



**Minerals and  
Materials Challenges  
for Our Energy  
Future(s): Dateline 2024**



# Minerals and Materials Challenges for Our Energy Future(s): Dateline 2024

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# Summary: Not One, But Many Possible Futures

## Framing Energy, Minerals, and Materials

In 2019, Rice University's globally recognized [Baker Institute for Public Policy](#) expanded the research focus of its [Center for Energy Studies](#) (CES) to include mining, nonfuel minerals, and broader materials considerations. The [Energy, Minerals, and Materials](#) program within CES fosters data-intensive research to provide a comprehensive understanding of the breadth of concerns – and opportunities – embedded in materials supply chains. There are many, and they are complex.

Our effort embraces the debates of the day while also anticipating future developments in materials and their supply chains. Importantly, we cover both inorganic, nonfuel minerals and the materials derived from them, as well as organic, carbon-based materials. Synthetic organic materials represent an enormous and dominant part of global materials markets that societies worldwide will continue to rely upon for years to come. Carbon-based materials and their chemical precursors are embedded in the traditional hydrocarbon value chains that have long been core to CES research.

Within CES and across Rice University, we are exploring the potential of advanced materials, such as carbon nanotube fibers (CNTFs) and advanced composites, to replace or reduce the need for many minerals and metals. These advanced materials offer new possibilities for performance gains and solutions for supply chain security and sustainability.<sup>1</sup>

This inaugural report consolidates key insights from several years of scoping, exploring, discussing, and networking through CES roundtables and external events aimed at developing a better understanding of the material requirements for “energy transitions.” This report also aligns with the core principles of CES: 1) energy transitions will vary significantly across regions and countries; 2) supply chains matter; 3) energy transitions require materials transitions; 4) sustainability is multifaceted; and 5) innovation and growth will shape the future of energy and economies.<sup>2</sup>

The following questions drive our research on minerals and materials supply chains:

- How will supply chain realities play out across competing end uses? What tensions might arise between producers and consumers?
- As pressures to demonstrate sustainability – broadly defined – continue to unfold, how will they impinge on the ability of extractive industries to respond to demand signals?
- What will be the effect of ever more complicated geopolitical and trade alignments?
- How will budget constraints ultimately dictate what businesses and governments can reasonably do?
- And finally, what will materials transitions for energy transitions even look like?

## The Current Policy and Political Landscape

As of June 2024, the Bipartisan Infrastructure Deal (BIL), Inflation Reduction Act (IRA), and CHIPS and Science Act are all in place, albeit with tax rules still evolving.<sup>3</sup> The Environmental Protection Agency's (EPA) clean vehicle rule has also been finalized but still faces potential court challenges.<sup>4</sup> Other initiatives are being pitched in a volatile U.S. election year, characterized by heated debates over government budgets and debt. International relations also remain tense, particularly as many other countries experience their own contentious elections.<sup>5</sup>

The United States' relationship with China is a significant factor to consider. To a large extent, recent trade actions taken against China are a reaction to its dominant position in minerals and metals supply chains.<sup>6</sup> The stringent tariffs imposed on Chinese goods are creating a complex political landscape for energy and materials that is likely to affect allied countries and influence fiscal and monetary policies to some extent.

Numerous "new green energy deals" emerged in the United States and globally, with a particular focus on improving post-COVID and post-2008 recession economies. The United States has noticeably shifted toward an industrial policy with \$303 billion allocated for energy transition investments in 2023. This commitment sits within an estimated global total of roughly \$1.8 trillion, nearly half of which is financed by debt, including approximately 17% in government debt. Electrified transport constitutes 36% of this investment, while wind and solar power account for 35%.<sup>7</sup>

All of these developments, and more, are placing minerals and materials in the limelight as policymakers, producers, customers (i.e., large, commercial and industrial buyers of bulk materials), consumers (i.e., individual buyers of final goods), and voters become increasingly aware of supply chain realities.

In their wake, a crucial question arises: Will policymakers and their backers really do whatever it takes to boost supply chains and strengthen the foundational industries essential for these initiatives, particularly domestically?

Producers across the minerals and materials landscape expect increased demand and considerable price appreciation due to these policies. Substantial taxpayer-backed commitments to "de-risk" green investments in energy technologies and key inputs, such as semiconductors (often considered a class of advanced material), come with promises of domestic content, new jobs, and economic development. While these promises seem to be "real" in light of assertive spending commitments, they represent only a fraction of what will be needed to achieve "net zero" decarbonization goals. But are these promises genuine? Do we want to develop energy technology manufacturing and project origination domestically while leaving the problems of supply sourcing in someone else's backyard? And what are we trying to source, and for what purposes?

## Minerals and Materials Challenges

The minerals and mining industries, the main focus of this report, face definitive challenges with respect to supply chains. Even without industrial policy and energy transition stimulus, these challenges would eventually influence the delivery and cost of metals and other inorganic materials for key end-use markets and applications. The challenges identified in this report are central to extractive industries and affect supply-demand dynamics for forward pricing. This report does not exhaustively cover all challenges but rather highlights key concerns regarding preparedness – or the lack thereof – among decision-makers, policymakers, customers, consumers, and voters. Without a comprehensive understanding of these challenges, it will be impossible to craft and implement effective responses and strategies.

Below is a summary of the key challenges covered in this report.

- **Minerals occurrences.** While the Earth is rich in elements, they do not occur in mineral form in equal abundance or quality. And although technology cannot alter the underlying geology, it can stretch the boundaries of commercial recoverability. However, political boundaries and trade patterns overlie the Earth’s mineral estate, and these realities cannot be ignored.
- **Commercialization.** The wide variabilities in mineral concentration and purity have implications for commercialization. These considerable variabilities dictate – as they always have – whether ventures can meet economic targets. As needs evolve for elements crucial to advanced technologies and materials, commercialization is further complicated by demand for coproducts of major metals introducing complex supply chain interactions.
- **Maturity of assets.** Mines are built to last decades or more. However, the age of the current mining and minerals processing fleet is a particular concern. As mining progresses, ore grades decline – similar to the maturation and decline of oil and gas fields. Maturity ultimately results in increased operating costs. The aging of the worldwide mining asset base also reflects the challenges in securing new investments and developing new projects. Older facilities are viewed as less favorable for “upgrades,” such as investments in environmental, social, and governance (ESG) projects, although there are ongoing efforts to capture incremental supply and key by-products from mined waste. The maturity of assets also raises the question of replacement, further straining future supply curves.
- **Project cycle times.** If attention has been galvanized by anything when it comes to ambitions for minerals and metals – as well as the status of the mining industry – it is the length of time that it takes to reach “paid metal” from new investment. An uncomfortable fact is that already long cycle times appear to be getting longer. This is particularly relevant for the U.S. and European mining industries, where realizing new projects is already challenging. The prolonged cycle times highlight the unlevel

playing field in global minerals supply chains, where those who control supply are able to exert significant influence over markets and economies.

- **China’s dominant market shares.** China’s role as both materials supplier and “factory to the world” stems from its rapid industrialization and substantial domestic resource base that supports its manufacturing. Another contributor is China’s surge in outbound investment as its need for raw materials surpasses its own supply capabilities. The accomplishments of Chinese industry and businesses are substantial, contributing to prosperity for both Chinese citizens and the world at large. However, heightened trade and security conflicts in the “new minerals world order” threaten to disrupt established views on energy, the environment, and even the post-World War II global order.
- **Competitiveness.** The primary concern in the “new minerals world order” is whether the United States and other major Western economies can regain “mojo” in mining and minerals processing to support domestic initiatives. Much of current energy policymaking is centered on energy transition technologies and businesses, with promises and incentives for domestic content. However, the decline in U.S. mining and processing competitiveness since the mid-1980s has been severe. It is worth considering whether leveraging the strength of the U.S. oil and gas industries and creatively deploying existing infrastructure footprints might better enhance domestic competitiveness.
- **Sustainability in the mining industry.** Transitioning from fossil fuels to metals-centric alternative energy technologies (“green” energy technologies) has intensified scrutiny of metals and minerals supply and value chains. In countries with established regulatory oversight, there is a level of confidence that new mines, mills, smelters, and refineries will achieve permissions based on sound planning and engineering. That confidence can extend to ongoing operations that have consistently demonstrated compliance. However, whereas regulatory requirements and devotion to safety once defined sustainability, this is no longer the case. Now, embracing green energy and materials means adopting “just and affordable” energy futures — largely supported by taxpayers. Ensuring that truly “green materials” are affordable and satisfy diverse expectations regarding environmental justice is a substantial challenge, further complicated by the maturing global mining fleet.
- **Markets.** Metals have a longer history of formal trading compared to oil, but metals trading remains far smaller despite recent growth. The sheer size of the global oil industry — in both physical and financial terms — and the much larger volumes of oil (and total hydrocarbons) traded daily enable effective price risk management. While oil markets are not without disruptions, smaller and less liquid metals markets are more susceptible to influence and occasional manipulation. Dominant players in smaller markets can exert outsized effects. More importantly, metals markets today lack transparency and clear price signals.

- **Old and new insecurities.** The politics around natural resource endowments have always been fraught. A range of factors — including pressures for access, geopolitical competition, sustainability aspirations, fluctuating markets and prices, and more — are combining to add complexities that will test governance skills. The assumption that moving away from legacy fuels would ease insecurities has proven false. Instead, not only is the shift to metals-dependent energy technologies heightening existing insecurities, it is also creating new ones.

Any single one of these mining and minerals challenges would be enough to contend with on its own. Together, they create a complex landscape with conflicting timelines and many uncertainties. Combined with other factors — including overall cost, public acceptance of energy transition projects, and workforce issues — the result is an almost infinite range of possible energy futures contingent upon materials evolution. Governments, businesses, and a growing web of stakeholder groups are positioning themselves to influence the search for solutions and options. Few, if any, of these possible outcomes will significantly impact greenhouse gas (GHG) emissions, as most agendas are driven by different priorities.

These observations and conclusions do not imply that success in mining and minerals is unattainable or that breakthroughs are impossible. Rather, they acknowledge that, based on available data and an understanding of the myriad commodities and business fundamentals, the path will be much longer and more arduous than typically presented to public audiences.

Much of the political debate around materials challenges is embedded in the conventional wisdom that the use of fossil fuels must end. “Ending fossil fuels” affects deliverability of materials from hydrocarbons value chains and more. The belief that the only suitable replacements are metals-centric green energy technologies — such as wind, solar, and batteries for power grids and electrified mobility — introduces substantial risk and uncertainty for materials supply chains.

Similarly, concerns about the fragility of minerals and materials supply chains are often rooted in competitiveness, or the (perceived) lack thereof. For the United States and Europe, concerns about competitiveness revolve around manufacturing finished goods, such as wind and solar equipment, battery electric vehicles (BEVs), and high-end electronics and microelectronics, which have implications for defense applications. A higher comfort level with China’s role as a dominant supplier, at least for civilian applications, could ease these tensions. That said, fostering more creative conversations about China and shifting global power dynamics is increasingly difficult.

Much less attention is paid to the demand side of the energy and materials equation, but this is starting to change as supply-side barriers and costs become more apparent. Realizations are growing that new digital technologies, initially appealing for their efficiency, are enormous energy hogs. Apart from the growing attention given to materials requirements for alternative energy technologies — particularly electrochemical (battery) energy storage, which is a substantial “materials sink” — it is

crucial to recognize that humans need minerals for biological and economic life. We utilize minerals, and the metals and chemicals derived from them, in every industrial sector, for agriculture, and across a host of consumer products and services.

Demand sensitivities will inevitably surface if efforts to accelerate green energy encounter fixed material supply limits. The inflationary pressures experienced by households in the United States and globally since May 2020 are partly attributable to government policies initially aimed at responding to COVID-19 and subsequently at stimulating economic recovery, including the rollout of green energy initiatives across most industrialized countries. As expectations grew for massive investments in wind, solar, batteries, and BEVs, metals prices followed suit. Cost increases have become embedded in vehicles of all types, appliances, housing construction, medical equipment, and a great deal more, including defense industry products, despite lackluster sales, new sources of supply, and other factors depressing commodities markets.

While defense constitutes a relatively small portion of global materials consumption, materials supply chain security remains a firm line in the sand for defense. Advances in materials and technologies have long moved back and forth between civilian and defense uses, as ripples from innovations broaden. Many technologies in the alternative energy mix are also valuable for defense. Military bases are under pressure to adopt “clean” energy sources, and service branches are shifting to “clean” fuels and electric transport. Field units and personnel need mobile power, and with rapidly evolving weapons systems — from drones to satellites — advanced materials are needed for batteries and components. Pandemic supply chain disruptions, new geopolitical tensions, and increased conflicts have heightened strategic and tactical-situational awareness of materials supply security for defense industries. Concerns about defense readiness are particularly influenced by China’s significant role in global supply chains. Materials security for defense can benefit from improved domestic supply chains, but the timeframe for such development is uncertain, meaning defense industries cannot rely on domestic supply and may push for other measures. The U.S. Department of Defense’s use of the Defense Production Act to stimulate strategic minerals investments has gained widespread attention as a possible solution, though its broader applicability remains in question.

## Innovations and Pathways Forward

The old adage, “optionality is great if you can pay for it,” certainly holds true for materials challenges. Numerous ideas exist for innovating minerals and metals extraction. Many projects target lower-grade resources that require more intensive processing with distinct trade-offs. In part, this reflects realities in the global resource base and access to exploitable resources. Not all ideas are new. For example, “in situ” mining has long been proposed as a possibility for fuels (e.g., uranium and oil shale) and even essential metals. Capturing remaining products embedded in mined waste is a high and increasing priority but involves significant technical and environmental considerations.

Mining and processing are also targets for digitization and automation (e.g., artificial intelligence/AI) just like any other economic sector. The hope is that digital technologies can speed exploration and enhance mining and processing efficiencies. As noted earlier, technology does not alter the Earth's underlying geology, but it can stretch the boundaries of commercial recoverability. For the ultimate geology game changers, frontiers such as the oceans and space attract plenty of interest.

If we cannot, or will not, extract the necessary raw materials needed for our energy futures, where does optionality lie? Most often the focus is on “re-X” – reusing, repairing, remanufacturing, repurposing, refurbishing, or recycling – to reduce the need for raw materials and improve “sustainability from a systems perspective.”<sup>8</sup> In particular, recycling is seen as a key solution for minerals and metals, with the consensus being that metals-dependent energy futures are unattainable without it. However, recycling is an industrial activity with its own requirements and sustainability trade-offs. Recyclers are as vulnerable to swings in commodities prices as primary suppliers. Recycling cannot provide nearly the volumes of material needed for the scale of green energy tech in the time frames envisioned, and opinions are that we are decades from that point. A distinct problem is the recycling of complex, advanced films and composites, especially those built using additive manufacturing. Consequently, designing for re-X, sustainability, and the whole system has gained popularity.<sup>9</sup> These approaches, however, face the challenge of long lead times due to inertia in current supply chain, manufacturing, and consumption patterns. Recovery of metals with minimal recycling for redeployment to other uses is clearly attractive. The tonnes of copper embedded in waste telecoms cables has been called one of the largest copper mining opportunities. Waste from battery manufacturing is another often-mentioned low hanging fruit.

An alternative approach is substitution, an age-old solution to persistent dilemmas. Whenever possible, we substitute materials based on performance and safety considerations, often in response to acquisition costs. For example, aluminum is often used in place of copper for electrical conductivity. Plastics have been substituted for metals for decades to reduce weight and cost and improve performance. **Could advanced materials serve as substitutes for other materials and help us leapfrog challenges associated with metals? Can the mining industry help to lead the charge?** New alloys have long progressed materials frontiers. As noted earlier, carbon-based materials are prevalent across sectors, segments, and end-use applications. CNTFs could unlock new possibilities for applications that require electrical and thermal conductivity and tensile strength. Advanced composites, some with metals content, will compete heavily with traditional metals and existing composites. Yet their development will entail deep knowledge of metals properties and metallurgical engineering. A great desire exists to increase the use of biomaterials for products ranging from consumer and medical-grade plastics to high-end composites in durable goods. Currently, bioplastics represent about 1% of plastics in use and, like biofuels, involve trade-offs in land, water, and energy balances.<sup>10</sup> Pursuit of new high-performance composites will require an active oil and gas industry and a strong value chain.

We continue to push the boundaries of materials and expand processes like additive manufacturing to innovate and commercialize advanced metal alloys, ceramics, and new composites. An important concept, which we have previously argued, is that governments should prioritize materials in policymaking before attempting to select technology “winners.”<sup>11</sup> This approach may seem limiting, but it avoids capital destruction, leaving both taxpayers and private investors better off. Prioritizing materials is crucial given the substantial capital already committed to green energy, with much more needed to reach typical “net zero” GHG targets. This is further amplified by efforts to bolster other essential industries, such as materials-dependent semiconductors.

Throughout the history of U.S. energy and industrial policymaking, we have often faced materials limitations. Over the past 50 years, developers have encountered challenges due to supply, cost, quality, and performance constraints. These issues were relevant during the Carter-era Synfuels Corporation initiative, the launch of civilian nuclear power, various waves of hydrogen enthusiasm, early attempts to deploy carbon capture at scale, and initial battery chemistry experiments aimed at attaining performance equivalent to gasoline and diesel vehicles.

The wind industry provides a snapshot of what progress could look like. For example, the 8-ton stainless steel turbine blades used in early 1980s wind energy designs in Medicine Bow, Wyoming, gave way to fiberglass and today’s sophisticated thermoplastics.<sup>12</sup> These innovations reduced weight and enabled much larger rotor diameters, firmly establishing carbon-based materials in wind energy and other sectors. The need for better, more durable carbon fiber composites to extend the life of wind power and other equipment is widely recognized. CNTFs are particularly well suited to surpass current carbon fiber in turbine blades and displace metals in conductive wiring, cable, and other fabricated parts. As a result, hydrocarbon value chains — the significant source of carbon for materials — are as critical to our energy futures, if not more so, as mining and nonfuel minerals.<sup>13</sup> The integrity, soundness, and preservation of both fuel and nonfuel minerals supplies are necessary for success.

Considering the many complexities and challenges in sourcing minerals and materials to secure our energy future, we are left with one of many lessons in energy and materials transitions: It may not be at all what people expect.

## Backdrop: State of the World

Transitioning from legacy fuels and systems to an all-electric energy future involves numerous considerations. The current landscape presents a range of complications, including the need to balance competing demands for minerals and materials, acknowledge China's strong and increasing influence in mineral supply chains, and address the intricacies of displacing carbon-based fuels. Ambitious goals for achieving green power grids and transitioning to electric vehicles must be carefully weighed against these factors. It is also important to recognize that in order to support aggressive energy transition scenarios, we will need substantially more minerals and materials than we have today and either significant expansions in mining capacity or more serious efforts to pursue alternatives and substitutes.

### Competing Needs

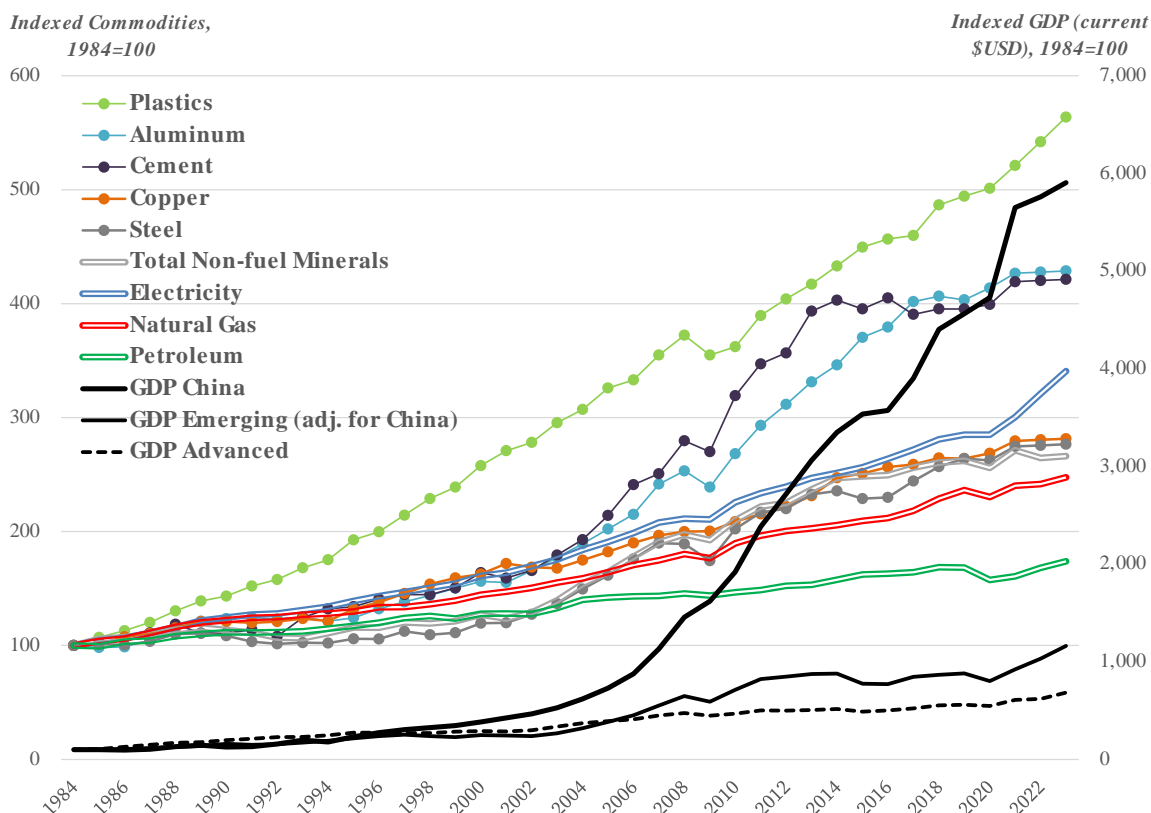
Minerals and materials are essential not only for energy, but also for life itself. Amid the “new thematic demand” for metals driven by energy transition ambitions, policymakers often overlook competing needs, which could pose unexpected barriers. General estimates are that energy transition use of metals like nickel, manganese, copper, aluminum, rare earth elements, and steel will account for 10%-30% of total demand during the next few years.<sup>14</sup> This means that other large consuming sectors – such as industrial, construction, infrastructure, transportation, and electronics/microelectronics as well as legacy energy businesses – will account for a much larger share of demand. In contrast, 80%-90% of lithium use is dominated by battery energy storage.<sup>15</sup>

Minerals and materials are used across numerous industries ranging from health care and agriculture to energy and defense. For example, minerals such as lithium, platinum, and titanium are important for pharmaceutical and health care treatments. Medical-grade metals and plastics are also essential for the health care industry. As such, occasional price pressures in the minerals and metals sector can impact health care access and affordability, a domain even more politically sensitive than energy and the environment. Another example is phosphates, which are of interest for new battery chemistries and are also integral to agricultural fertilizers. Additionally, elements used in energy applications are found in a wide array of consumer and industrial products. And, in the defense sector, depending on the source, 40 to 50 elements are deemed “critical,” with some posing very high risks.<sup>16</sup> All of these elements also have extensive civilian applications.

Despite receiving widespread attention, the fastest-growing commodity group is not minerals or metals, but rather plastics and resins (**Figure 1**). That trend highlights the significant history of materials substitution. Plastics and resins not only have original uses, but have also steadily replaced other materials – such as metals, glass, and wood – or have become integrated with other materials into various composites to manage costs and achieve better quality and performance. It is a trend widely expected to continue. Currently, plastics and polymer composites constitute around half of the

material content in combustion engine vehicles and are likely to occupy an even greater share in BEVs as manufacturers strive to reduce weight and improve battery range and performance.<sup>17</sup>

**Figure 1 – Growth in Key Commodities (Indexed to 1984)**



**Source:** Author using data from the Energy Institute (EI), U.S. Geological Survey (USGS), World Mining Data (WMD), American Chemistry Council (ACC), International Aluminum Institute (IAI), International Copper Study Group (ICSG), Steel Institute, and the International Monetary Fund (IMF).

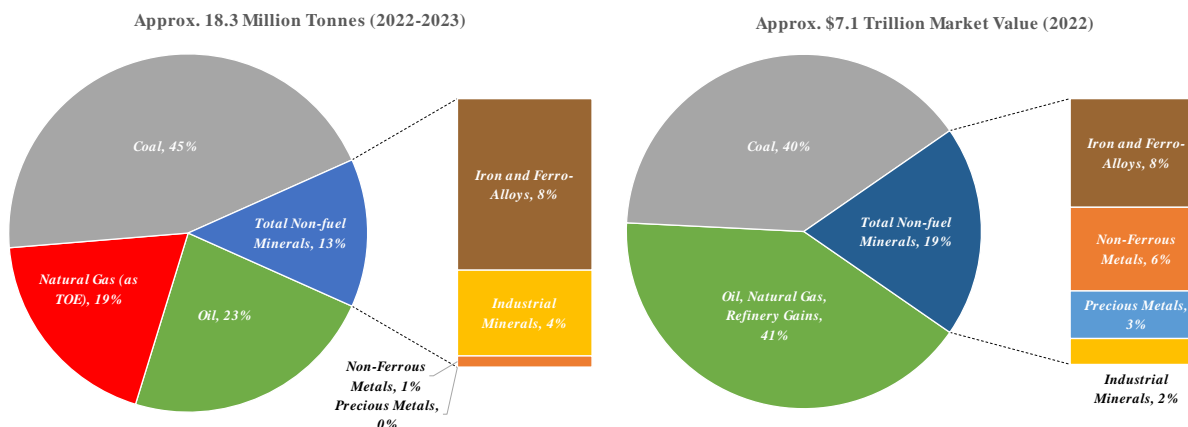
## China’s Growing Influence in Minerals and Materials Supply Chains

Generally speaking, gross domestic product (GDP) is a significant driver of commodity demand. A key factor since the late 1990s has been China’s growth and development (**Figure 1**). As China has industrialized and increased its investment in defense, it has become the single largest consumer of energy fuels and electricity and the most important producer and consumer of metals and other materials. While China has abundant domestic minerals resources, they are insufficient to meet its own needs. China’s domestic imbalance triggered significant outbound investments that have become integral to both energy and materials supply chains. Furthermore, China’s manufacturing sector now dominates the production of energy transition technologies. These developments and their implications are addressed in greater detail later.

## Displacing Carbon-Based Fuels and Materials

The size and scope of nonfuel minerals in global commodities production and value are often misunderstood. In both tonnage and total market value (**Figure 2**), achieving a sufficient supply of nonfuel minerals to displace the fuels and materials derived from carbon-based minerals (coal and hydrocarbons) is a very heavy lift.

**Figure 2 – Global Fuel and Nonfuel Commodities Market Shares by Tonnage and Value**



**Source:** Author's estimations using data from EI, WMD, and USGS.

**Note:** Natural gas as tonnes of oil equivalent (TOE).

A hard truth for the mining industry – and for policymakers – is the role that coal plays in generating revenue for mine operators, equipment and service vendors, and host communities and locations. Revenue and profits from the production and sale of both thermal and metallurgical coal are essential to the health of the mining industry overall. Divesting from coal assets is therefore as difficult as shifting away from hydrocarbons, especially given coal's ongoing significance for global energy, as it still accounts for one-third of global energy consumption.

Mining operators anticipate that their products will come to rival the market value of hydrocarbon commodities. Hydrocarbons store energy until it is released for use, and they also serve as material reserves until their molecules are converted. This dual function creates a powerful leveraging effect between energy and materials that metals lack.

Technologies like wind and solar convert resources to energy when they are available, with an average efficiency of 20%–30%.<sup>18</sup> To ensure reliability, wind and solar energy must be accompanied by external energy storage and/or backup energy sources. The most popular solution for external energy storage is electrochemical (batteries), which need recharging to be beneficial. In effect, a battery is an energy customer until it can discharge. Given the high variability and low efficiencies of wind and solar, this means that to replace any British thermal unit (Btu) equivalent of legacy carbon-based energy with these sources requires a domino effect including but not limited to: 1) securing sufficient raw materials to build enough wind and solar capacity to replace fossil fuel

thermal generation (and phase out nuclear energy where societal and political preferences dictate); 2) providing sufficient energy storage; 3) devising solutions for reserve energy generation; and 4) implementing other retrofits, expansions, or new grid infrastructure buildouts. Without these measures, electric power grids are at risk of failure. Plenty of examples exist across countries, including in large economies, where wind and solar energy are effectively backed by coal, natural gas, and oil to ensure reliability.

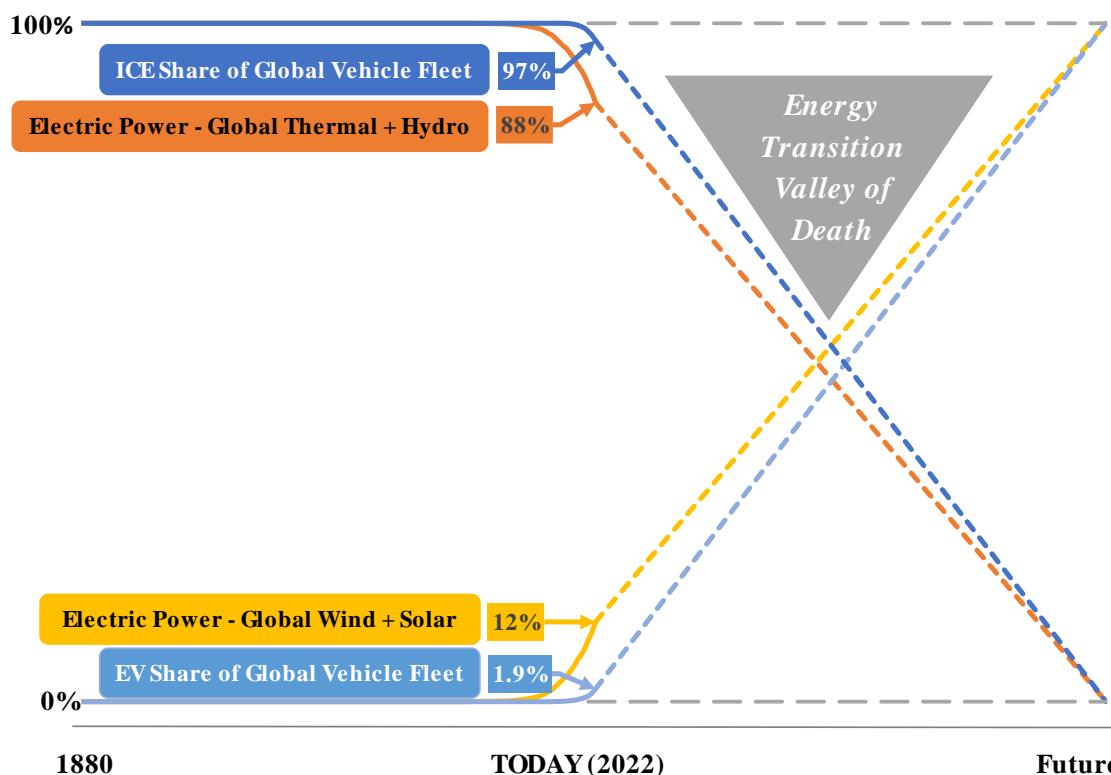
Similar considerations apply to fully electrified transportation. Even if BEVs reach performance levels equivalent to gasoline or diesel internal combustion engine vehicles, a domino effect unfolds in materials sufficiency for battery manufacturing and power grid support for vehicle recharging. Creative uses of BEVs for electric power storage and balancing are envisioned, and there are high expectations for how BEVs will integrate with electric power and internet systems. Beyond fully autonomous driving, which would entail futuristic smart roads, the ultimate goal is for BEVs to provide near-continuous real-time feedback on everything from when they are parked and not in use (an electricity demand-side management tactic) to consumer behavior during operation (e.g., what we listen to while driving, where we stop to shop, etc.) and road conditions and safety.

Power demand is already rising quickly in many locations as data centers for the ever-expanding use of information technology – from cloud storage for streaming entertainment to crypto mining and AI – far exceed what our systems can handle. Fully electric transport will exacerbate requirements for backup energy generation capacity and storage to ensure safe, functioning power grids. The aggregation of these needs will likely be more significant than current outlooks imply.

## Aspirations for Green Power Grids and Electric Vehicles

In spite of the host of considerations entailed in transitioning from legacy fuels and systems to an all-electric energy future, the aims are notable. For power grids, the now-orthodox view is that wind and solar should account for anywhere from 50%-100% of electric power, even with all of the associated operational concerns. That increase compares to about 12% today (**Figure 3**). While hydroelectric generation and nuclear energy represent nearly emissions-free power sources once in operation, neither are popular solutions, although it is noteworthy that there has been little scrutiny of environmental and social acceptance for other alternatives.

**Figure 3 – The Global Energy Transition Valley of Death**



**Source:** Author using data from Energy Institute Annual Statistical Review, International Energy Agency (IEA), and International Organization of Motor Vehicle Manufacturers (OICA). Based on Gabriel Collins and Michelle Michot Foss, “The Global Energy Transition’s Looming Valley of Death.”<sup>19</sup>

The worldwide, light-duty passenger fleet is estimated to include roughly 1.5 billion vehicles in service. Analysis from the International Energy Agency (IEA) suggests global sales of electric vehicles (EVs) – including fully electric, BEVs, and hybrids and plug-in hybrids – to be approximately 14 million for 2023. Of this amount, roughly 72% (the 2022 share) are believed to be BEVs, for a total of about 40 million EVs in use, accounting for nearly 2% of the global passenger fleet (**Figure 3**).<sup>20</sup> At the current rate of sales, it would take more than a century to completely flip the global passenger fleet from internal combustion engine vehicles (ICEVs) to EVs of all types, and about 150 years to convert to fully BEVs. Both time horizons are well beyond proposed 2050 “net zero” milestones.

Sales of EVs have grown quickly in recent years (from a small base), and many observers think sales growth will continue, if not accelerate. The IEA projects 38 million sales of EVs by 2030, but despite this growth, global oil demand will likely remain unchanged from previous years as consumption simply migrates from EV-using advanced economies to the rest of the world, an important point to keep in mind with respect to longer-term outlooks.<sup>21</sup> Some forecasts predict even stronger EV sales growth, with proprietary estimates topping 50–60 million by 2033.<sup>22</sup> Clearly, doubling or

tripling current EV and, in particular, BEV sales would mean removing all impediments that auto manufacturers and their vendors face, not least in materials supply chains, along with all impediments to consumer adoption and use.

## Energy Transition Outlooks

For these and other reasons, every major review of minerals and materials requirements to support ambitious energy transition scenarios indicates a substantial increase in minerals tonnage above what is in use today. World Bank researchers project that total demand for key minerals could nearly double from 2020 to 2050.<sup>23</sup> The IEA suggests that demand for key minerals by 2040 could grow four to six times over 2020 levels, depending on energy scenario.<sup>24</sup> Current proprietary research aligns with these projections, estimating significant increases in demand for commercial battery chemistry metals and supporting commodities such as aluminum and copper, potentially even exceeding public domain outlooks. All of these projections imply a need for substantial expansions in mining and minerals processing capacity, even when considering metals recovery from recycling, reductions in metals use, and other measures. **The problem is what mining operations, for what minerals, for what battery chemistries, and for what applications?**

With respect to the huge category of plastics and resins materials upon which so much is contingent (**Figure 1**), it is often assumed that these products can be provided as hydrocarbon fuels are phased out. This implies a reduction from roughly 100 million barrels per day (MMBD) of global oil-equivalent use to about one-third that amount. With that reduction, the “fuels cut” would shrink from more than 80% to less than 30%, while petrochemicals, from which plastics and resins are mainly derived, would grow from around 12% to 65% or more. Societies would face an enormous shift from the prevailing energy and materials mix.<sup>25</sup>

Of consequence is that no existing “net zero” scenario fully incorporates oil and gas value chain financial balances with losses in revenue from fuels sales. For many, the future of plastics lies in biomaterials, which currently comprise only about 1% of the market. The contribution of material from recycled plastics currently ranges from approximately 9% to 20%, depending on polymer feedstock. Plastics recycling is more difficult than recycling for many metals, although inroads are being made.

These outlooks are contingent on a host of factors, with the breadth and timing of energy technology shifts being unpredictable. Such shifts depend on government fiscal policies, budgets, and human adoption behaviors. Every researcher and research group assumes healthy doses of public sector support for green materials sourcing, manufacturing, and adoption of wind, solar, other alternative energy technologies, batteries, and electrified transport. In wealthy countries, consumers are voters with competing priorities and sensitivities to inflation and interest rate pressures that tend to accompany aggressive public spending.

Cost estimates for energy transition investments are massive and rising; a safe assumption is that costs will be higher than anticipated. One estimate suggests \$275 trillion, averaging \$9.2 trillion per year until 2050.<sup>26</sup> In a world where large infrastructure projects can easily escalate by 30% to 50%, especially if they are opposed, the risk of cost overruns is meaningful.

Every country will be different. Countries without robust electric power grids may rely on different products, such as electric two- and three-wheel devices, rather than the heavier vehicles preferred in America. Alternatively, these populations may continue to rely on transport powered by conventional fuels. These fuels are typically low quality due to underinvestment in sovereign-controlled refining, exacerbated by chronic subsidies of petroleum fuels, and the influence of “diesel mafia” who control supply-demand gaps in too many locations. Additionally, many countries suffer from nontechnical power grid losses, with electric power thieves exploiting weak systems, often in collusion with sovereign-controlled power organizations.

