Ocean freight	Maritime transport	Fuel, vessel, and route conditions
Port/terminal cost	Handling and storage	Infrastructure constraints
Inland freight	Port-to-site delivery	Distance, fuel, road/rail availability
Inventory policy	Days of acid coverage	Trade-off between resilience and working capital
Supply disruption	Availability constraint	Can force throughput reduction independent of price

Note. Model acid cost as delivered cost, and link consumption to ore type and operating conditions.

7. TC/RCs and Concentrate-Grade Economics

7.1. Treatment and refining charges

TC/RCs transfer part of the concentrate-market balance into the mine's realized revenue. Treatment charges are commonly quoted per dry metric tonne of concentrate, while refining charges are linked to payable copper. Consequently, concentrate grade matters twice: it changes the amount of concentrate shipped per unit of contained copper and the effective treatment cost

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per pound of payable metal. Penalties for arsenic, fluorine, chlorine, mercury, or other deleterious elements can further reshape netback.

Figure 4 illustrates the direction of the concentrate-grade effect. The figure is conceptual rather than contractual, but it makes the key point that higher concentrate grade can lower effective deductions per unit of copper even if the nominal TC remains unchanged.

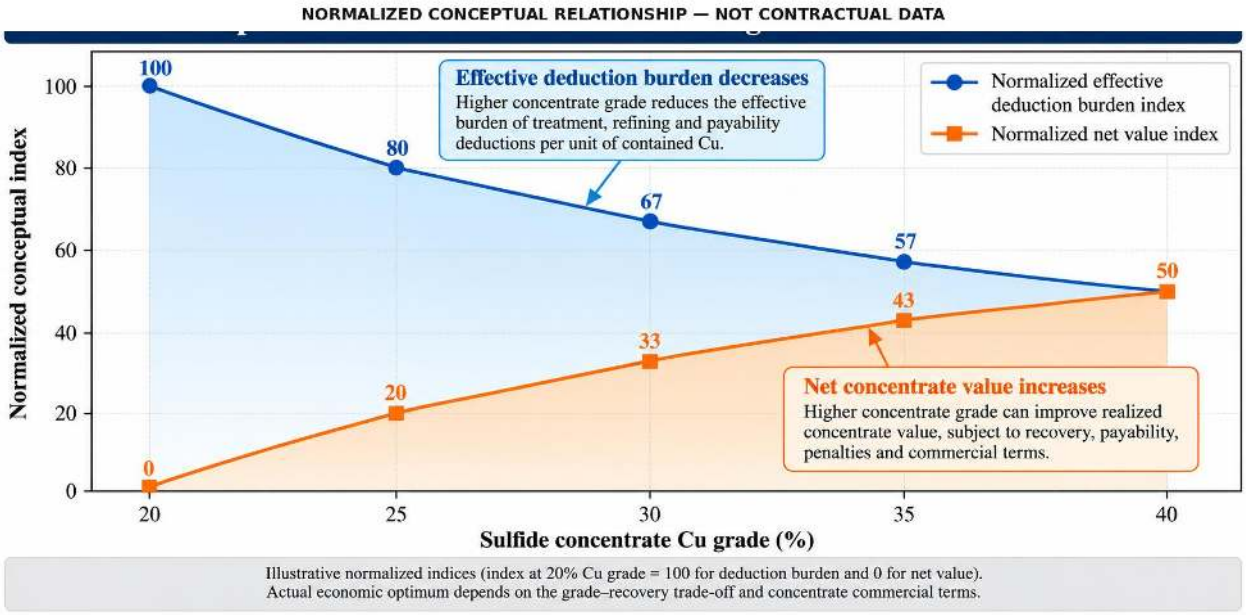

Figure 4. ***Concentrate grade–TC/RC–net revenue relationship.***
Note. Author-generated normalized conceptual relationship only; not contractual or project-calibrated data. The figure demonstrates directionality of concentrate-grade, TC/RC, and net-revenue effects rather than benchmark commercial terms.

