DFV INSIGHT

A THREE-PART SERIES

Understanding the Copper Market

Usua U. Amanam, Ph.D.

DOLBY FAMILY VENTURES

Introduction to the Dolby Family Ventures Copper Series. Over the last several years, Dolby Family Ventures ("DFV") has created a shortlist of critical materials we believe most important to the future global economy, which we envision will be increasingly decarbonized, electrified, and regionalized in its strategic supply chains. Our efforts have focused on identifying metals with structural supply/demand challenges, whose value chains require novel solutions for rebalancing. Copper sits at the top of that list. Copper's value lies in its ability to combine many functional traits into a single material, including high conductivity, malleability and ductility, corrosion resistance, and closed-loop recyclability. As the metal has garnered increased attention, we felt it would be appropriate to share with a wider audience why we remain attracted to opportunities in a market we first invested in in 2018 and have expanded further into over recent years. This is a three-part series covering supply, demand, and innovation. The objective is to formalize perspectives, update references, and share our learnings from past efforts with fellow investors. We try to avoid duplicating arguments made in widely circulated briefs and reports like S&P Global's Copper in the Age of AI (S&P Global, 2026) and, for brevity, do not discuss topics like midstream processing or recycling. We also recognize we are not the first investors to highlight this opportunity. Articles by firms like Extantia Capital and World Fund discuss the value chain and highlight how specific start-ups are addressing sector challenges. Others, including Andreessen Horowitz, have promoted thoughtful pieces by portfolio companies that do the same. Our approach in this series is to more systematically analyze the underlying drivers of primary supply and global demand trends to show why the projected gap cannot easily be addressed, and how venture capital can capitalize on this, while ultimately promoting a more fluid and accessible copper market.

Summary of Part 1. Part 1 explains why we believe copper has the most durable demand-side story of various critical materials. Its superior end-use diversification and GDP-driven growth mean demand is highly resilient, putting unending stress on supply. Projections show this leads to a deficit, the magnitude of which is larger, in both absolute and percentage terms, when measured against other materials. We end by making the case that material substitution is unlikely to occur at a magnitude necessary to matter. In Part 2, we examine the long-term, supply-side trends that, taken together with what we have discussed here, create the conditions for the increased adoption of innovative solutions.

Setting the Stage. Economic opportunity arises when demand outpaces supply, and the durability of the factors influencing that behavior is critical in decision-making for early-stage venture capital for two reasons. First, the companies in which we invest take time to grow into businesses capable of addressing global commodity challenges. Second, we desire problems that cannot easily be solved by conventional means, and whose persistence indicates a need for a novel approach. Thus, we discuss the factors that, when taken together, influence our view of durability; they include demand diversification, the magnitude at which projected demand outpaces supply, and the materiality of substitution risk.

Demand Diversification and Resilient Growth Driver. Diversification across end-use sectors makes a metal more "resilient and less exposed to single point failures of demand" (BHP, 2024). This type of diversification is widely accepted for copper, even if only qualitatively, but it is less well understood for other metals. Below, we quantitatively rank demand-side diversification to help with prioritization, using the adjusted-Herfindahl-Hirschman Index (a-HHI) developed by the S&P DJI Index Investment Strategy team. This metric measures end-use concentration risk and controls for the variability in data granularity across sources (S&P Global, 2022). In Figure 1, a-HHI is calculated for six key minerals highlighted by the International Energy Agency (IEA) in recent editions of its Critical Minerals Outlook (IEA, 2025). Across multiple datasets and a sensitivity analysis, copper shows the lowest concentration. Meaning, slowdowns in any given end use have a more muted effect on overall demand, and by extension the projected supply/demand imbalance, than they would for other metals. But why should this matter if DFV remains confident in the primary demand

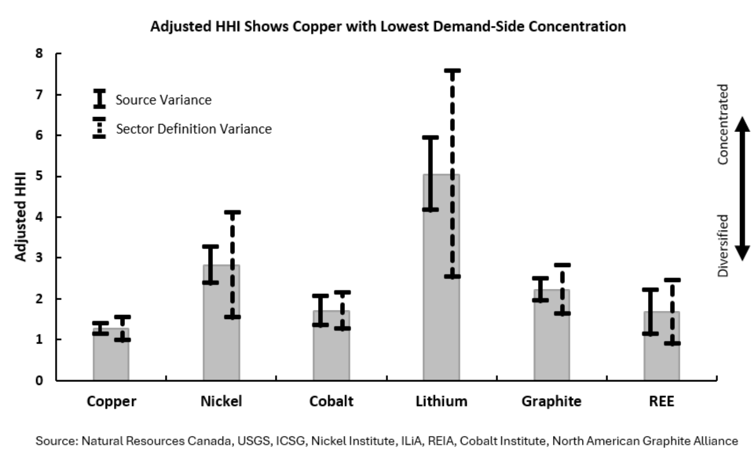

Figure 1. *Application of S&P Dow Jones Indices' adjusted Herfindahl-Hirschman Index (a-HHI) for demand-side concentration analysis. Methodology discussed with Head of U.S. Index Investment Strategy and first author on a-HHI paper.*

accelerant for most of these critical materials: the energy transition? If the transition proceeds slower than projected, whether because of policy reversals or implementation drag, the magnitude of the problem we are trying to solve shrinks, with direct implications for supply-side innovators and their backers. This is particularly relevant in the US today, as well as in other regions.