International trade is a source of tension and potential conflict, particularly regarding the vulnerabilities of minerals and materials supply chains, which are critical for both national defense and economic security. On defense, conversations regarding materials security extend beyond the United States to the North Atlantic Treaty Organization (NATO) and other regions, especially the Indo-Pacific where supply chains are much more difficult to protect. Domestic content realized through open, competitive markets can serve both military and civilian needs. However, when public funds are used to subsidize sales of products like BEVs, promises of domestic content — such as manufacturing investment and jobs — become highly politicized and distorted.

There are no guarantees. Assertive outlooks that drive technology shifts to meet stated targets, such as net-zero GHG reductions to reach a theoretical state of global temperature, are particularly vulnerable to beliefs that may not fit political realities, heightening political, policy, and regulatory risk and uncertainty. BEVs are the big-ticket item, and as this report reaches publication, adoption of BEVs has hit speed bumps. In the United States and elsewhere, government subsidies have not overcome affordability and performance concerns among car buyers. Significant investments must be made in power generation and grids to accommodate BEVs, and a number of prickly issues such as financing roads without revenue from gasoline sales taxes will take years, or even generations, to resolve. Plenty of news coverage has amassed on slowing BEV sales, with an increasing interest in hybrid vehicles as a middle ground.<sup>27</sup> At least one group has put forth a “delayed transition” scenario.<sup>28</sup>

From a materials standpoint, the question is whether materials supply chains can support — and markets can accommodate — energy transition and net zero targets. One observer noted that “minerals will be the pacesetter” for energy transition visions.<sup>29</sup> The ultimate challenge for minerals and materials supply chain businesses and investors is determining which version of the energy transition will apply, with what assumptions for technology and materials inputs, and over what time horizon. The “valley of death” is a

well-known concept in venture capital finance. The hope is to avoid littering the valley of death with energy transition failures (**Figure 3**).

## Many Challenges, All of Them Grand

In a nutshell, minerals and metals are essential for life. The pursuit of metals-centric alternative energy technologies for both civilian and defense uses is creating new opportunities but also imposing new obligations on extractive industries and businesses. The demand for, or the “call” on, metals and materials is largely driven by the energy transition choices being made. Emphasis is being placed on lower-energy-density technologies that require comparably more material inputs to yield equivalent amounts of energy, similar to legacy fossil fuels. The objective is to avoid emissions associated with the latter. However, it is important to emphasize that customers, consumers, and voters must be willing to make the switch. The trade-offs involved in replacing high-energy-density fossil fuels with green energy technologies that require high materials inputs relative to energy outputs are not yet fully understood. At present, the share of green energy technology is very small (**Figure 3**), leaving the full extent of the materials footprint uncertain. This uncertainty raises the prospect of political and investment risks as more information and experience accumulates. It is worth repeating that disruptions in minerals and materials supply chains would occur even without accelerating the production of metals-centric alternative energy technology. This is because the fundamentals underlying supply and pricing present a number of challenges. Each of these challenges, and all of them combined, represent distinct hurdles to our future energy and economic prospects.

## Challenge of Minerals Occurrences

Mineral occurrences are not evenly distributed around the globe, with significant variations in chemistry and concentrations. Minerals of interest are typically classified into broad groupings that reflect geology and deposition, as outlined here:

- Silicates constitute some 90% of rock-bearing minerals on Earth and are made up of silica and oxygen with myriad elements. Examples are quartz and mica.
- Oxides are constituted of oxygen and other elements like iron. Hematite is a common oxide mineral.
- Sulfates are constituted of sulfur and oxygen. Gypsum and barite are typical.
- Sulfides are composed of sulfur with metallic elements. Galena is a common lead-bearing sulfide ore, chalcopyrite is a common copper-bearing mineral, molybdenite is source rock for molybdenum (or moly), and so on. Sulfides are an important minerals group for key metals.
- Carbonates are constituted of carbon and oxygen with other elements. Calcite and dolomite are examples.
- Native elements include gold and copper metals or nonmetallic diamonds. Native elements are just that: mineral occurrences of metals and diamond as elements.

- Halides are halogen elements such as chlorine and fluorine. An example is halite, or table salt, a combination of sodium and chlorine.

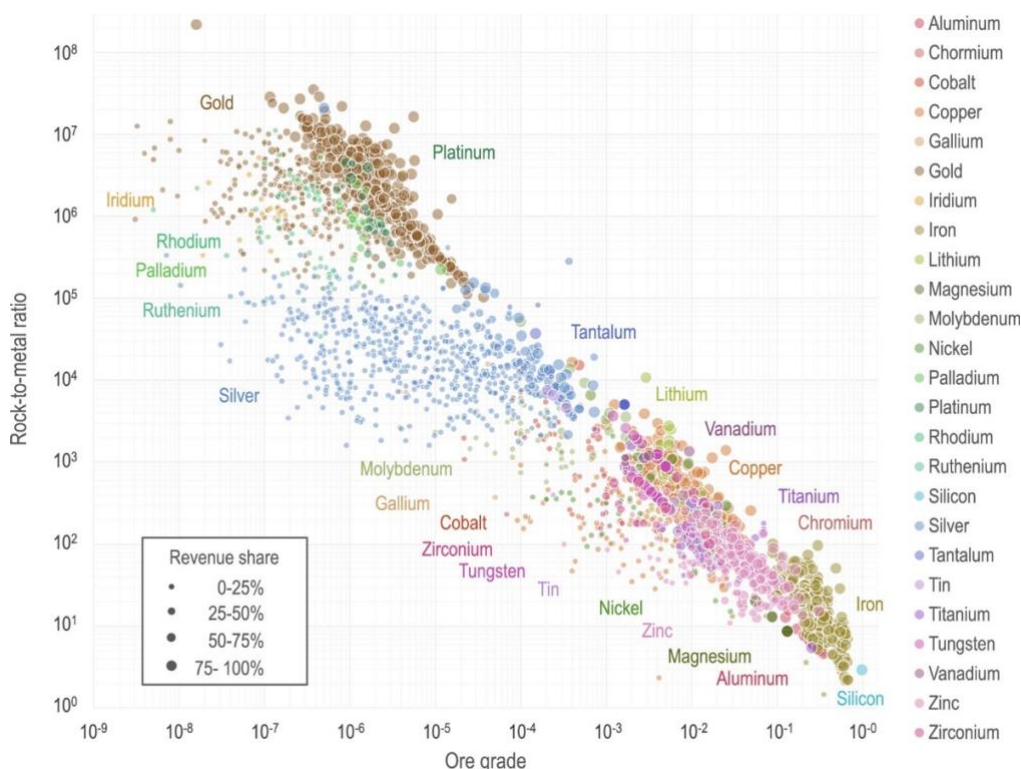
Some define additional groupings such as hydroxides, which are made up of hydrogen, oxygen, and other elements. Examples include limonite for iron, bauxite for iron and aluminum, and manganite for manganese. Another is phosphates, a broad grouping of mineral forms including phosphorous.

These groupings of minerals occurrences reflect minerals chemistries and bear implications for extraction. Copper can be extracted from sulfides and also from carbonates such as malachite and azurite. Oxides and hydroxides can both contain iron. Nickel can be extracted from hydroxide limonites and also sulfides.

Mineral groupings, chemistry, and occurrences, together with extraction and end-use parameters, dictate demand, supply, and price fundamentals. For instance, lithium, a primordial (i.e., “Big Bang”) element is the most lightweight of elements that are solid at room temperature and a good conductor of electricity and heat. This makes lithium highly desirable for batteries, but as an alkali metal (others include sodium and potassium), it is also highly reactive and flammable. Lithium does not occur freely in nature, a consequence of reactivity. It is also widely dispersed. Lithium is extracted from spodumene, a mineral found in igneous granitic pegmatites such as at Australia’s Greenbushes mine, the world’s largest hard-rock lithium mine. As a soluble element, lithium occurs in seawater in very low concentrations, at a maximum of 0.25 parts per million (ppm), and in brines where lithium has eroded from igneous rocks into trapped geothermal basins. In brines, the concentrations can be much higher. For example, Chile’s Salar-de-Atacama has 2,700 ppm.

Brine-based lithium is in carbonate form, while spodumene yields lithium in hydroxide form. Which form will battery makers and their customers prefer? Cobalt has been a useful addition to lithium-ion batteries (LIBs) for both improved energy density and – in light of lithium’s reactivity – stability. Yet cobalt is iconic as a “conflict mineral,” sourced mainly in the Democratic Republic of the Congo (DRC), which supplies nearly 80% percent of the world’s cobalt. Labor practices there have fueled debates about human rights and minerals sustainability. In battery chemistries that use less cobalt, lithium hydroxide is the preferred form, implying a preference for mined lithium (spodumene) or additional processing costs to convert lithium carbonate to hydroxide.<sup>30</sup> And so the trade-offs go.

**Figure 4 – The USGS Rock-to-Metal Distribution**



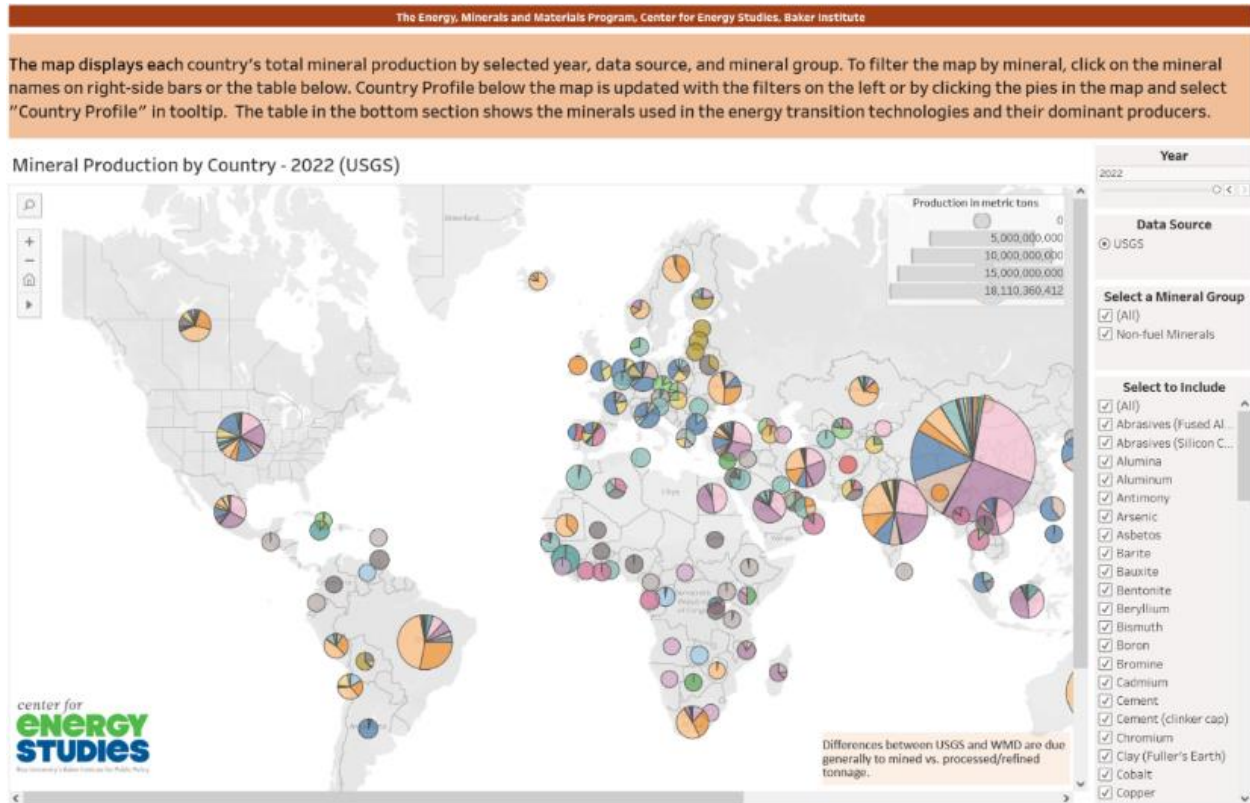
**Source:** Nassar et al.<sup>31</sup>

The United States Geological Survey’s (USGS) “rock-to-metal” research and publications, including supporting information on waste, provide perhaps the best high-level lens on variabilities in worldwide occurrences of key minerals (**Figure 4**).<sup>32</sup> These variabilities – the relative effectiveness of Earth’s processes for concentrating elements – have both broad and deep implications for commerciality, supply chain logistics, and sustainability. We are likely to experience “misfits” between occurrences of metallic elements for materials and energy technology of choice. Platinum, one of the least well-concentrated elements, is essential to nearly every application involving hydrogen, including electrolysis to separate hydrogen from water and as a catalyst in fuel cells to convert hydrogen and oxygen to heat, water, and electricity. No good substitutes exist. The most promising is palladium, another member of the platinum-group metals (PGMs). Other PGMs include ruthenium, rhodium, osmium, and iridium, all of which are equally scarce.

The rock-to-metal ratio provides a rough guide on relative scarcity and, by inference, on ore grades and how much rock will be waste versus “paid metal.” In fact, a great deal is waste, well above 95%, and often as much as 99% per metric tonne, for most metals of interest. Deviation from averages and medians exist within distributions of occurrences and active operations, but the prevailing pattern is formidable. Waste is the bane of the mining industry, a point taken up in more detail later.

The geographic distribution of fuel and nonfuel minerals production reflects underlying resource endowments, influencing supply and value chains (**Figure 5**). China’s position as the largest global producer of minerals from its own domestic resources is immediately evident. No nation on Earth possesses every mineral within its resource base, leading many nations to rely on net producers and exporters to balance their requirements.

**Figure 5 – A Global Tour: Nonfuel Minerals Production**



**Source:** Baker Institute Global Minerals Production Dashboard, based on CES vetted and converted data from the USGS and World Mining Data.<sup>33</sup>

**Note:** From our dashboard, users can explore production histories for individual countries. The dashboard includes a table of market shares for major country producers of key energy transition materials and the alternative energy technologies that rely on those materials.

The term “critical” as applied to minerals indicates import dependency relative to strategic importance, with the definition of criticality varying by nation.<sup>34</sup> However, labeling minerals and materials as critical does not fully capture the sensitivities involved. Mineral concentrates delivered from mines and mills (beneficiation) are just the first steps. These concentrates must be further processed to achieve finished metals. Value-added processing and finishing are central concerns for many minerals-rich countries when it comes to Chinese control of and influence over supply chains (as the example of nickel, described later, illustrates well). Additionally, market concentration can further intensify during the manufacturing of intermediate and final goods.

In an age of globalized supply chains, many nations, including the United States, are dependent on imports of both raw materials and processed or finished metals and fabricated components. Much of the aluminum used in the United States arrives in the form of finished metal and fabricated materials for construction, as well as in goods essential for the final assembly of products, such as aircraft and vehicles, including those for defense. Layers of complexity are embedded in materials supply chains, involving both raw inputs and manufactured products.

Policymakers are actively debating whether we can move away from global supply chain interdependencies. If so, then the United States, or any other nation choosing this path, must turn to domestic or “friendly” resources for raw materials and manufacturing. This requires assertive policies to “reshore” and reinvigorate domestic content while also addressing two main shortcomings: raw materials supply and manufacturing capacity. This is where industrial policies come to the fore, along with their associated burdens and potential unintended consequences.

The form and quality of key elements and the mineral ores containing them are as important as their overall distribution. Shortcomings in mineral occurrences can be mitigated through more intensive processing to lower-grade resources, but these strategies bear distinct consequences. Increased obligations of land, energy, water, and other inputs will be required, raising environmental concerns. Projects focused on lower-grade resources will almost certainly entail larger scale and bigger volumes in order to spread costs, impacting commodity markets. Excessive “loss leaders” can do irreparable harm to investment returns and capital flows.

Indonesia’s nickel industry is a useful case study for understanding the complex interplay of factors associated with mineral occurrences, including global distributions, considerations of form and quality, the global trade flows that reflect these realities, and the schisms developing around those trade flows.<sup>35</sup> For many end-use applications, only the highest purity will suffice. For instance, Class 1 nickel, which is nearly 99% pure, is typically required for most stainless-steel products and is the main nickel commodity traded on the London Metals Exchange (LME), the major metals pricing marketplace. Class 1 nickel is also required for the most common commercial lithium-ion batteries, such as the nickel-manganese-cobalt (NMC) chemistry. The more common nickel-bearing minerals are found in laterites, which constitute about 60% of the global resource base. Indonesia, New Caledonia, and the Philippines are among the largest nickel producing countries and host large laterite deposits. Russia’s substantial nickel sulfide deposits and operations, such as those at the Polar Division (Norilsk) complex, supply about 20% of the world’s Class 1 metal, by many accounts. Other significant producers of nickel from sulfides include Australia, which also has laterite deposits, and Canada. Russian nickel, which is more expensive to mine (underground) but cheaper to process, has long set the premium price – until recently.

While China’s strength in minerals and metals is rooted in its domestic resources, its outbound investments are essential for supporting its industrial base, exports, and growth imperatives. China produces only about 3% of global nickel output. Indonesia,

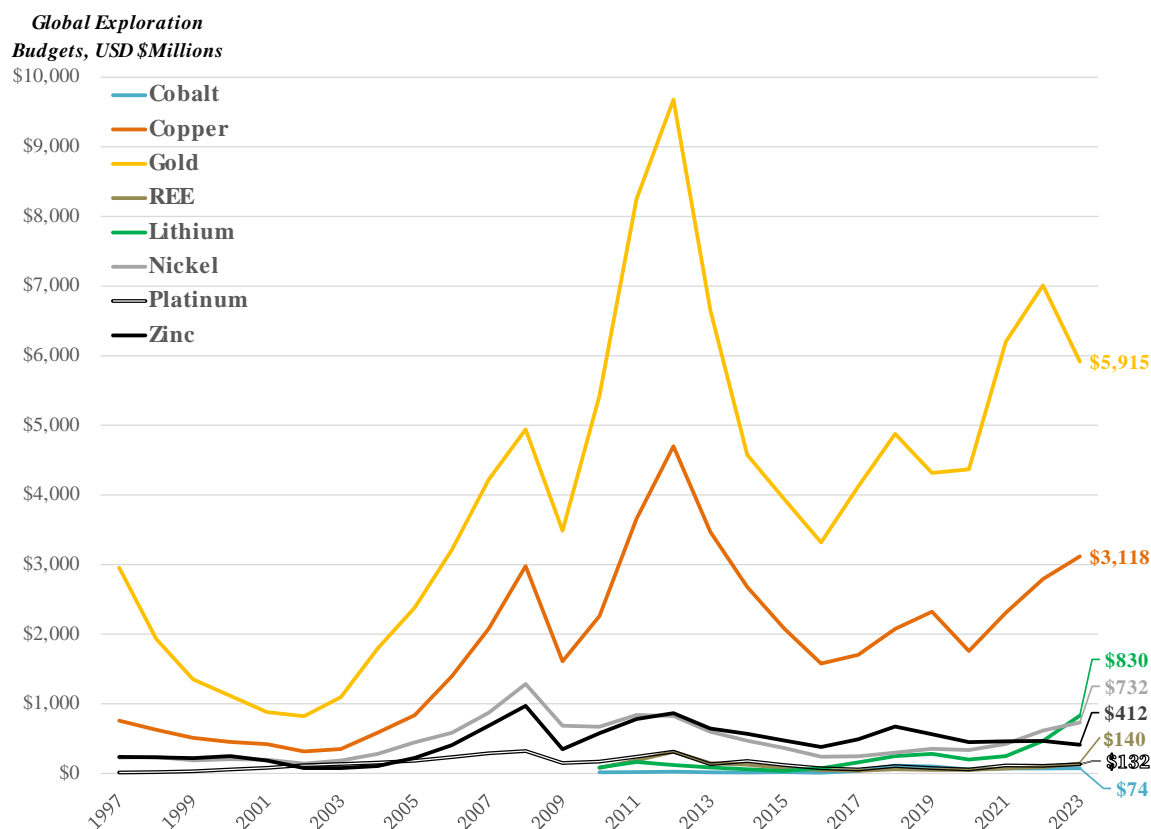
which accounts for nearly half of global nickel supply and holds significant resources, has long sold nearly all of its nickel production in the form of nickel pig iron (NPI) to China. China hosts enormous processing, finishing, and other value-adding manufacturing capabilities, producing more than 50% of global stainless-steel output from its own furnaces.<sup>36</sup> Chinese companies, such as Tsingshan, the world's largest stainless-steel producer, own and operate upstream mining and processing facilities in Indonesia and the region, with plans to add steel production and battery manufacturing. High pressure acid leach (HPAL) technology is being used to upgrade lower-quality laterite ores to the Class 1 standard, despite being a more expensive and resource-intensive process. The strategy and increased volumes, with expectations of more, are upending Russian dominance and impacting nickel prices across the board. The Indonesia model is likely to be repeated not only in Southeast Asia, but also worldwide for other commodities.

Emerging Chinese investments to secure strategic positions in mineral-rich countries will further expand China's prowess in capturing the resources it needs from abroad. A distinct investment scheme is evolving in which Chinese businesses demonstrate willingness to accept lower-grade mineral occurrences due to their ability to build scale and offset the high costs of processing. So far, Chinese businesses have been able to take command of supply chains even while host countries exert pressure to ensure at least some value-added processing and manufacturing in their home markets (e.g., Indonesia's nickel export restrictions). Through these arrangements, China is able to secure global supply chains for its own domestic downstream and manufacturing while also remaining firmly in the driver's seat for new capacity in key locations.

## Challenges in Commercialization

Mining exploration entails drilling, and drilling constitutes considerable up-front capital commitments. While AI and machine learning are increasingly utilized in exploration, they work best with extensive data (including Bayesian-style revisiting of original hypotheses on occurrences). Exploration activities for copper and other metals closely follow price trends, with recent years showing generally rising exploration budgets for different metals (**Figure 6**). The mining industry's distinct bias toward gold (primarily) and copper in exploration spending is due to the relative ease of realizing value from these commodities. Gold, a key hedging commodity, tends to attract the most interest in exploration investment. If copper were to be valued as a precious metal (and many arguments could be made for that treatment), it too could become a destination commodity and financial hedge, though this would result in a variety of repercussions across its numerous end uses.

**Figure 6 – Global Mining Exploration Budget Trends**



**Source:** Compiled by author using S&P Global data, accessed via license.

**Note:** The figure depicts total exploration expenditures at all stages. REE is rare earth elements (lanthanides).

Following successful prospecting, the immediate goal from first production of paid metal is to optimize mine planning. Mine operators today make commercial decisions about extraction at every stage, constantly sampling and testing concentrations of targeted metal-bearing minerals and, as mining progresses, adjusting plans based on ore grades in mineralized zones and market prices. This approach is similar for brine deposits used for lithium, bromine, and other elements.

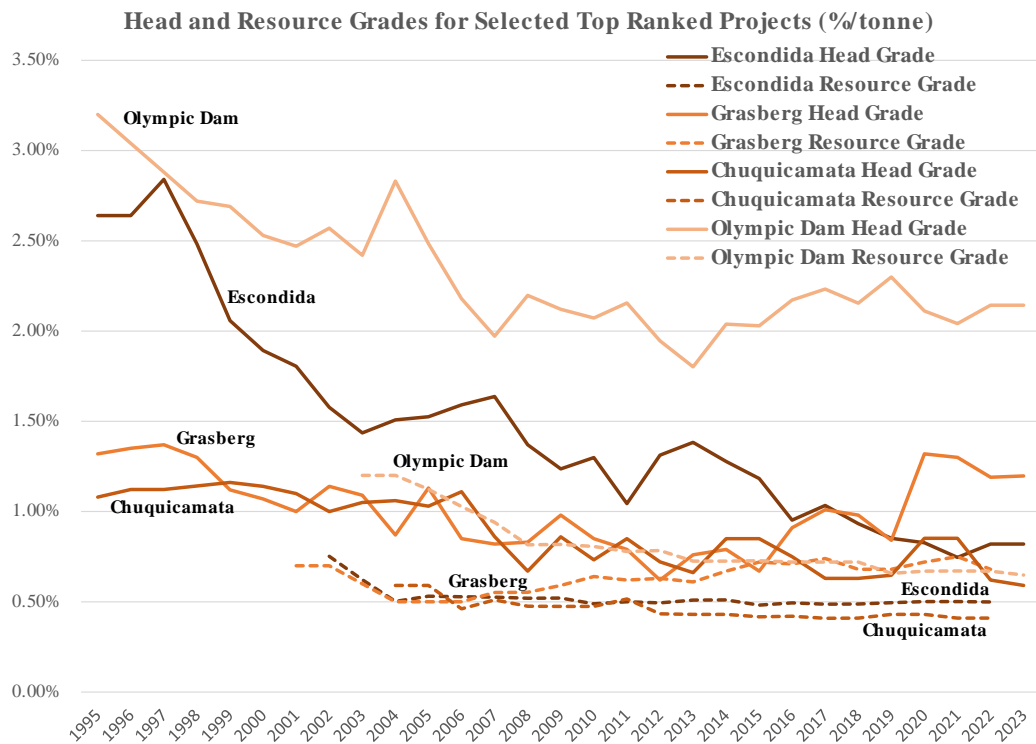
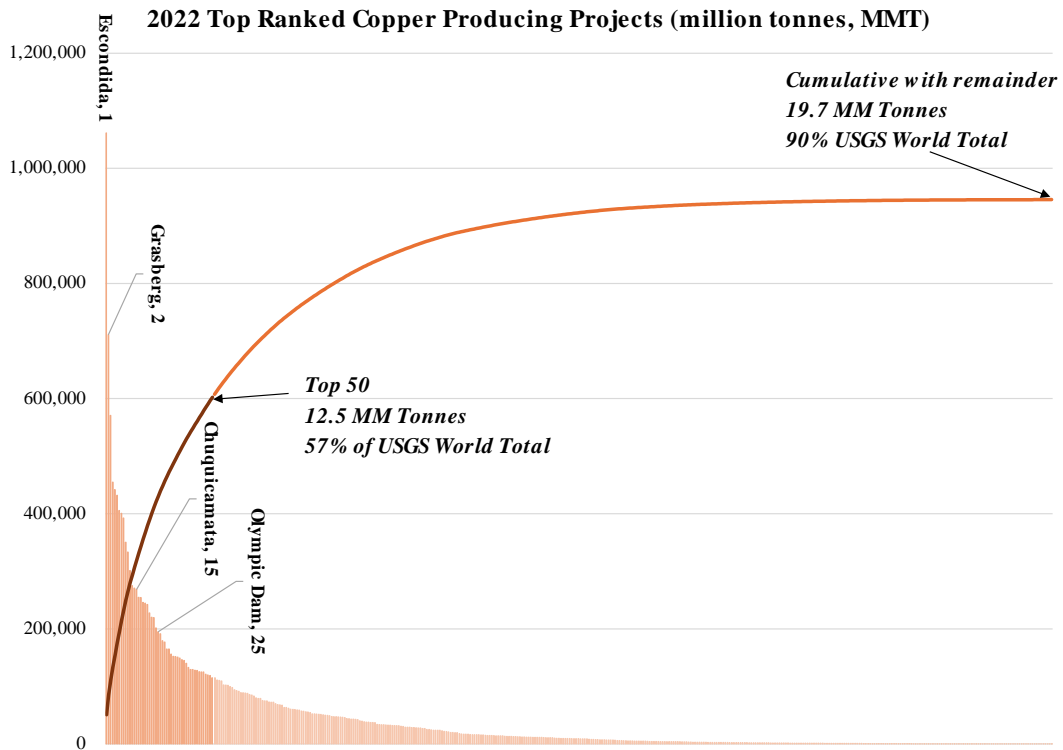
Mine operators aim to commercialize all commodities by separating and concentrating minerals in mills. Efforts are underway to expand processing at existing facilities to capture by-products of more exotic elements such as gallium (primarily from the aluminum value chain), germanium and indium (mainly from zinc processing), and tellurium (from copper refining).<sup>37</sup> At times, prices of coproducts (for instance silver and gold produced with copper) can boost overall revenue, sustaining output. However, a very real risk exists: If the price of a primary commodity collapses (for example, copper), the output of key metals of interest could decline (tellurium). Additionally, pursuit of less common products means finding additional offtake for increased tonnages of the primary metals or facing inevitable market consequences of excess supply.

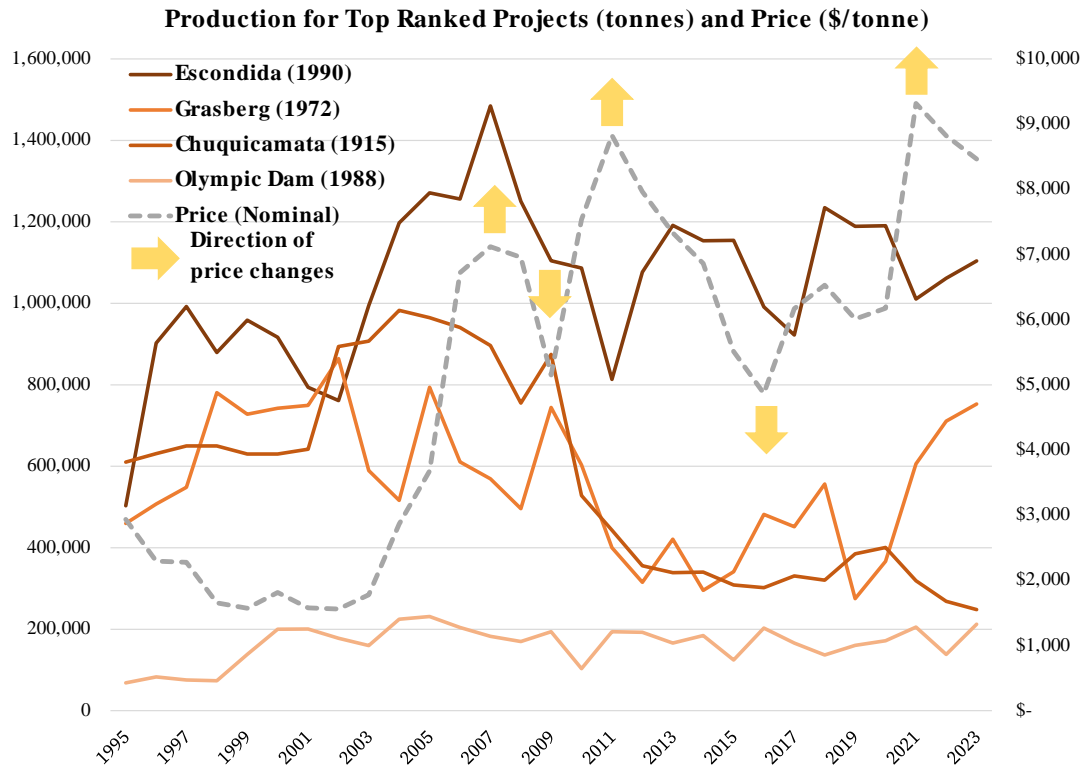
The mining industry is actively discussing cost escalation of both exploration and development, driven by various challenges addressed in this report along with inflation pressures and increasing capital costs in recent years. Cost increases tend to be “sticky,” lagging behind price declines and creating stress as profit margins diminish. Additionally, as mines age, head grades (average grade of ore to the mill) decline, further adding to cost management pressures.

Copper exemplifies the challenges of commercialization. In **Figure 7** (top), the distribution of global copper supply is notable. The drop-off among leading producers – and between the top 50 projects and the remainder – is steep. The middle and bottom panels of **Figure 7** feature the four projects selected among the rankings in the top chart. They reflect different geologies and locations. Escondida, a porphyry oxide/sulfide, and Chuquibambilla, a porphyry silicate/sulfide, are in Chile. Grasberg, a porphyry sulfide, is in Papua New Guinea. Olympic Dam is an IOCG – iron oxide, copper gold (oxide/sulfide/silicate) – in Australia. Project start-up years are in parentheses. The middle panel illustrates head (average grade of ore to the mill) and resource grades (estimated grade based on sampling) at each location and changes over time – which are striking given the status and importance of these operations. The copper data encompasses ore grades for resources that could be captured in future years. Capital expenditures (capex) can stabilize head grades and even boost production if the properties are amenable. For Escondida and Grasberg, this clearly has been the case. The bottom panel of **Figure 7** compares production and price. Production is slow to adjust when commodity prices change. When prices rise, it can take a long time to ramp production back up and even longer to achieve new organic growth due to long cycle times from exploration to development. Conversely, during price declines, mine operators reduce copper output while attempting to sell higher-priced coproducts, if they can. During prolonged low-price periods, mining projects and associated facilities are moved to “care and maintenance,” as in the case of Australian nickel. This standard but expensive practice means that restoring production in response to favorable price signals takes time.

As the supply curve drops sharply (**Figure 7** top), copper is also less frequently – though still principally – the primary commodity across projects in the sample. Copper projects also produce gold, silver, cobalt, molybdenum, zinc, and other elements. Historically, higher market values for gold relative to copper have supported copper production. Nickel projects can yield copper, as do the huge laterite deposits in Indonesia and Australia. And so, for instance, price pressures on nickel, as described earlier, could result in tighter copper supply if too many nickel operations are curtailed. A number of Australian nickel producers are facing this situation due to the growth in output from Indonesia.<sup>38</sup> How reductions in nickel output might influence copper supply will hinge on prevailing conditions in copper markets.

**Figure 7 – Commercialization Challenges: A Copper Illustration**





**Source:** Compiled by author using S&P Global data, accessed via license.

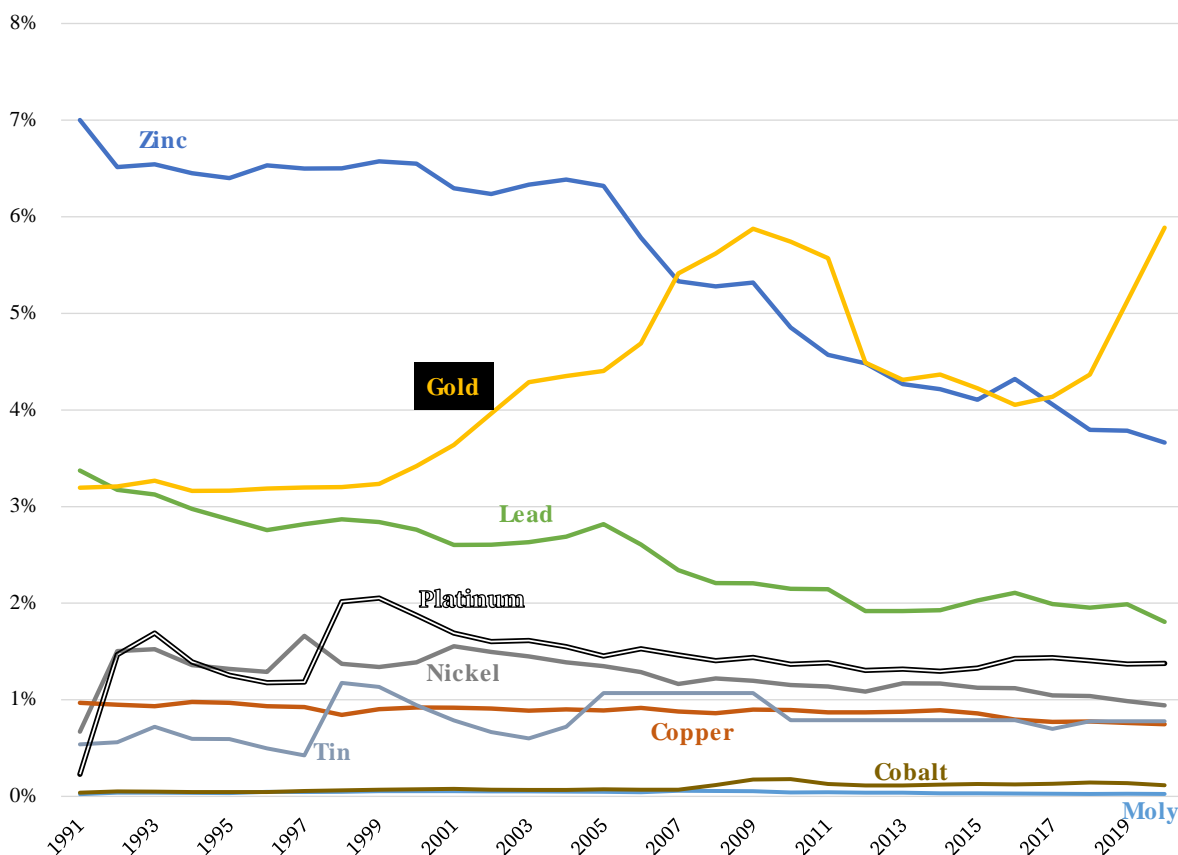
**Note:** Head and resource grades for copper projects are estimated or modelled by S&P Global. Ore grades for booked reserves tend to be close to head grades, while grades for resources (estimated mineral concentrations based on sampling, often referred to as mineralization occurrences) tend to be lower than both head grades and reserves (and reflect lower levels of confidence).

The challenges of commercialization reflect, but also contribute to, significant volatility in metals prices, often more pronounced than for other commodities. Volatility is further complicated by the lack of market depth and structure for traded metals, leading to the use of bilateral contracts for supply and purchase. Overall, the complexities of commercialization should inject humility into attempts to forecast how much of any metal might come into the marketplace in years ahead, and at what cost to customers.

## Challenge of Maturing Assets

Worldwide head grades for active projects in each year are shown in **Figure 8**, which includes the copper mines profiled in **Figure 7**.