7.2. Market balance, payability, and penalties

Contemporary market assessments and smelter-economics analyses show that TC/RCs are not stable constants; they respond to concentrate availability, smelter capacity, benchmark negotiations, spot-market tightness, and concentrate quality (Benchmark Mineral Intelligence, 2025; CRU, 2026; Fastmarkets, 2024; Han, 2026; S&P Global Commodity Insights, 2021a, 2021b, 2022, 2026a, 2026b; Shanghai Metals Market, 2023; Sumitomo Metal Mining Co. & Sumitomo Corporation, 2023; Tankard et al., 2026). For project valuation, commercial terms should therefore

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be represented as market scenarios rather than hard-wired as one benchmark across the entire mine life. Joint copper-price–TC/RC modeling should likewise arise from concentrate-market fundamentals, especially concentrate availability, smelter capacity, quality, and contract structure, rather than from an assumed universal correlation sign.

Table 4 separates the principal concentrate commercial mechanisms and their financial direction.

Table 4. ***TC/RC mechanisms and concentrate-grade effects***

Commercial term	Typical basis	Effect on mine revenue
Treatment charge	US$/dry t concentrate	Higher charge reduces net revenue; effective $/lb falls as grade rises
Refining charge	cents/lb payable Cu	Direct deduction from payable metal value
Payability	% of contained Cu/Au/Ag	Determines saleable metal basis
Penalty	Element- and threshold-specific	Reduces value; may constrain marketability
Premium/credit	Quality- or by-product-specific	Raises realized value
Freight	US$/wet or dry t product	Stronger burden for lower-grade concentrate
Price participation/quotational period	Contract-specific	Links settlement to price timing and contract structure

Note. Actual contracts are project- and market-specific; the table identifies mechanisms rather than prescribing benchmark values.

8. CAPEX, Sustaining Capital, and Timing of Cash Outflow

8.1. Capital categories

Decompose capital into initial development, growth or expansion capital, deferred capital, sustaining capital, replacement capital, and closure-related capital. This decomposition matters because identical total CAPEX can produce different NPVs when spending occurs at different times. Front-loaded capital carries the greatest discounted burden and creates the largest financing requirement, whereas deferred expenditure can preserve value when it is genuinely optional rather than merely postponed.

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Figure 5 contrasts front-loaded and staged capital profiles. The conceptual result is not that deferral is always beneficial, but that timing must be valued together with the production enabled by each capital tranche. All CAPEX shares displayed in the figure are hypothetical and are not derived from a disclosed project dataset.