Copper's diversification ties its demand more closely to general economic development than others, giving it a highly certain, long-term growth driver. In short, as countries develop, per capita copper consumption increases. This is most evident in China, where its dramatic GDP growth since the 1990s has made it by far the largest consumer of copper globally. While the future rate of China's growth is uncertain, we are confident that the phenomenon will persist across populous regions such as India and Southeast Asia, which are earlier in their respective development timelines. Figure 2 is an analysis we did, showing the copper consumption arc that economies experience as they develop and mature. Importantly, more than half of the world's population lives in regions that have not yet seen significant per capita GDP growth. While other critical metals may reflect this well-known pattern, not all that do meet other 'durability' criteria. For example, lithium demand is highly concentrated in electric vehicles and stationary storage. As a result, even though use may be positively correlated with economic development, growth prospects for that metal are most strongly tied to the behavior of two end-use applications, not the broader global economy[1].

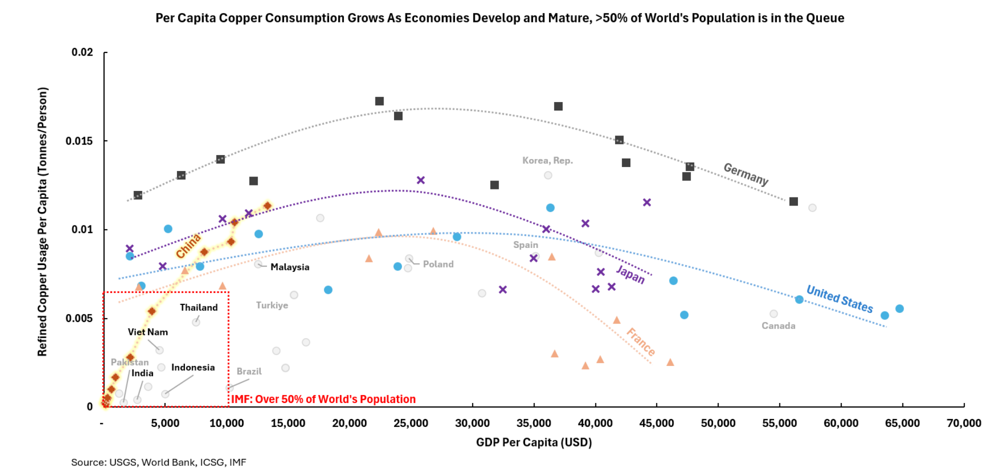

Figure 2. *Adaptation of figure 6 in Hosking Partners' 'Where's a copper when you need one' (Davidson, 2023). Graphic shows the arc of copper consumption, growing as countries industrialize and develop, followed by a peak and ultimate decline for high income economies. Growth in per capita consumption is expected in regions like SE Asia and India over the coming decades.*

As a final note, as US supply-chain policy increasingly focuses on domestic supply/demand dynamics, it is worth recalling that copper, like any commodity, trades in a global marketplace. Overall demand, regardless of where consumption occurs, affects local prices and availability. Thus, we typically view these markets through a global and/or allied-nations lens.

Magnitude of Forecasted Demand Outpacing. The larger the delta between forecasted supply and demand, the more attractive the opportunity for our capital. Various research organizations, such as S&P Global, IEA, and BNEF, publish projections using distinct methodologies and future demand scenarios that help us determine what this looks like for different critical materials. In Table 1, we present projections from the IEA's 2025 Stated Policies Scenario (IEA, 2025), which shows copper running at a market deficit in both the near and long term. Not only that, but copper will have a larger gap to close, as a percentage of overall demand, than most other critical materials. BNEF's 2024 projections show similar relational trends across the six materials, while standalone reports by Wood Mackenzie and S&P Global also highlight what is shown here (Wood Mackenzie, 2025a; Wood Mackenzie, 2025b; Wood Mackenzie, 2025c; S&P Global, 2026). We believe that the more pronounced the shortfall, the more incentivized stakeholders will be to solve the problem with novel approaches and/or innovations, and the more insulated an investor will be from shocks that eliminate the opportunity[2].

Critical Materials Supply Shortages, IEA Stated Policies Scenario (2025)

		Copper	Lithium	Cobalt	Nickel	REE	Graphite
Supply / Demand Balance (kT)	2030E	-1,646	32	45	165	9	-199
	2040E	-9,592	-426	-33	-844	2	-977
Supply / Demand Balance (%)	2030E	-5%	7%	14%	4%	8%	-2%
	2040E	-28%	-46%	-10%	-15%	1%	-9%

Table 1. *The table shows the projected supply/demand balance in the IEA's 2025 Stated Policies Scenario. Negative numbers represent a supply shortfall, while positive numbers indicate a supply surplus. Values are calculated as the difference between 'supply' and 'primary supply required'. Cu and Ni numbers match data download and live data explorer tool, but differ from report.*

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[1] We believe that despite this, the opportunity in lithium is compelling, and as such, it is also on our shortlist.
[2] The story of Indonesian nickel over the past ten years is both a cautionary tale of how quickly market shifts can render in-flight innovation obsolete and one that shows how impactful a different approach to processing ore (high-pressure acid leaching) can be on a market (Brunelli et al., 2026). We explore novel ore processing technologies in Parts 2 and 3.

Immaterial Substitution Risk. Material substitution is a demand-side phenomenon that reduces projected deficits and, by extension, the investment case for supply-side solutions. Understanding what that looks like for the critical materials in consideration is therefore important. However, forecasting material substitution is an imprecise, qualitative exercise. In fact, in the national/regional critical minerals strategies we reviewed, the term "subjective" is used more than once in methodology sections. In addition, substitution is bidirectional, meaning that a material that is substituted for in one instance may serve as the substitute in another, further complicating the matter. For example, restrictions on the use of lead solder in printed electronics within the EU (2003), as well as the mandate to replace lead pipes in drinking water systems across the US (2024), only stand to increase the use of copper in those applications over time, since it is a substitute of choice. In Table 2, we normalize substitutability data from four reports to show the high degree of variance across credible sources and ultimately to make the case that recent empirical data is likely sufficient to determine substitution risk in the future.