**Figure 8 – Historical Head Grades**



**Source:** Author using S&P Global data, accessed via license.

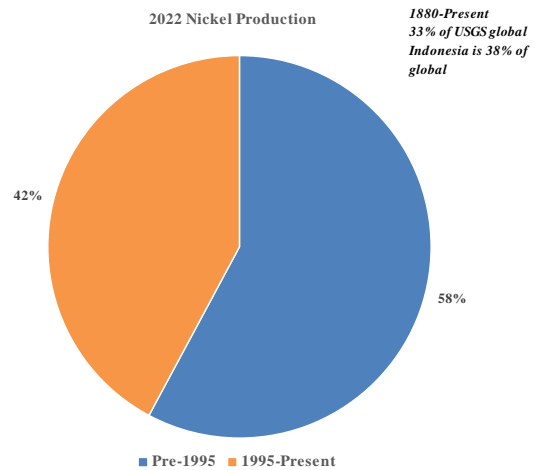
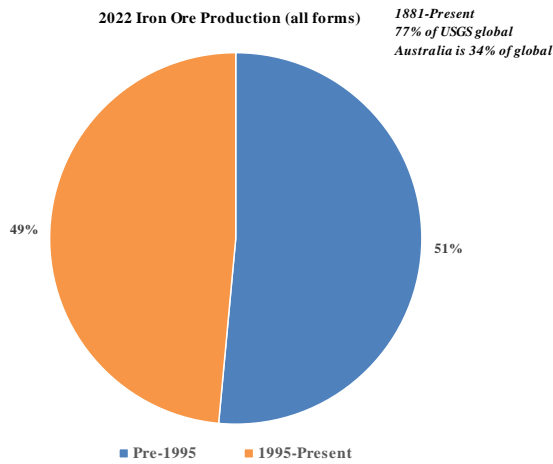
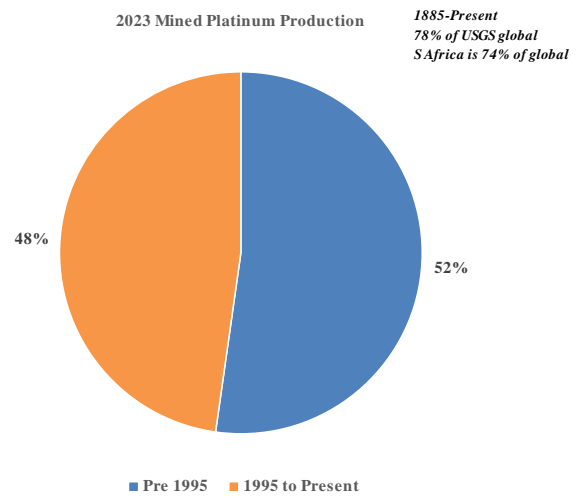
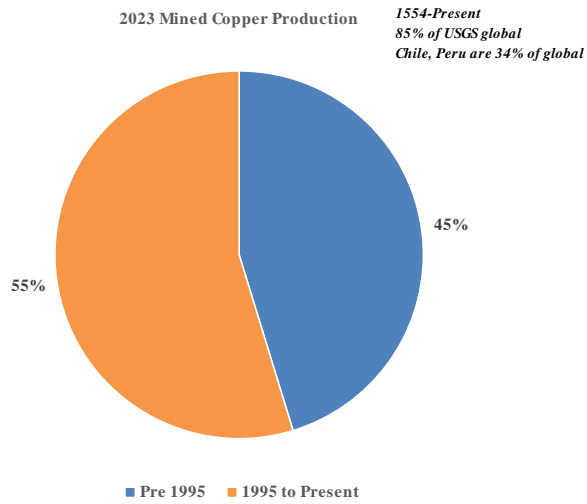
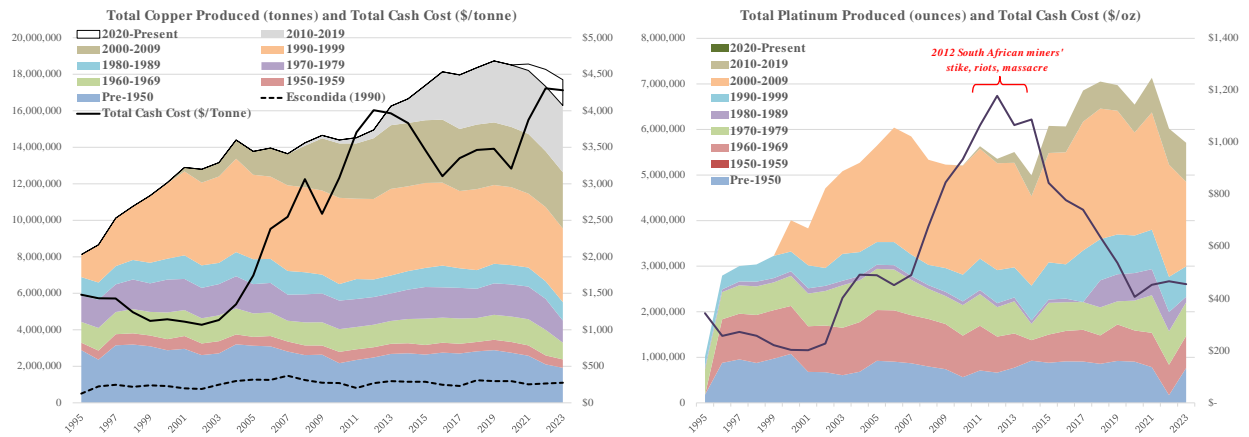
**Note:** Worldwide head grades estimated by author based on recovered ore per tonne for operating projects.

As depicted in **Figure 6**, cycles and prolonged droughts in exploration can happen, given that exploration budgets closely follow price trends. Extended droughts in exploration can contribute to supply-demand imbalances later. The lack of long-term exploration efforts sustains older assets, which remain in or return to service in order to satisfy demand, resulting in lower ore grades as these older mining assets come to dominate the global fleet. With lower grades comes more intensive beneficiation and processing and higher costs. Decommissioning mining projects is expensive and fraught with hazards. In the United States, Europe, Canada, Australia, and elsewhere, these hazards have triggered extensive regulatory safeguards. Even with these safeguards in place, abrupt price cycles and other events have led to public interest issues at abandoned mine sites, including acid mine drainage and other water contamination problems derived from heavy metals and other toxic materials in tailings. Given the complexities and costs associated with decommissioning mines and initiating new projects, the industry has typically preserved continuous operations at legacy assets to the extent possible. By pursuing incremental extraction from lower-grade resources and waste, the industry is adapting to operations within its existing footprint.

**Figure 9** offers a comprehensive snapshot of the asset base for copper, platinum, iron, and nickel. For copper and platinum, **Figure 9** illustrates detailed “vintaging” of capacity additions across decades and trends in average operating expenses (opex). For platinum, both production and opex reflect the impact of the horrific miners’ strike in 2012. Notably, for all four metals, a significant portion of commodity supply comes from assets put into operation before 1995, many of which are generally much older (also illustrated by the copper demographics in **Figure 9**). Mines are built to last, and their footprints are remarkably durable. Many projects originated during “metals rushes,” including during the 1970s in coincidence with the surge in oil and commodity prices.

The long Production histories of the projects in these samples are noteworthy. Indeed, worldwide, many of these projects are rooted in discoveries made as territories were claimed, colonies formed, and later, countries were established. Many of these discoveries were themselves based on traditions among Indigenous and ancient humans regarding minerals occurrences. Over time, many, if not most, of the mine sites and active projects in these data samples were abandoned, often more than once, for extended periods. They were later revitalized due to shifts in market conditions or technological advancements and underwent multiple changes in ownership and control. This pattern is generally consistent across all commodities for which sufficient data is available.

**Figure 9 – Lens on Asset Maturity: Copper, Platinum, Iron Ore, Nickel**

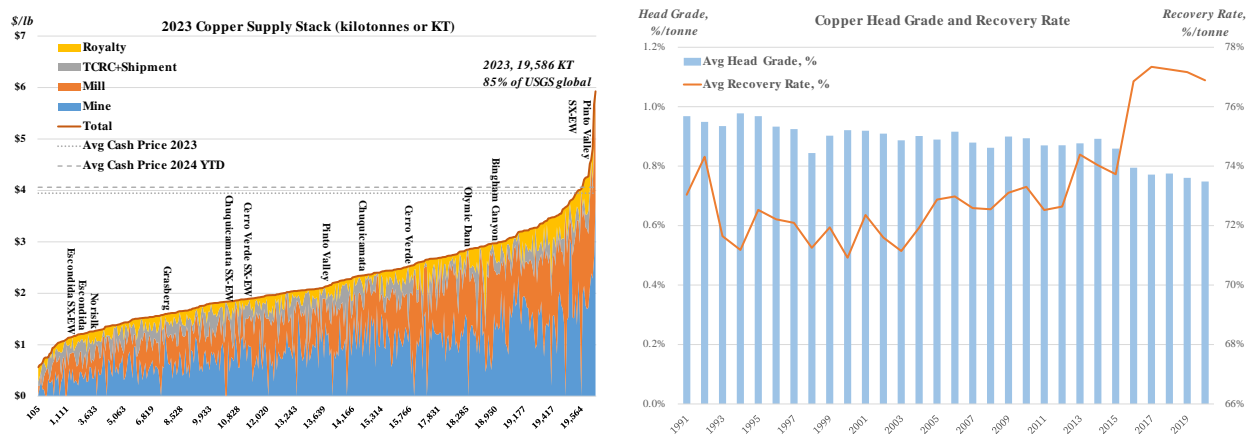


**Source:** Compiled by author using S&P Global data, accessed via license.  
**Note:** Iron ore includes concentrates, fines, lump, and pellets.

The consequences of an aging mining fleet are evident in supply stacks for current production. Using copper again as the example (**Figure 10**), global supply costs rise sharply as copper is delivered to markets from more expensive and typically older projects (see the top panel of **Figure 10**, with notable properties indicated including two in the United States, Pinto Valley, and the venerable Bingham Canyon). A few of the higher opex mines are newer but burdened by labor or fiscal commitments or other factors. The rapid increase in mining and milling costs along the supply stack reflects the challenges of lower head grades, as it simply takes more effort to extract rock and capture metal.

The bottom panel of **Figure 10** joins head grade and recovery rate (amount of metal after processing relative to original amount in ore). Metal-bearing minerals and ores are depleted as extraction proceeds. The maturity of mining assets is a key factor underlying diminished ore grades. In some cases, capital investments in extending mine operations, upgrading beneficiation (i.e., separating mineral particles from gangue or waste rock, usually via flotation), or extracting more metal from waste (tailings) can improve operating results, provided market conditions and other variables justify the effort. The introduction of solvent extraction-electrowinning (SX-EW) in the copper industry has been a notable example of technology improvement. Examples of SX-EW deployment are highlighted in the top panel of **Figure 10**. SX-EW can both extend production beyond original mine plans and projections and lift recovery rates (**Figure 10**, bottom). Roughly 20% of global copper supply is currently produced with SX-EW. Hopes are that SX-EW can help achieve and sustain production of coproduct metals and boost output of other key metals and materials. However, technology can only stave off production declines due to maturing mining assets for so long.

**Figure 10 – Copper Supply Stack and Historical Grades**



**Source:** Compiled by author using S&P Global data, accessed via license.  
**Note:** TC/RC is treatment and refining charges.

For the mining industry, safety is the first priority. Older facilities pose distinct risks of incidents such as tailings dam failures and accidents, which the industry cannot afford.

Older facilities operating in locations where safeguards are weak pose a heightened threat to industry integrity. Older and more expensive projects are not the best candidates for ESG investments, although younger projects may be more expensive precisely because of ESG-related delays and costs. While operators strive to identify efficiencies and reduce costs wherever they can, many ESG or sustainability initiatives represent cost increases necessary to maintain a “license to operate” amid political and social pressures, adding to “resource nationalism” risks.

Beyond normal depletion as extraction proceeds and the artifact of assets mature, declining ore grades for major metals are a widely acknowledged phenomenon within the mining industry. This raises an important question: Are declining ore grades symptomatic of finite resource availability? Ever since the Club of Rome’s 1972 report, “The Limits to Growth,” the Malthusian fear of shortages has been debated for extracted commodities, other natural resources (water), and agricultural output.<sup>39</sup> These fears were prominent during the crude oil price shock caused by the 1973–74 oil embargo and production cuts by Arab countries in retaliation for support of Israel. Those events impacted other commodities and led to the nationalization of various assets. Fears of shortages fed debates about “peak oil,” initially for supply and then for demand, especially post-pandemic.<sup>40</sup> During 2020–21, many believed that preferences were substantially changing, and the post-COVID-19 world would be one of green energy and reduced oil demand. Yet, as always, the world is circular in thought patterns if not materials use, and scarcity fears resurfaced regarding mineral endowments. The past 50 or so years revealed many lessons on the ability of extractive industries to push resource boundaries. As with anything, past success does not guarantee future results for minerals and metals, and assumptions about resource scarcity can be simplistic.<sup>41</sup>

The history of human use of metals is a story of understanding what can be extracted from different kinds of occurrences. So far, we have managed to satisfy needs by stretching extractive metallurgy relatively effectively. Our human experience makes questions about ore grades, asset maturity, and commercialization pertinent to ongoing supply from existing assets.

Ore grades and commercialization are also pertinent to the exploitation of lower-quality resources – and the technologies needed to recover them – largely because these resources make up the bulk of Earth’s real estate.<sup>42</sup> This applies to recoverable resources at existing locations (**Figure 7**) and new, greenfield projects like Indonesia’s nickel laterites. Managing energy, emissions, water, and waste is crucial in using lower-quality resources sustainably, and innovations will be essential for this purpose.<sup>43</sup>

## Challenge of Project Cycle Times

The giant Weda Bay complex controlled by Tsingshan Holding Group, referenced in our nickel case study, serves as a good illustration of cycle time. Discovered in 1996 (reported in 1997) Weda Bay has an estimated 9.3 million tonnes of producible reserves.<sup>44</sup> Despite initial indications of a sizeable nickel resource dating back to 1981,

the property only entered production in 2020, nearly 25 years after discovery and 40 years after initial indications. This project is located in Indonesia, which, while bearing a number of logistical hurdles, is a country that has long hosted extractives industries — including oil, gas, liquefied natural gas (LNG), mining and processing (with a leading position in aluminum smelting), and coal. Indonesia’s complex social and cultural fabric introduces political and national risks and uncertainty, but it is generally viewed as welcoming relative to other locations. Weda Bay is also a good example of the exception to the rule on age and cost of projects: It is relatively young in terms of commissioning date but ranks in the upper third of the global nickel supply cost curve. This ranking is a function of the massive scale being pursued to achieve eventual unit cost advantages across the mining and processing complex and industrial park, where HPAL processing, metal fabrication, and other manufacturing are planned.<sup>45</sup>

By comparison, the ongoing saga surrounding Resolution Copper in the United States seems almost reasonable at 52 years and counting.<sup>46</sup> The first indication of a sizeable deep copper deposit in a long-established copper mining district in Arizona came in 1972. Resolution Copper was formed with the takeover of the closed Magma Mine in 2004, which originally started in 1910. Formal permitting was initiated in 2013 for what project backers indicated would be a 1.5% grade copper deposit located 5,000–7,000 feet underground and capable of yielding about 120,000 tonnes per day for 40 years. Project proponents are still seeking approvals from a complicated milieu of stakeholders including Native American groups (11 directly involved and 21 that are federally recognized in Arizona);<sup>47</sup> tribal and nontribal local communities; local, state, and federal governments; nongovernmental organizations (NGOs), which are now ubiquitous in project development cycles for all industries; and many other entities, particularly the many subsets that exist within each major stakeholder group.

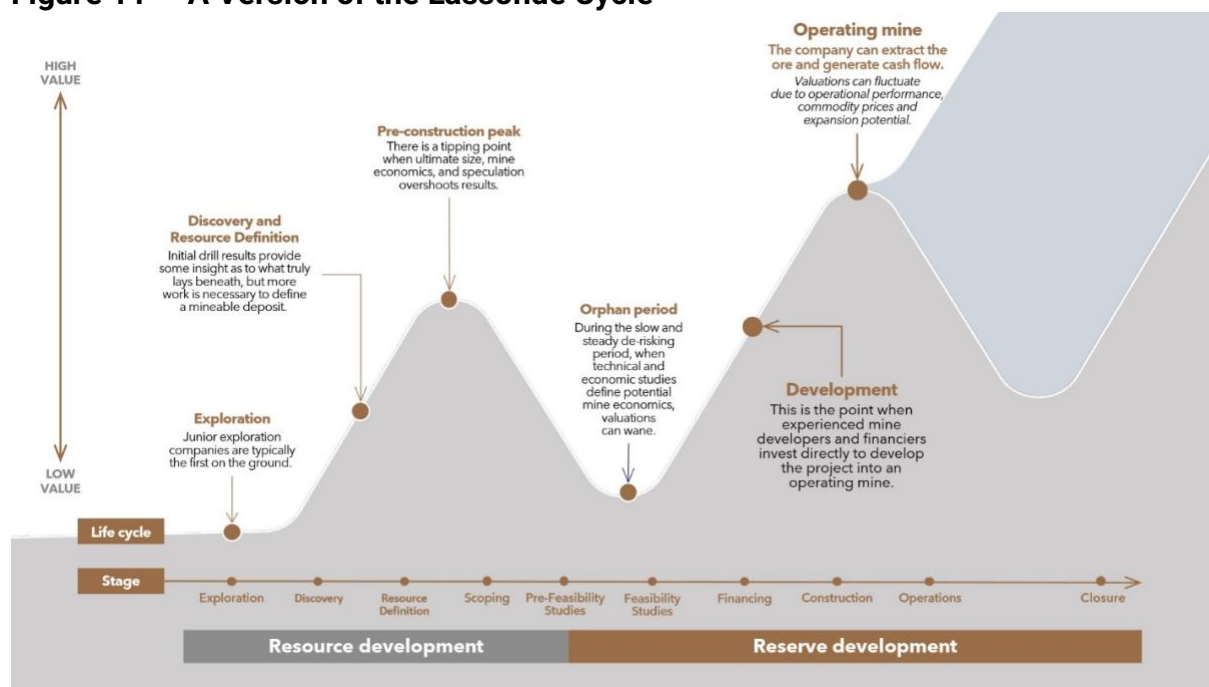
Clearly, project cycle timelines for mining are lengthy for many reasons. Whether domestically or abroad, much has been written about this issue, and numerous efforts are underway to address it, including proposed permitting reforms making their way through Congress. But what are the problems to be solved?

### *Achieving a Better Understanding of the Mining Life Cycle – It Is What It Is*

The first major problem is the need for a better understanding of the mining life cycle. This should be essential homework for policymakers, assuming they recognize and understand the need for raw materials to support energy transition aspirations.<sup>48</sup> As the Weda Bay and Resolution snapshots above and the trends in exploration budgets, ore grades, and maturity of mining assets all show, today’s operating mines have been around, in one form or another, for a long time. The minerals occurrences they exploit have been known and used by humans for even longer. Depictions of today’s mining project development life cycle often follow the “Lassonde cycle.” Named after its creator, Pierre Lassonde, this cycle is a famous portrayal of shifts in the value of public shares of mining companies as they progress through mining development (**Figure 11**).<sup>49</sup> These shifts in value inherently occur along the general path to achieving a

project as the project's risk profile changes over its life. Coupled with commodity price cycles, the mining life cycle is nothing if not brutal and unforgiving. It takes a certain temperament to navigate the stop-start process toward commercialization and, hopefully, ultimate realization of value (i.e., returns of and on capital investment).

**Figure 11 – A Version of the Lasso Cycle**



**Source:** Resource Capital Funds.<sup>50</sup>

In his original version, Lassoonde put the discovery phase (for investors and speculators) at one to two years, development (including investment analysis) at two to three years, and production (as well as revaluation) at two to three years. These timeframes may have been applicable for gold projects in the early 1990s, Lassoonde's primary focus, or they may reflect the short attention spans of investors. Indeed, gold does seem get to market quickly.<sup>51</sup> Lassoonde's cycle has been applied to Oyu Tolgoi, a prominent copper-gold project, indicating a lead time of approximately 15 years from concept to first production.<sup>52</sup> However, considering prospecting by a Mongolian-Russian joint survey dating back to the 1980s and the confirmed discovery in 1996, the total timeline is at least 10 years longer.<sup>53</sup>

Timelines will vary for different commodities and locations. For example, lithium can come to market faster, depending upon occurrence and technology. However, for major metals projects, 20 years is a reasonable estimate.<sup>54</sup>

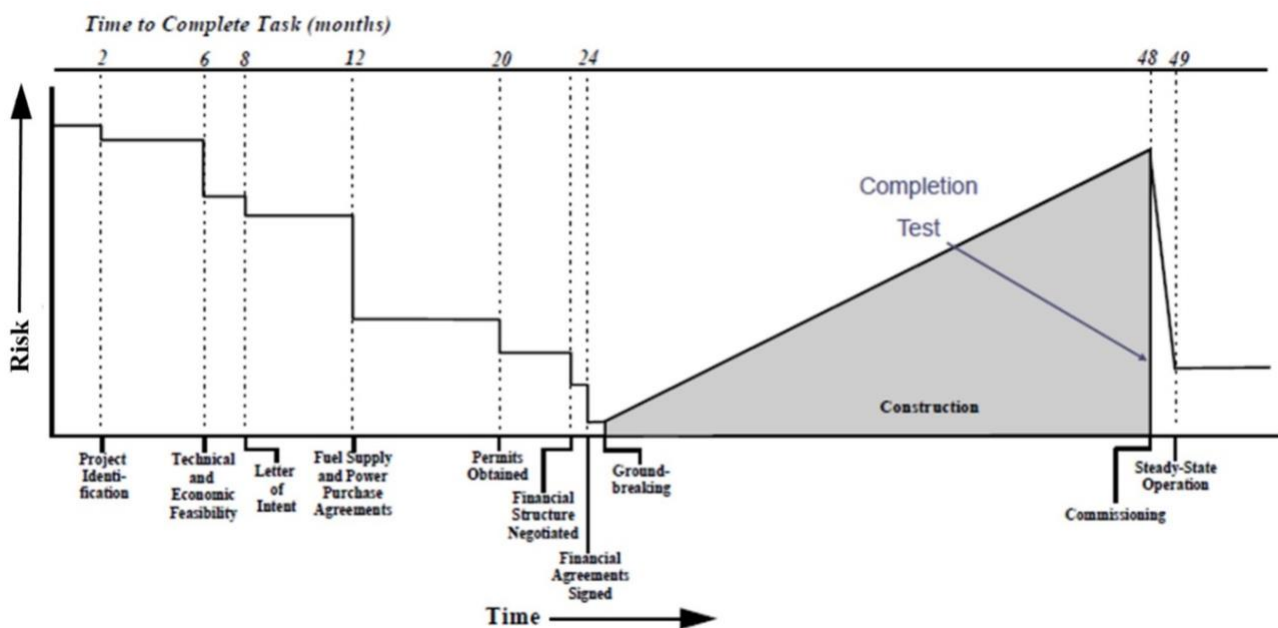
### *Understanding That Risk is Relative*

Exploration and development seem to do best where occurrences have long been known. The term "closeology" is a pun on a hard and fast rule in geology – new

discoveries are often made in close vicinity to existing production. A copper discovery in Zambia, widely touted as a proof of concept for AI-supported exploration, is such a case. The Mingomba discovery lies in the long-established copper belt of Central Africa. Mingomba is located just across the border and roughly 2 kilometers from the recently commissioned and operating 400,000-tonne per year copper mine Kamao-Kakula in the Democratic Republic of the Congo. Notably, the AI-supported exploration effort, costing about \$250 million thus far based on company reports, is on par with traditional (pre-AI) exploration expenditures by major mining groups. Project backers now face at least \$2 billion in capex commitments to commercialize a high-grade underground deposit (with reports indicating grades in the 3%–5% range), comparable in depth to Resolution Copper but located in the heart of the African continent.<sup>55</sup>

Depictions of the mining cycle, as illustrated in **Figure 11**, generally convey a message of “de-risking” as the cycle progresses.<sup>56</sup> Initially, the primary concerns in assessing risk are whether the resource exists and the extent of mineralization. During the development phase, questions shift to the feasibility of construction and the project’s sensitivities. Few projects survive beyond the early concept and exploration stages. Those that do often face lengthy hurdles or “project gates” (e.g., feasibility, agreements, permits, financing, etc.) before reaching a final investment decision (FID) as shown in **Figure 12**. Project risk diminishes as each project gate is conquered, but any project gate can encompass risks that could easily kill the project. Too often, ill-conceived projects somehow move forward due to political support, creating difficulties later. Risks increase again with groundbreaking and construction until the project is commissioned and enters operation.

**Figure 12 – General Project Development Cycle**



**Source:** By author, based on Taylor DeJongh.<sup>57</sup>

Once projects are commissioned, in operation, and generating revenue, they become very attractive targets (as captive “iron in the ground” or, in corporate risk parlance, “maximum cash impairment”) for government incursions in various forms. These can include changes in fiscal regimes (e.g., increased taxes, royalties, or other revenue streams), pressure to renegotiate agreements, and equity ownership for sovereign companies. Such interventions constitute a category of risk often termed “creeping expropriation,” as they fall short of outright takeover or “nationalization.” A more correct conclusion is that projects are never fully de-risked. What actually happens is that they reach a point where the risk-weighted reward (in net present value/NPV terms) is sufficiently tolerable for backers, who have already absorbed political and country risk, to proceed and/or continue. Once the “license to operate” is attained, project development and operations become an ongoing risk-management and mitigation process.

### *Some Development Hurdles are Really, Really Big*

Back to the case of Mingomba — competition is intensifying for access to resources in the Central Africa copper region. A major issue for the mining industry is inadequate transportation infrastructure to move products to markets. Transport logistics are a substantial consideration in every part of the world where additional tonnages can be produced and delivered. In Central Africa, two routes are under development in a high-profile, head-to-head match between the United States and European Union (EU) on one side, and China on the other. The U.S. and EU support the expansion and modernization of the Lobito Corridor west through Angola to the Atlantic Basin, while China is funding a revamp of the Tanzania-Zambia rail to the Indian Ocean.<sup>58</sup> Both routes require investments to upgrade port and harbor export points. Regardless of direction — whether to Durban in South Africa along the existing main route for ore shipments through the Indian Ocean, or across the Democratic Republic of the Congo and Angola to the Atlantic, or even through Tanzania — very real security risks can periodically undermine trade movements. These countries and areas largely fall into a loose category of “fragile states” that own the largest resource endowments in the hunt for metals.

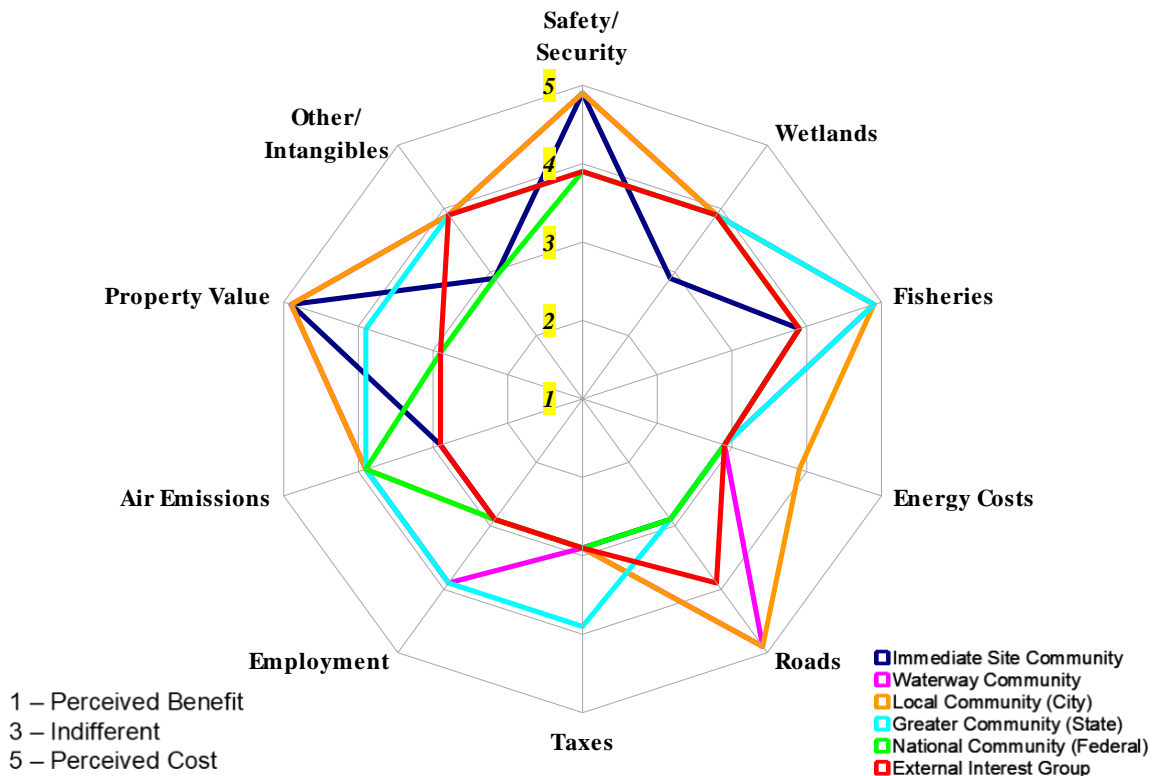
Such considerations add years to project cycle times and entail a level of political support that carries, by itself, inherent risks and uncertainties. Politics in wealthier countries will debate how much public support they are willing to provide to green materials enterprises, introducing new complexities. There are stark and growing differences in “style,” the approaches that tend to be used by sponsor countries — including the U.S., U.K., EU, Russia, China, and new entrants such as Saudi Arabia — as they position around their multinational companies and projects in resource-rich host countries. Beyond, and integral to, project development cycles, these considerations play into China’s role in global minerals and materials supply chains, U.S. (and allied) competitiveness, and the endless geopolitical ructions that must be managed.

## *What Do Stakeholders Really Want?*

In the case of Weda Bay and other nickel projects in Indonesia, and increasingly elsewhere, resource-owning sovereign governments seek not only a share of economic value from the ore, but also the added value from processing and manufacturing. This includes associated jobs, economic growth, taxes, and other revenues from industrial development. Indonesia is using export controls to ensure its goals are met, and other governments will likely use the same or similar approaches.<sup>59</sup> In many respects, sovereign government positioning is all about exerting control. Western project developers and operators tend to prefer commercial freedom to manage and mitigate technical and market risks and uncertainties. These preferences have always differed from non-Western interests. They are coming under pressure with the demographic shifts to a more diverse investing landscape, as alluded to above. From the nationalizations of the 1970s to various forms of government intervention today, whether creeping expropriation or more overt actions, we are firmly in a time of heightened resource politics, making project cycle times vulnerable.

Beyond financial considerations, stakeholder interests and concerns vary significantly. Another essential bit of homework for policymakers is to build a better understanding of nonmonetary values, particularly those that do not easily translate into financial terms. Plenty of effort has been made over years and decades as project proponents, consultants, researchers, and others have defined, documented, measured (to the extent possible), and reported the enormous variance in stakeholder positions regarding projects of any sort. **Figure 13** provides an example, depicting positions of different stakeholder groups on different issues associated with U.S. LNG import terminals in the early to mid-2000s. Although drawn from experience in a different industry, the point remains — stakeholders will see things very differently depending upon frames of reference and points of view.

**Figure 13 – How Different Can They Be? Stakeholder Dimensions (LNG Case Study)**



**Source:** Michot Foss et al.<sup>60</sup>

**Note:** Illustration of maximum scores of stakeholder groups on issues for all projects in sample of 25 (U.S. and Canada) that did not achieve licensing.

How do we resolve these dilemmas? Assuming that values rooted in cultural and societal traditions and norms can translate into monetary benefits to satisfy stakeholders' concerns is overly simplistic and can lead to adverse reactions. Conversely, assuming that there are no potential monetary benefits at stake overlooks important signals, such as the significance attached to engagement or "consultation," as commonly phrased. In particular, local and Indigenous interests may desire active participation in projects. This has contributed to a tendency toward equity interests in natural resource industries and infrastructure as project developers and host sovereign government jurisdictions work to find solutions. Consequently, project cycle times are affected. It is important to emphasize that engagement and consultation will not necessarily shorten the development path. Rather, it is hoped that the process of engagement and consultation will preserve the license to operate through various challenges as the project life cycle proceeds.<sup>61</sup>

### *What Are We Trying to 'Streamline?'*

In this day and age, it is impossible to imagine large projects – or even small ones – proceeding in the United States or other democratic-leaning, industrialized, wealthy

countries without opportunity for public input. And public input takes time. As noted above, there is no guarantee that consultation will shorten development cycles. Consultation in the United States usually comes in the form of intervention in regulatory dockets, adding layers of complexity as issues are revealed. Larger and more complex projects, sensitive locations, and weaker governance and sociopolitical norms (where perceived weakness can be exploited by project opponents) further complicate the process — even in locations where industries have previously or historically operated. In particular, NGOs have evolved to become nimbler and more adept at using intervention, almost always ensuring extended timelines for permitting and development. Lessons learned from past experiences, like those in **Figure 13**, indicate that NGOs can exert significant influence even when local host communities are largely in favor of proposed projects.

On these latter observations, a particular sore point in the United States is the National Environmental Protection Act (NEPA), an iconic law passed in 1970 ahead of the inaugural Earth Day on April 22 of that year. NEPA is lauded for enabling public interest and criticized for contributing to lengthy reviews and cost escalations for major projects. The politics enmeshed in calls for NEPA reform reflect deep social divides across jurisdictions and branches of government. Even in the executive branch, agencies are often pushed to adopt and implement rules that may contradict existing regulations, stated policy, or overall policy intent (assuming that policy positions are sincere).<sup>62</sup>

One divide is the promotion of green energy over traditional “brown” energy infrastructure. Some advocate for reform that exclusively benefits green energy technology, overlooking the continued importance of legacy energy fuels and carbon-based materials for decades to come. Another divide exists between national imperatives and state and local preferences, particularly within the U.S. environmental NGO community. These differences have historical roots dating back to the conservation movement of the mid-1800s, and they inevitably lead to contradictory positions when it comes to advocacy. For instance, there is often strong support for green energy technology and electric vehicles but tepid enthusiasm for critical industries, such as mining, that support these technologies. Conflicts within NGOs are arising over large-scale deployment of green energy tech like wind and solar.<sup>63</sup> Divisions are especially strong if public lands are involved, since that is the origin of much of the conservation movement in the United States.

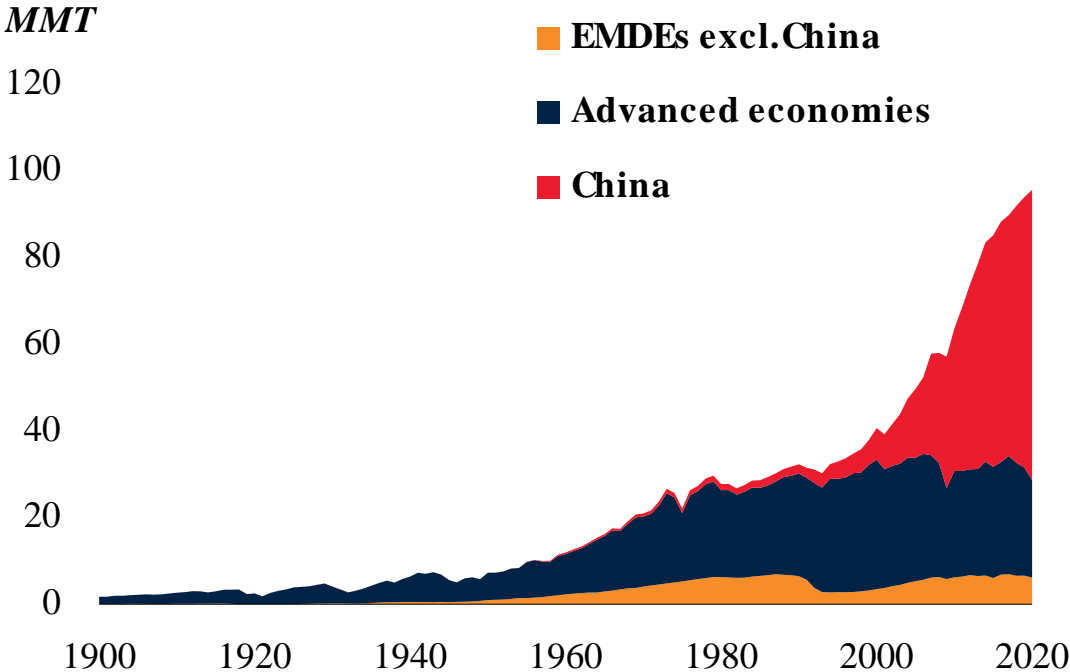
There is also a divide between support for green energy technology and ambivalence toward reliance on external materials sourcing, what that means for supply chain integrity, associated risks and uncertainties, and even geopolitical fissures. An increasingly troublesome divide is the preference for more autocratic approaches over messier democratic ones. While beyond the scope of this report, that topic is significant in the context of China’s role and the concept of “minerals wars.”<sup>64</sup>

All in all, attempting to determine what exactly should be streamlined, by whom, and when, within the current milieu, is nothing if not heroic – and a good reason to expect little relief for project cycle times and cost impacts.

## Challenges Emanating From China’s Dominant Market Shares

China’s growth in consumption of metals (**Figure 14**) has simply been enormous – certainly beyond any expectations of how the country would develop following its accession to the World Trade Organization (WTO) in December 2001. China’s well-documented struggle to develop its automotive industry was aimed not only at economic development, but also at achieving economic parity with the United States and Europe. While some believe that China’s long-term demand for metals will cool, there is no substantial evidence to support this view. That said, China’s political economy is nothing if not complex – and often opaque. Headwinds, such as demographic effects of a rapidly ageing population, will surely cloud the picture.