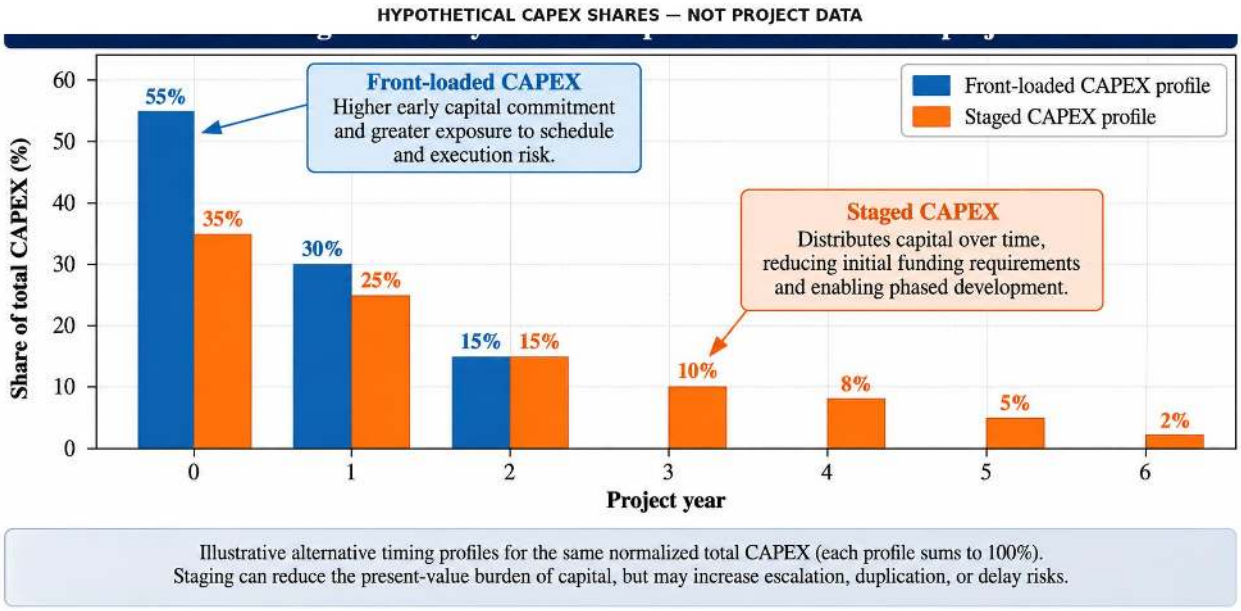

Figure 5. ***CAPEX timing and discounted project value.***
Note. Author-generated hypothetical CAPEX shares and timing profiles only; not a specific project estimate. The figure demonstrates discounting and staging effects, and the displayed percentages are illustrative.

Studies on mining capital-cost estimation, investment valuation, real options, financing, and discounting show that both estimation error and timing uncertainty can materially alter project value (Bang & Trellevik, 2023; Guo et al., 2021; Harmony Gold Mining Company Limited, 2025; Nourali & Osanloo, 2020; Shivute, 2024; Suárez Nieto et al., 2024; Zhang et al., 2020). A critical model should therefore distinguish quantity risk, unit-cost risk, escalation, schedule overrun, contingency, and the possibility that selected capital can be delayed, staged, or avoided. Estimate maturity is itself a risk driver: conceptual, scoping/PFS, DFS, and construction-control estimates do not share the same degree of engineering definition. A transparent risk model should therefore identify estimate class or maturity, quantity growth, unit-rate uncertainty, contingency philosophy,

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escalation, and schedule exposure separately rather than compressing them into one CAPEX-overrun percentage.

Table 5 provides a compact capital taxonomy for integrated copper projects.

Table 5. ***CAPEX and sustaining-capital categories***

Category	Examples	Valuation issue
Initial CAPEX	mine development, oxide plant, concentrator, infrastructure	Largest early cash burden and financing need
Deferred CAPEX	Later plant modules, tailings lifts, fleet additions	Timing may create option value
Sustaining CAPEX	component replacement, ongoing mine development	Should follow asset usage, not flat annual ratios
Expansion CAPEX	Throughput increase, debottlenecking	Value depends on future market and feed availability
Replacement capital	major equipment renewal	Linked to asset life and reliability
Closure capital	Demolition, rehabilitation, water treatment	Often back-ended but may require early security

Note. Capital categories should be time-phased and linked to the physical assets or operating decisions that trigger expenditure.

9. OPEX Variability and Operating Leverage

9.1. Cost drivers by process route

Mining, crushing, grinding, flotation, leaching, solvent extraction/electrowinning, water management, labor, maintenance, and administration create different cost structures. Oxide circuits can be particularly exposed to acid and solution-management costs, whereas sulfide circuits can be dominated by comminution energy, grinding media, reagents, tailings handling, and concentrate logistics. Using a single life-of-mine average unit cost obscures the fact that ore hardness, strip ratio, grade, recovery, and reagent demand change over time.