	Substitutability in Data Source (0 = Most, 1 = Least) | Relative Substitutability Ranking in Data Source (#1 = Least)							
	Graedel et al. (2015)		Chadha & Sivamani (2021)		DOE , Medium Term (2023)		EU Commission (2023)	
	Substitutability	Relative Rank	Substitutability	Relative Rank	Substitutability	Relative Rank	Substitutability	Relative Rank
Copper	0.7	#1	0.8	#4	0.7	#2	0.7	#7
Lithium	0.4	#5	0.9	#2	1.0	#1	0.9	#5
Cobalt	0.5	#4	0.7	#6	0.3	#4	1.0	#2
Nickel	0.6	#3	0.6	#7	0.7	#2	0.9	#6
Heavy REE	0.6	#2	0.9	#3	N/A	N/A	1.0	#1
Light REE	0.4	#5	1.0	#1	N/A	N/A	1.0	#2
Graphite	N/A	N/A	0.7	#5	0.3	#4	1.0	#2

***Table 2**. The table shows how sources have ranked the substitutability of various critical minerals over time. Substitutability numbers have been normalized to a 0-1 scale, with 0 being the most substitutable and 1 the least. Because data sources use distinct methodologies, general comparisons across sets are not applicable. Relative ranking, however, may show the subjectivity of this effort and/or how changing market dynamics impact how experts view substitutability from year to year. Note: Substitutability numbers are rounded for ease of viewing.*

The existence of long-used copper substitutes, like aluminum and cross-linked polyethylene, provides enough of a historical basis to answer whether substitution matters on a timeline relevant for us. We do not think it does. Frank Messner conducted an in-depth study on the dynamics of copper substitution. In it, he argued that "material substitution is an evolutionary and path-dependent process," not merely a function of relative price (Messner, 2002). His conclusion is consistent with the findings of other researchers. In a comprehensive review of substitutability across over 60 materials, a team from Yale shows how much substitution risk varies by application, complicating efforts to predict what overall substitution could look like for a metal (Graedel et al., 2015). Here, again, the importance of demand-side diversification becomes evident. Constraints and performance needs vary by use case, and by extension, so does substitutability. In the context of copper, one expert with whom we spoke frames this as a marginal cost-of-substitution curve, one in which the easiest substitution decision is made first and subsequent ones get progressively harder. Most simply, this can be seen in the increase in the copper-to-aluminum price ratio required to trigger more substitution (BHP, 2024). Figure 3 shows data with which some will be familiar. It presents the copper-to-aluminum ("Cu/Al") price ratio from 2010 to 2025, with the net substitution rate for copper overlaid. What is most important about this graph is not the expected positive correlation, but that the absolute net substitution rate is nominal relative to the projected supply deficit in future scenarios. If, in times when the primary substitute is favored due to price, we would expect consequentially high substitution rates, and that has just not occurred. Over the past decade-plus, historically high Cu/Al price ratios have translated to no more than low single-digit rates, which, for us, implies that the risk is inconsequential. We estimate that in 2009, in the midst of the last supercycle, the rate peaked at <3% (Anglo American, 2021). In summary, substitution is a complex, multi-variable process that is more challenged when end-use demand is diversified. For long-established primary substitutes, such as aluminum, recent empirical data indicate that substitution is unlikely to close the projected supply/demand gap in any material way.

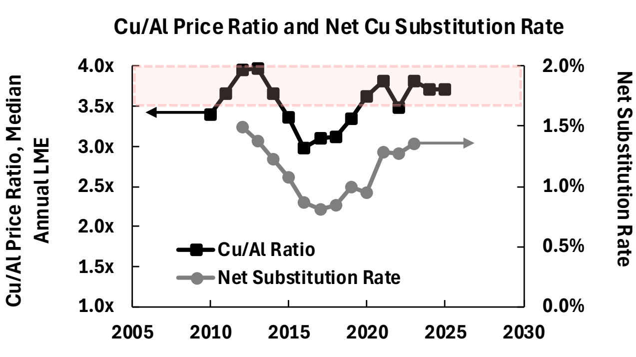

***Figure 3**. The graph shows that even when the price ratio makes the substitution of copper with its primary replacement, aluminum, attractive, the overall net substitution of the metal is inconsequential in the context of the projected supply gap. Forbes estimates the substitution ratio to be 3.5x - 4x, while BNEF, in its 2024 Transition Metals Outlook, estimates it to be ~1.6x.*

Conclusion. Some critical materials are more important to the future of the global economy than others. Some are also more compelling for early-stage investors. We argue that copper has the most attractive demand-side characteristics of a cohort of metals often cited as vital to the energy transition. These dynamics and the momentum of the trend suggest an increasing opportunity over the coming years. As early-stage investors, we require durable trends in the sectors we invest in as a critical input for decision-making. We show that copper has that by measuring the breadth of demand-side diversification, the magnitude of the projected supply/demand deficit, and assessing the muted risk of material substitution. When coupled with supply-side limitations, which we discuss in Part 2, we believe copper offers the most appealing opportunities to us as early-stage venture capital investors.

Summary of Part 2. In Part 1, we discussed why copper's demand-side dynamics appear favorable for early-stage investment. We made the case that a diversified buyer base will soon face an increasing shortfall, one amplified by the complexity of substitution and a growing trend in usage. In Part 2, we highlight long-known, persistent supply-side trends that limit the ability of stakeholders to respond to industry needs. We show that while new mine ("greenfield") developments are required, miners' existing capital allocation strategies create a significant opportunity at existing mine sites ("brownfield") to grow the economically mineable ore base ("reserves") and maintain or increase production. Brownfield sites, however, are not without their own challenges. The productivity gains that have helped miners maintain operational profitability of their long-lived assets over the years have since ceased. That carries negative implications for supply but creates an opportunity for novel solutions. We conclude by highlighting the critical role innovation has historically played in unlocking capacity at brownfield sites, paving the way for a forthcoming final article that analyzes how venture capital can support this industry through investment.