**Figure 14 – Global Metals Demand**



**Source:** World Bank.<sup>65</sup>

**Note:** EMDEs are emerging and developing economies, as defined by the World Bank.

China’s output from domestic production has been relatively stable, giving China the largest market share of total mined tonnage worldwide (**Figure 15**) with other nations and regions far behind (see **Figure 16** and compare with **Figure 5** our world tour).

**Figure 15 – Trends in Minerals Supply, World and China**

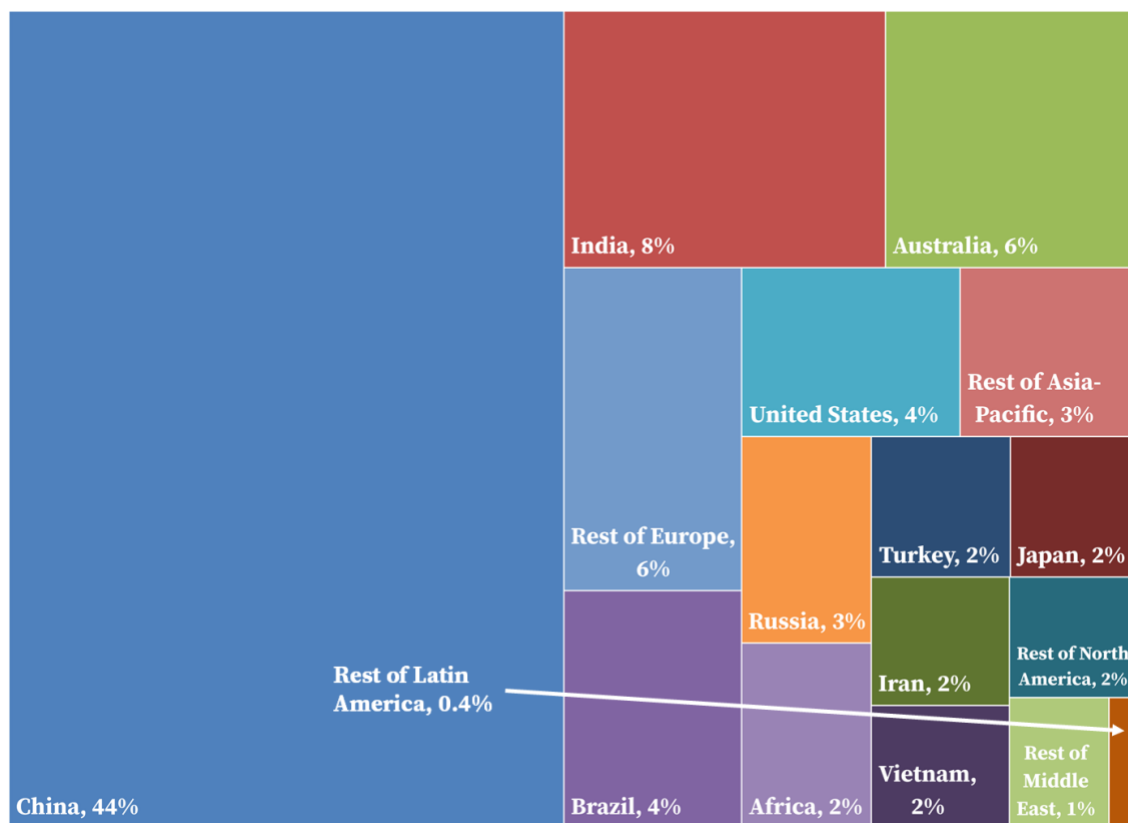
*Total Worldwide Mined Tonnage, MMT*



**Source:** Author using CES database.

**Note:** This figure includes aluminum but excludes alumina, cement, aggregate, and stone and iron products other than usable ore to yield mainly metallic minerals. 2016 world production declines were mainly in commodities for industrial and construction materials and fertilizers. 2021 world gains were mainly attributable to post-pandemic recovery in commodities for industrial and construction materials and growth in metals output, including aluminum, iron ore, and titanium.

**Figure 16 – Market Shares, Total Minerals Tonnage, 2022**



**Source:** Author using CES database.

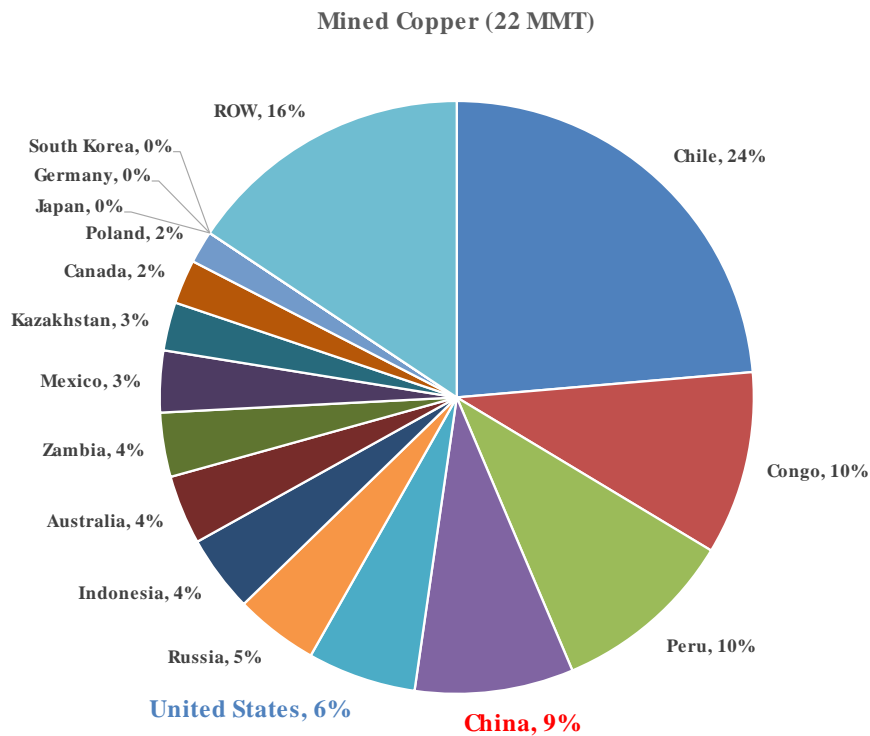
**Note:** The total 16 billion metric tonnes includes cement, aggregates, stone, and all iron products. Reported by USGS and compiled by CES.

As noted earlier, for all of its strength in domestic output, China’s own production cannot meet its internal needs. Nor is China the largest producer of many minerals and metals that are essential for its push into the array of metals-dependent industries and businesses that are key to its five-year plans. For those commodities in which China’s domestic mined production is not dominant, Chinese outbound investments have been directed toward projects in countries that are the leading resource owners and suppliers of minerals and metals of interest. The varied distribution across countries for a group of high priority commodities is illustrated extensively in **Figure 17**; Chinese activity can be discerned in nearly all. But it is through expansion of China’s own processing capacities – sometimes raising concerns about overcapacity – that China has gained significant control over the output of finished metals. Estimates of capacity are also provided in **Figure 17**, and the reality is stark.

China controls 9% of mined copper but has 42% of refined, a good example of the prevailing pattern. Current Chinese copper smelting capacity is estimated at 50%-60% of global supply and expected to nearly double. China dominates in alumina refining, where gallium can be captured, and produces about 90% of global gallium supply. From

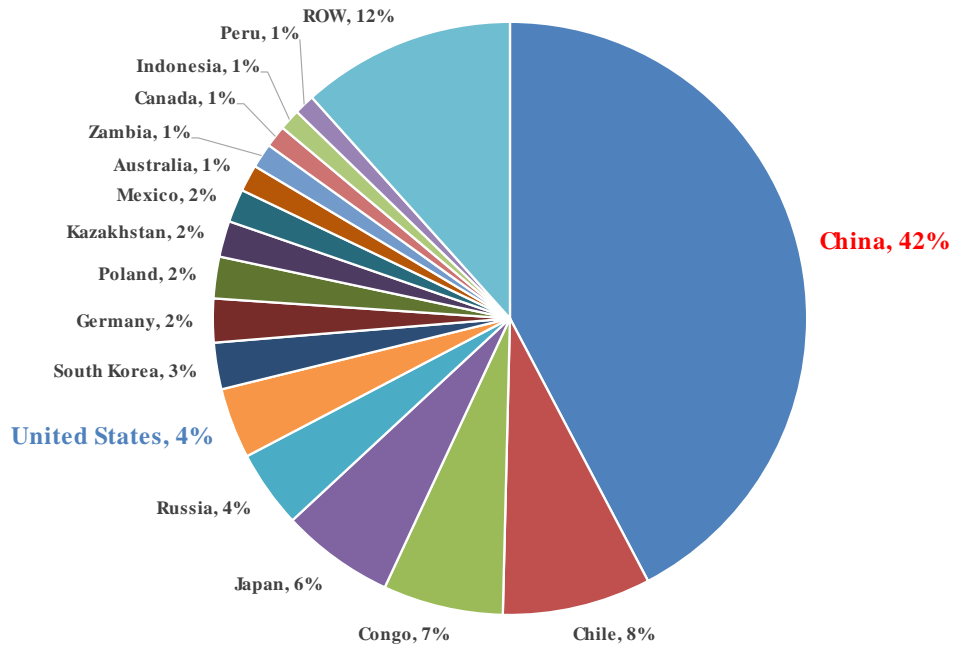
its own resources, China supplies 72% of the world’s natural graphite and 70% of rare earth elements (REEs). China’s domestic production of mined zinc constitutes 32% of global supply, and while information on China’s zinc smelting capacity is sparse, it is likely to be at least half of global capacity. Zinc smelting is a primary source of germanium and indium, with China supplying about 90% of germanium and 59% of indium for world needs. Strikingly, China produces little cobalt and no platinum and yet commands major shares in these metals post-processing. A similar story holds for lithium. China has been processing all of the REE production from the lone U.S. mine in California, Mountain Pass, along with imports from other locations. Efforts are being made to separate and refine REE at the facility and produce magnets in the U.S. <sup>66</sup>

**Figure 17 – China’s Domestic Market Shares of Selected Commodities, 2022 (World in Tonnes/T or Million Tonnes/MMT)**



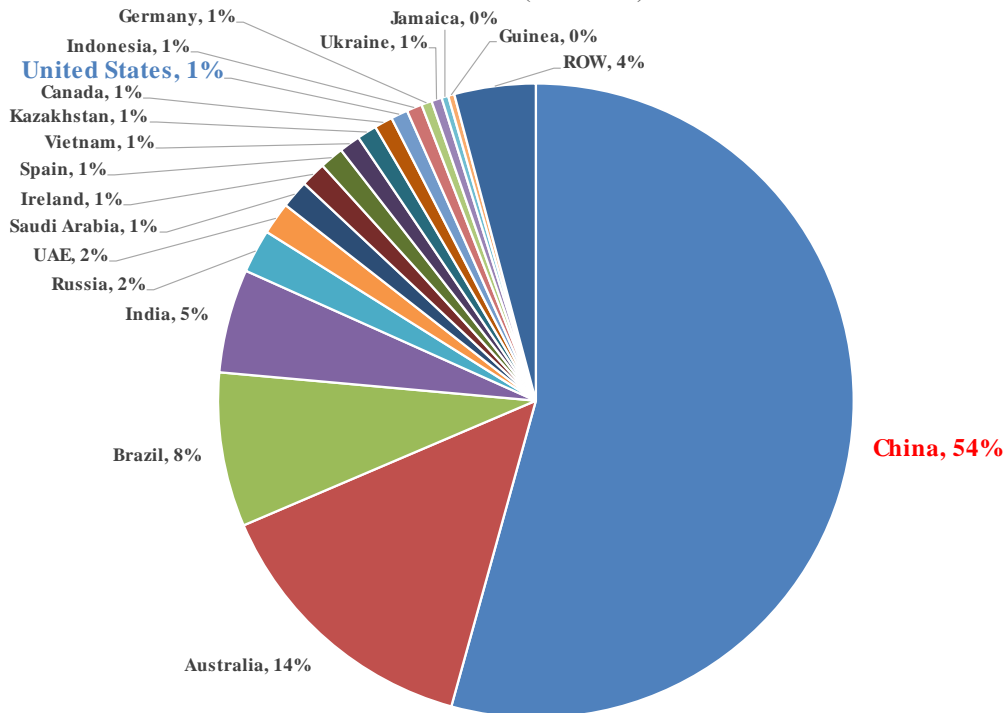
China accounts for only 9% of global mined copper.

Refined Copper (26 MMT)



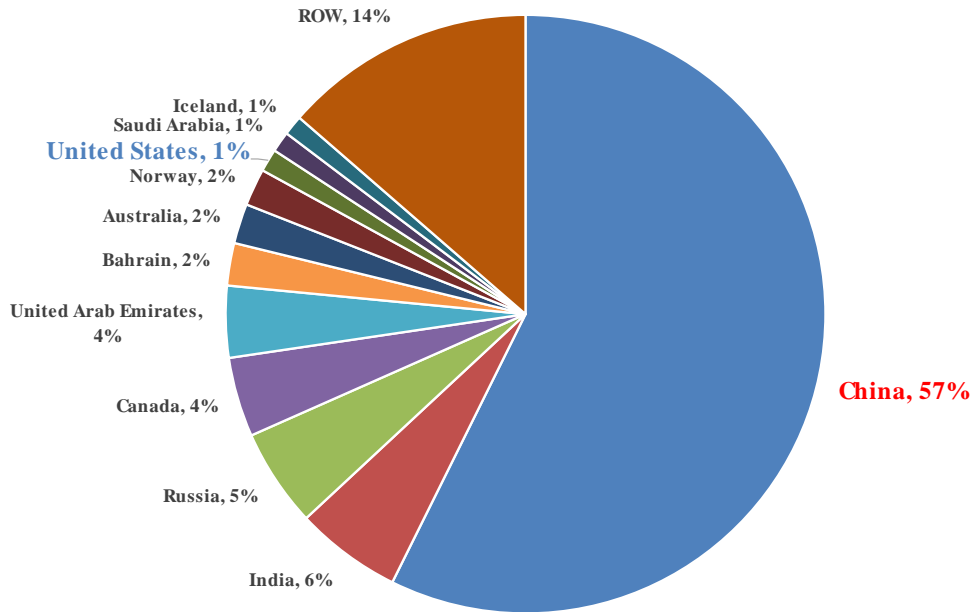
China controls roughly 50% of global copper refining capacity.<sup>67</sup> Chinese copper smelting capacity is expected to expand an additional 45% by 2027.<sup>68</sup> The United States has three active copper smelters.

Alumina (140 MMT)



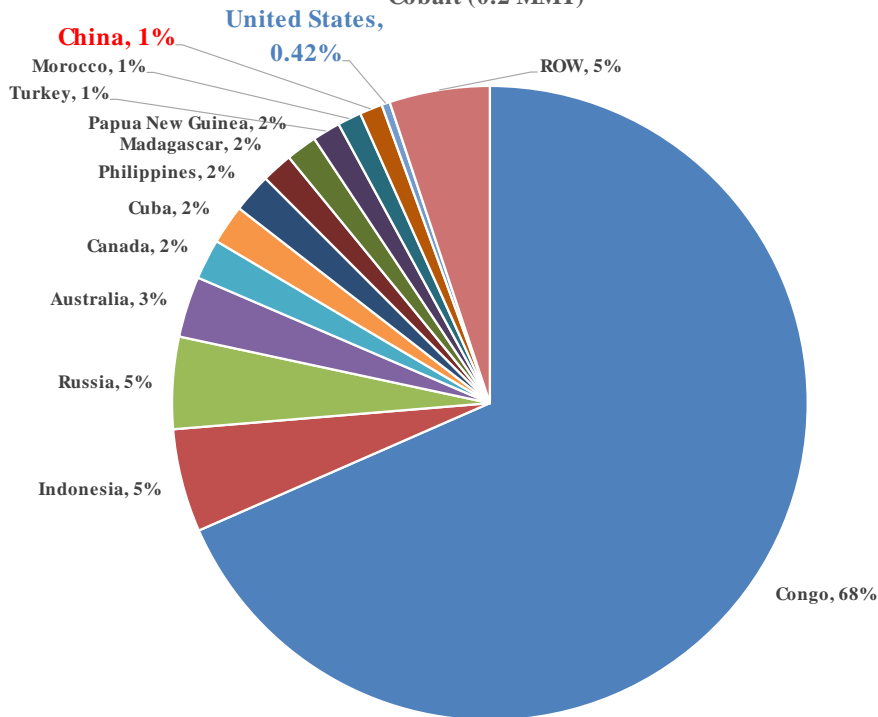
As of 2024, China is the top alumina producer with 58% of world output<sup>69</sup>.

Aluminum (70 MMT)

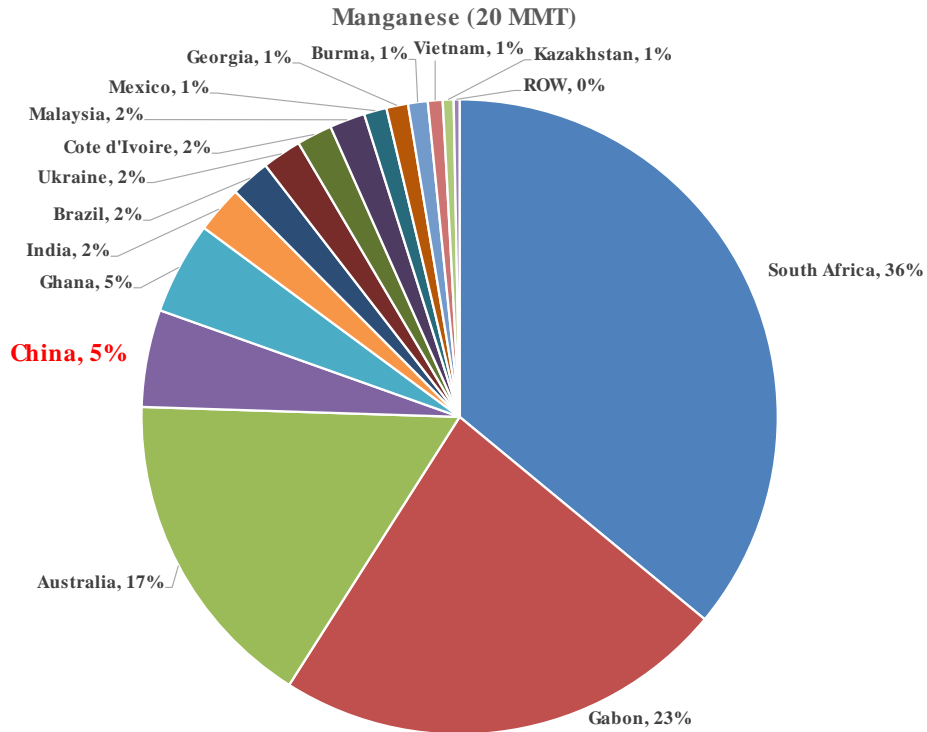


China's share of aluminum smelting capacity is about 59%.<sup>70</sup>  
 The United States has four active aluminum smelters.

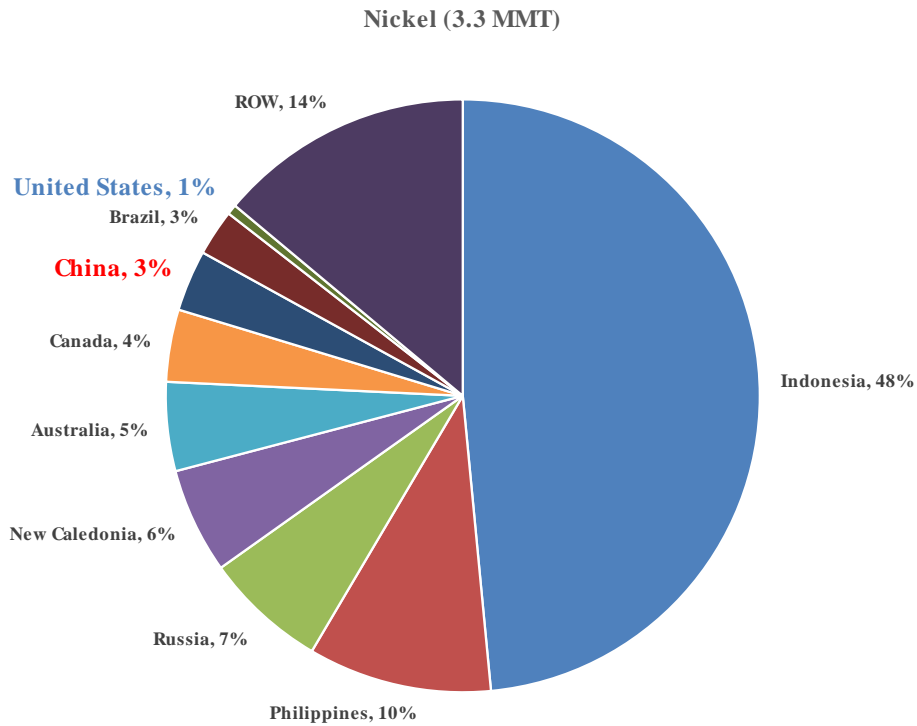
Cobalt (0.2 MMT)



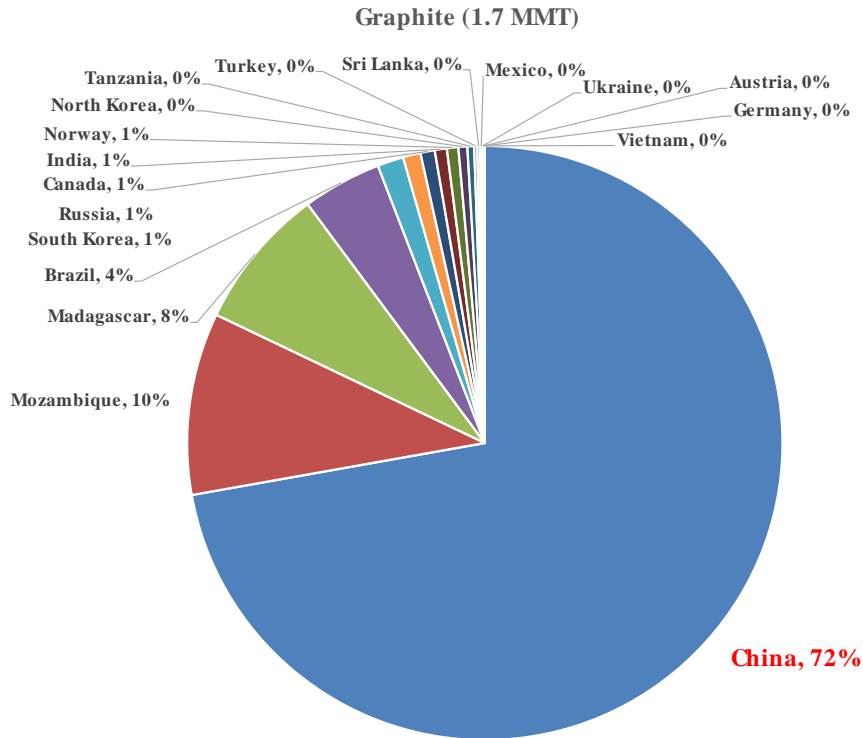
China produces 1% of global cobalt but controls 68% of global cobalt processing.<sup>71</sup>



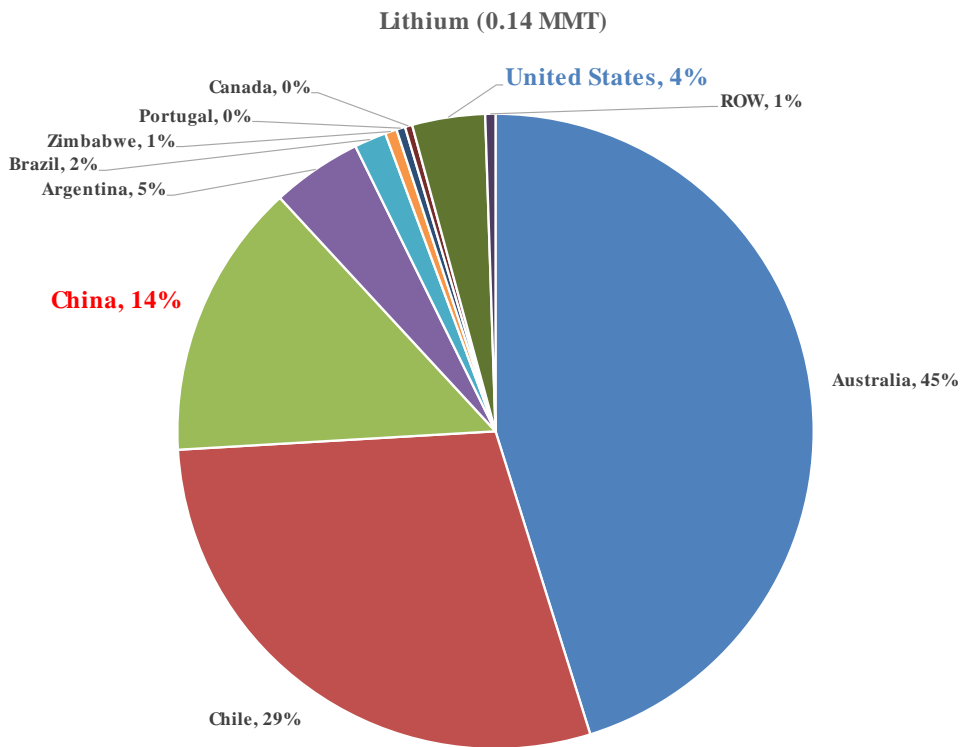
The United States does not produce manganese. China contributes about 5% of global mined output but controls about 90% of global manganese processing capacity.<sup>72</sup>



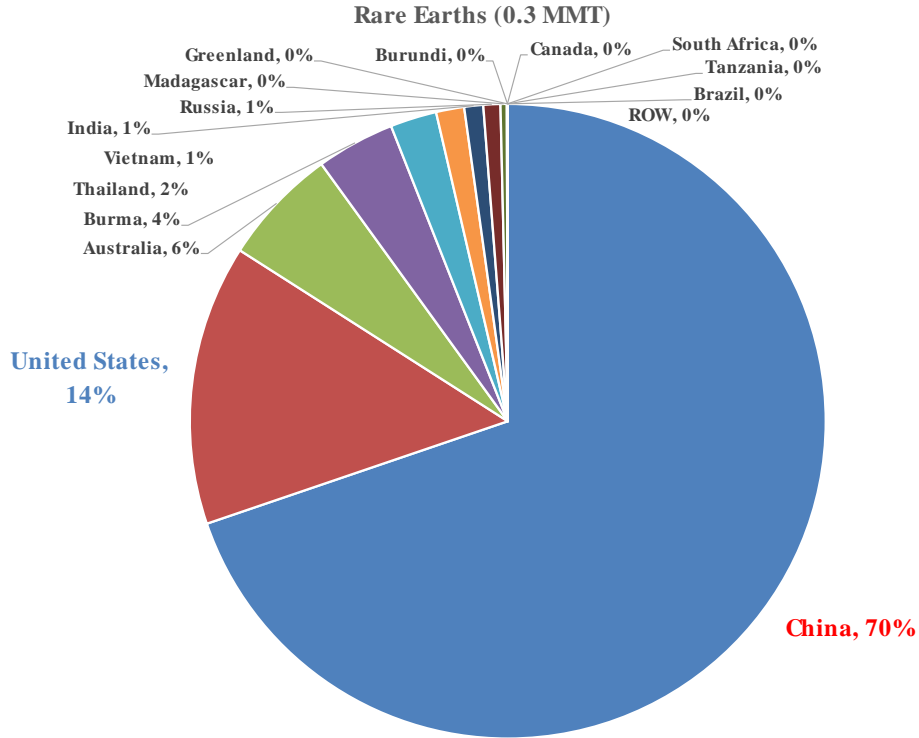
China takes nearly 100% of Indonesia's nickel pig iron output and supplies about 50% of global stainless steel.<sup>73</sup>



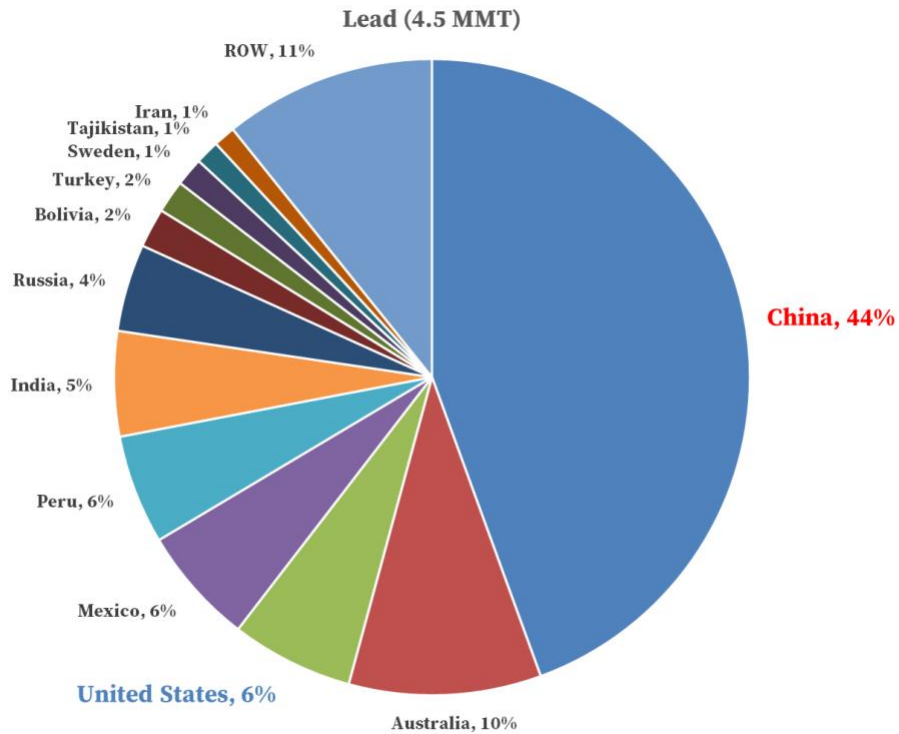
The United States currently does not produce natural graphite. China refines more than 90% of global graphite.<sup>74</sup>



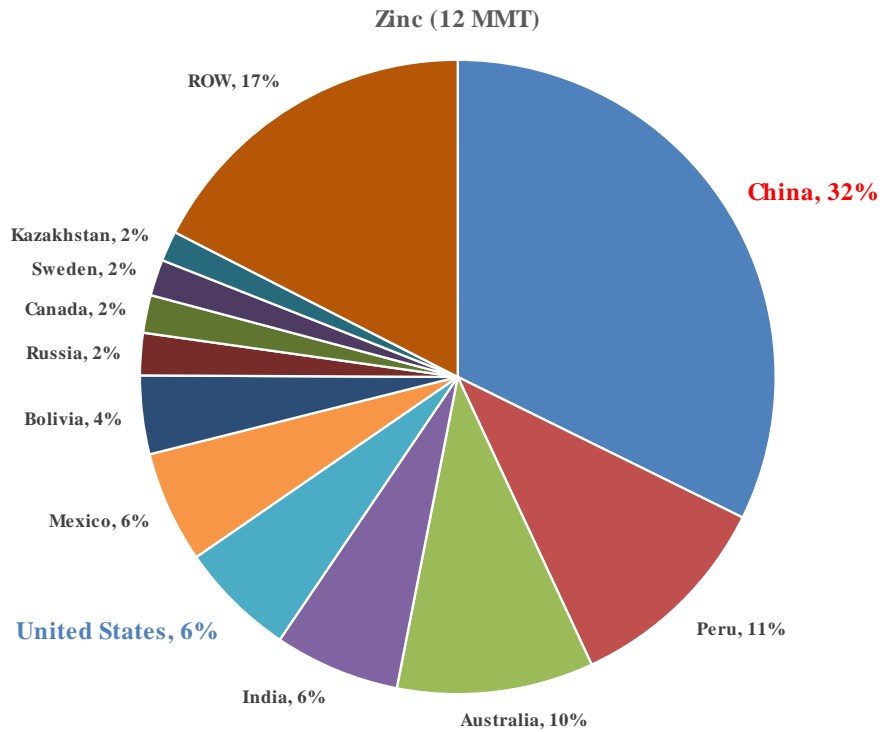
China controls 60% of global lithium processing.<sup>75</sup>



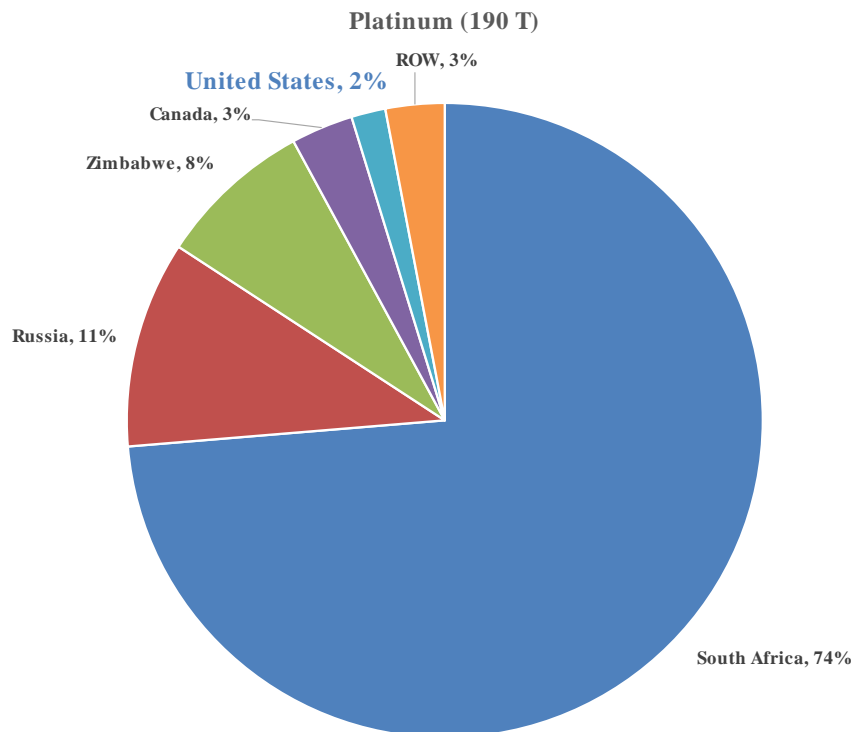
China controls 85% of global REE refining and 87% of neodymium-iron-boron (NdFeB) magnet manufacturing.<sup>76</sup>



China has 42% of world primary **refined** lead (224.6 MMT). About 65% of global lead supply is secondary (recycled).<sup>77</sup> The United States has no active lead smelters.

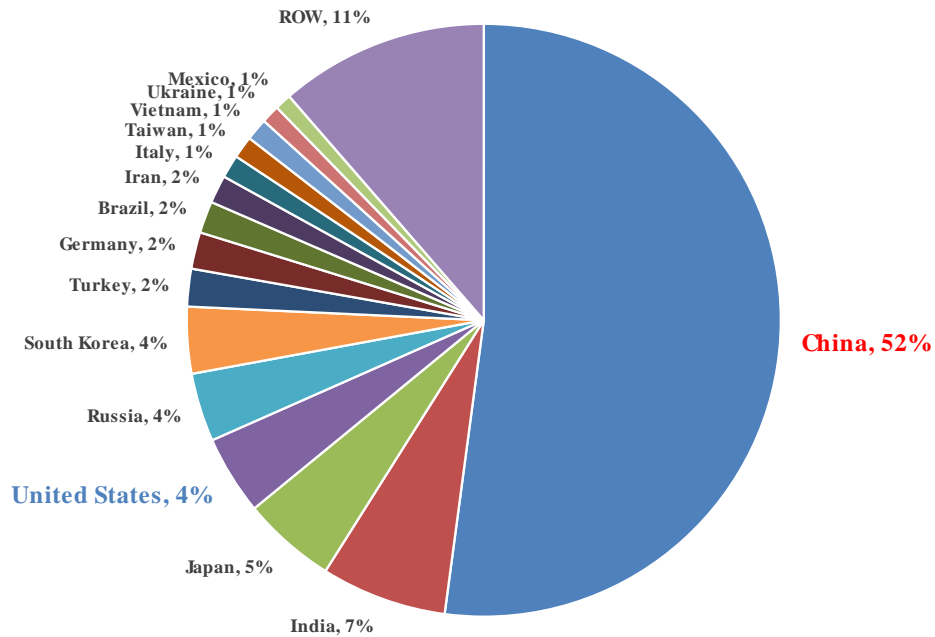


World zinc smelting capacity is about 15.9 MMT (2019), with China constituting at least half.<sup>78</sup> As noted, the United States has one active smelter.



China does not produce platinum but is the largest buyer of platinum worldwide, taking 32% of global output.<sup>79</sup>

Iron and Steel (Raw Steel, 1,900 MMT)



China's domestic steelmaking capacity is about 46% of global capacity. China is investing heavily abroad in Asia and, to a lesser extent, in Africa.<sup>80</sup>

**Source:** Author using CES database.

**Note:** U.S. lithium production is an estimate from a proprietary source (USGS does not report).

Chinese control over the output of these metals is viewed by many as both constraining and threatening, particularly for metals closely associated with green energy initiatives. The country has been an assertive international investor to meet its internal needs. Likewise, China's expansion of domestic industries that fueled its metals consumption is now extending internationally. Chinese companies are positioning in direct competition with Western businesses across various sectors such as BEVs, electronics and microelectronics, telecoms, and more. Consequently, China's domestic suppliers and capacity will remain critical as the country continues to assert its influence abroad. China's presence abroad and the repatriation of ores for domestic processing and fabrication, coupled with its vast export capacity, are major factors influencing global minerals and materials politics.