Research on environmental cost, water recovery, energy use, and copper-process decarbonization demonstrates that inputs previously treated as stable utilities increasingly have both economic and strategic importance (Badakhshan et al., 2023; Röben et al., 2021). These costs

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may correlate with carbon policy, power-market conditions, water scarcity, and infrastructure investment, so a single percentage increase in OPEX cannot adequately capture the risk.

9.2. Operating leverage and margin compression

Operating leverage is strongest when a project has high fixed costs or high exposure to volatile inputs. Near the economic margin, a relatively small change in unit OPEX can cause a disproportionate change in free cash flow and may change the optimal cut-off grade or routing decision. The appropriate stress test therefore varies OPEX alongside grade, recovery, and price, rather than assuming cost shocks against an unchanged production plan.

10. Freight, Product Form, and Netback

10.1. Product-specific logistics

Cathode, concentrate, and sulfuric acid occupy different logistics chains. Cathode is high-value and compact, concentrate is bulkier and often moisture-bearing, and acid is a hazardous bulk liquid whose delivered cost can vary sharply with distance. Port handling, storage, inland haulage, ocean freight, insurance, and demurrage therefore have different unit bases and risk profiles. Integrated projects should not collapse these flows into a single logistics percentage of revenue.

Figure 6 maps the distinct logistics chains and shows why netback must be calculated by product form.

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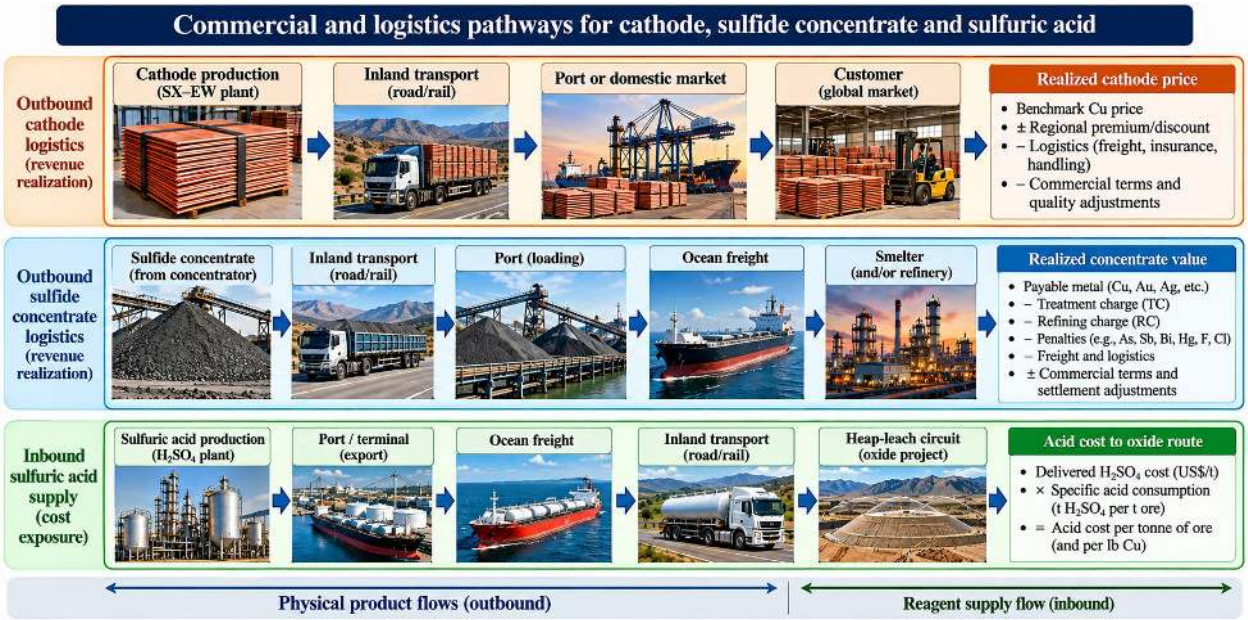

Figure 6. Mine-site value versus delivered/realized value by product form.
Note. Conceptual logistics map developed for this review and adapted from product-specific freight and netback relationships synthesized from the cited literature.