Copper projects have become harder to develop over the decades, subjecting miners to increasing risk. The declining success rate of greenfield exploration has been discussed at length in several publications. In general, it is due to "increasing political, regulatory, and tax issues," which restrict the total area that can be reasonably developed and thus explored. In combination with "declining grades, rising costs . . . as well as the difficulties of exploring [deeper]", it has led to a dearth of top-tier deposits entering the development pipeline (Schodde, 2025). The preceding quotes are well-suited for the 2026 copper market; however, they reflect comments made by industry observers 15+ years ago during the last period of sustained, elevated commodity prices ("supercycle"). Since then, top-tier deposits, which generate the bulk of the value associated with exploration activities, have accounted for less than 3% of all significant discoveries (Schodde, 2026). Greenfield exploration has always been a challenging business, though, one whose difficulties drove large mining companies away from it in the 1980s. For context, an analysis of 100 of the most significant mines to come online from 1989-2008 models and estimates that the median IRR of exploration activities was below the industry's average cost of capital[1] (Doggett and Leveille, 2010). And, in a separate and more recent study, researchers showed that between 1997 and 2020, the expected returns for copper exploration, on average, were negative (Castillo & Roa, 2026). This is despite a steady stream of innovations introduced across drilling, geochemistry, geophysics, and other areas during these periods. It remains to be seen whether the newest technologies, such as agentic and generative AI, can avoid being just another helpful advancement and instead have a paradigm-shifting effect on exploration similar to that of airborne electromagnetic geophysics and new geologic models for porphyry systems (Schodde, 2025).

While we believe that new exploration technologies will improve discovery rates and expand the project pipeline more quickly, we argue that most new deposits will still have to contend with the realities of post-discovery development timelines. The discovery-to-mine conversion rate has generally slowed across project vintages since the 1950s (MinEx Consulting, 2026). One primary driver is increased project complexity, which inherently increases unit costs (BHP, 2024). The growth of project complexity follows the natural trajectory of resource extraction: easier-to-mine deposits are exploited first and depleted, ultimately driving stakeholders to pursue harder-to-mine zones or sites. Chuquicamata is a good example, showing this evolution at a single site, but there are others (Bloomberg, 2024). Longer lead times and increased unit costs mean lower IRRs for (prospective) projects, all else equal, increasing the riskiness of development and reducing the appetite to pursue these more complex assets.

Figure 1 and Figure 2 illustrate this increased post-discovery risk through schedule delays and rising development costs. Figure 1 is part of a 2024 McKinsey analysis that shows copper projects carrying higher levels of execution risk when compared to other metals; roughly one-third experienced delays of more than 30% (McKinsey, 2024). We view schedule delay as a distinct, albeit compounding, risk factor to the long development timelines previously discussed. Delays cause deviation from a baseline underwriting case, negatively impacting project economics, and leading to potential suspension or abandonment. Occam Edge's database of more than 900 energy and industrial infrastructure projects, which includes ~10 major copper mines brought to FID since 2012, shows how delays are associated with increased cost overruns, relative to a base case. Residual damage from failed or underperforming efforts can color subsequent decision-making for projects, exacerbating the problem.

[1] The authors calculate a 7.4% median IRR for exploration in Table 6 of the publication and presume an 8% cost of capital for all base case assessments. We separately calculated the median and average industry WACC. This was done with data from Aswath Damodaran's website. It was ~9% during the period 1998-2008, which represents the second half of the study's data set.

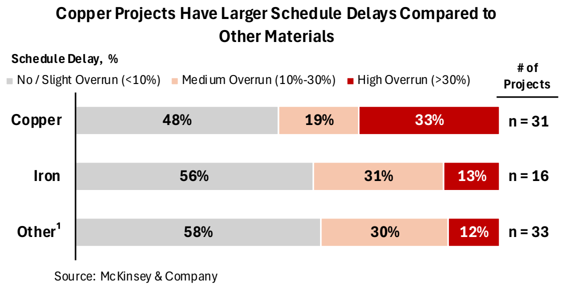

Figure 1. *Redrawn from McKinsey's 'The capex crystal ball: Beating the odds in mining project delivery', Exhibit 2.*

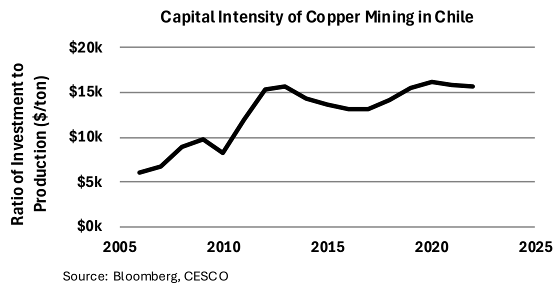

Figure 2. *Redrawn from Bloomberg's ' Aging Copper Mines Are Turning Into Money Pits Despite Demand', third figure.*

Figure 2 shows rising development costs in Chile, the world's largest copper-producing and reserves-bearing country. This phenomenon, however, is not unique to the country, and multiple industry stakeholders, including BHP, have further discussed the trend (BHP, 2024; S&P Global, 2025a; Miningmx, 2025).