The prevailing concerns related to China's presence in minerals and materials supply chains are as follows:

- **Potential influence on supply and pricing.** China has a history of manipulating supply, such as withholding REE releases from its stockpile in 2011. The recent reorganization of Chinese REE producers into a sovereign-controlled megastructure (with more consolidation likely to come) represents the "sum of all fears" regarding mineral supply chain tensions.<sup>81</sup> More recent actions related to restrictions on

exports of gallium, germanium, and natural graphite have exacerbated worries that China could restrict critical, strategically sensitive materials – and do more of the same for materials and manufactured gear for both civilian and military use.<sup>82</sup> Scenarios along these lines keep plenty of people up at night (along with attendant and growing alarm about security in the Indo-Pacific region and beyond). Widely ignored is that these actions, and any resulting price shocks, might also affect Chinese manufacturers who also depend on reliable and affordable supply. An alternative and more realistic anxiety is that China’s ability to achieve rapid and gigantic (by historic standards) economies of scale could cause commodity prices to fall, undermining Western investments. This is already playing out across the commodities landscape, as seen with nickel, solar panels, batteries, EVs, and more.<sup>83</sup>

- **Large-scale environmental damage as China pursues resources.** Achieving “responsible sourcing” goals can be challenging if suppliers do not operate responsibly. Generally speaking, the world is better off if commodities can be extracted and delivered to markets in ways that make the most efficient use of energy, water, land, and other inputs, with minimal emissions (including hazardous materials and not just GHG emissions) and minimal damage to communities and host economies. Chinese operators are as capable of meeting these objectives as other operators. A question – merely a question – is whether more sustainability risk lies in the apparent approach of pursuing lower-quality, more accessible resources requiring more intensive, very large-scale processing. The harsh reality is that higher-quality resource occurrences are the exception rather than rule. To acquire them requires a variety of logistical trade-offs along with other considerations, particularly if they are in remote locations. While Western companies are also pursuing – and will be forced to pursue – lower-quality occurrences due to scarcity of better opportunities, Chinese companies seem to have an affinity for this model. This approach is evident in copper, cobalt, and nickel and likely applies across all minerals.<sup>84</sup>
- **Chinese outbound investment style and its implications.** Discussions on China’s “going out” strategy eventually come around to the Belt and Road Initiative (BRI), China’s global infrastructure development strategy. Many observers have written about the extent to which “partner” governments are exposed to risks, such as debt repayment, that exceed their fiscal capacities. On the flip side, BRI also poses costs to China with indications that the Chinese government is, and has been, making efforts to rein in its own “Wild West” of outbound investors, especially from provincial and municipal jurisdictions. Ultimately, the Bank of China will be the last resort should things go awry. While there is a level of comfort in China’s hard currency reserves to withstand shocks that might emanate from bad investments, it would be best to avoid that situation altogether.

Western governments and companies are left with the problem of how to compete effectively against China’s influence. Countertactics that aim to mitigate the impact

of BRI and China's general outbound investing are expensive and politically complex. The Central African copper projects and alternative rail routes are illustrative, as are nickel in Indonesia; lithium, niobium, and other targets in South America (a "new" Monroe Doctrine contest? Some would call it that.<sup>85</sup>), and more. China also has long engaged with host governments in ways that other nations never could or would (save for the former Soviet Union). For example, before China stepped up its investment in minerals, Chinese oil and gas companies were negotiating with (and getting burned by) governments like Sudan. Bauxite mining in Ghana is another example that demonstrates the combination of things that are wrapped into BRI arrangements – including dams, railroads, and other infrastructure that host governments want and the Chinese need for their projects. The influx of Chinese businesses and workers into countries where China is making major investments has led to substantial disruptions to local businesses and labor markets.<sup>86</sup> As Chinese national oil companies (NOCs) were venturing abroad in the late 1990s, the same debates surfaced, and most observers concluded that Chinese ventures were expanding the global supply pie to the benefit of all.<sup>87</sup> Is this time different?

- **Potential involvement of Chinese partners in projects involving Western companies.** This issue presents a significant challenge when it comes to devising countermeasures. In a world in which miners struggle to pierce capital markets, China is emerging as a key investor.<sup>88</sup> As the largest customer for many mining suppliers, it is logical for China to extend financing for projects undertaken by Western companies and groups. The Komoa-Kakula project in the Democratic Republic of the Congo is a prime example. Western investors and governments are often reluctant to back projects in fragile states where ESG questions are prominent.<sup>89</sup> However, these locations also tend to be smack in the middle of geopolitical hot spots when it comes to resource access and Chinese influence. Miners are left with few choices. Chinese companies have long been partners – sometimes partners of choice – on major projects in an array of industries and businesses. This means getting on the same page with Western management about the risks and uncertainties to be managed. In the Democratic Republic of the Congo, Chinese companies face similar challenges as Western operators, including labor controversies, artisanal or informal mining dilemmas, human rights issues, and more. The alternative is to halt development, a decision that, given the rising demand and prices for green materials, is often deferred.
- **What if China was not actively in the game?** Take China out of the picture and conversations today would be completely different, though the challenges would be equally demanding. Indeed, the global economy itself would be unrecognizable, a scenario that surely is one for the "up-at-night" scenario crowd. The difficult truth is that through aggressive outbound investments China has helped enlarge the global energy (oil, gas, coal, uranium), minerals/metals, and materials pies. In effect, China has compensated for decades of declines in metals output in the United States and energy and metals output in Europe.

**Table 1 – Two Voices on China**

**Viewpoint 1: Chinese Politics and Changes in the Institutions of Resource Nationalism**

By [Steven Lewis](#), C.V. Starr Transnational China Fellow, Baker Institute

Chinese politics under Xi Jinping are increasingly impacting the country’s approach to resource nationalism. On the one hand, China demonstrates a strong commitment to transitioning to electric vehicles, and the result is predictable: Chinese enterprises and governments at all levels are going abroad to secure the mineral resources necessary for this transition. On the other hand, Xi’s centralization of power at the highest ranks of the Chinese Communist Party and his appointment of inexperienced loyalists to key ministries and state enterprises calls into question the future stability of his control over the institutions of resource nationalism.

Three trends in Chinese politics are directly affecting China’s plans to transition to a more sustainable energy economy:

**1. Centralization of Authority:** Xi Jinping has consolidated power within the Communist Party, allowing the Party to control both ministry and state enterprises. Xi’s desire to become China’s “core leader” was made clear at the 19th Party Congress in 2017 when he amended the Party constitution to allow himself to become de facto General Secretary for life. However, it was not until the 20th Party Congress in 2022 that he was able to replace the lieutenants of his predecessor, Hu Jintao, within the Politburo, the top of the Party, and in the Central Committee. Xi chose many leaders from the generation below him, primarily men in their 50s. He mainly selected them for their loyalty to him, not their expertise or experience managing a planned economy with a large private component. The Central Committee of the Party used to have many leaders of state enterprises and even private enterprises, but now there are very few. In summer 2023, when he should have been working with his lieutenants to hold a Third Party Plenum to cement his plans for the next Five Year Plan, Xi fired senior leaders, including the foreign minister and the defense minister, reportedly for policy mistakes and potentially for corruption. Additionally, earlier this year, China’s stock market took a huge tumble because regulators aggressively choked back the development of video gaming.<sup>90</sup> They likely underestimated the importance of China’s digital content economy, which is a cornerstone for many of China’s top technology conglomerates. As a result, shareholders in China and around the world are rightly wondering if China’s regulators are experienced enough to effectively manage the country’s vast economy.

**2. Elimination of Party Factions:** Xi has set about eliminating the so-called “factions” of central Party leaders who represent different economic interests, schools of thought, and regulatory practices. Although his predecessors still served as the decisive hand waiting at the head of the table, they routinely held Politburo meetings to hear competing theories, explanations, and positions. This contributed to the view that the Party was led by people who listened and learned. Xi has eliminated the “leadership

small groups” that served as informal arenas for contending views on economic policy and introduced new rules for Party members, forcing them to give up ties to their home regions, alma maters, and especially foreign countries. The result has been to reduce channels for dissent and alternative viewpoints. It has also limited the ability of those affected by new policies to communicate their concerns to the top levels of Party and government.

**3. Economic and National Security Policy:** Finally, Xi has delegated economic policy to his premier, Li Qiang, a lieutenant from Xi’s days who ran Zhejiang Province and later went on to helm Shanghai. Meanwhile, Xi himself more directly controls national security policy, even creating a National Security Committee at the top of the Party. The problem for his premier and other ministers – and also the Party secretaries of China’s wealthiest cities and provinces – is that when it comes to China’s resource economy, it is not clear how much of China’s resource nationalism Xi himself intends to directly control. Strategic ties to Russia may demand that Xi pick up the phone and call Vladimir Putin to push forward new infrastructure projects for oil, gas, and potentially minerals. The same must be true with negotiations for minerals from Vietnam. But what about nickel from Indonesia, for example, where the Chinese side has been run by private actors from Wenzhou in Zhejiang? The Indonesian government itself is uncertain how much control over nickel exports it should exert. There are only so many hours in the day, even for autocrats like Xi, and as he increasingly surrounds himself with loyalists who do not have as much experience managing a large private sector, the potential for missteps in national resource policies is increasing.

Investors within China and from overseas now have to weigh the enormous demand of the Chinese economy against the increasing unpredictability of Xi’s version of resource nationalism.

## **Viewpoint 2: US Competitiveness and China**

By [Gabriel Collins](#), Baker Botts Fellow in Energy & Environmental Regulatory Affairs, Baker Institute<sup>91</sup>

For renewable energy technologies, such as wind turbines, solar panels, and batteries, the United States should aim to steer Chinese firms rather than fight them. Chinese companies dominate these supply chains, which are not easy to replicate quickly or cost-effectively in the United States or OECD countries without leveraging Chinese firms’ intellectual property. A “steering” approach would capitalize on the reality that Chinese manufacturers of renewables and batteries need American and European markets.

Data from the International Renewable Energy Agency (IRENA) indicate that in 2022, the U.S. and European markets combined added about 70% as much wind and solar capacity as the Chinese domestic market and almost 1.5 times what the rest of the world installed. This market power could be leveraged to require an “American edition”

of products that comply with stringent standards, including audited, open-source software with trusted datalink and internet connection hardware.

As the world's largest collective consumer marketplace, OECD countries could and should condition China's market access upon reciprocal protections and accommodations. Even better, policymakers could insist that Chinese firms seeking market position in North America or the EU localize their production of key goods. They could also require that Chinese firms produce more of these items in friendly or neutral jurisdictions, such as Vietnam or Mexico, for instance.



Strategic acceptance of certain Chinese-origin goods would also maximize the United States' capacity to invest in cutting-edge energy transition technologies, such as next-generation nuclear reactors. Wind and solar energy are seen as legacy sources where the main competitive advantage comes from having low manufacturing costs. In China's case, this is cemented through the use of coal to power production facilities, ample subsidies, and in some instances, slave labor. Rather than spending hundreds of billions of dollars (or more) to effectively buy outdated technology back from China, the United States would be far better off investing and deploying incentives to develop energy technology "offsets" that take its economic and strategic position to the next level. By focusing on advanced technology development and leveraging existing resources, such as natural gas, the United States can ensure a more effective and sustainable energy transition.

## Challenge of Competitiveness: A US Dilemma

The new minerals world order looks firmly established from the perspective of southeast Missouri's world-class, roughly 25-mile-long Viburnum Trend lead-zinc district. A typical operation extracts 32 tonnes of ore per day from six miles of underground workings about 1,000 feet below the surface. Eight tonnes are milled to yield two tonnes of concentrates. Concentrates are loaded onto trucks and mainly delivered to Mississippi River docks in St. Louis. From there, they head to China for processing. Smelted product returns to Missouri's traditional and still productive lead-acid battery manufacturers. As noted in **Figure 17**, no lead is smelted in the United States, and one zinc smelter remains in operation in Tennessee. Missouri miners are happiest when their zinc concentrates can be smelted at home, as netbacks are better. Copper separated in their mills also goes abroad due to insufficient domestic copper smelting and refining capacity.<sup>92</sup>

As detailed in the previous section, China not only dominates supply chains because of its domestic production and outbound investment flows, but more because of its processing capacity. That capacity handles both domestic production as well as imported concentrates, cementing China's position in global minerals and metals supply chains. The United States (**Table 2**) and other industrialized nations contributed to China's rise in this area by withdrawing from mining and processing businesses.

**Table 2 – US Competitiveness, Selected Metals and Years**

Facility					
	1970	1995	2022	1995	2022
<b>Copper (Tellurium, PGMs, Arsenic, Bismuth, Antimony)</b>					
<b>Mines</b>	1.6	1.9 / 19%	2.3 / 21%	0.4 / 4%	1.9 / 9%
<b>Metal (Smelters)</b>	1.6	1.3 / 6%	1.0 / 4%	0.7 / 6%	11.0 / 42%
<b>1970 World Share</b>	23%				
<b>Zinc (Indium, Germanium, Gallium)</b>					
<b>Mines</b>	0.5	0.64 / 9%	0.77 / 6%	0.95 / 13%	4.2 / 32%
<b>Metal (Smelters)</b>	0.9	0.6 / 12%	0.22 / 2%	1.1 / 21%	6.7 / 50%
<b>1970 World Share</b>	18%				
<b>Lead (Bismuth, Tin, Antimony)</b>					
<b>Mines</b>	0.5	0.4 / 14%	0.3 / 6%	0.4 / 13%	2.0 / 45%
<b>Metal (Smelters)</b>	1.2 (50% primary)	0.4 / 10%	0.0 / 0%	0.4 / 14%	~5.7 / 46%
<b>1970 World Share</b>	35%				
<b>Alumina (Gallium)/Aluminum Metal</b>					
<b>Mines</b>	Alumina – 6.6%	4.5 / 11%	1.2 / 1%	2.2 / 5%	76.0 / 54%
<b>Metal (Smelters)</b>	Metal – 3.6%	3.4 / 17%	0.9 / 1%	1.9 / 10%	40.0 / 57%
<b>1970 World Share</b>	34% (metal)				

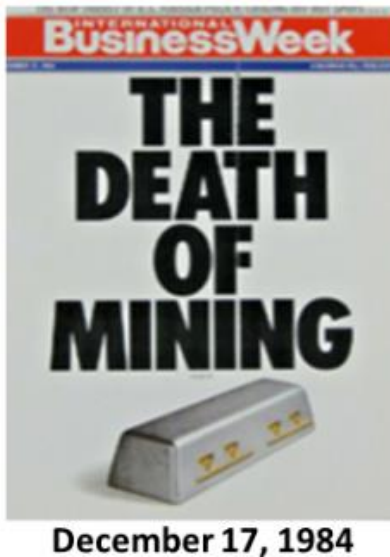
**Source:** Based on work by Michael S. Moats, Missouri S&T.<sup>93</sup> CES database and other sources for 2022 update.

**Note:** Data are million tonnes and percent share of world. Coproduct potential in parentheses.

Many factors have played into the decline of mining and smelting in the United States since 1970. Domestic mines and smelters fed the country’s industrialization and World War II effort. Then, during the 1960s, new facilities in other countries began to bite into U.S. market shares. Labor costs rose and were higher in the United States than in other locations. Environmental regulatory oversight added to complexity, and domestic mines and smelters that remained in operation matured, making decisions to continue operations more difficult. For most smelters, the combination of these factors in the face of lower prices for their product through the 1970s–90s proved too much (**Figure 18**).

Flash forward to today, and the pattern continues. In 1980, about 30 aluminum smelters operated in the United States. As of the end of 2023, there were only five. In 2024, one of the few remaining smelters in Missouri was curtailed and slated for closure. High electric power prices were cited as a key determinant.<sup>94</sup>

### Figure 18 – The Definitive Take on US Decline



**Source:** Image from author's own vintage copy.

Despite the decline of mining and smelting in the United States, there are still several options to bolster its capacity, many of which are currently being pursued along with new ideas and basic research and development. Project developers, some already receiving U.S. government funding or competing for public support, are aiming to boost domestic capacity while also establishing positions abroad.<sup>95</sup> Examples include reshoring processing with U.S. funding for an Australian REE operator in Texas and supporting overseas mining projects that would export to U.S. facilities.<sup>96</sup> The United States now has its first natural graphite processing facility, vertically integrated with mined production delivered from Mozambique.<sup>97</sup> Additionally, efforts are underway to extract metals from Superfund sites – many of which are associated with brownfield minerals facilities and locations.<sup>98</sup> A new aluminum smelter is also being launched, and a copper smelter may possibly be reopened.<sup>99</sup> These initiatives, if successful, could boost the supply of coproducts and by-products.

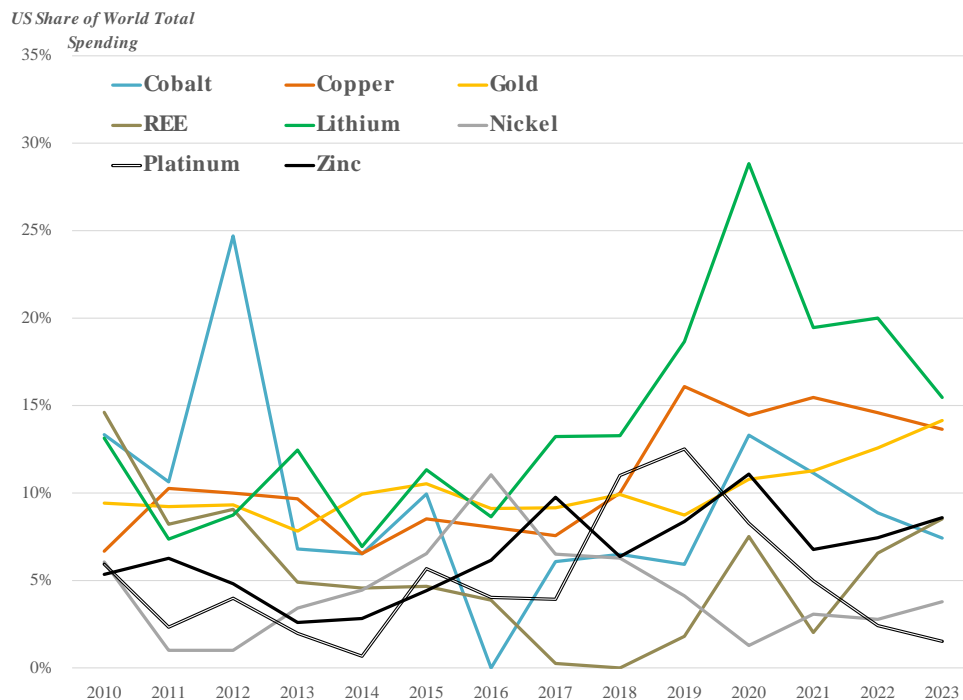
None of these projects will be easy, and there are no guarantees of success. All of the projects are also subject to the conditions detailed above on project development cycles. There are no free passes even for U.S. government-backed efforts. These dilemmas are linked to project cycle times and raise questions about what should be streamlined in the permitting process. Should permitting businesses that entail hazardous processes and materials be prioritized over legacy fuels and infrastructure

because they are deemed essential for favored green energy technology? This question is critical for policymakers and stakeholders to consider.

Thus far, U.S. backing for domestic mining has appeared uneven, which gets noticed.<sup>100</sup> Government support for mining seems tepid, given high-profile withdrawals of federal lands and the tendency to back off from upstream projects, even those that have progressed through reviews.<sup>101</sup> Congressional pressure has corrected executive branch tendencies on mining to some extent but not enough to alleviate concerns. With respect to the developments in processing highlighted earlier, the notion of “mining abroad, processing at home” seems to be gaining traction, with numerous international partnerships already established or underway.<sup>102</sup> Yet, there is little conversation regarding the impediments to processing that lie in how we tend to apply environmental reviews and oversight.

To achieve a renaissance in U.S. minerals and mining will require enhancing both upstream and midstream capacity. U.S. minerals exploration budgets are relatively robust, all things considered (**Figure 19**, compare to **Figure 6**). However, volatility in exploration capex stems not only from fluctuations in commodity prices, but also from a lack of political and regulatory clarity. The current status quo of domestic mining with insufficient processing is suboptimal. Promoting domestic processing without sufficient domestic feedstock increases pressure on international partnerships and global supply chains, which may not always be resilient.

**Figure 19 – US Mining Exploration Budget Trends**



**Source:** Compiled by author using S&P Global data, accessed via license.

## Challenge in Achieving Sustainability

In regards to achieving sustainability in mining, safety remains the top priority, with greater transparency around operations and enhanced metrics closely following. As covered in the section on project cycle times, while consultation may not necessarily shorten timelines, there is hope that engagement will preserve licenses to operate over the long-term. That said, mining, minerals, and metals are facing new scrutiny of sustainability, including the imperative to demonstrate “responsible sourcing” (relative to labor, environment, and how companies generally conduct themselves). Additionally, there is competition to position around the push for green materials “certification.” This is an active – and bumpy – front for the industry worldwide.

### Table 3 – Voices: Sustainability

#### Viewpoint: Take A Systems Perspective

By [Rachel A. Meidl](#), Fellow in Energy and Sustainability, Baker Institute<sup>103</sup>

Sustainability as a framework extends beyond financial markets, encompassing a broad range of fields and reflecting the relationship between an entity, product, or technology and the environment, economy, and society. It is bound by the principles of resource management that aim to provide ecological, social, and economic equilibrium, recognizing the inherent trade-offs across the three. Choosing whether to focus attention and resources on ESG issues more narrowly or on sustainability more broadly is not only a question of perspective, but also of intention. The true risks and opportunities of sustainability cannot be captured with a restricted focus on ESG standards alone. Achieving a realistic and just energy transition will involve trade-offs that ultimately drive the most pareto-efficient outcome.

However “sustainability” is defined, efforts to ensure it must be commercially and financially viable, preferably on a standalone basis. As we explore and test ideas, concepts, and projects, we are learning that it is a lot easier to implement sustainability in practice when projects are profitable or have a clear path to profitability, with considerable headroom. Too often, sustainability is applied to thin-margin businesses, such as extractive industries and commodities production, where we then try to engineer risk-reward dynamics in the financial marketplace. Additionally, targeted sustainability metrics are layered on top of environmental and social requirements that project developers must meet in order to achieve regulatory permissions to proceed and remain in compliance.

Without recognizing relationships with and within the system, things in isolation cannot be sustainable (e.g., paper straws, bioplastics, solar panels, electric vehicles, etc.). For example, an electric vehicle is not sustainable if the social and environmental externalities across the lithium-ion battery supply chain are not considered, including mining, processing, smelting, trade, transportation, manufacturing, and disposal, along

with the lack of recycling and recovery options for batteries at their end of life. The geopolitics and human rights violations involved in such processes and transactions — as well as the potential of operating in sensitive environments and collaborating with corrupt regimes or ineffective governments that have weak or absent environmental, safety, and labor laws — can also affect a system’s overall sustainability profile.

### *Recent Sustainability Advancements*

An enormous amount of attention is being directed toward minerals and materials sustainability. Good reviews exist on a host of fronts, as highlighted below.<sup>104</sup>

- Governments are trying to better coordinate their approaches to domestic mineral industries and activities.<sup>105</sup> This often involves gathering data and information on domestic resources for prospecting and development. Increasingly, governments — sometimes in collaboration with industry — are focusing on sustainability metrics, usually in the form of ESG goals, to encourage early consultation and streamline permitting pathways.
- The mining industry is working to reduce energy consumption and emissions. A popular idea is to switch from diesel fuel, which powers surface and underground mining operations worldwide, to electrification. This transition coincides with automation goals, which could reduce emissions and improve safety metrics but may negatively impact the labor force in many countries and locations.
- Miners aim to reduce waste and water usage to the extent possible, with water scarcity being a particular constraint in a number of locations. For example, Chile’s Antofagasta region has seen decreased copper output as a direct result of water shortages.<sup>106</sup> Waste reduction is a much tougher target, potentially unattainable for the foreseeable future. Success in these areas would be more feasible if operations focused on higher-grade locations. This is unlikely, although at the corporate level — particularly among the largest and publicly traded companies and groups — there is intense pressure to achieve “high grading” of portfolios. Alternatives include improving tailings management (for safety and public protection), capturing residual minerals from waste, and developing creative options for water resources (e.g., a community interface).
- Another popular concept is the “digital mine,” which uses advanced software, models, and analytics to optimize efficiency and enhance safety. Automation and digitization are transforming practices in energy and water management and beneficiation. Miners are increasingly adopting remote technologies and automation, with AI, drones, and robotics revolutionizing mine planning (including where to place explosives), extraction and removal, and more. These advancements aim to optimize output, reduce costs, and diminish the mine-human interface on the safety front. Downstream digital mine innovations are expected to improve logistics,

emissions tracking, and supply chain management. In a world in which increased reporting of sustainability metrics is expected, the digital mine will help companies of all types, at least to some extent, as they focus on measuring and reporting.<sup>107</sup> A widespread view is that measurement and reporting will help with capital markets and mine financing. However, depending on what is actually measured and reported, the mining industry, like others, may come under criticism for “greenwashing” (see discussion below on offset credits for emissions).

### *Persistent Sustainability Hurdles*

The mining industry cannot function without equipment suppliers, chemical providers, and various service providers. The mining industry ecosystem, as with any other, entails hordes of secondary and tertiary participants, all of which can impact sustainability goals. The equipment and service sector must respond to many imperatives, such as fuel switching for emissions reductions. Likewise, many mining operations are contracted to third parties, increasing pressure on contractors and vendors to adopt new technologies, materials, innovations, and practices to align with visions of sustainability. Sustainability in the mining industry can only move as fast as the supporting businesses, which in turn can only move as fast as commitments and financing from their mining industry clientele. Such is the sustainability “do loop” that exists worldwide across all sectors.

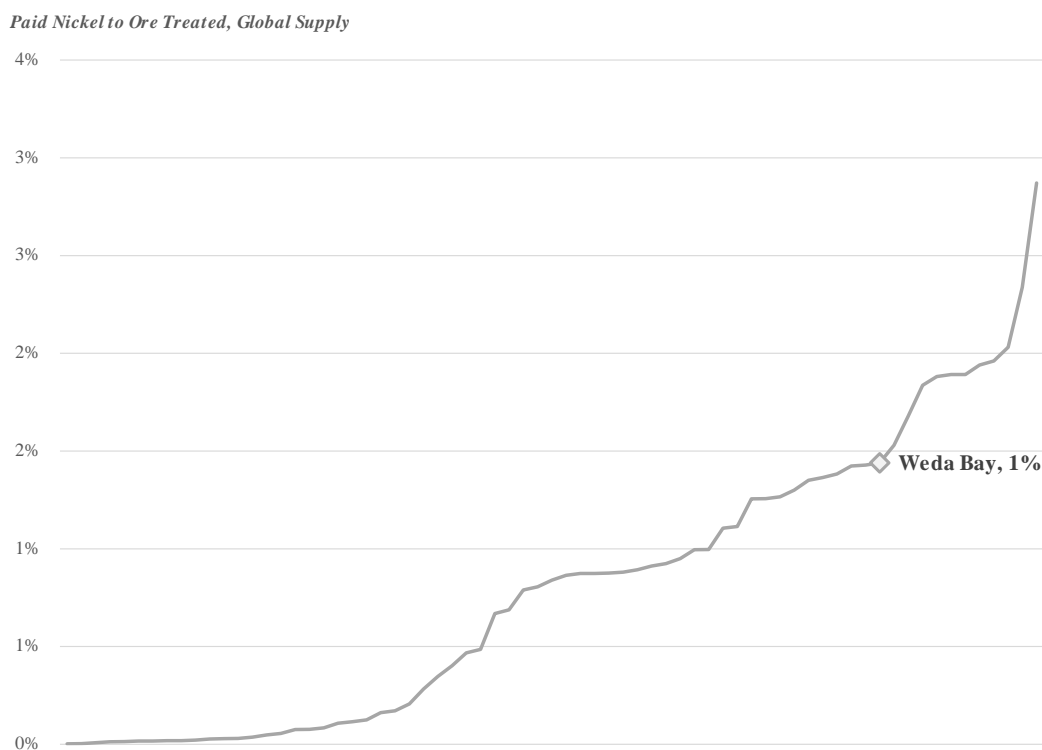
Sustainability in the mining industry faces unlevel playing fields across countries, investors, and participants. Attempts are being made to negotiate principles and best practices through major industry associations, but for a variety of reasons, industry and government bodies are both having trouble with specifics. From an industry point of view, it is important to recognize that every location and situation will be different, with commercial imperatives often taking precedence over sustainability. There is a broad consensus on sound mining practices, but specific targets set by governments are likely to be resisted (company targets are a separate matter). For many governments, much of the conversation around sustainability constitutes a threat to economic development goals and, frankly, revenue generation from the exploitation of endowments. These debates often devolve into “West versus Rest” arguments. Developing countries, in particular, view “Western” norms as unfair, unequal, constraining, and downright inconvenient. They resent what they see as global capital market bias toward these norms. Because of this and other challenges, achieving agreement on sustainability principles and standards will take a long time.

Beyond the complexities of achieving sustainability across the mining industry ecosystem and addressing the unlevel playing field of participants, there are a variety of other challenges in minerals and mining sustainability. Each of these challenges are discussed below.

## What Should We Do About Waste?

In an industry where waste constitutes, by far, the majority of volumetric production, the primary focus is on containment of waste (see supplemental material related to **Figure 4** and **Figure 20** below for nickel).<sup>108</sup> This mainly revolves around safe and secure disposal and containment of tailings throughout the lifespan of mines, processing facilities, and beyond.

**Figure 20 – Example of Waste: Nickel Case Study**



**Source:** Compiled by author using S&P Global data, accessed via license.<sup>109</sup>

**Note:** Weda Bay in Indonesia shown for context.

Tailings dams are constructed to store waste material produced during mining operations, and tailings incidents happen every year, posing serious risks to people and property.<sup>110</sup> A disastrous tailings dam failure in Brazil in 2019 triggered a surge in attention to mining sustainability, prompting coordinated responses from industry and government.<sup>111</sup> Indeed, the incident demonstrated the need for continuous unified responses to instill confidence in mining practices and avoid stringent government actions.

The mining industry can, and does, reclaim mined land during operations and the decommissioning stage at a mine's end of life. However, as alluded to earlier, in the United States and elsewhere, unexpected closures due to factors including commodity

price fluctuations, maturing assets, and higher opex can result in abandoned mined lands (AMLs) and processing facilities. In the United States, AMLs are a designated category of the Superfund program.<sup>112</sup> A great deal of work has been done to determine the best alternatives for remediation of AML sites, but it is ongoing, expensive, and almost always in the hands of the public sector for the public interest. Very large, disturbed areas constitute unique challenges that, admittedly, may never be fully remediated.

In the United States and elsewhere, the amount of waste created from a century or more of mining provides relatively cheap feedstock for leaching out residual metals. From a mining point of view, that feedstock represents a potential resource to be recovered.<sup>113</sup> Tests for copper at active sites are underway, some involving new leaching technologies, supported by funding from the U.S. Department of Energy (DOE). This includes funds for green energy options at mine sites, such as geothermal energy.<sup>114</sup> However, the feasibility of these projects depends on whether the cost of complying with EPA requirements is outweighed by the value of recovered materials. For instance, various forms of waste, including red mud from iron, bauxite, and nickel mining; slag and other waste from smelting and metal making (blast furnaces); and coal ash from power plants, are being explored for their potential to yield residual target metals, REE, and other valuable coproducts and by-products.<sup>115</sup> The potential for utilizing slag to extract iron ore for battery production is currently in development.<sup>116</sup> The ability to harvest incremental products from hard rock mining waste — specifically tailings associated with gold, silver, copper, molybdenum, and other projects — was demonstrated decades ago. However, harvesting these materials, usually via heap leaching, must be undertaken carefully to avoid disturbing the containment measures meant to reduce risks in the first place.<sup>117</sup>

### *What Should We Do About Energy Use and Emissions?*

Mining operations account for around 14% of global GHG emissions, excluding fugitive methane emissions associated with coal extraction. The bulk of the GHG emissions are a result of the fuel for electricity used in metals processing (mainly steel and aluminum).<sup>118</sup> It would be a bit odd to advertise minerals and materials as green if their suppliers were not forced into the same “spreadsheet decarbonization” mode as everyone else. Numerous initiatives are therefore underway to “green up” mining and processing. While some adjustments will be useful anyway, many others will have too low of an impact relative to costs, and more substantial fixes will take decades or more to implement. Equipment and service suppliers and vendors — who are also subject to the pressure to decarbonize — must catch up, along with operations in more remote locations, such as the Central African copper projects.

Mine operators use lots of diesel and so, as mentioned, most ideas revolve around the use of different fuels or even the electrification of service trucks and heavy equipment. In a few cases, demonstrations are underway. In a favorable situation, electric service trucks could be coupled with automation to lower vehicle emissions and eliminate

human drivers, boosting safety metrics. But all of this requires access to affordable, reliable electricity, preferably greenish power, at reasonable costs and with the reliability mine operators need.<sup>119</sup> As detailed at the outset of this report, satisfying green energy diktats, while also ensuring reliability, is no easy task with intermittent wind and solar that require extensive system support.

Other than electrification, hydrogen is an option that gets significant airtime. Aspirations for green hydrogen are high in Chile, where the mining industry could anchor development with desalinated water for industry as an added bonus.<sup>120</sup>

An example mentioned earlier, the Viburnum Trend mine in Missouri, has six miles of workings, which means six miles from the production shaft to the active mine face. Ventilation is a prerequisite for mine safety, since trucks and equipment all use diesel. A second production shaft closer to the mine face would enable electrification but constitutes a permitting and cost hurdle that is unlikely to be conquered any time soon without substantial changes in the business context. These types of realities will occur across a multitude of projects both in the United States and abroad, and across various commodities and types of operations (i.e., surface and underground).

For any of these fuel-switching concepts to be realized, several key requirements must be met: accessible and reliable sources of wind and solar (reliable meaning backup power, energy storage, or other solutions for intermittency), nuclear power, or carbon capture and storage (CCS) schemes to ensure decarbonized power; high-quality, anticorrosive materials such as platinum for hydrogen electrolysis and CCS; capable and well-paid equipment suppliers and vendors; and substantial financial backing to make these initiatives affordable. In short, a lot of resources and coordination are needed.

For the bulk of emissions — which come from metals processing — it helps to be located where energy is cheap and preferably already “greenish.” Returning to the aluminum storyline above, more than half of aluminum smelting worldwide is supported by coal-fired electric power.<sup>121</sup> About a third of smelters worldwide are colocated at hydroelectric sources. That colocation provides an additional benefit of access to rivers for transport and water for industrial use. Only a small portion of aluminum smelting is done with assistance from wind power. While many visions abound on this front, the conditions must be favorable, and reliability must be assured in order to protect continuously operating smelters. It is also important to consider the processes themselves and what can be done to advance more efficient smelting.

The importance of aluminum in decarbonization schemes is reflected in the U.S. government’s support for a new proposed smelter designed to “demonstrate commercial-scale decarbonization solutions.”<sup>122</sup> Expectations are for the smelter to be built within the Ohio/Mississippi River basins. Ironically, as described earlier, the most recent smelter shutdown in Missouri was linked to energy costs, highlighting that government supported hydroelectric power remains the most viable option for producing “green aluminum.”

Aluminum production and hydroelectric power have long been interconnected. Many governments have leveraged hydro development to build and bolster large industries. Iceland, for example, has positioned itself as a prime location for green metals production, courtesy of its abundant hydro and geothermal energy resources. Consequently, U.S. and European aluminum producers have relocated operations to Iceland to take advantage of its affordable, green electricity and favorable stance on metals production, although this may change.<sup>123</sup> Iceland is now among the top 10 exporters of finished aluminum.

In the United States and elsewhere, hydroelectric power has often been opposed by environmental and conservation groups. Aluminum smelting in the United States initially evolved with the provision of low-cost electricity produced by the U.S. Federal Power Authorities (FPAs). These entities, established as part of Franklin D. Roosevelt's New Deal, operated large-scale dams and turbines designed to boost post-Depression economic recovery. They were built with very low-interest federal loans and helped spur agriculture and industrial development.<sup>124</sup>

FPAs, now known as Power Marketing Associations (PMAs), constituted the suite of federally built and operated facilities that both managed flood control in river basins and provided electricity. Many smelting operations were located to take advantage of these facilities. For example, aluminum smelting in the Pacific Northwest was once a prominent example of FPA hydro-based industrialization. However, none of those facilities remain in operation. Environmental activism aimed at decommissioning dams, coupled with resulting higher prices for electric power, were key factors in the decline of the U.S. aluminum smelter fleet.

Steelmaking has traditionally relied on coal and/or petroleum coke-fueled blast furnaces (BFs) for smelting iron ore and blast oxygen furnaces (BOFs) for converting virgin ore and iron scrap into steel. A popular alternative is the electric arc furnace (EAF), which was mainly used for scrap iron but is now increasingly used for virgin iron. This shift emphasizes the growth of green power sources for steel plants. The high-temperature electric arc in EAFs is produced by deploying natural graphite electrodes, a resource primarily controlled by China (**Figure 17**) and listed as a critical mineral by the United States and Europe. Natural graphite is also the subject of much discussion related to U.S. taxpayer backing of domestic supply (as with the Mozambique-linked processing initiative). As the use of EAFs continues in efforts to decarbonize steel production, the supply and cost of graphite will become a serious issue. During the EAF process, graphite is destroyed, necessitating constant replacement. While synthetic graphite can be a substitute, it is more expensive and derived mainly from the hydrocarbon value chain.