The evidence on freight, transport, and metal-market logistics supports explicit modeling of product-specific netback (Ero Copper Corp., 2026; Pereira et al., 2016). Even where freight is small relative to gross metal value, it can materially affect marginal ore, concentrate-grade strategy, acid sourcing, and the relative economics of remote projects.

10.2. Netback as the common comparison metric

A common mine-site netback makes oxide and sulfide products more comparable. For cathode, the bridge runs from quoted price to premium/discount and outbound logistics. For concentrate, the bridge runs from contained payable metal to TC/RCs, penalties, and freight. For acid, the relevant value is reversed: supplier price becomes a delivered input cost. This symmetry helps show where each route is most vulnerable to external markets.

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11. Taxes, Royalties, and Fiscal Architecture

11.1. From pre-tax to post-tax value

Pre-tax economics can be a useful technical comparator, but investment decisions are driven by post-tax cash flow. Royalties may be revenue-based, profit-based, or contingent; corporate income tax depends on taxable income and depreciation; withholding taxes affect distributions; and other levies can be linked to assets, transactions, or employee profit sharing. Fiscal terms can therefore change the relative attractiveness of process routes even if their pre-tax margins are similar.

Fiscal-regime research shows that the form and timing of royalties and taxes can materially change investment incentives and cash-flow distributions (Benninger et al., 2024; Castillo & Hancock, 2022; Inter-American Development Bank, 2020; Jou & Lee, 2023). The modeling lesson is to calculate fiscal liabilities from their legal tax bases rather than applying an aggregate percentage to EBITDA or revenue.

Table 6 summarizes the principal channels through which fiscal terms affect project value.

Table 6. ***Tax and royalty effects on post-tax valuation***

Fiscal item	Typical base	NPV mechanism
Mining royalty	revenue, margin, or profit	Reduces project cash flow; may be insensitive to accounting profit
Corporate income tax	taxable income	Interacts with depreciation, losses, and allowances
Withholding tax	dividends/interest	Affects distributions and financing structure
Depreciation allowances	eligible capital base	Changes tax timing and therefore NPV
Profit sharing	profit or statutory base	Creates labor-linked fiscal/operating burden
Stability agreement	Defined taxes/period	Reduces some fiscal uncertainty but may have conditions
Indirect taxes/VAT	transactions and purchases	Can create working-capital timing effects

Note. Fiscal systems are jurisdiction-specific; project models should reproduce the applicable tax bases, timing rules, and loss carry-forward provisions.

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11.2. Fiscal uncertainty and route comparison

Fiscal uncertainty matters most when a project has long construction and operating lives. A change in royalty design can affect high-revenue, low-margin years differently from profit-based taxation. Integrated projects should therefore test fiscal changes together with commodity prices and route-specific margins, rather than as an isolated NPV percentage shock.

12. Working Capital, Closure, and Late-Life Cash Flow

12.1. Working capital as a timing variable

Working capital is often small relative to total life-of-mine revenue but important to early cash flow. Receivables delay cash collection, concentrate and cathode inventories trap value, reagent stocks improve resilience but consume cash, VAT balances may be recoverable only with delay, and payables partially offset these requirements. During ramp-up, working-capital assumptions can therefore influence peak funding and the date of cash-flow breakeven. Operationally, working capital should be built from explicit drivers where data permit—for example, receivable days, cathode or concentrate inventory days, reagent-inventory policy, VAT-recovery lag, and accounts-payable days—rather than represented only as a fixed percentage of revenue or OPEX.