An important contributing factor to all of this is the environmental, social, and governance ("ESG") requirements that miners increasingly must meet. The capital associated with it can be hard to quantify, but the impact on development and operations is well understood. Of the ~90 copper projects recently analyzed by MinEx Consulting, nearly a quarter were stalled due to environmental and/or social reasons, outpacing those delayed due to poor economics (MinEx Consulting, 2026). The term 'social license to operate' is now commonly used across the industry to refer to the informal, ongoing approvals miners must secure from local communities to operate, and it is largely informed by ESG factors (OXFAM, 2025). One specific area where this repeatedly and increasingly arises is water usage. In our own analysis of ~15 prominent copper mines[4], we see a common theme: businesses are spending additional capital to respond to calls and/or requirements to improve water stewardship or alleviate constraints. This includes i) creating one of the larger desalination plants globally (Escondida), ii) using 100% untreated seawater for operations in lieu of freshwater withdrawals (Centinela), and iii) achieving >95% water reuse (Las Bambas). These new ESG-focused efforts increase costs and risks for new and existing projects, but are, rightfully, part of the cost of doing business.

Miners have pursued brownfield strategies as they aim to maintain capital discipline. Increased risk means that the forecasted returns required to greenlight a project must rise ("hurdle rate") to compensate the miner for a higher probability of loss. While we have not yet seen a study that shows this occurring over time in a given portfolio, industry anecdotes from individuals such as David Humphreys, former Chief Economist at Rio Tinto and Norilsk Nickel, point to changes to capital allocation strategies as an indicator of such a phenomenon: more capital is being assigned to brownfield projects, as it is considered easier to meet hurdle rates when expanding or extending the life of an asset a mining company already knows. This is particularly relevant today, as talk of a new supercycle becomes more frequent. Those that experienced investment-related economic pain during the previous one have spent the last decade prioritizing capital discipline and operational excellence. Wood Mackenzie analyzed a set of copper-focused and diversified miners responsible for ~50% of global production, and found that between 2019 and 2024, ~80-95% of capital allocated after dividends and share buybacks went to sustaining capex and brownfield expansion (Wood Mackenzie, 2025). Even funds earmarked for exploration are increasingly used at existing sites[2]. Brownfield budgets have steadily grown in size relative to greenfield ones, and, in 2025, reached a ratio of ~1.75 to 1 (S&P Global, 2025b; S&P Global, 2026). Three recent examples further show the industry's strong focus on maximizing the value of existing assets: (i) CODELCO, which is amongst the largest copper producers globally, believes "supply expansion will largely depend on brownfield projects, as new greenfield developments face increasing challenges (CODELCO, 2025)," (ii) ~80% of investment dollars in the 2024-2033 Chilean project portfolio are allocated to brownfield efforts (ITA, 2025), and (iii) BHP "expect[s] high-quality brownfield projects to be prized in the industry in the face of growing copper demand" and that "the experience, technical capability developed through years of production and detailed ore body knowledge remain as major advantages, particularly when it comes to more complex projects (BHP, 2024)". As a final point, we believe the shift in allocation drives a feedback loop that only increases the importance of brownfield sites, with new research showing that exploration budgets are the dominant determinant of the frequency and quality of discoveries (Castillo & Roa, 2026).

[2] Or, in the case of junior miners, it is increasingly "directed toward development rather than exploration" (S&P Global, 2026).

Producing profitably from brownfield sites has become more difficult, though, negatively impacting the ability to maintain and/or grow production at those mines. Productivity gains within the industry have waned in recent years. Unless reversed, we expect this trend to negatively impact operational profitability, and by extension, the ability to convert uneconomical ores and stockpiles into reserves at these sites. Many have reported on how declining ore grades impact production costs. Less discussed is how successful the industry has actually been in managing down production costs over time (Jara et al., 2010). All else equal, if productivity gains outpace the inflationary behavior at a mine, costs can stay low. MinEx Consulting's 2010 presentation shows that, on average, the industry has historically been able to do this. Cost reductions are attributed to various innovations implemented at mine sites across time, including Wilfley tables for gravity separation (1895), froth flotation (1910), the 100x increase in drilling rates (1907-2005), the 18x growth of the capacity of hauling trucks (since 1960s), more general economies of scale since the post-war period, and solvent extraction-electrowinning (1980s) (Humphreys, 2019). It is important to stress that innovations that reduce production costs also increase the amount of material a company can produce economically at a site. Solvent extraction-electrowinning ("SX-EW") is a strong example of that. It enabled the efficient processing of previously uneconomical low-grade oxide ores at existing sites. In Figure 3, we use USGS data to show the dramatic effect it had on US copper production, which was in decline for years through the 1970s.

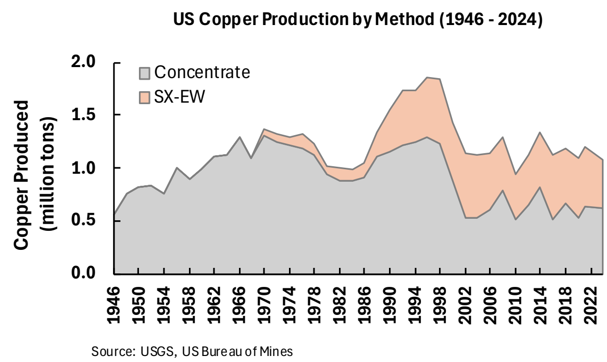

***Figure 3.** Data show the impact that the innovation of leaching low-grade oxide ores has had on the US copper industry.*

As we noted earlier, though, productivity gains have ceased, and there appears to be a secular shift reflecting the exhaustion of gains from the previous waves of innovation. Data from Chile, Peru, the US, Australia, and Canada, which together constitute ~45% of global copper production, show what is likely to be a broader industry dynamic (Aydin, 2018; Humphreys, 2019; Sanchez & Hartlieb, 2020). Figure 4 illustrates this, specifically, for Chile and the US through ~2015.