Hydrogen has been promoted as an alternative for direct reduced iron (DRI), currently achieved with carbon monoxide and hydrogen to feed EAFs. This approach could be expanded, as it aims to eliminate GHG emissions associated with traditional furnaces. Another intermediate method is to combine hydrogen with fossil fuel-based reductants for improved furnace efficiency (e.g., a natural gas and hydrogen blend). A third

approach is to utilize hydrogen-based electricity in lieu of thermal or even hydroelectric power if the former is opposed. All options involve risks and uncertainties associated with hydrogen supply and value chains, especially the need for steel metallurgy (stainless) at facilities to offset the risk of failure from hydrogen embrittlement.<sup>125</sup> Hydrogen is also being considered for decarbonizing aluminum production, with similar considerations. In the United States, the development of DOE-backed regional hydrogen hubs includes visions of connections with heavy industries like aluminum and steel. For example, Kentucky, the likely site of the proposed new U.S. aluminum smelter, is part of the Appalachian Regional Clean Hydrogen Hub (ARCH2).<sup>126</sup> The journey from announced hubs to implemented, affordable green metal products will depend heavily on sustained federal backing for years to come.

What if green energy solutions are not available? Even when they are, the impracticalities are typically insurmountable. Based on all evidence reviewed thus far, many mining and metals facilities are already vulnerable to reliability issues and cost increases. This is particularly true when such facilities are connected to grids with inadequate infrastructure. Some grids may also be experiencing policy-induced stresses associated with intermittent wind, solar, and other sources. In many international locations, electric grids are simply inadequate, plagued by nontechnical losses, insufficient capacity, mismanagement, and constant disruptions. In remote and logistically challenging areas, “inside the fence” solutions may be necessary. For the mining industry and downstream metals, as with so many other industries and businesses, a solution can be the use of carbon offset credits. This may entail exposure to the inadequacies of nascent offset credit schemes and markets. Additionally, organizations will have to verify the legitimacy of their underlying decarbonization projects, ensure the veracity of reporting, consider costs, and much more. This may include responding to claims of “greenwashing” if underlying projects and approaches are not deemed “sincere.”

### *Can Recycling Help?*

Recycling is often seen as an essential response to sustainability imperatives, with many believing that if the United States (and other societies) are to make huge commitments to metals- and materials-intensive green energy technologies, recycling simply has to be a part of the picture. Yet, recycling is not straightforward, and metals recovery from recycling varies by commodity and feedstock. Well-established practices exist for recovering commodities like lead (e.g., 99% of lead-acid batteries are recycled), iron, copper, and aluminum from scrap and waste.<sup>127</sup> Gold is also readily recycled from many sources, and platinum is routinely recovered from catalytic converters in conventional vehicles.

More difficult to recycle are other metals, such as those embedded in batteries and advanced additive-manufactured materials and composites.<sup>128</sup> The real problem is timing. Raw materials are needed immediately to meet aggressive green energy targets, but it will take years, even decades, before sufficient feedstock and capacity for

recycling can yield meaningful tonnages back to manufacturers. One estimate suggests that by 2040, recycling could help reduce new supply requirements by 30%, while the BEV sector might not achieve materials circularity until 2050.<sup>129</sup> The latter projection, of course, is contingent on numerous variables affecting BEV manufacturing and adoption.

Moreover, the recycling industry is as sensitive to commodity prices as mining businesses are. Recycling is also an industrial activity subject to all of the same risks and uncertainties as the mining industry, including origination, permitting, hazardous and toxic materials treatment, public safety, and public interests.

A critical question is what can and will get recycled as a result of the new green energy deal mix. The news now regularly reports on waste associated with damage (**Figure 21**) and lifespan retirements of alternative energy technologies, along with the enormous growth in electronic waste (e-waste) and plastics. The growing waste streams from wind turbine blades, solar panels, batteries, and more – along with hurdles in expanding recycling to accommodate these waste streams – raises serious questions about promoting alternative energy technologies.<sup>130</sup>

**Figure 21 – Adding to Recycling Feedstock**



**Source:** Images of spring 2024 storm season from public domain news sites across the United States.<sup>131</sup>

Repurposing is also a viable option. For example, some in the auto industry believe that large-format batteries used in BEVs could be, and perhaps should be, perpetual devices, especially in light of the natural resource commitments. Industry insiders view the potential for large-format BEV batteries to extend well beyond warranty life. These batteries could be repurposed to provide electric power storage options in remote

locations and for sensitive communities.<sup>132</sup> To achieve such an outcome, a focus on safety in supply chain logistics and U.S. interstate commerce is essential, given that post-use lithium-ion batteries are deemed hazardous waste.<sup>133</sup> For that matter, addressing the transport of waste that bears hazardous material liabilities will be crucial for the success of any recycling or repurposing initiatives.

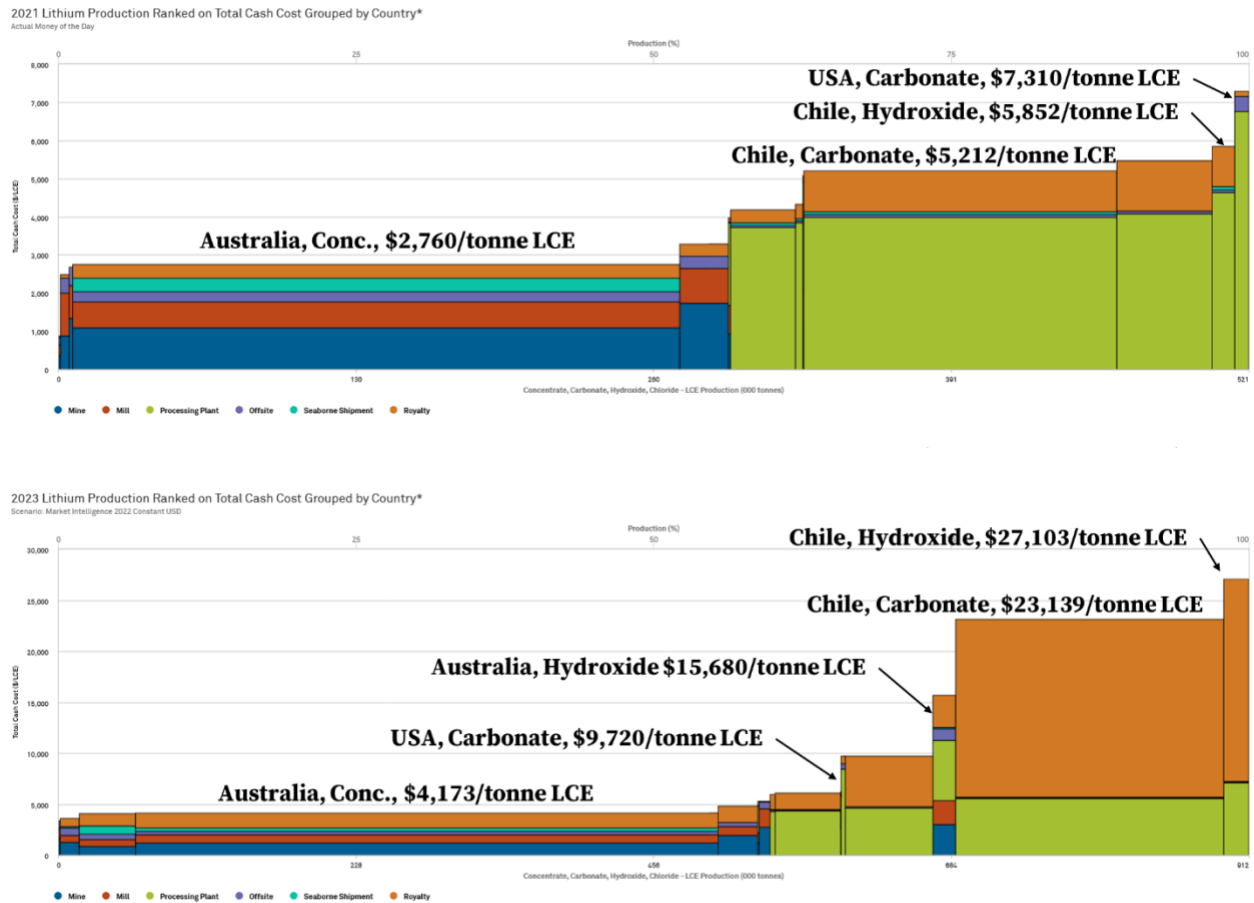
### *Who Will Pay for it All?*

There is (absolutely) no free lunch.

Evidence is accumulating that mining and metals suppliers, along with host governments, are seeking “green premiums” to offset the costs of sustainability and the generally higher expenses involved in the project development cycle. These premiums aim to capture additional economic rent from resource endowments and position companies favorably in capital markets through “responsible sourcing” and “green certification” initiatives. The premiums being sought and disclosed are reportedly 30% to 40% above the base commodity price. Notable examples include “green steel” made with “green hydrogen” in Europe, green aluminum in Quebec and elsewhere, low-emission and socially responsible nickel production in Australia, and low-emission and socially responsible copper and lithium production in Chile. These trends, based on abundant market news and intelligence, are shaping future industry pathways. Legacy producers, such as aluminum smelters that use hydroelectric power, stand to benefit significantly if the market accepts these pricing schemes.

Chile’s lithium brine operations provide an example of how green premiums linked to sustainability could be implemented. To address community concerns – including those of Indigenous groups in Chile’s Salar de Atacama – a new royalty regime was implemented through the Chilean Economic Development Agency (CORFO). CORFO owned the concessions prior to 1979. The new regime features a sliding scale royalty when end user lithium prices exceed \$10,000 per tonne of lithium carbonate equivalent (LCE). The maximum rate is 40% (\$40,000/tonne LCE). The result has been an estimated quadrupling of royalty payments for 2023 over 2021 (**Figure 22**, compare bottom and top panels), bringing total cash costs to the levels shown. In addition, separate payments of about 3.5% of annual sales value have been negotiated directly with Salar community interests. Other lithium producing countries have increased their “takes” of economic rent created with resource extraction, and the pattern is extending to other minerals and metals as emphasis on green materials evolves.

**Figure 22 – Comparative Lithium Costs Pre (2021) and Post (2023) CORFO Royalty Regime in Chile**



**Source:** Data compiled by author using S&P Global data. Images accessed via license. Enhancements by author.

Sustainability-related local and regional conflicts often center on energy and water for operations. Natural evaporation of produced brines in the Atacama requires little energy or fresh water (the latter being contrary to opinion). By contrast, hefty commitments of both will be entailed if direct lithium extraction (DLE) is used to expand production, as being considered. Hopes are that energy inputs can derive mainly from ample solar resources in the Atacama desert and that fresh water can be provided from desalinated seawater. These will require extensive capex injections, environmental reviews (a great deal is unknown especially with regard to large scale desalination), and permissions. Outreach strategies include ideas for providing fresh water to communities. Similar dynamics are playing out elsewhere, including in the U.S. Clearly, both lithium prices and fiscal regimes must be supportive.

Meeting the demand for green premiums is challenging in light of brutal cost consciousness faced by alternative energy technology developers and manufacturers, whether for wind and solar or in the auto industry for BEVs.<sup>134</sup> This situation raises the specter of government price guarantees to support domestic minerals and materials

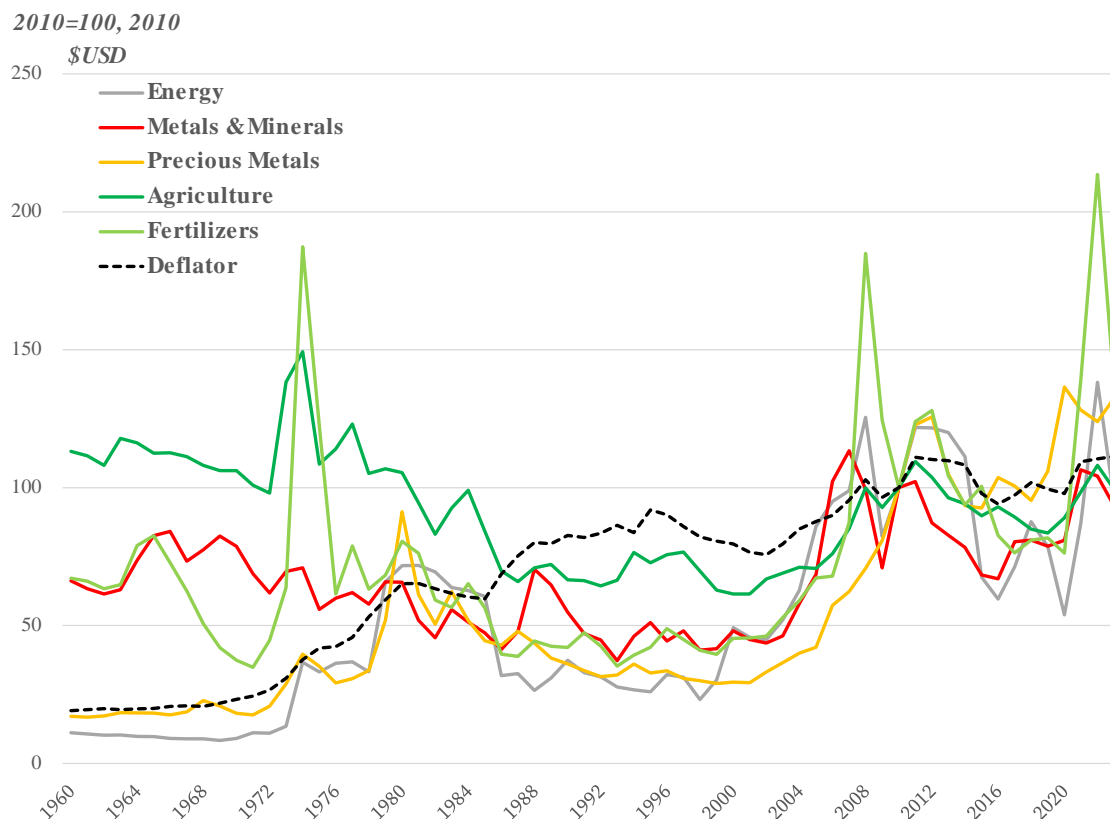
producers and suppliers unable or unwilling to invest in sustainability, or much else, in the face of volatile commodity markets and prices.<sup>135</sup> Price guarantees, along with government support for green materials business concepts, would increase the overall social cost of energy transition scenarios. The price tag could even exceed the doubling of costs suggested at the outset of this report and boost chances of falling into the “valley of death” (**Figure 3**). Just when the United States rolled out price guarantees during the Synfuels Corporation program in response to the 1970s price shock, oil prices collapsed rendering the initiative into a valley of industrial relics.

## Market Challenges

Two aspects of market challenges bear particular attention. One is the landscape for minerals and metals commodities trading. The other is financing for minerals, metals, and materials projects. These aspects are interconnected, as investors expect project developers and operators to mitigate price risk through hedging. A pertinent question going forward is whether commodity markets can support hedging in ways that align with capital markets.

All commodities tend to move in tandem, albeit with differences that reflect the fundamentals of their respective industries (**Figure 23**). Commodities producers need energy to operate, and energy producers require various metals and minerals. Higher costs for energy and metals affect agriculture, as raw materials for fertilizers are derived from hydrocarbons supply chains, which are in turn influenced by oil and natural gas prices. The 1973 oil price shock had global repercussions, causing costs to become embedded. The long sag from the mid-1980s to 2000 discouraged drilling for oil, gas, and minerals. Thus, the long-run price trends in **Figure 23** are reflected in other, preceding data on exploration budget cycles (see **Figure 6** for worldwide trends and **Figure 19** for U.S. trends). Since 2000, energy cost escalations and China’s enormous influence on global metals consumption (**Figure 14**) have contributed to rising costs of operating mining assets, as they have in other businesses and sectors.

**Figure 23 – General Commodity Price Trends**



**Source:** World Bank Pink Sheet, compiled by author.<sup>136</sup>  
**Note:** Annual index is based on real, inflation-adjusted prices.

Several factors contribute to cost escalation in operating mining assets, including occurrences and opportunities, ore quality, project maturity, prolonged project cycle times, and sustainability pressures (which contribute to cycle times). These, along with temporal stresses like more expensive energy for operations, appear to be offsetting gains from technical improvements and efficiencies, such as those in copper production and the adoption of SX-EW. Indeed, the metals rush for green new deals could exacerbate market volatility. Efficiency gains and new supply from investments may clash with demand, destabilizing markets and creating insecurities. Preserving cash flows – with cash flow waterfalls being crucial for project investors and financial backers – becomes an even greater imperative in this kind of forward scenario.

Volatilities across some of the metals featured in this report, compared with crude oil for context, are summarized in **Table 4** and pictured in **Figure 24**. An argument often made in support of green new deals and accelerating energy transitions is that they would reduce exposure to the price risk long associated with oil. However, as the panels in **Figure 24** demonstrate, metals are every bit as capable of introducing volatilities as strong as those of crude oil. An extraordinary spike in crude oil volatility took place

during the pandemic, when oil traded as low as a negative \$40 on April 20, 2020. Without that event, oil price volatility measures would be much lower, comparable to metals in **Table 4**. The pandemic sparked convictions that oil demand would never recover from those disruptions. Many thought that the tipping point of peak demand had been reached. Indeed, metals prices (and volatilities) at the time reflected associated beliefs that metals demand would supplant oil demand in the post-pandemic world. Instead, as we publish this report in September 2024, we are still searching for peak oil demand. The greater concern now is insufficient investment in oil supply to close gaps as green new deals experience growth pains. Meanwhile, most metals prices generally have fallen from their pandemic and post-pandemic highs, threatening investment in exploration, development, processing, metals recovery from waste, and recycling.

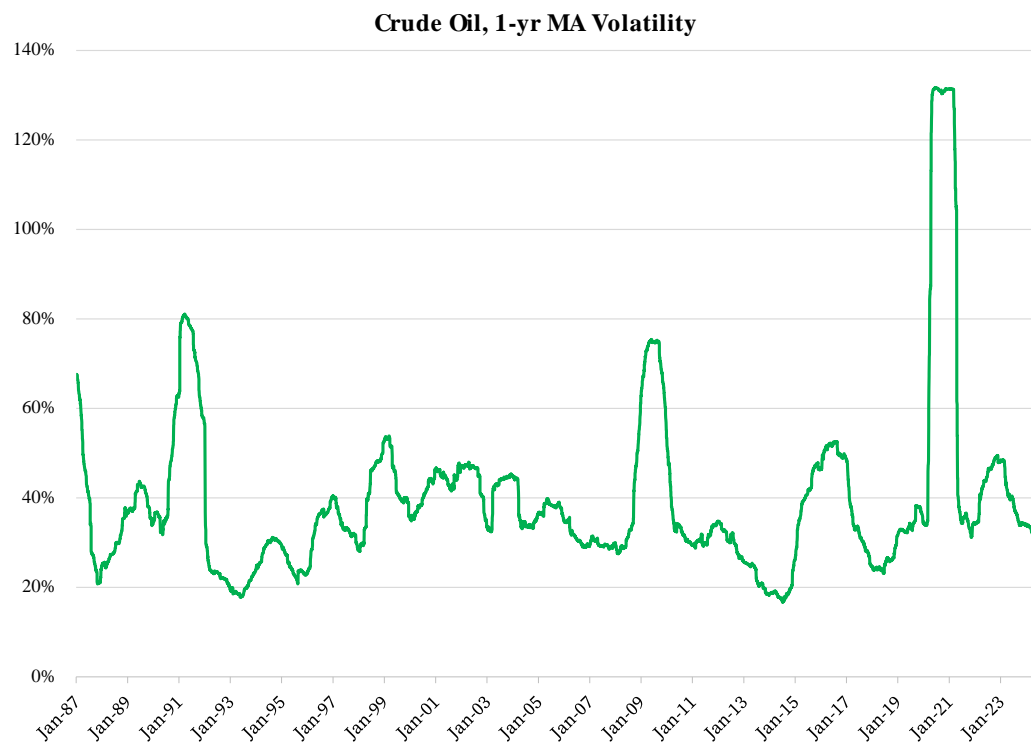
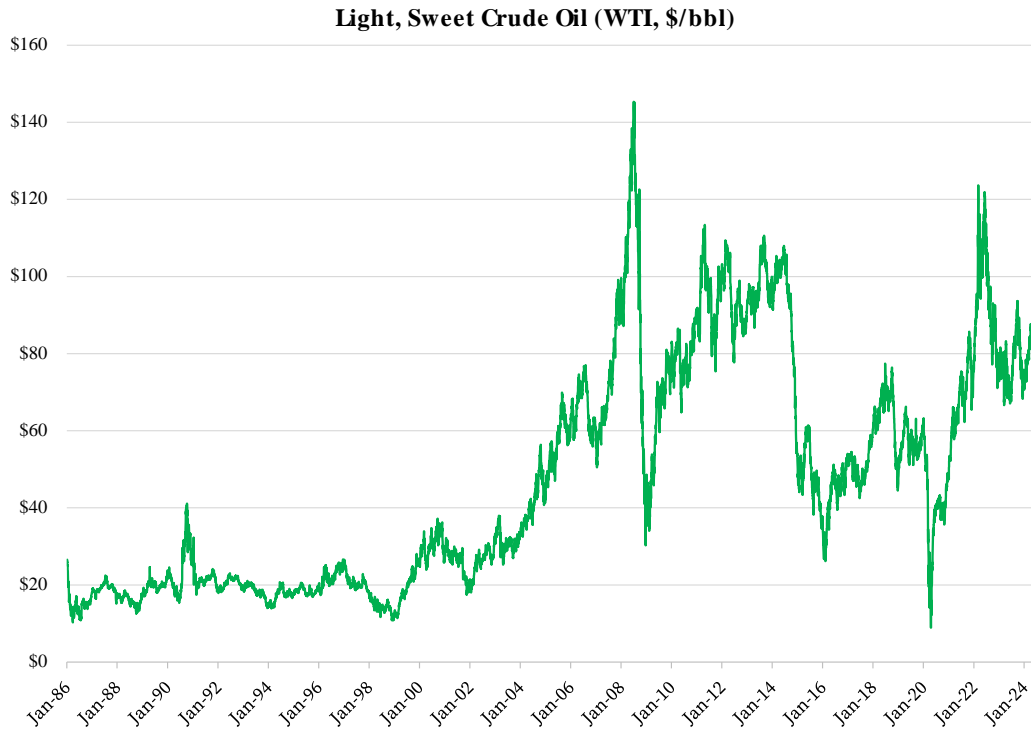
**Table 4 – Volatility: 1-Year Moving Average Annualized**

Commodity	Max	Min	Standard Deviation	Average
Crude Oil, WTI	132%	17%	21%	41%
Iron	61%	10%	11%	30%
Copper	55%	13%	8%	24%
Aluminum	35%	13%	5%	21%
Tin	53%	8%	9%	26%
Nickel	76%	21%	11%	36%
Gold	33%	9%	5%	16%
Platinum	46%	11%	7%	23%
Silver	61%	11%	11%	29%

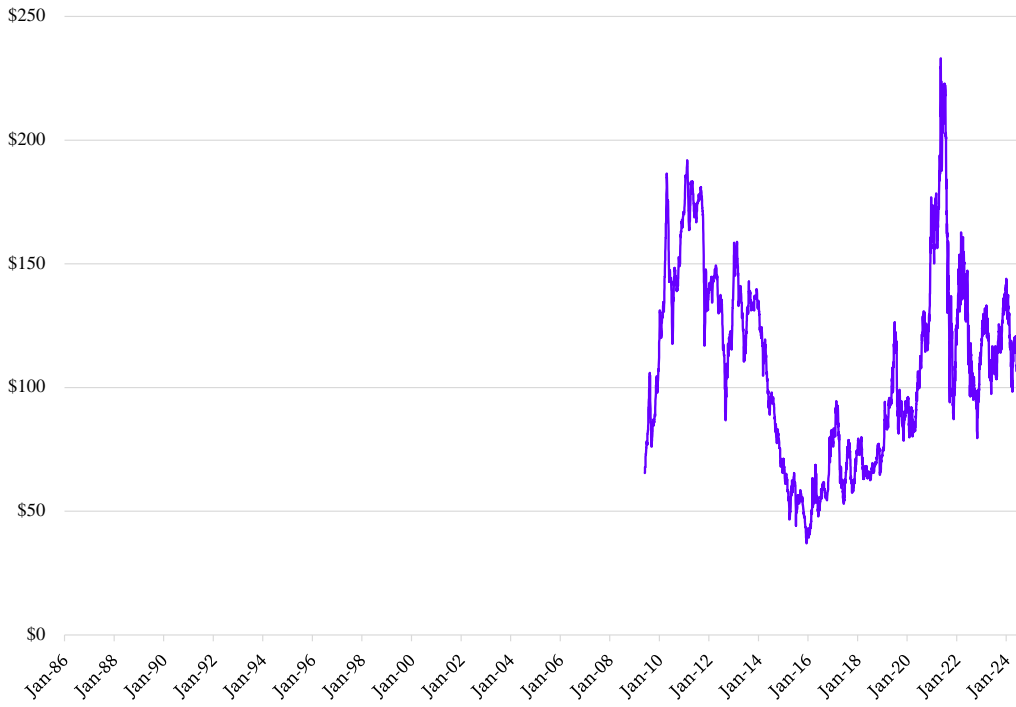
**Source:** Author using on-spot prices from S&P Global for metals, and U.S. Energy Information Administration (EIA) for crude oil (WTI, West Texas Intermediate).

**Note:** For period from Jan. 4, 1999, through June 2024.

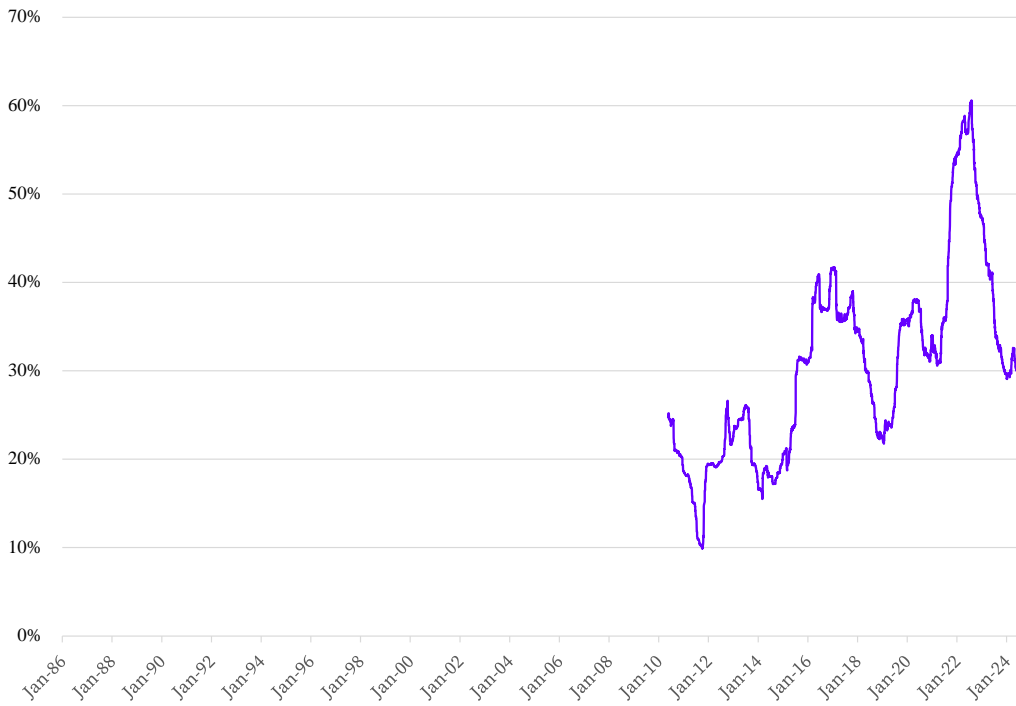
**Figure 24 – Comparative Price and Volatility Trends: Oil and Metals (through 1H2024)**



**TS01021: The Steel Index Iron Ore Fines 62% (\$/tonne)**



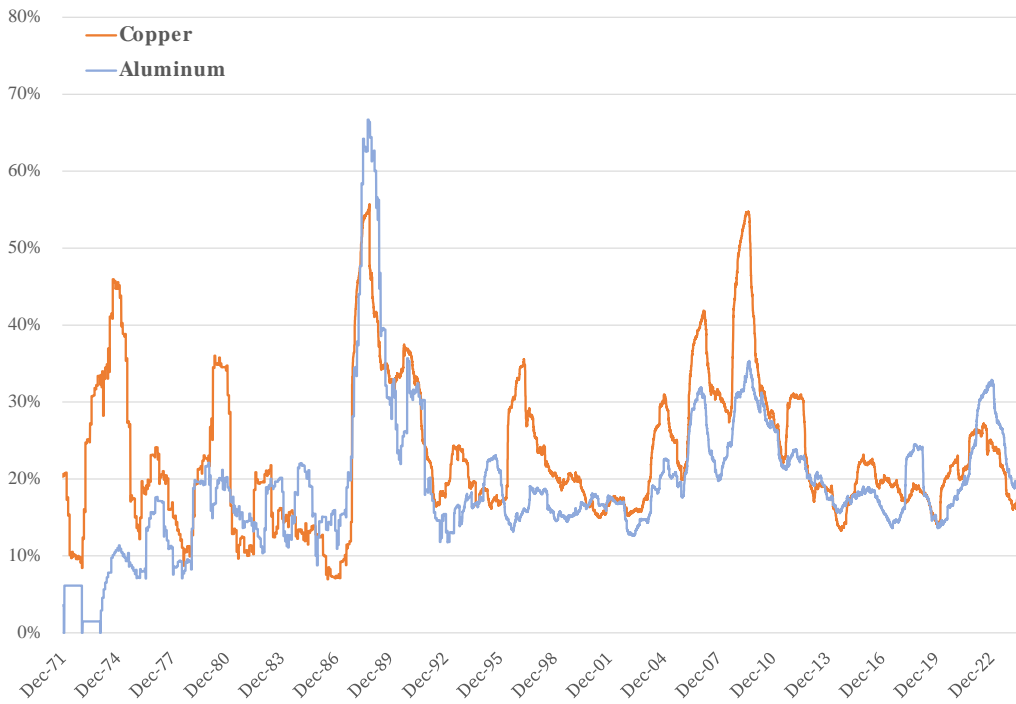
**Iron Ore for Steel, 1-yr MA Volatility**



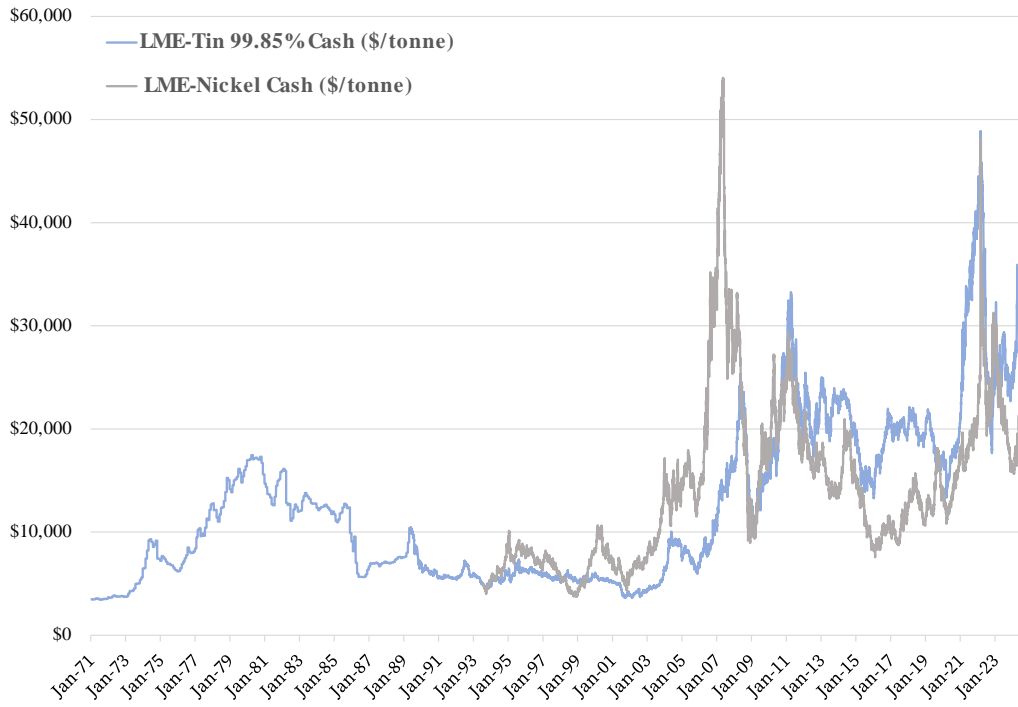
### Copper, Aluminum



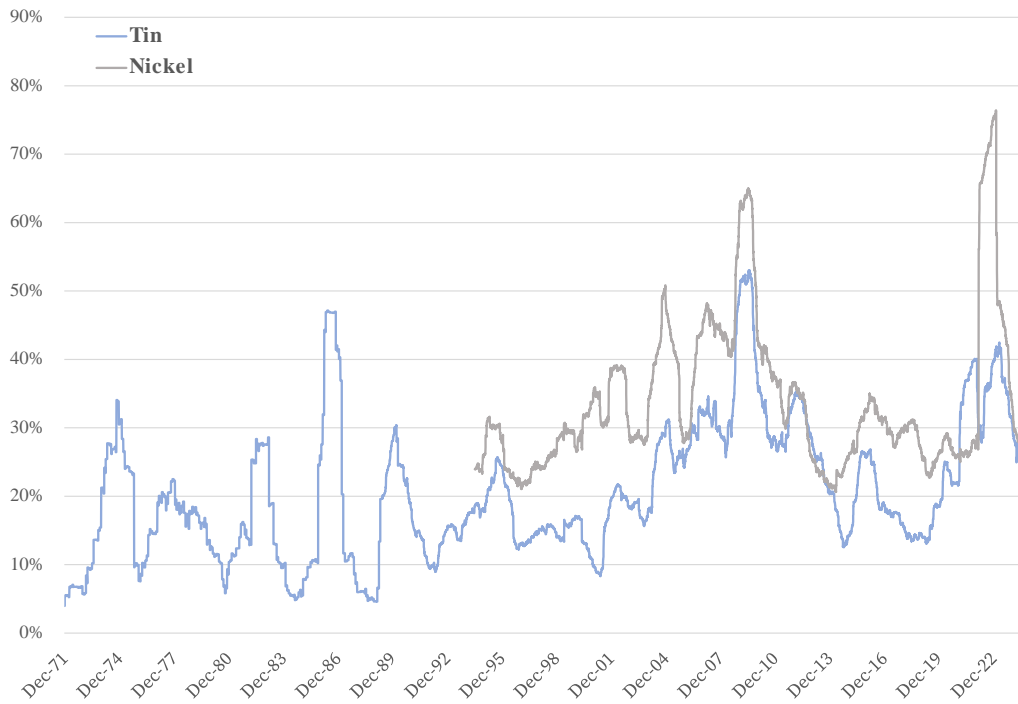
### Copper, Aluminum 1-yr MA Volatility

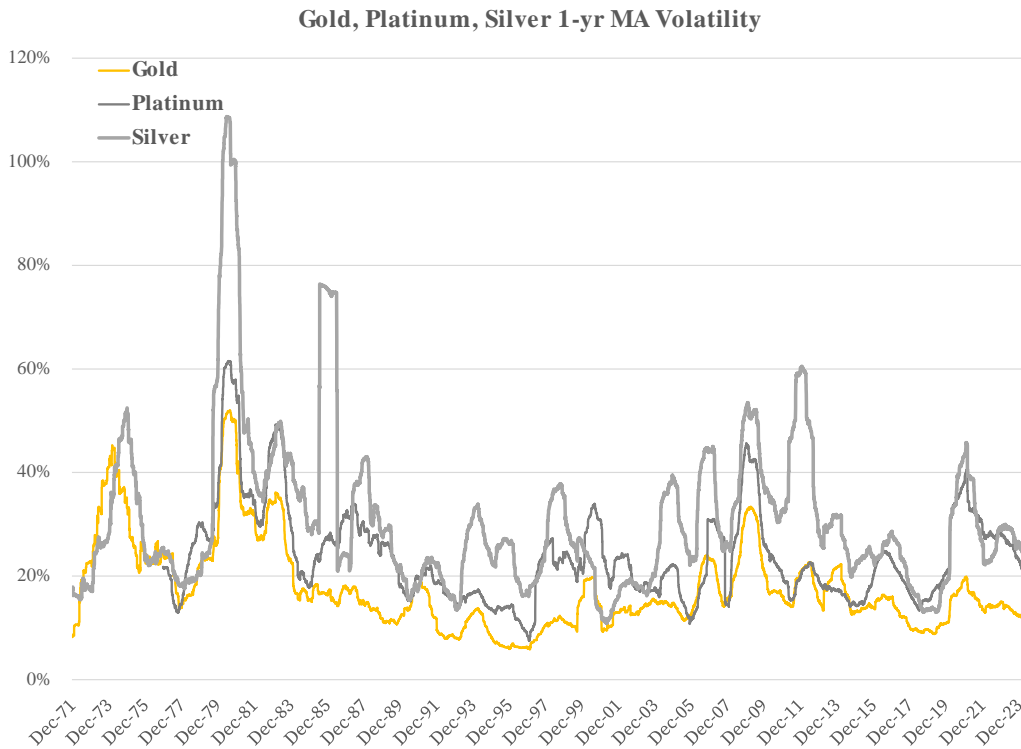
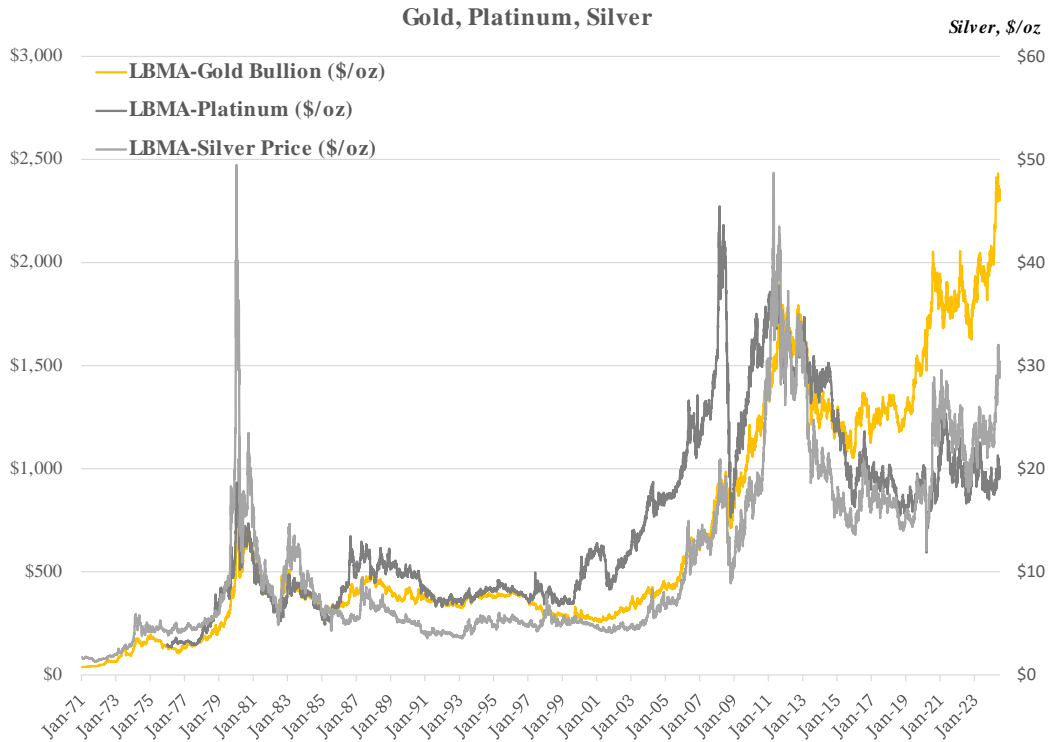


### Tin, Nickel



### Tin, Nickel 1-yr MA Volatility





**Source:** Author using U.S. EIA data for oil and S&P Global data for metals. Volatilities computed by author. Iron ore fines derived from Platts. All using daily settled prices.