12.2. Closure and post-closure liabilities

Closure obligations mirror working capital in one important respect: although they are commonly back-ended, their present value and funding requirements can affect the project much earlier. Models should link progressive rehabilitation, closure guarantees, water treatment, tailings stewardship, demolition, and post-closure monitoring to physical disturbance and regulatory requirements. Simplified terminal lump sums can understate both escalation and the cost of long-duration care. Closure uncertainty should also be decomposed into physical-scope growth, changing water-treatment duration, evolving regulatory standards, inflation/escalation, revised tailings obligations, and financial-assurance requirements; these mechanisms should not be collapsed into one undifferentiated percentage shock.

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Recent work on closure preparedness, post-mining transitions, land-use planning, and environmental liabilities supports a life-cycle view in which closure is integrated into project design rather than appended after production (Dvořáček et al., 2021; Galo et al., 2022; Gregory, 2021; Guimarães et al., 2025; Hodge & Brehaut, 2023; Hudbay Minerals Inc., 2026; Measham et al., 2024; Santos et al., 2025; Worden et al., 2024). This matters financially because closure strategy can alter sustaining capital, land disturbance, guarantee requirements, post-closure treatment obligations, and residual liability.

12.3. The late-life cash-flow problem

Late-life operations can become economically fragile as grades fall, strip ratios rise, and fixed costs are spread over fewer payable tonnes. Closure timing is therefore not independent of commodity price. A project may rationally close earlier under adverse prices, but early closure can accelerate rehabilitation and severance costs. Conversely, extending mine life can preserve optionality while increasing sustaining and closure-management costs. These interactions are poorly represented by a fixed final-year closure charge.

13. Sensitivity, Scenario Analysis, Risk-Adjusted Value, and Conclusions

13.1. From sensitivity to probability distributions

One-factor sensitivity remains useful because it identifies variables with the greatest local leverage on NPV. Its limitation is that it decomposes the economic system into independent shocks. Scenario analysis improves realism by moving variables together—for example, a weak copper-price environment may coincide with adverse exchange-rate, financing, power-cost, or freight conditions, while concentrate-market tightness may move TC/RCs in a different direction. Monte Carlo analysis goes further by sampling joint distributions, but its results are only as credible as the assumed distributions, correlations, and decision rules. Risk reporting should therefore extend beyond expected NPV where appropriate and include the median, selected percentile outcomes, probability of negative NPV, and downside-tail measures. No single

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percentile is universally appropriate; the choice should match the decision context and stakeholder risk tolerance.

The literature on stochastic mine planning, Monte Carlo simulation, uncertainty propagation, and risk-adjusted valuation shows that geological, market, and operating uncertainty can be embedded directly in planning rather than treated as a separate post-processing adjustment (Alghani & Hakam, 2025; Ardhiansyah et al., 2023; Ardian & Kumral, 2020; Armstrong et al., 2021; Brikaa et al., 2023; Buchholz et al., 2022; Cardozo et al., 2022; Carelos Andrade & Dimitrakopoulos, 2024; Carelos Andrade et al., 2024; Chatterjee & Dimitrakopoulos, 2020; Cáceres & Emery, 2026; Furtado e Faria et al., 2022; Gilani et al., 2020; Jia et al., 2023; Jiang & Dimitrakopoulos, 2025; Kamel et al., 2023; Lamghari & Dimitrakopoulos, 2022; Lilford, 2023; Madziwa et al., 2023b; Maier, 2021; Mostafaei et al., 2022; Paithankar et al., 2020, 2021; Paravarzar et al., 2021; Rimélé et al., 2020; Ronyastra et al., 2023, 2024). A recurring conclusion is that flexibility has economic value only when the model lets the operating plan respond to information as uncertainty resolves. In real-options terms, an option exists only when management has an executable decision, an observable trigger, a defined exercise rule, decision timing, implementation cost, and physical or contractual feasibility. Volatility by itself does not create option value (Brennan & Schwartz, 1985).

Table 7 compares the principal risk-analysis methods, while Figure 7 shows the recommended methodological progression.