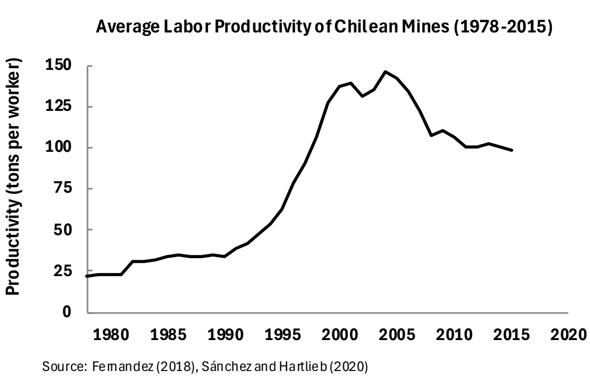

***Figure 4a.** Redrawn from Figure 3 in 'Innovation in the Mining Industry: Technological Trends and a Case Study of the Challenges of Disruptive Innovation' (Sánchez & Hartlieb, 2020).*

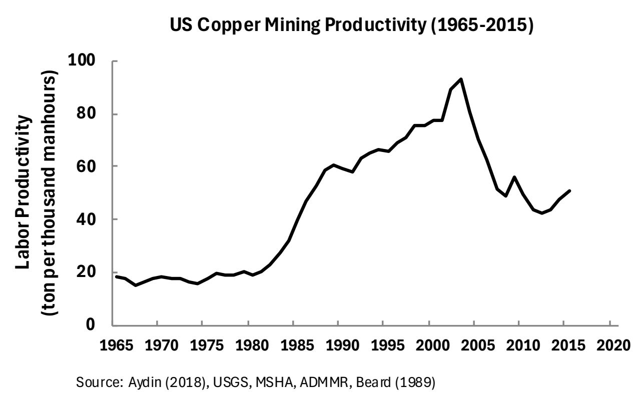

***Figure 4b.** Redrawn from Figure 1 in 'Fifty years of copper mining: the US labor productivity' (Aydin, 2018).*

While conversations with some of the authors of the papers cited above confirm that no material reversals have occurred since publication, we wanted to analyze how tightly production costs have correlated with grade declines since then. We examined the relationship between ore grade and production costs and tracked the general operating history of ~15 mines responsible for ~25% of global production[3, 4]. The sample set also covers four of the top five mines by production over the past few years. In Figure 5, we show a nontrivial negative correlation across most mines, indicating that operations will continue to move up the cost curve, compressing margins, unless new productivity interventions are employed. Critical, long-producing mines like Escondida and Grasberg have shown the ability to better manage unit costs over the past decade through effective mine planning and by transitioning to new zones, respectively. We view these as harbingers. Not shown in the graph are new efforts being implemented at

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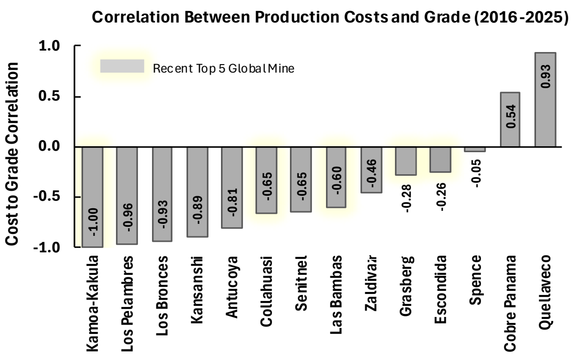
[3] Production costs are reported differently by miners. We control for these variances, adjusting unit costs to ensure they represent only the cost of producing copper from the ore, exclusive of cost adders sometimes included like transportation, royalties, etc., as well as adjustments for items like by- or co-products. More information and data available upon request from author.

[4] Mines analyzed from 2016-2025, unless otherwise noted: Escondida, Grasberg, Kamoa-Kakula ('22-'25), Las Bambas, Collahuasi, Los Bronces, Quellaveco ('22-'25), Los Pelambres, Antucoya, Zaldívar, Cobre Panama ('19-'23), Kansanshi, Sentinel, and Spence. Cumulatively, these mines cover ~25% of global production capacity.



Source: Company filings and press releases

Figure 5. *Production costs at select mines show strong negative correlation to grade.*

other sites to effect change, including coarse-particle flotation and novel leaching techniques. While there are limits to how much miners can fight escalation, our takeaway from the analysis is that there are still ways to reduce the strength of the correlation between grade and costs. In Part 3, we examine further why and how this can be done.

Conclusion. While greenfield opportunities exist and are critically important, structural barriers make accessing supply from new discoveries particularly challenging, reflecting a long-term trend in the copper sector. The increased risk with greenfield developments has led the industry to invest more capital into brownfield sites, though these are not without their own long-running issues. We argue that the next supply wave points to a need for innovations that can deliver step-change productivity gains to help the industry meet the demand call. We examine this in Part 3 of the series.

Summary of Part 3. Part 3 focuses on how certain venture-style innovations, if successful, will affect the supply/demand equation, viewed through the lens of four portfolio companies. We discuss technology adoption at brownfield sites, the power-law and widening opportunity for upstarts in greenfield exploration, and summarize why our portfolio companies have taken their respective market positions, as well as how, if successful, they will matter to the industry. While our perspectives on what makes for compelling venture opportunities in this space are, by nature, embedded in (continued) investment decisions, we do not go into further detail here. For a deeper discussion around current and go-forward hypotheses, and how market dynamics have shaped them, please reach out to the author.

- **Transition Metal Solutions** develops site-specific chemical additives that improve existing leach operations and enable economic processing of low-grade mineralogies currently considered waste.
- **Esper Satellite Imagery** accelerates the earliest stages of greenfield exploration with a satellite-based sensor that delivers affordable, high-resolution hyperspectral data services to (junior) miners and their technology vendors.
- **Vorticity** leverages GPUs and custom-built software to accelerate computationally expensive geophysical methods, enabling efficient identification of copper porphyry deposits at depth.
- **Kuprion** manufactures a novel nanocopper formulation that solves critical thermal and electrical challenges faced by those designing or building AI and high-power compute solutions, showing why copper's properties are sought after in many current and future applications.