**Note:** LME is London Metals Exchange. LBMA is London Bullion Market Authority. Bbl is barrel, MA is moving average.

Although participation in metals trading has grown, crude oil still dominates other commodities and some financial instruments. The vast liquidity in oil markets, with volumes in oil futures contracts alone about 10 times the daily volumes of physical product in the marketplace, enables effective hedging practices that are not only acceptable, but also required by investors and lenders. While gold and copper have strong market presence, they pale in comparison to crude oil. The lack of liquidity in metals markets hinders access to capital markets and encourages the use of bilateral contracts with thin spot markets available for clearing imbalances. Most metals and minerals are not traded in open markets, resulting in insufficient price discovery to enable risk-taking. Highly sought elements, such as tellurium, indium, gallium, and germanium, fit into this category.

**Table 5 – Commodity Trading Volumes and Open Interest**

Commodity (Futures)	Volume	Open Interest
Oil	926,555	1,750,497
Gold	301,670	503,537
Copper	273,932	308,168
Silver	162,492	174,695
Platinum	46,330	82,778
Aluminum	10,728	3,180
Cobalt	124	17,199
Lithium Hydroxide	114	22,177
Molybdenum Oxide	20	996

Source: CME Group as of April 9, 2024.<sup>137</sup>

The lack of liquidity is coincident with a lack of confidence in the exchanges, primarily due to insufficient oversight and a lack of surveillance. This deficiency can lead to various market irregularities and uncertainties.

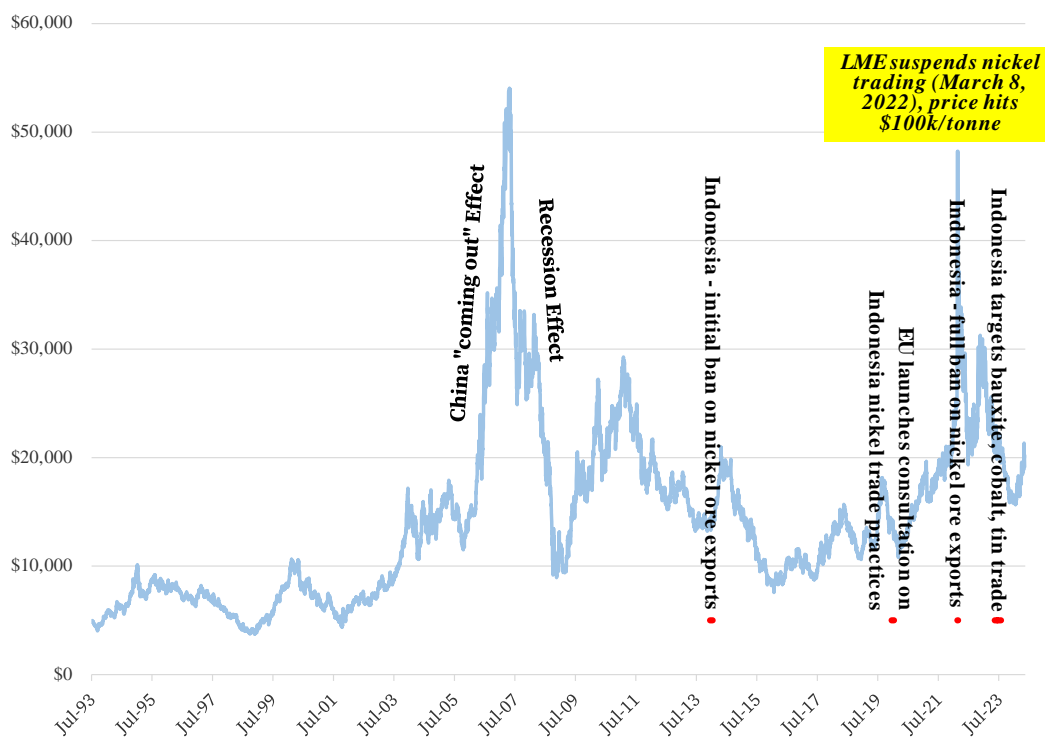
### *Trading Skirmishes*

On March 27, 1980, the price of silver collapsed after an attempt was made to “corner the market.” This event contributed to the exit of metals trading from the United States and the strengthening of regulatory practices.<sup>138</sup> Consequently, the LME, established in 1571, became the global hub of metals trading.

Flash forward to March 8, 2022, when the price of nickel on the LME skyrocketed to \$100,000 per tonne during that day (**Figure 25**). Large positions to short the nickel prices had been taken by Tsingshan’s management and its chief executive officer in anticipation of their own development plans for projects in Indonesia and elsewhere (see previous discussion on nickel in Indonesia). Tsingshan expected nickel prices to

come under pressure and so placed bets accordingly. Russia’s invasion of Ukraine upended this strategy by creating uncertainty about Russian exports of Class 1 nickel, driving prices higher. The need to cover expensive bets by Tsingshan and all of the market participants who had followed the short – which were all backed by bankers – led to chaos on the LME, prompting the exchange and its regulator, U.K.’s Financial Conduct Authority (FCA), to halt trading. That action contrasted with the U.S. Commodities Futures Trading Commission’s decision not to suspend trading during the 1980s silver collapse. Nor did the U.K.’s central bank, the Bank of England, intervene as the U.S. Federal Reserve Bank did during the silver episode. But plenty of other damage was done, including roughly \$11 billion in bank losses for Tsingshan alone and immense pressure placed on the LME to “right the ship” and restore confidence.<sup>139</sup>

**Figure 25 – Nickel Trading Events**

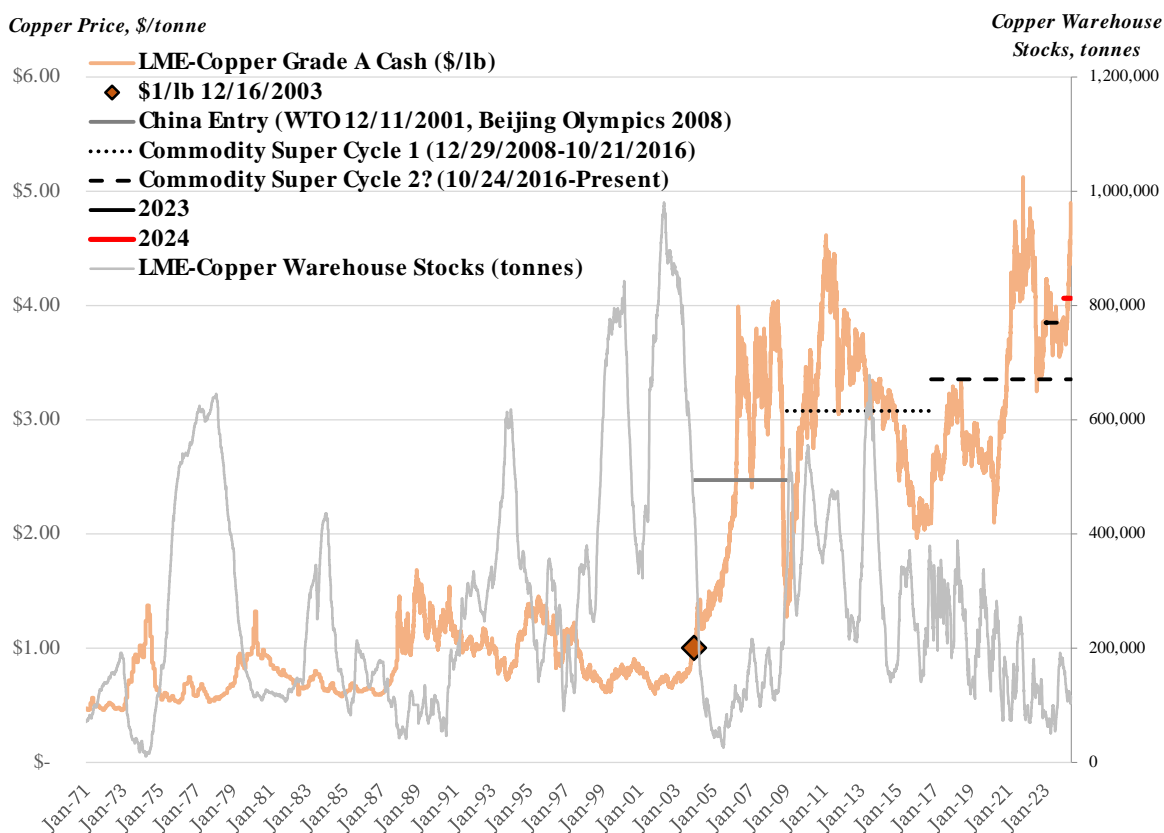


**Source:** Author using S&P Global data, accessed via license, and other sources including the U.S. International Trade Commission.<sup>140</sup>

One notable aspect of the nickel case is LME’s ownership by China’s Hong Kong Exchanges and Clearing. Market participants in Chinese exchanges such as Shanghai, Dalian, and Zhengzhou often take positions at LME. While liquidity is deepening in China, the extent of oversight and surveillance is still evolving. Apart from financial trading of commodities, various incidents in the physical trade of commodities have undermined market stability in China and elsewhere. Critical to commodity trading is information on stocks, as price movements are often inverse to changes in inventory (see **Figure 26**, with notable events and cycles). The LME certifies warehouses, as do other

exchanges. Chinese interests hold substantial positions in physical commodities inventories, with estimates suggesting that 30% to 40% or more of LME warehouse capacity is owned by those interests. Thus, it is fair to be concerned about the management of warehouses and stocks and whether holders of inventories could act in ways that could influence pricing on exchanges.<sup>141</sup>

**Figure 26 – Commodity Price ‘Eras’: Copper Example**



**Source:** Author using S&P Global data, accessed via license, and other sources.

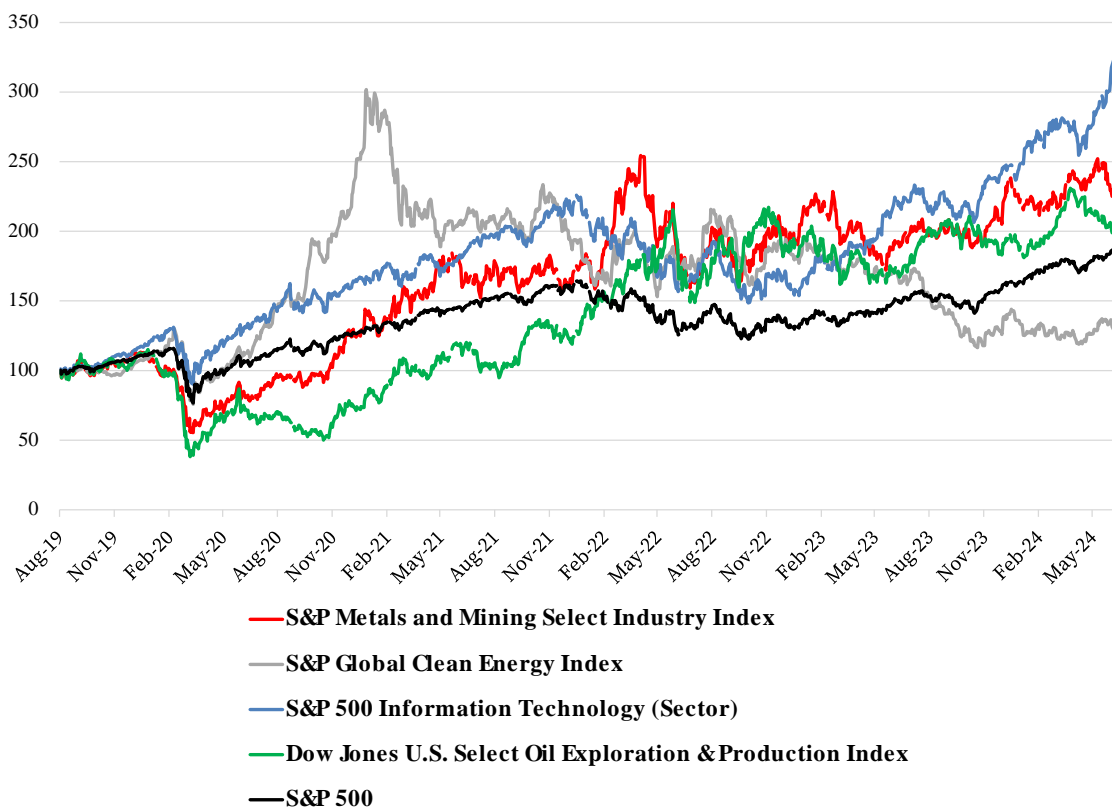
### Capital Markets and Mining Finance

By every account, capital markets are not favorable toward the mining industry. Safety, pollution, social ills, and other risks are off-putting to capital providers who now have years of high-tech returns and tend to view basic industries with skepticism.<sup>142</sup>

That said, investors ultimately seek returns, and in recent years, the mining industry has stacked up well relative to competing opportunities, at least as far as mining shares go. For some time, mining has been on the rise, surging beyond the five-year horizon shown in **Figure 27**. Mining shares have outperformed the S&P 500, oil and gas sectors, and notably, global clean energy indices, which have been underperforming all major sectors. Interestingly, the clean energy index appears to have had its own peak,

coinciding with the oil volatility spike and investor sentiments toward oil demand and green new deals, as described in the introductory sections to this report. How the erosion in values of clean energy shares fits in with the minerals demand story is an interesting puzzle. While clean energy technology faces a number of proof-of-concept hurdles, it is not yet a “valley of death” situation. It does warrant close monitoring as the industry and investor priorities for returns continue to evolve.

**Figure 27 – Comparative Equities Indexes**



**Source:** S&P Dow Jones Indices, accessed via license.

**Note:** Five-year total returns.

In reality, as noted earlier, mining, minerals, and metals may not be as dependent upon green new deals as commonly believed, at least across a broad slate of commodities. The fundamentals, as outlined previously, weigh heavily on prospects for forward supply. Fears of widespread commodity price collapses are unwarranted under a “business as usual” scenario (if not under the continued Chinese dominance case). Analyzing the copper supply stack in **Figure 10** within the context of **Figure 26**, and the copper price eras as defined, provides useful guidance. A sharp price decline clearly would knock out a substantial portion of the supply curve with significant ramifications across economies and not just sectors. This is true across the board for all commodities, in particular key metals.

In the two-way debate over whether minerals supply constraints will hinder energy transitions, or whether slower shifts in energy technology will diminish the prospects for minerals and metals, there will be winners and losers in all directions. For thematic investors in minerals and metals, the energy transition storyline poses a conundrum: Can “policy push” industries and businesses, those primarily driven by policy initiatives, survive when profitability is aspirational, at best?<sup>143</sup> The next 12 to 18 months will be crucial in revealing sensitivities, as corporate capital spending strategies undergo stress testing. Post-pandemic inflation has exposed interest rate dependencies in both clean energy technology and mining, as well as specialty materials. Large tranches of federal spending, embedded in the Inflation Reduction Act and other subsidies, intensified concerns about government fiscal deficits and debts. The obligations are additive to other post-pandemic spending and, before that, post-2009 financial recession recovery efforts. Ultimately, the pace and timing of materials-dependent energy transition policies will likely be determined by the politics of government budgets and, in the United States and Europe, the appetite for Chinese dominance in supply chains for and manufacturing of wind, solar, batteries, BEVs, and much else.

## Challenges of Old and New Insecurities

Would transitioning from legacy fuels to alternative energy sources mitigate security risks as so many hope? The concept of energy transitions entails many trade-offs and conflicting assumptions. Initially, attention quickly focused on whether traditional oil exporting countries would face severe destabilization due to the loss of revenue and economic activity associated with the global oil industry. Those worries have been supplanted by questions about whether a pendulum swing to mining, minerals, and metals can be accompanied by improved outlooks for broad social benefits from resource wealth.

The perception of a “resource curse” or the “paradox of plenty” – in which natural resource-rich societies do not reap expected benefits from monetizing their endowments – remains an old dilemma that still begs answers. This is despite concerted efforts by companies, donor countries, multilateral institutions, NGOs, civil societies, and host governments to improve transparency, governance, and fiscal management, and to optimize revenue use for education, training, and much else. Historical experience has fostered determination to avoid repeating past mistakes for mining, minerals, and metals should the energy transition storyline persist. Yet much, if not all, of the real or perceived paradox lies in weaknesses and/or failures of governance that are deeply embedded in societies. As large economic rents accrue from resource extraction, they can amplify ineffectiveness of governance that already is inadequate for socioeconomic development.

Additionally, there is a growing realization that green energy deals may not be very affordable, certainly for a very long time. Affordability underlies the push for “justice” as part of the energy transition political arrangement.

The call for social justice is playing out in three ways. First, relative to the problem of social benefits from resource extraction, is how to ensure more just outcomes in the creation of and distribution of benefits. However, minerals and metals share similar boom-bust dynamics with other commodities, meaning significant wealth and opportunity when prices are good and activity levels are high, but income and budget erosion when they are not. Countries dependent upon mining and minerals revenues have previously attempted to build producer associations with cartel-like quota management to assert some modicum of market control. For tin, copper, and more recently nickel and lithium, clusters of resource-rich countries are in active conversations about how to coordinate. The problem, as always, is maintaining discipline. Sovereign and “rainy day” funds offer potential solutions to balancing boom-bust cycles, albeit with appropriate governance.

Second, the emphasis on affordability and social justice is being linked to sustainability goals as they pertain to societies and communities proximal to, or that host, extractive industry operations. Social justice imperatives add to complexities of the project development cycle no matter where projects are located.

Finally, the emphasis on affordability, social benefits, and social justice is taking on new meaning when it comes to taxpayer backing of – and, thus, political support for – green new deals and the energy transition storyline. In some circumstances, as here in the United States, promises of domestic content and jobs are a direct consequence, creating a feedback loop to supply chain stresses. Overall, as public opinion has played out, voters and taxpayers in many countries appear to take a dim view of the energy transition project if they are affected by higher costs for energy, housing, transport, goods, and services. As these cost increases tend to be regressive, that only reinforces social justice disparities.

The contextual background provided above raises three key geopolitical considerations: resource nationalism, the new minerals world order, and more broadly, political risks associated with fragile states and the supply chains linked to them.

### *From Resource Curse to Resource Nationalism*

Following the waves of nationalizations in the 1970s, exemplified by Chile’s consolidation of copper mining assets into Corporación Nacional del Cobre (National Copper Corporation of Chile/Codelco), the overt government takeover of extractive industry assets seemed to decline, if not disappear entirely. Throughout the 1990s and early 2000s, the trend shifted toward full or partial privatization of state-owned enterprises (SOEs). Such was the case for national oil companies and many electric power SOEs, if not for mining, as the world experienced broad efforts to “liberalize” economies.<sup>144</sup> The “Washington consensus” on open trade and competitive markets, a hallmark of efforts to counter endless debt default cycles among developing countries, spurred this movement. However, like other “fads and fashions,” the consensus faded as events took over.<sup>145</sup> The 2008 financial recession, the surge in oil prices in 2011, new

discoveries of oil in Guyana and elsewhere, the pandemic, subsequent borrowing and spending, and now energy transition borrowing, spending, and positioning are creating new trends, with industrial policy most evident. Creeping expropriation, as detailed earlier, continues to be the main risk when it comes to governments intervening in their resource industries and businesses.

In 2018, Indonesia nationalized Grasberg, the world's second-largest copper-producing asset.<sup>146</sup> While rattling old political risk cages, the move seems more compatible with "resource nationalism" tendencies among net exporting countries. A new spin on old inclinations, "resource nationalism" revolves around increasing economic rent capture by controlling access. **Figure 25**, the trajectory of nickel prices, includes a brief litany of actions pursued by the Indonesian government to limit or prevent exports of nickel so as to promote investment in processing and manufacturing domestically, as laid out in previous sections. These kinds of policies epitomize the budding definition of nationalist tendencies toward natural resources. A developing resource nationalism thread links the pursuit of green premiums that are legitimized by sustainability imperatives with other tendencies. The example of stiffer fiscal terms for lithium in Chile (**Figure 22**), including rent capture for social benefits as a condition for licensing, is one that will likely get repeated for other commodities and locations.

Clearly, market volatility exacerbates all of these issues. As noted, resource-owning governments have long sought ways to mitigate exposure to commodity price changes and volatility, viewing control as a crucial lever. Alternatives that promote fiscal prudence to protect government income and budgets should be considered.

### **Table 6 – Voices: Resource Nationalism and Political Risks in Latin America's Mining Sector**

#### **Viewpoint: Learn from History**

By [Francisco J. Monaldi](#), Fellow in Latin American Energy Policy and Director of the Latin America Energy Program, Baker Institute<sup>147</sup>

Historically, Latin America's extractive sectors have seen recurrent episodes of resource nationalism, particularly in oil and gas, but also in mining. These episodes are characterized by increased state control over the industry and investment expropriation. They typically occurred in cycles induced by structural forces, such as high resource prices/rents or the conclusion of successful investment cycles that bolstered production and reserves. During such episodes, governments increase taxes, renege on contracts with private investors, and enhance state intervention. Ideology and institutions can limit or exacerbate the intensity of these events in each country, but the cycle is typically driven by structural factors. Conversely, during periods of resource price declines, or when a new investment cycle is needed, countries tend to move toward sector liberalization, reducing state involvement.

Given Latin America's significant concentrations of critical minerals, particularly lithium and copper, and the potential for increased profitability in their extraction, the region faces growing political risks associated with resource nationalism. We are already witnessing a drive for more government control ("nationalization"), higher government-takes in Bolivia, Chile, and Mexico, and the recent cancellation of a major copper mine concession in Panama.<sup>148</sup> Moreover, in addition to state control and higher takes, governments are increasingly pursuing domestic value-added and local-content policies, some of which resemble Indonesia's protectionist mining processing requirements that restrict raw material exports. Local and Indigenous communities are also challenging permits on environmental grounds and pushing for direct revenue sharing arrangements.

The failure of state royalty-distribution schemes to promote development in mining regions may further exacerbate these trends.

### *A New Minerals Great Game?*

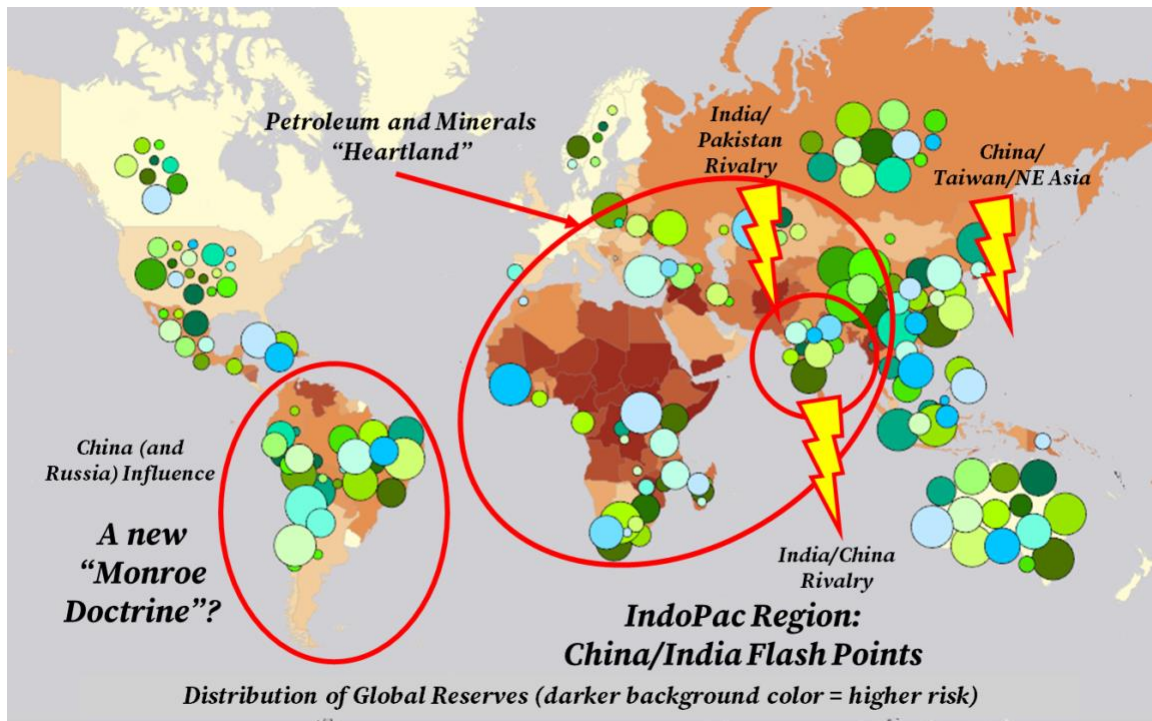
Competing geopolitical interests have historically shaped the "oil great game." Similar dynamics are now emerging in what can be termed the new "minerals great game." This new competition spans from Africa to Central Asia, a region known as the Petroleum and Minerals Heartland (see **Figure 28**) and that encompasses the old Silk Road and its intense rivalries. A new twist is the desire of Saudi Arabia, a global leader in oil production, to play the game in interesting ways. Linked to its ambitions for diversification, Saudi Arabia views green energy and materials as integral to its post-oil economic survival and competitiveness, should an end to oil actually happen. The Saudis are expanding the role of their mining SOE, Ma'aden, through joint ventures with the Saudi sovereign fund (Public Investment Fund/PIF), providing incentives for domestic minerals development and engaging in outbound opportunities. Importantly, their objectives include working to build leadership in mining, minerals, and materials within the heartland "super region," which is of particular interest to the United States and Europe. The question remains whether Saudi Arabia can leverage its substantial wealth in useful ways, as both supplier and customer countries work to find common ground on the array of mining, minerals, and metals challenges.<sup>149</sup>

### *Fragile States and Supply Chain Insecurities*

In the past, when international oil companies and governments were at odds in great game maneuvering — e.g., oil and gas pipeline routes exiting Caspian fields — China was an emerging market, not nearly as surefooted as the country is today. As profiled throughout this report, with China's growing roles in Indonesia, Central Africa, and elsewhere, its influence is now ubiquitous. This necessitates including China in strategic calculations in constructive ways, particularly regarding Middle East security and global power politics. As depicted in **Figure 28**, many geopolitical flashpoints involve Chinese influence and sway. The dilemma is not just China's intentions. Russia,

Iran, and other governments in China’s orbit are active in these geographies. The increasing presence of Chinese interests in South America is raising questions about U.S. territorial security. Indo-Pacific fragilities necessitate stronger ties with India. Northeast Asia tensions mean boosting longtime associations with Japan and Korea.

**Figure 28 – Mapping Conflict Minerals and Risks**



**Source:** Author enhancements to image from International Institute for Sustainable Development.<sup>150</sup>

Mitigating geopolitical risks and uncertainties and their potential solutions surpass any single country’s capacity, underscoring the importance of cooperation. This implies getting on the same page among large countries as to priorities. Alone and together, various initiatives for partnerships and outreach are being undertaken by a host of large economies.<sup>151</sup> Much is at stake. At present these agreements appear to be “Balkanizing” in their effect, but it is early days yet. Mining and metals have crept into G20 and G7 deliberations and communiqués, fostering encouragement that member governments are moving up the learning curve.<sup>152</sup>

Many of these issues will eventually come down to defense preparedness, crucial both domestically and within the broader geopolitical context. Minerals and materials supply chains are a defense readiness priority. The amalgam of minerals, materials, and technologies within these supply chains carries significant implications for defense industries, necessitating careful calculus on responses. Defense budgets are increasingly supporting investment in minerals and metals sourcing and processing, a trend that is likely to continue. Defense stockpiles are getting fresh looks as to what

they should include, how they should be managed and by whom, and who should have access.

On the flip side, securing minerals and materials supply chains may require layers of protection that involve defense agencies and industries. This could encompass safeguarding shipping lanes, keeping the peace in sensitive locations, and ensuring the security of neighboring and allied nations, in particular “friendlies” upon whom we will rely for much of the minerals and materials content we are trying to source.

## Options, Alternatives, and Policy Inferences

This report covers a wide range of ideas. The mining industry is poised to explore and test many, if not most or all, of the innovative concepts discussed here, particularly those related to sustainability. There is significant potential for creativity in the technical aspects of minerals, materials, mining, and processing. As noted, the hope is that capital markets follow and are friendly to industry initiatives. The main problem lies in setting sensible goals and priorities for energy, minerals, and materials overall and gaining traction in these areas. As always, the geological realities remain as they are, and the key objective is to expand commerciality.

**It is vital to reiterate that the dominant, pervasive thematic driver of energy transition demand is both intertwined with and distinct from mining and minerals fundamentals.**

Clarifying this point is a key objective of this report. The challenges for this sector, as highlighted throughout this document, are longstanding, given the essential role of minerals and metals in many applications. Political agendas are fluid. The June 2024 EU parliamentary voting “greenlash” has revealed the vast political risks and uncertainties associated with current energy and environmental policies.<sup>153</sup>

Political backlash against ambitious green energy and materials policies exacerbates market tensions for nonenergy and defense customers and consumers of minerals and metals. It is essential to focus on the status of mining and minerals processing, regardless of viewpoints regarding future consumption. Ultimately, it is vital to address basic considerations of competitiveness in order to achieve any version of energy and economic success in the years ahead. From workforce and labor to investment and trade, there are a multitude of opportunities for repair and reinvigoration. Dabbling in industrial policy too often exacerbates distortions and glosses over more important, albeit more difficult, imperatives. Everything needs to be on the table, including long-held, almost sacrosanct beliefs in how environmental protections should be ensured.

Finally, societies, industries, and governments will benefit most from having a range of choices and the freedom to make informed decisions. To conclude, several concepts should be prioritized, as highlighted below.

- **Promote advanced materials research and design.** It can be discouraging to navigate numerous U.S. and other government programs and initiatives without

seeing a strong push for a fundamental paradigm shift in materials building blocks. New and advanced materials can alleviate many, if not all, of the dilemmas embodied in the nine challenges addressed here. We should prioritize and focus efforts to leapfrog current materials and technologies. As stated at the outset, much of advanced materials design will involve carbon materials like CNTF. Replacing tonnes of copper with CNTF in automobiles and aircraft, and developing new, lighter, and stronger composites for a wide range of products, are goals worth pursuing. These efforts can, and should, align with the “design for re-X” concepts. Can an ICEV hypercar built with advanced materials for super efficiencies compete with BEVs on a full life-cycle basis? That is a valid and important research question that deserves to be tackled.<sup>154</sup>

- **Protect and preserve the oil and gas industry, especially our domestic base.** This may seem an odd recommendation given the tenor of these times. The oil and gas industry remains a principle and vital source of carbon-based energy and materials for the foreseeable future. We must recognize the **value of carbon** in energy systems, materials, and everyday life. Carbon-based fuels are poised to experience yet another round of efficiency gains. The global hydrocarbon industry serves as an irreplaceable hedge against the uncertainties inherent in new technology development and deployment. Developing better strategies to support and sustain this industry requires urgent attention.
- **Prepare for failures.** Historically, intense government, industry, and public mobilization to accelerate spending and achieve often poorly articulated and defined outcomes has frequently overlooked the potential for failure. While the goal is to succeed, the reality is that only a very small number of start-ups and commercialization efforts survive. The valley of death for new ventures is both wide and deep. As this report was completed, it seems likely that many intended outcomes of current laws and regulations may not materialize, given the odds. When it comes to government-led capital infusions, failure rates are even higher because of political influences. The task of preserving “corporate memory” to learn from mistakes and to achieve some optionality is hard enough in the private sector and nearly impossible in the public one. That places responsibility on private actors for building the exit ramps that are integral to good strategic planning and execution.

## Acknowledgements

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## Notes

<sup>1</sup> CES is operating two projects for Rice Carbon Hub, <https://carbonhub.rice.edu/>. One project entails the use of solid carbon for soil remediation. The second involves assessing the competitiveness of CNTF against metals.

<sup>2</sup> “Center for Energy Studies,” Rice University’s Baker Institute for Public Policy, <https://www.bakerinstitute.org/center/center-energy-studies#-4062963801>.

<sup>3</sup> The White House, “Fact Sheet: The Bipartisan Infrastructure Deal,” November 6, 2021, <https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/>; The White House, “Inflation Reduction Act Guidebook,” January 2023, <https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/>; The White House, Fact Sheet: Chips and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China,” August 9, 2022, <https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/>; and Internal Revenue Service (IRS), “Credits and Deductions Under the Inflation Reduction Act of 2022,” updated July 29, 2024, <https://www.irs.gov/credits-and-deductions-under-the-inflation-reduction-act-of-2022>.

<sup>4</sup> U.S. Environmental Protection Agency (EPA), “Final Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3,” updated June 17, 2024, <https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-standards-heavy-duty>.

<sup>5</sup> These include an effort to achieve permitting reform, taken up again in sections on Challenge of Project Cycle Times and Challenges in Achieving Sustainability. Congress failed to include reform in the IRA as originally envisioned. The lack of meaningful changes to how mining and infrastructure projects are reviewed and licensed is widely viewed as a dampening effect on energy-related investments. The Committee for a Responsible Federal Budget (<https://www.crfb.org/>) provides excellent insights on U.S. government appropriations and fiscal policy. The Congressional Budget Office (CBO) released a dim view in its June 18, 2024, budget revision report (*An Update to the Budget and Economic Outlook: 2024 to 2034*, June 18, 2024, <https://www.cbo.gov/publication/60039>).

<sup>6</sup> The White House, “Fact Sheet: President Biden Takes Action to Protect American Workers and Businesses From China’s Unfair Trade Practices,” May 14, 2024, <https://www.whitehouse.gov/briefing-room/statements-releases/2024/05/14/fact-sheet-president-biden-takes-action-to-protect-american-workers-and-businesses-from-chinas-unfair-trade-practices/>.

<sup>7</sup> Drawn from “Energy Transition Investment Trends 2024,” *Bloomberg New Energy Finance* (BNEF), 2024.

<sup>8</sup> Rachel A. Meidl, “Schrödinger’s Cat Paradox: Carbon Is the Enemy. Carbon Is Not the Enemy” (Houston: Rice University’s Baker Institute for Public Policy, August 9, 2023), <https://doi.org/10.25613/5ED9-S212>; Meidl and Kenneth B. Medlock III, “The Pride and Prejudice of Sustainability: Rethinking Sustainability From a Systems Perspective” (Houston: Rice University’s Baker Institute for Public Policy, November 8, 2023), <https://doi.org/10.25613/20CH-3Z48>.