Table 7. ***Sensitivity versus scenario versus Monte Carlo methods***

Method	Question answered	Strength	Main limitation
Deterministic base case	What is the value under one coherent set of assumptions?	Transparent reference	No probability information
One-factor sensitivity	Which input has greatest local leverage?	Simple and communicable	Breaks correlations and nonlinear interactions
Scenario analysis	What happens under coherent states of the world?	Captures joint narratives	Limited number and subjective probabilities

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Method	Question answered	Strength	Main limitation
Monte Carlo	What is the distribution of outcomes?	Quantifies downside and dispersion	Sensitive to distributions and correlations
Stochastic optimization	What plan performs best across uncertainty?	Integrates uncertainty into decision	Computationally and data-intensive
Real options	What is the value of flexibility?	Values delay, expansion, contraction, switching	Requires explicit exercise rules

Note. Methods are complementary. Increasing mathematical complexity is useful only when it improves the representation of causal uncertainty and available decisions.

Figure 7 places these methods on a continuum from static valuation to adaptive decision analysis. Any distributions shown are illustrative rather than empirical probability distributions for a specific asset.

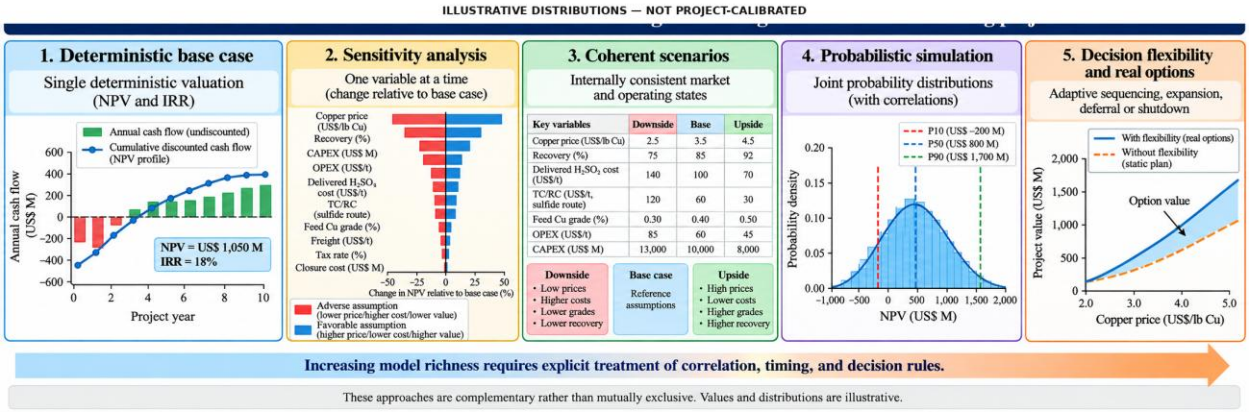

Figure 7. ***Tornado sensitivity → scenario matrix → Monte Carlo → adaptive decision progression.***
Note. Author-generated illustrative distributions and normalized outputs only; not project-calibrated probabilities. The figure demonstrates the methodological progression from deterministic sensitivity to adaptive decision analysis.

13.2. Research gaps

The strongest research opportunities lie at the interfaces among technical and financial models. Copper-price scenarios are often disconnected from acid price, TC/RC, freight, exchange rates, and power prices even though these variables may share macroeconomic drivers. Ramp-up is frequently deterministic despite commissioning evidence that throughput and recovery evolve stochastically. Mine planning often propagates grade and recovery uncertainty but simplifies it

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before financial reporting. CAPEX overrun, OPEX inflation, closure escalation, and fiscal changes are commonly stressed independently even though they can co-occur in inflationary or politically uncertain regimes. Future studies should infer these dependencies from causal market mechanisms or time-varying empirical structure rather than assigning fixed signs to copper–acid or copper–TC/RC correlations across all regimes.

Table 8 consolidates a forward research agenda for risk-adjusted copper-project valuation.