Opportunity and Technology Adoption at Brownfield Sites. Innovation can deliver value at existing mine sites in two primary ways: (i) by reducing cash costs for existing operations; and/or (ii) by profitably increasing production volumes. In Part 2, we showed that productivity gains have generally ceased, implying that miners need new tools to keep cash costs low. We also examined how the deployment of solvent extraction-electrowinning unlocked significant capacity at brownfield sites in the US, converting low-grade uneconomical ores into those profitable to produce. This reclassification of resources into reserves remains consequential today. From 2001-2014, "[n]early 80% of the industry's gross new reserves . . . came not from new discoveries, nor from finding new copper zones within, alongside, or beneath existing deposits. Instead, almost all of these reserve additions came from re-classifying what had been considered waste rock into minable ore" (Goehring & Rozencwajg, 2021). Though this was primarily attributed to elevated prices during the period, the inverse (i.e., reducing cash costs) yields the same net result. Considering these factors, we have come to view unlocking the full potential of these sites, through both avenues initially mentioned, as an attractive value proposition for venture capital funding.

Over the last few years, Dolby Family Ventures has reviewed many brownfield-focused technologies. The ones we find most attractive share a few common traits. First, their efficacy is maintained at the scale required for these operations (e.g., contending with daily ore throughputs of up to hundreds of kilotonnes). Second, they can easily manage the heterogeneity of ores at and across different mine sites. Third, they do not require an entirely new workflow or flowsheet but fit into existing processes seamlessly, and because of that, have an appropriate go-to-market strategy. This last criterion warrants additional context, given the prevailing narrative that the mining industry is reluctant to deploy innovative solutions. Technology adoption behavior is driven by the structure of a customer's business, which, for miners, entails high initial capital outlays and the need to maximize uptime to achieve necessary returns. When a company decides to develop and bring a project online, it should be able to achieve projected returns if the base underwriting case materializes, absent the need to deploy any additional innovation. Thus, new technologies that risk disrupting cash flows are carefully considered before adoption. In fact, the sector has a supplier-dominated innovation profile for that reason. Trusted vendors incorporate ready-made innovations, often derisked elsewhere, into existing equipment, processes, and/or flowsheets, helping miners avoid that risk (Sanchez & Hartlieb, 2020). It is perhaps most evident today in the autonomous haulage systems and drilling rigs provided by the likes of Komatsu, Caterpillar, Epiroc, and Sandvik. Our view is that the scalability, breadth, and method of delivery greatly influence whether an innovation has a chance at having an outsized impact on this specific market. These traits are among the primary reasons we built conviction in Transition Metal Solutions ("Transition").

Transition Metal Solutions (Invested Q2 2024). Transition's site-specific additives improve existing leach operations and enable the economic processing of low-grade mineralogies currently considered waste. They do this with off-the-shelf chemical compounds that, when added to a leach solution, unlock the latent potential of indigenous microbial communities that already drive copper production. Their technology platform abstracts away the (microbial) heterogeneity seen across space and time at a site, delivering custom-tailored leach enhancers to specific heaps or stockpiles. Having a distinct mechanism, the technology complements existing physicochemical process optimization developed and deployed by expert metallurgists and mining engineers. This adds a layer of microbial ecosystem optimization that can be consequential to successful leach cycles. Importantly, their end-to-end process runs at a speed that fits into existing leach preparation workflows and requires no additional permitting or infrastructure.

Informed by their own direct experience with copper mines, the team built the technology and operational approach around the natural constraints any innovation like this will face upon deployment. As such, their strategy is built around the three tenets previously discussed: scalability, breadth, and viability of the delivery method. In a time when the industry is actively searching for improved leaching solutions to unlock value across existing portfolios (see FCX's Leach Initiative, BHP's Full SaL, RIO's Nuton, ANTO's Cuprochlor-T), ones that are easy to transfer from site to site, like Transition's, can shape how comfortable customers can get adopting the new technology, ultimately influencing how impactful the solution could be across the industry writ large. If Transition continues to execute and the scaled-up readout is as favorable as projected, the solution could be an important vector for expanding miners' margins and helping the industry unlock the value of low-grade sulfide ores, not too dissimilar to how solvent extraction-electrowinning enabled the production of low-grade oxides in the 20th century.

Note: The technology is also applicable at greenfield sites. We view brownfield deployments, not only as an immediate opportunity, but also as a way to offer new mine developments commercial proof points of efficacy.

The Opportunity in Greenfield Exploration. Despite the challenges associated with greenfield exploration, it remains a critical part of the future supply base and a meaningful opportunity for venture capital. The reduction of grassroots budgets by the majors, alongside juniors diverting funds away from exploration to development, creates space for new entrants. However, investing in greenfield exploration or junior mining carries significant risk. The value capture exhibits a power-law distribution, one with which venture capital is familiar. In the Doggett and Leveille analysis we discussed in Part 2, 4 out of the 100 most significant mines brought to production between 1989-2008 were estimated to account for ~75% of total returns, while the median trailed the cost of capital. Commenting on the difficulty of the business, David Humphreys, former Chief Economist at Rio Tinto and Norilsk Nickel, reminded us that "nothing beats finding a new, big orebody." We agree. The risk-return profile is well understood by us and others in the venture ecosystem. That is one of the reasons we believe venture capital is well suited to support greenfield exploration efforts for the industry. As a result, we have two portfolio companies operating in this part of the value chain – Esper Satellite Imagery ("Esper") and Vorticity – each with varying degrees of exposure to the aforementioned risk-return profile.

Esper (Invested Q3 2023) pairs a proprietary satellite-based hyperspectral sensor with an AI model trained on geologic data to deliver meter-scale mineral mapping. This approach, which uses surface reflectance to infer chemical composition and identify areas of interest, has long been used in exploration; however, it has historically been constrained by the challenge of translating raw spectra into reliable geological interpretations. "The complex mixtures of minerals and the presence of spectrally similar phases often complicate classification algorithms and classification accuracy. . . . These factors contribute to conflicts between remote sensing data and ground-truth geological observations" (He, 2025). A small cohort of start-ups, including Esper, looks to leverage advances in compute to unlock the full value of this technology. Esper aims to do so by combining higher-resolution sensors with new AI models trained on geochemical and geophysical data. (Junior) miners and their technology vendors already use hyperspectral data collected in a handful of ways, including by satellite and aerial means, as inputs for modeling and decision-making. For those leveraging publicly available data, Esper will have to prove to these customers that its solution not only consistently delivers ground-truth geological observations but is also markedly better than their current data sources to warrant material data service payments. If successful, they have the chance to be a valuable efficiency driver for the billions spent every year on copper (and other mineral) exploration, allowing miners to reach drill targets faster and more cheaply.

Vorticity (Invested Q1 2022) is a scientific computing company with a business unit focused on uncovering copper porphyries at depth under sedimentary cover as a project developer. Today, shallow porphyry systems account for most of global copper production, and porphyry deposits remain a primary focus of exploration and development for the industry, largely because they offer the highest risk-adjusted return profile of any deposit type. A recent paper published in SEG Discovery makes the case that exploration efforts should be focused on porphyry orebodies at depth, even in areas with mature exploration histories, like the Southwest US, noting that an "area's discovery potential may be enhanced if artificial intelligence and machine learning are able to access and process much of the extraordinary amount of data from porphyry Cu deposits and exploration that has been accumulated in [mature regions since the early part of the 20th century]" (Wood & Schodde, 2026). While the authors make a strong argument for why large miners are best positioned to execute on this[1], Vorticity believes that deploying novel tools can help shift expected value and make the project development model work better for these opportunities. The company utilizes modern GPUs to process high-resolution geophysical data. This hardware acceleration enables more robust 3D geophysical inversions and the efficient generation of complex multiparameter, multidimensional subsurface models. The expanded computing power allows for advanced model-space exploration, running families of inversions to quantify uncertainty and map entire mineral systems at a continental scale rather than just isolated targets. It then deploys AI to interpret these complex subsurface models to make discoveries. By integrating machine learning with these physics-based models, they can rapidly evaluate large datasets to pinpoint and rank high-confidence exploration zones that human analysis alone might miss. Proving the viability of this approach, Vorticity has already shown recent success in making discoveries. Moving forward, the value that can be created for the market and business, if a high-quality deposit is delivered, goes without saying.

Exploiting the Character Traits of Copper to Drive Demand, Kuprion (Invested Q4 2018; Acquired by ESI Q2 2023). In Part 1, we showed that copper's unique mix of functional traits translates to widespread and diverse end-use applications. We end the series by looking at how Kuprion leverages those properties to create new demand in applications critical to the future global economy, highlighting the idea that there are known and unknown end-uses for copper yet to be unlocked that may impact the supply/demand balance. Demand for compute has accelerated rapidly since the launch of ChatGPT, and the thermal loads and power densities required for AI and high-performance computing have pushed existing materials to their limits. Kuprion's ActiveCopper solves that with its superior thermal and electrical conductivity, and widespread material compatibility. Its properties also create additional degrees of freedom for new architectures, advanced packaging, and other ways currently being used to scale compute in lieu of Moore's Law. Developed over nearly a decade at Lockheed Martin, ActiveCopper is a drop-in-ready nanoformulation that unlocks the use of bulk copper throughout electronic interconnect systems. Kuprion's solution has widespread applicability (e.g., antimicrobial properties make it effective for wound care), but has been specifically highlighted by its parent company, Element Solutions, for its ability to accelerate corporate growth in AI. There are three primary emerging pain points it is currently addressing. First, it improves power density in printed circuit boards ("PCBs") by replacing thin PCB traces with highly conductive power trenches, enabling high-current power delivery for AI GPUs. Second, its tunable coefficient of thermal expansion eliminates the mismatch of expansion behavior between copper interconnects and the advanced glass packaging substrates, or any substrate for that matter, the industry is targeting for high-performance computing. Third, it improves the reliability of i) PCBs subjected to extreme heat loads in high-power applications and ii) systems subjected to high-duty cycle AI inference workloads. Similar to how IBM's dual-damascene process enabled the use of copper interconnects in place of increasingly problematic aluminum in the 1990s, Kuprion's nanoformulation addresses similar application-based limitations (e.g., copper oxidation), allowing the semiconductor industry to leverage the performance advantages it has long known copper would provide across the entire interconnect system. As electrification, decarbonization, and AI continue to penetrate the global economy, we would expect more instances in which the need to drive performance or eliminate a bottleneck can only be met by specific metals/materials, such as copper. That need will create new demand centers for copper, thereby keeping pressure on supply.

Conclusion. Across this series, we have argued that copper pairs the most durable demand profile among critical materials with a supply base that cannot easily respond, and that the resulting gap rewards innovation. This creates an opportunity for venture capital to support the industry. Dolby Family Ventures remains focused on partnering with teams addressing problems across the value chain of the most consequential commodity for our electrified and decarbonized future. If you are building a business in this market, want to connect about the series at greater depth, or would like to discuss other investment hypotheses and areas, please reach out to the author at *usua@dolbyventures.com*.

[1] A recent study by Castillo & Roa (2026) also implies that those with the balance sheets that enable persistent investments over the long horizons of exploration (i.e., large miners) benefit from cumulative learning and are advantaged.