Table 8. ***Research gaps in risk-adjusted copper-project valuation***

Research gap	Why it matters	Promising modeling direction
Copper–acid price dependence	Oxide margin is exposed to two markets	Joint regime-switching or copula scenarios
Copper–TC/RC dependence	Sulfide netback responds to concentrate balance	Market-balance-linked stochastic terms
Stochastic ramp-up	Early cash flow has highest discounted weight	Bayesian/empirical commissioning distributions
Recovery and grade uncertainty	Technical uncertainty propagates to revenue	Geometallurgical simulation linked to DCF
CAPEX overrun and delay	Cost and schedule risks interact	Joint cost-schedule risk models
OPEX inflation and energy volatility	Can compress margins and alter routing	Index-linked operating-cost scenarios
Fiscal-regime uncertainty	Post-tax value can change nonlinearly	Scenario trees with tax-rule states
Closure-cost escalation	Long-duration liabilities are uncertain	Probabilistic closure cash-flow models
NPV-at-risk / probability of negative NPV	Downside is hidden by expected NPV	Full distribution and tail metrics
Flexible oxide/sulfide scheduling	Integrated routes create switching options	Stochastic optimization and real options
Integrated technical–financial digital twins	Models are often siloed	Dynamic coupling of mine, plant, market, and cash flow

Note. Research priorities are derived from the synthesis in this review and are intended to connect physical process uncertainty with financial decision metrics.

13.3. Implications for practice

For practitioners, three principles follow. First, every financial variable should have a physical or contractual origin: recovery should come from metallurgy, acid consumption from ore response, TC/RCs from concentrate-market terms, sustaining capital from asset life, and closure obligations from disturbance and regulation. Second, timing should be preserved until the final valuation step;

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life-of-mine averages are useful for communication, but not as substitutes for time-resolved modeling. Third, represent uncertainty where it enters the system and propagate it through the model, introducing correlations only when a defensible causal or empirical basis exists.

13.4. Conclusions

The value of an integrated oxide–sulfide copper project cannot be understood from copper price alone. It emerges from the interaction of two process and commercial systems: an oxide route exposed to sulfuric-acid consumption, delivered reagent cost, solution management, and cathode realization, and a sulfide route exposed to comminution intensity, concentrate grade, payability, TC/RCs, penalties, and smelter logistics. A valuation model that collapses these differences into average life-of-mine assumptions can produce a precise NPV while obscuring the mechanisms that actually create or destroy value.

The principal methodological conclusion is that timing and dependence matter as much as average assumptions. Early production delays, front-loaded capital, working-capital build, and adverse combinations of copper price, acid cost, TC/RCs, freight, exchange rates, and OPEX can have disproportionate effects because discounted cash flow is path-dependent. Conversely, staged capital, stockpiling, routing flexibility, and adaptive operating decisions can preserve value when they are physically feasible and explicitly represented.

A robust valuation framework should therefore progress from a transparent deterministic base case to one-factor sensitivity, coherent multi-variable scenarios, probabilistic simulation, and, where decisions can adapt, stochastic optimization or real-options analysis. The goal is not mathematical complexity for its own sake, but a traceable connection between ore, process performance, commercial terms, fiscal rules, cash-flow timing, and uncertainty. That connection underpins more resilient comparisons of integrated copper projects and research that is technically grounded, decision-relevant, and explicit about uncertainty.

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Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental or project datasets were generated. Numerical values used in conceptual Figures 2–5 and 7 are author-generated illustrative or normalized values intended only to demonstrate mechanisms; they are not calibrated to a specific copper project. The assumptions are described in the figure notes and surrounding text so that the conceptual relationships can be reproduced. All project-specific factual statements and externally sourced quantitative claims are traceable to the cited literature.

Author Contributions

Conceptualization, methodology, critical analysis, literature synthesis, visualization, and manuscript preparation: Antonio Clareti Pereira.

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