<sup>9</sup> Meidl, “Disentangling Circular Economy, Sustainability and Waste Management Principles” (Houston: Rice University’s Baker Institute for Public Policy, July 29, 2021), <https://www.bakerinstitute.org/research/disentangling-circular-economy-sustainability-and-waste-management-principles>; Meidl, “A Circular Economy Doesn’t Necessarily Imply

Sustainability” (Houston: Rice University’s Baker Institute for Public Policy, August 3, 2021), <https://www.bakerinstitute.org/research/circular-economy-does-not-necessarily-translate-sustainability>.

<sup>10</sup> U.S. Congress, House of Representatives, Committee on Energy & Commerce, Subcommittee on Energy, Hearing on The CLEAN Future Act: Driving Decarbonization of the Transportation Sector, 117th Cong. 1st sess. (May 5, 2021) (statement of Michelle Michot Foss, “Minerals & Materials Supply Chains – Considerations for Decarbonizing Transportation”), <https://www.bakerinstitute.org/research/minerals-materials-supply-chains-considerations-for-decarbonizing-transportation>.

<sup>11</sup> U.S. Congress, “Hearing on The CLEAN Future Act.”

<sup>12</sup> The author visited (and entered the nacelle of) the Medicine Bow all-metal wind turbine in 1984. James Bailey, “The Medicine Bow Wind Energy Project,” Historic Reclamation Projects, U.S. Bureau of Reclamation, 2014, <https://www.usbr.gov/history/ProjectHistories/Wind%20Electric%20Power%20Project.pdf>.

<sup>13</sup> Michot Foss, “The ‘Criticality’ of Minerals for Energy Transitions. Hydrocarbons? Yes, Hydrocarbons” (Houston: Rice University’s Baker Institute for Public Policy, February 8, 2021), <https://www.bakerinstitute.org/research/the-criticality-of-minerals-for-energy-transitions-hydrocarbons-yes-hydrocarbons>.

<sup>14</sup> Kathleen Quirk, CEO of Freeport-McMoRan, in a view common across the mining industry, commented on electrified transport as a “new thematic demand driver” for copper at the Veriten energy conference on June 7, 2024.

<sup>15</sup> Based on Wood Mackenzie’s Future Facing Commodities Forum, March 27, 2024.

<sup>16</sup> For example, see Claudiu Pavel and Evangelos Tzimas, “Raw Materials in the European Defense Industry,” European Commission, Joint Research Centre, 2016, <https://publications.jrc.ec.europa.eu/repository/handle/JRC98333>.

<sup>17</sup> American Chemistry Council, “Chemistry and Automobiles,” 2023, <https://plasticmakers.org/wp-content/uploads/2023/02/Chemistry-and-Automobiles-March-2023.pdf>.

<sup>18</sup> See Table 1 in Michot Foss, “Mining, Minerals, and Materials” for capacity factors estimated for various electric power generation technologies in the United States. For instance, roughly 78,000 wind turbines in the United States generate about 338 billion megawatt hours (MWh) of electricity. Based on nameplate capacity of the turbine units, they should contribute 1,708 billion MWh except for variability of the resource (“Mining, Minerals, and Materials in the Age of Sustainability and Alliances” [Houston: Rice University’s Baker Institute for Public Policy, written in partnership with the Future Minerals Forum, February 8, 2024], <https://www.bakerinstitute.org/research/mining-minerals-and-materials-age-sustainability-and-alliances>). See Figures 6–8 in Peter R. Hartley, Medlock, and Shih Yu (Elsie) Hung for the preponderance of incidences when both wind and solar generation are absent and other sources/solutions are required (“ERCOT and the Future of Electric Reliability in Texas” [Houston: Rice University’s Baker Institute for Public Policy, February 7, 2024], <https://www.bakerinstitute.org/research/ercot-and-future-electric-reliability-texas>). As quoted in Bailey: “One is immediately confronted by three problems in any program to make use of wind power on any significant scale: 1) its low energy density necessitates a large capture unit; 2) the energy must be captured from moment to moment and its availability varies; and 3) energy storage involves considerable additional costs. These factors have limited the historical use of wind power almost exclusively to small-scale systems.”

<sup>19</sup> Gabriel Collins and Michot Foss, “The Global Energy Transition’s Looming Valley of Death,” (Houston: Rice University’s Baker Institute for Public Policy, January 27, 2022), <https://doi.org/10.25613/Y18Q-PM32>.

<sup>20</sup> International Energy Agency (IEA), *Global EV Outlook 2024*, April 2024, <https://www.iea.org/reports/global-ev-outlook-2024>.

<sup>21</sup> IEA, *World Energy Outlook 2023*, October 2023, <https://www.iea.org/reports/world-energy-outlook-2023>.

<sup>22</sup> WoodMac’s forecast has sales of all EVs growing from 16 million in 2023 to 54 million by 2033 (WoodMac, Future Facing Commodity Forum). BNEF, in their “Long-Term Electric Vehicle Outlook,” starts from a much higher 2023 base than the IEA’s of more than 20 million in total EV sales, with dramatic growth to exceed 68 million by 2033 (BNEF, *Electric Vehicle Outlook 2023*; IEA, *Global EV Outlook 2024*).

<sup>23</sup> Kirsten Hund et al., “Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition,” World Bank Group, 2020, <https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf>.

<sup>24</sup> The IEA puts growth multiples between 2020–40 at 42x for lithium, 25x for natural graphite, 21x for cobalt, 19x for nickel, and 7x for rare earths (IEA, “The Role of Critical Minerals in Clean Energy Transitions,” 2021, <https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf>). The IEA 2024 update follows suit: “Demand for copper rises by 50% by 2040, while demand for nickel, cobalt and rare earth elements doubles, and graphite ... increases by four times ... lithium stands out ... with eightfold growth by 2040” (“Outlook for Key Minerals,” 2024, <https://www.iea.org/reports/global-critical-minerals-outlook-2024/outlook-for-key-minerals>).

<sup>25</sup> Based on the original IEA net zero outlook (IEA, “Net Zero by 2050: A Roadmap for the Global Energy Sector,” May 2021, <https://www.iea.org/reports/net-zero-by-2050>), as summarized by Mark Finley, CES Fellow in Energy and Global Oil after release.

<sup>26</sup> See the following report and additional web resources: Mekala Krishnan et al., “The Net-Zero Transition,” McKinsey Global Institute, January 2022, <https://www.mckinsey.com/capabilities/sustainability/our-insights/six-characteristics-define-the-net-zero-transition>.

<sup>27</sup> For a good synopsis of current conditions, see Mark P. Mills, “Tapping the Brakes on Electric Vehicles,” *City Journal*, January 29, 2024, <https://www.city-journal.org/article/tapping-the-brakes-on-electric-vehicles>; and Mills’ comprehensive report: “Electric Vehicles for Everyone? The Impossible Dream,” Manhattan Institute, July 12, 2023, <https://manhattan.institute/article/electric-vehicles-for-everyone-the-impossible-dream>. In early 2024, in a clear argument for middle ground, Toyota Motor Corporation released its “1:6:90” rule in a communique to dealers. Materials requirements for only one BEV would yield six plug-in hybrids or, even more pronounced, 90 hybrids (Toyota, “Beyond Zero Vision,” <https://www.toyota.com/electrified-vehicles/beyond-zero-vision/>).

<sup>28</sup> “A Delayed Energy Transition,” Wood Mackenzie, April 15, 2024, <https://www.woodmac.com/reports/energy-markets-a-delayed-energy-transition-150261256/>. For a synopsis, see Simon Flowers and Prakash Sharma, “Is Net Zero by 2050 at Risk?” *The Edge*, Wood Mackenzie, April 18, 2024, <https://www.woodmac.com/news/the-edge/is-net-zero-by-2050-at-risk/>.

<sup>29</sup> U.S. government representative at industry roundtable, no attribution requested, March 2024.

- <sup>30</sup> Colin Dessemond et al., “Spodumene: The Lithium Market, Resources and Processes,” *Minerals* 9, no. 6 (2019): 334, <https://doi.org/10.3390/min9060334>.
- <sup>31</sup> Nassar et al., “Rock-to-Metal Ratio.”
- <sup>32</sup> Nedal T. Nassar et al., “Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes,” *Environmental Science & Technology* 56, no. 10 (April 25, 2022): 6710–21, <https://doi.org/10.1021/acs.est.1c07875>.
- <sup>33</sup> “Global Minerals Production Dashboard,” Rice University’s Baker Institute for Public Policy, <https://www.bakerinstitute.org/global-minerals-production-dashboard>; U.S. Geological Survey (USGS), “National Minerals Information Center,” <https://www.usgs.gov/centers/national-minerals-information-center> (For USGS interactive mapping tools, visit USGS, “Mineral Resources Online Spatial Data,” <https://mrdata.usgs.gov/>); World Mining Data, <https://www.world-mining-data.info/>.
- <sup>34</sup> How do we establish minerals and materials “criticality” in the U.S.? The effort flows both up from basic science and down, based on determinations of vulnerabilities with annual updates. U.S. Department of Energy, “What Are Critical Materials and Critical Minerals?” ; U.S. Department of Energy, “Notice of Final Determination on 2023 DOE Critical Materials List,” 88 Fed. Reg. 51792 (August 4, 2023), <https://www.federalregister.gov/documents/2023/08/04/2023-16611/notice-of-final-determination-on-2023-doe-critical-materials-list>; Steven M. Fortier et al., “Annual Review 2022: Critical Minerals,” *Mining Engineering Magazine*, May 2023, <https://apps.usgs.gov/minerals-information-archives/articles/USGS-Critical-Minerals-Review-2022.pdf>. Executive Order 14017: America’s Supply Chains, executed on February 24, 2021, directed reviews of supply chain risks and vulnerabilities pertaining to both raw materials and manufacturing and sought recommendations (Exec. Order 14017, 86 Fed. Reg. 11849 [March 1, 2021], <https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains>). Executive Order 14017 referenced previous executive orders, in particular Executive Order 13953 targeting critical minerals (Exec. Order. No. 13953, 85 Fed. Reg. 62539 [October 5, 2020], <https://www.federalregister.gov/documents/2020/10/05/2020-22064/addressing-the-threat-to-the-domestic-supply-chain-from-reliance-on-critical-minerals-from-foreign>).
- <sup>35</sup> Michot Foss and Jacob Koelsch, “Need Nickel? How Electrifying Transport and Chinese Investment Are Playing Out in the Indonesian Archipelago” (Houston: Rice University’s Baker Institute for Public Policy, April 11, 2022), <https://www.bakerinstitute.org/research/need-nickel-how-electrifying-transport-and-chinese-investment-are-playing-out-indonesian-archipelago>.
- <sup>36</sup> “China Drives Global Stainless Steel Production Growth,” MEPS International, January 31, 2024, <https://mepsinternational.com/gb/en/news/china-continues-to-drive-global-production-growth>.
- <sup>37</sup> In keeping with the copper illustration, see Nassar et al., “Global Tellurium Supply Potential From Electrolytic Copper Refining,” *Resources, Conservation and Recycling* 184, (September 2022), <https://doi.org/10.1016/j.resconrec.2022.106434>. For related news, see “Rio Tinto to Build New Tellurium Plant at Kennecott Mine,” *Business Wire*, March 8, 2021, <https://www.businesswire.com/news/home/20210308005509/en/>; and “Bingham Canyon, Copper Mine, Utah, USA,” *Mining Technology*, July 27, 2022, <https://www.mining-technology.com/projects/ingham/>.
- <sup>38</sup> “The Nickel Price Crash and the Road to Recovery in Australia,” *Mining Technology*, April 23, 2024, <https://www.mining-technology.com/features/nickel-price-crash-australia-crisis-recovery/?cf-view>. As of writing, riots in New Caledonia, if persistent, could alter views (Gus Trompiz, “Explainer: What New Caledonia Riots Mean for the Nickel Industry,” *Reuters*, May 22,

2024, <https://www.reuters.com/markets/commodities/what-new-caledonia-riots-mean-nickel-industry-2024-05-22/>).

<sup>39</sup> The book remains available in its entirety: Donella H. Meadows et al., *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (New York: Universe Books, 1972), <https://www.clubofrome.org/publication/the-limits-to-growth/>. Low and falling ore grades were linked to metals prices (W.G.B. Phillips and D.P. Edwards, "Metal Prices as a Function of Ore Grade," *Resources Policy* [September 1976], <http://web.mit.edu/2.813/www/readings/Metal%20Prices%20Ore%20Grades%201976%20Phillips%20and%20Edwards.pdf>).

<sup>40</sup> A more nuanced view of metals production is offered in a report by Kristín Vala Ragnarsdóttir and Harald U. Sverdrup. They also present arguments for recycling, which bears its own complications. Of note is the authors' worries about insufficient capacity from alternative energy sources to offset "peak oil" irrespective of metals inputs and likely because of their overarching message about "real" limits ("Limits to Growth Revisited," *Geoscientist Online*, October 2015, <https://www.geolsoc.org.uk/Geoscientist/Archive/October-2015/Limits-to-growth-revisited>).

<sup>41</sup> The past-prologue, ore grade debate is taken head on with optimistic views on technology-enabled discoveries in Magnus Ericsson et al., "Why Current Assessments of 'Future Efforts' Are No Basis for Establishing Policies on Material Use—A Response to Research on Ore Grades," *Mineral Economics* 32 (March 25, 2019): 111–21, <https://doi.org/10.1007/s13563-019-00175-6>.

<sup>42</sup> For an excellent case study of how mining practices have influenced copper extraction, raising questions about whether use of trends in ore grades may overstate supply-side pressures, see Nadine Rötzer and Mario Schmidt, "Decreasing Metal Ore Grades—Is the Fear of Resource Depletion Justified?" *Resources* 7, no. 4 (December 19, 2018): 88, <https://doi.org/10.3390/resources7040088>. For an explanation of how the Indonesian case serves as an example of a bet on processing technology (HPAL) to extract nickel from low-grade laterite resources, see Michot Foss and Koelsch, "Need Nickel?"

<sup>43</sup> Norman J. Page and S. C. Creasy, "Ore Grade, Metal Production, and Energy," *Journal of Research of the U.S. Geological Survey* (1975), <https://www.usgs.gov/publications/ore-grade-metal-production-and-energy>; Guiomar Calvo, José Luis Palacios, and Alicia Valero, "The Influence of Ore Grade Decline on Energy Consumption and GHG Emissions: The Case of Gold," *Environmental Development* 41, (March 2022), <https://doi.org/10.1016/j.envdev.2021.100683>; and Ricardo Magdalena, Valero, and Calvo, "Limit of Recovery: How Future Evolution of Ore Grades Could Influence Energy Consumption and Prices for Nickel, Cobalt, and PGMs," *Minerals Engineering* 200, (September 2023), <https://doi.org/10.1016/j.mineng.2023.108150>.

<sup>44</sup> Michot Foss and Koelsch, "Need Nickel?"

<sup>45</sup> See project summary at "Weda Bay Nickel Project," *NS Energy*, December 23, 2020, <https://www.nsenergybusiness.com/projects/weda-bay-nickel-project/?cf-view>.

<sup>46</sup> See project history and details for Resolution Copper at <https://resolutioncopper.com/>.

<sup>47</sup> For background, see "Copper Mining in AZ and Tribal Lands," Superfund Research Center, The University of Arizona, <https://superfund.arizona.edu/resources/modules/copper-mining-and-processing/copper-mining-az-and-tribal-lands>. For information on the land swaps at heart of the contentions, see Anita Snow, "Oak Flat Timeline: Native American vs. Pro-Mining Interests," *AP News*, June 28, 2023, <https://apnews.com/article/oak-flat-sacred-apache-copper-mine-26fa76965cf75a4addb4108c4818af09>; Mrinmay Dey and Ernest Scheyder, "Native American Group Seeks to Overturn US Court Ruling on Rio's Arizona Copper Mine," *Reuters*, April 16, 2024,

<https://www.mining.com/web/native-american-group-seeks-to-overturn-us-court-ruling-on-rios-arizona-copper-mine/>; and U.S. Department of Agriculture (USDA), Tonto National Forest, “Resolution Copper Project and Land Exchange Environmental Impact Statement,” <https://www.resolutionmineeis.us/project-overview>.

<sup>48</sup> There are, of course, a multitude of “takes” on what was really understood and intended by the fleet of laws and rules on the books (or soon to be on the books) for the United States (see Summary: Not One, But Many Possible Futures). In general, serious questions could be raised regarding policy and regulatory actions taken since 2020, whether raw materials constraints were fully appreciated and whether a “mining renaissance” in the United States truly was a hoped for or planned outcome. For a good example of current commentary, see Holman W. Jenkins, Jr., “Anatomy of an EV Policy Error,” *Wall Street Journal*, May 28, 2024, [https://www.wsj.com/articles/anatomy-of-an-ev-policy-error-poor-strategy-the-us-researched-and-followed-anyway-a24e5e98?mod=opinion\\_lead\\_pos9](https://www.wsj.com/articles/anatomy-of-an-ev-policy-error-poor-strategy-the-us-researched-and-followed-anyway-a24e5e98?mod=opinion_lead_pos9). For questions regarding intentions and preparedness, see Michot Foss, “Building a Clean Energy Future Means Securing Vital Minerals Today,” *The Hill*, July 28, 2022, <https://thehill.com/opinion/energy-environment/3577676-building-a-clean-energy-future-means-securing-vital-minerals-today/>.

<sup>49</sup> Pierre Lassonde, *The Gold Book: The Complete Investment Guide to Precious Metals* (London: Penguin Books, 1990). Lassonde’s is a book of practical rules, almost always violated. Research into how well the Lassonde cycle prevails when applied to actual projects and company market cap valuations yields general support for concept but also highlights the many deviations and vagaries. A central idea in Lassonde’s concept – that company share price would decline as the mineral asset was depleted – was not supported by such research. This was likely because in the case of gold, price reflects demand for the commodity as a financial instrument, suggesting many lines of potential future research beyond what the authors indicated (Timothy Rijdsdijk et al., “Confirming the Lassonde Curve Through Life Cycle Analysis and its Effect on Share Price: A Case Study of Three ASX Listed Gold Companies,” *Resources Policy* 77 [August 2022], <https://doi.org/10.1016/j.resourpol.2022.102704>).

<sup>50</sup> “Phases of Mining,” Resource Capital Funds, January 9, 2024, <https://resourcecapitalfunds.com/insights/mining-and-minerals-101/phases-mining/>. For another version with useful background, see “The Lassonde Curve – Understanding the Mining Life Cycle,” Small Cap Investor, April 1, 2023, <https://www.smallcapinvestor.ca/post/the-lassonde-curve-understanding-the-mining-life-cycle>. For a version that injects some humor into the storyline, see Frank Holmes, “The Journey From Exploration To Production: Understanding The Lifecycle Of A Mine,” U.S. Global Investors, April 19, 2023, <https://www.usfunds.com/resource/the-journey-from-exploration-to-production-understanding-the-lifecycle-of-a-mine/>. For a source that frequently informs other websites, see Nicholas LePan, “Visualizing the Life Cycle of a Mineral Discovery,” *Visual Capitalist*, September 12, 2019, <https://www.visualcapitalist.com/visualizing-the-life-cycle-of-a-mineral-discovery/>.

<sup>51</sup> At least relatively, based on a recent analysis of mining projects by S&P Global analysts. They estimate 15.2 years on average for 70 gold mines (Paul Manalo, “Discovery to Production Averages 15.7 Years for 127 Mines,” *S&P Global*, June 6, 2023, <https://www.spglobal.com/marketintelligence/en/news-insights/research/discovery-to-production-averages-15-7-years-for-127-mines>).

<sup>52</sup> “The Lassonde Curve – Understanding the Mining Life Cycle.”

<sup>53</sup> An intriguing historical fact is that the company initially engaged was Magma Copper Company, which got its start in Arizona’s copper district in 1890 and was eventually absorbed

into Resolution Copper. For an interesting and full treatment of Oyu Tolgoi, see Sergei Diakov, Samand Sanjdorj, and Galsan Jamsrandorj, *Discovery of Oyu Tolgoi: A Case Study of Mineral and Geological Exploration* (Amsterdam: Elsevier, 2019), <https://doi.org/10.1016/C2017-0-04170-8>.

<sup>54</sup> S&P Global's results (Manalo) are compatible with the IEA's estimate of 16–18 years to production (with variations among locations) put forth in its inaugural minerals report (IEA, "The Role of Critical Minerals in Clean Energy Transitions").

<sup>55</sup> For news and details on Mingomba, see William Clowes, "AI-Powered Miner Says It Found Huge Copper Deposit in Zambia," *Bloomberg*, February 5, 2024, <https://www.bloomberg.com/news/articles/2024-02-05/bill-gates-backed-miner-finds-world-class-zambian-copper-deposit?sref=QKIHH2Pn>; Cecilia Jamasmie, "Gates, Bezos-Backed KoBold Metals Says Zambia Copper Find Largest in a Century," *Mining.com*, February 5, 2024, <https://www.mining.com/gates-bezos-backed-kobold-says-zambia-copper-find-largest-in-a-century/>; "The Central African Copper Belt," *Geology for Investors*, updated June 9, 2017, <https://www.geologyforinvestors.com/deposits-central-african-copper-belt/>; "On the Ground at Mingomba," *Mining for Zambia*, March 22, 2023, <https://miningforzambia.com/on-the-ground-at-mingomba/>; and Harry Dempsey, "Bill Gates-Backed Mining Company Discovers Vast Zambian Copper Deposit," *Financial Times*, February 4, 2024 <https://www.ft.com/content/28c36ea0-fd3a-48be-b49c-76fe63b9a0f2>. The USGS describes the Central African Copper Belt as two geographically separate copper provinces – Congo Copper Belt (CCB) and Zambian Copper Belt (ZCB) (Murray W. Hitzman et al., "Cobalt–Styler Deposits and the Search for Primary Deposits," USGS Open-File Report 2017–1155, 2017, <https://doi.org/10.3133/ofr20171155>).

<sup>56</sup> In Rijdsdijk et al., the authors describe a de-risking continuum over time from exploration target through mineralization, inferred resource, indicated resource, and reserve, with increasing cost but also increasing confidence.

<sup>57</sup> Drawn from presentations by Taylor DeJongh shared with author during international development training programs, 2001–13.

<sup>58</sup> For an excellent summary of the transportation logistics politics in Central Africa, see Brian Gicheru Kinyua, "U.S. and China Back Competing Rail Corridors to Zambia's Copper Belt," *The Maritime Executive*, February 11, 2024, <https://maritime-executive.com/article/u-s-and-china-back-competing-rail-corridors-to-zambia-s-copper-belt>.

<sup>59</sup> Michot Foss and Koelsch, "Need Nickel?"

<sup>60</sup> Michot Foss et al., "Defining Community and Economic Benefits Associated With Large Energy Infrastructure Projects: LNG Case Study," proprietary report, The University of Texas at Austin's Bureau of Economic Geology, Center for Energy Economics, 2007. Case study conducted for the BEG-CEE LNG research consortium (2002–11) on 25 LNG import facilities under development in the United States and Canada with information drawn from regulatory dockets and other materials.

<sup>61</sup> The demands associated with project origination and development, particularly as related to host communities and Indigenous populations, are an ongoing interest within CES and other Baker Institute programs and centers, as well as outside groups and organizations. Specific observations come from a workshop on resource politics hosted by the Energy, Minerals, and Materials and Latin American Energy Roundtable programs at the CES on September 7–8, 2023, as well as follow-on exchanges. Comments also reflect prevailing views and content expressed during sessions at the Prospector and Developers Association of Canada annual convention from March 3–6, 2024, in Toronto and at the Future Minerals Forum in Riyadh, January 10–12, 2023, and January 9–11, 2024. An example of Indigenous consultation efforts that incorporate

active participation is the First Nations Major Projects Coalition (<https://fnmpc.ca/>). First Nations groups in Canada have taken equity positions in oil and gas pipeline, LNG projects, and minerals and mining, with backing from Ottawa and some provinces. A good illustration of views on consultation are those related to Canada's huge "Ring of Fire" region during special sessions at the Prospectors & Developers Association of Canada (PDAC) convention (Andrew Grant et al., "Indigenous Consultation is Key to the Ring of Fire Becoming Canada's Economic Superpower," *The Conversation*, March 20, 2024, <https://theconversation.com/indigenous-consultation-is-key-to-the-ring-of-fire-becoming-canadas-economic-superpower-225742>).

<sup>62</sup> The litany of permitting reform in the United States is instructive. Key, current actions and news are listed below in rough chronological order.

- A case was made for permitting reform as part of the IRA, but it was not incorporated into final legislation, leading to a separate effort controversial for its inclusion of legacy infrastructure (Kelsey Tamborrino, "Manchin's Pitch to Energy Leaders: IRA Without Permitting Reform a Missed Opportunity," *Politico*, September 23, 2022, <https://www.politico.com/news/2022/09/23/manchins-pitch-to-energy-leaders-ira-without-permitting-reform-a-missed-window-00058558>).
- A new legislative round was kicked off in May 2023 ("Manchin Moves Ball Forward on Permitting Reform," U.S. Senate Committee on Energy and Natural Resources, May 2, 2023, <https://www.energy.senate.gov/2023/5/manchin-moves-ball-forward-on-permitting-reform>).
- That legislation was upended by an April 30, 2024, White House, Council on Environmental Quality "rule" that includes NEPA "modernization" for selected infrastructure projects and may or may not survive court challenges – to either the Council on Environmental Quality or the implementing agencies like the EPA and the Federal Energy Regulatory Commission (FERC) for electric power transmission and other portions (The White House, "Biden-Harris Administration Finalizes Reforms to Modernize Environmental Reviews, Accelerate America's Clean Energy Future, Simplify the Process to Rebuild our Nation's Infrastructure, and Strengthen Public Engagement," press release, April 30, 2024, <https://www.whitehouse.gov/ceq/news-updates/2024/04/30/biden-harris-administration-finalizes-reforms-to-modernize-environmental-reviews-accelerate-americas-clean-energy-future-simplify-the-process-to-rebuild-our-nations-infrastructure/>; The White House, "FACT SHEET: Biden-Harris Administration Delivers on Permitting Progress to Build America's Infrastructure and Clean Energy Future Faster, Safer, and Cleaner," April 30, 2024, <https://www.whitehouse.gov/briefing-room/statements-releases/2024/04/30/fact-sheet-biden-harris-administration-delivers-on-permitting-progress-to-build-americas-infrastructure-and-clean-energy-future-faster-safer-and-cleaner/>).
- The White House action elicited a rapid senatorial reaction ("ICYMI: Manchin Statement on Final Rule for NEPA Review Process," U.S. Senate Committee on Energy and Natural Resources, April 30, 2024, <https://www.energy.senate.gov/2024/4/manchin-statement-on-rulemaking-implementing-nepa-permitting-reforms>; Zack Budryk, "Manchin Vows to Introduce Resolution to Overturn Biden Permitting Rule," *The Hill*, April 30, 2024, <https://thehill.com/policy/energy-environment/4633491-joe-manchin-west-virginia-congressional-resolution-overturn-biden-permitting-rule/>). The Congressional Review Act (CRA) resolution was announced May 8, 2024 ("ICYMI: Manchin, Graves, Sullivan to Introduce Bipartisan, Bicameral CRA Resolution on NEPA Phase II Final Rule," U.S.

Senate Committee on Energy and Natural Resources, May 8, 2024, <https://www.energy.senate.gov/2024/5/icymi-manchin-graves-sullivan-to-introduce-bipartisan-bicameral-cra-resolution-on-nepa-phase-ii-final-rule>).

- A CRA resolution of disapproval to overturn the final tax rule related to EV subsidies and domestic materials content was introduced on May 16, 2024, reflecting deeper discontent with White House policymaking that relaxes domestic content targets (“Manchin Leads Bipartisan, Bicameral Group to Introduce CRA Resolution of Disapproval to Overturn Administration’s Final 30D EV Tax Credit Rule,” U.S. Senate Committee on Energy and Natural Resources, May 16, 2024, <https://www.energy.senate.gov/2024/5/manchin-leads-bipartisan-bicameral-group-to-introduce-cra-resolution-of-disapproval-to-overturn-administration-s-final-30d-ev-tax-credit-rule>).
- A new push for congressional permitting reform was announced in light of news regarding rapid electric power load growth (Ethan Howard, “Sens. Manchin, Barrasso Craft Bipartisan Permitting Reform Bill Amid Growing Load Forecasts,” *Utility Dive*, May 22, 2024, <https://www.utilitydive.com/news/manchin-barrasso-permitting-reform-bill-demand-hearing-aep/716809/>).
- Sen. Joe Manchin, a central figure in the permitting reform debate and the wider debates on energy and climate policy, announced his departure from the Democratic Party (Lisa Mascaro, Kevin Freking, and Leah Willingham, “Democratic Sen. Joe Manchin of West Virginia Registers as Independent, Citing ‘Partisan Extremism,’” *AP News*, May 31, 2024, <https://apnews.com/article/joe-manchin-congress-west-virginia-senate-a4eb66f2cb773f822b6b607945cdeaef>).
- On July 22, 2024, permitting reform legislation led by Sens. Manchin and Barrasso was finally released, <https://www.energy.senate.gov/2024/7/manchin-barrasso-release-bipartisan-energy-permitting-reform-legislation>.

<sup>63</sup> One commentator, Robert Bryce, has initiated a “rejection database” for wind and solar projects (“Renewable Rejection Database,” <http://0v9.95b.mywebsitetransfer.com/renewable-rejection-database/>). The complex positions of supporters and opponents are revealed in closer looks at individual cases.

<sup>64</sup> Jon Emont, “China is Winning the Minerals War,” *Wall Street Journal*, May 21, 2024, [https://www.wsj.com/finance/commodities-futures/china-dominant-mineral-mining-global-supply-chain-e2b7840e?mod=itp\\_wsj](https://www.wsj.com/finance/commodities-futures/china-dominant-mineral-mining-global-supply-chain-e2b7840e?mod=itp_wsj). This story was recirculated in social media, for instance, by Senator John Cornyn ([@JohnCornyn], “China Is Winning the Minerals War,” X post, May 22, 2024, <https://x.com/JohnCornyn/status/1793227292308557959>). The author posted a rejoinder on LinkedIn: Michot Foss, “Dear Folks at the Wall Street Journal,” LinkedIn post, May 24, 2024, [https://www.linkedin.com/posts/michelle-michot-foss-b8255517\\_need-nickel-how-electrifying-transport-and-activity-7198707914608447488-9IW/](https://www.linkedin.com/posts/michelle-michot-foss-b8255517_need-nickel-how-electrifying-transport-and-activity-7198707914608447488-9IW/).

<sup>65</sup> From the World Bank 2022 commodity markets report: John Baffes and Peter Nagle, *Commodity Markets: Evolution, Challenges, and Policies*, World Bank Group, 2022, <https://www.worldbank.org/en/research/publication/commodity-markets>.

<sup>66</sup> REE processed in China is returned to the United States in products like magnets, indicative of the two-pronged problem of materials supply and manufacturing capacity. Since third quarter of 2023, MP Materials, operator of Mountain Pass, has been producing separated and refined rare earths including NdPr (neodymium-praseodymium) oxide, cerium chloride, lanthanum carbonate, and SEG+ (samarium, europium, gadolinium and other elements, a heavy rare earths

or HREE concentrate). MP Materials is still ramping up its separation facility, with about 600 tons of NdPr produced since start up. The company is building a downstream metal, alloy, and magnet manufacturing facility in Fort Worth, Texas, which will begin producing NdPr metal later in 2024, and, in late 2025, finished NdFeB(neodymium, iron, boron) magnets for General Motors. Historically, REE extraction in the United States has been burdened by the presence of radioactive elements such as thorium. While important progress is being made to diversify REE supply chains, low prices for REE products as Chinese producers release inventory with slowing economic conditions since spring 2024 will have bearing on profitability of suppliers in the U.S. and elsewhere. Michot Foss and Koelsch, "Of Chinese Behemoths: What China's Rare Earths Dominance Means for the U.S." (Houston: Rice University's Baker Institute for Public Policy, December 19, 2022), <https://doi.org/10.25613/5ZTC-WP59>.

<sup>67</sup> Koelsch et al., "Chinese Firms Position for an Energy Transition Copper Supercycle" (Houston: Rice University's Baker Institute for Public Policy, April 5, 2021), <https://www.bakerinstitute.org/research/chinese-firms-position-energy-transition-copper-supercycle>.

<sup>68</sup> "China Tightens Grip on Copper, Key to World's Energy Transition," *Bloomberg*, November 12, 2023, <https://www.bloomberg.com/news/articles/2023-11-12/china-tightens-its-grip-on-the-greenest-metal-of-them-all>.

<sup>69</sup> As of February 2024, see "Top 5 Alumina Producers That Keep the China Market Ahead," *AL Circle*, February 29, 2024, <https://www.alcircle.com/news/top-5-alumina-producers-that-keep-the-china-market-ahead-109061>.

<sup>70</sup> Based on "China's Aluminum Production Exceeds 10 Million Tonnes in Q1 2024, With an Annual Output Rise of 4% in March," *AL Circle*, April 9, 2024, <https://www.alcircle.com/news/chinas-aluminium-production-exceeds-10-million-tonnes-in-q1-2024-with-an-annual-output-rise-of-4-in-march-110456>; and United States Geological Survey (USGS), "Aluminum," 2023, <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf>.

<sup>71</sup> Daniel Quiggin and Richard King, "Cobalt Refining Power Gives China an Advantage in the Race for EV Battery Dominance," Chatham House, July 4, 2023, <https://resourcetrade.earth/publications/critical-metals-ev-batteries>.

<sup>72</sup> Eri Silva, "Manganese Sulfate Bottleneck Looms Over US, European EV Manufacturers," *S&P Global Market Intelligence*, January 24, 2023, <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/manganese-sulfate-bottleneck-looms-over-us-european-ev-manufacturers-73926378>.

<sup>73</sup> Michot Foss and Koelsch, "Need Nickel?"; "China Drives Global Stainless Steel Production Growth."

<sup>74</sup> Siyi Liu and Dominique Patton, "China, World's Top Graphite Producer, Tightens Exports of Key Battery Material," *Reuters*, October 20, 2023, <https://www.reuters.com/world/china/china-require-export-permits-some-graphite-products-dec-1-2023-10-20/>.

<sup>75</sup> Alex Scott, "The Great Lithium Race," *C&EN Global Enterprise*, October 31, 2022, <https://pubs.acs.org/doi/10.1021/cen-10038-feature1>.

<sup>76</sup> Michot Foss and Koelsch, "Of Chinese Behemoths."

<sup>77</sup> The World Lead Fact Book 2023, International Lead and Zinc Study Group, [https://www.ilzsg.org/wp-content/uploads/SitePDFs/1\\_ILZSG%20World%20Lead%20Factbook%202023.pdf](https://www.ilzsg.org/wp-content/uploads/SitePDFs/1_ILZSG%20World%20Lead%20Factbook%202023.pdf).

<sup>78</sup> *The World Zinc Fact Book 2020*, International Lead and Zinc Study Group,

[https://www.ilzsg.org/wp-content/uploads/SitePDFs/2\\_ILZSG%20World%20Zinc%20Factbook.pdf](https://www.ilzsg.org/wp-content/uploads/SitePDFs/2_ILZSG%20World%20Zinc%20Factbook.pdf).

<sup>79</sup> "Platinum Quarterly: Q1 2024," World Platinum Investment Council, May 13, 2024,

[https://platinuminvestment.com/files/475579/WPIC\\_Platinum\\_Quarterly\\_Q1\\_2024.pdf](https://platinuminvestment.com/files/475579/WPIC_Platinum_Quarterly_Q1_2024.pdf).

<sup>80</sup> Masanobu Nakamizu, "Latest Developments in Steelmaking Capacity 2023," Organisation for Economic Co-operation and Development (OECD), 2023,

[https://one.oecd.org/document/DSTI/SC\(2023\)3/FINAL/en/pdf](https://one.oecd.org/document/DSTI/SC(2023)3/FINAL/en/pdf).

<sup>81</sup> Michot Foss and Koelsch, "Of Chinese Behemoths."

<sup>82</sup> Matthew Blackwood and Catherine DeFilippo, "Germanium and Gallium: U.S. Trade and Chinese Export Controls," U.S. International Trade Commission, Executive Briefings on Trade, March 2024,

[https://www.usitc.gov/publications/332/executive\\_briefings/ebot\\_germanium\\_and\\_gallium.pdf](https://www.usitc.gov/publications/332/executive_briefings/ebot_germanium_and_gallium.pdf);

Wenxin Fan and Sha Hua, "China Tightens Its Chokehold on Graphite Needed for EV Batteries," *Wall Street Journal*, October 20, 2023, <https://www.wsj.com/world/asia/china-tightens-its-chokehold-on-graphite-needed-for-ev-batteries-6cda0bc3>.

<sup>83</sup> Michot Foss and Koelsch, "Need Nickel?"

<sup>84</sup> Koelsch et al., "Chinese Firms Position." We were able to discern quality of asset in the data used for that commentary and have observed similar trends in asset data from other sources. Most often the indicator is age of asset where current operations exist, with respect to expected mine life.

<sup>85</sup> For a sample of current sentiments, see Senator Jim Risch's comments ("Risch: Monroe Doctrine Is Vital as Ever as China, Russia, Iran Exert Influence in Our Hemisphere," U.S. Senate Foreign Relations Committee, April 15, 2024,

<https://www.foreign.senate.gov/press/rep/release/risch-monroe-doctrine-is-vital-as-ever-as-china-russia-iran-exert-influence-in-our-hemisphere>).

<sup>86</sup> The author observed China's activity directly in Ghana and elsewhere through 13 years of U.S. Agency for International Development (USAID) contract and cooperative agreement technical assistance implementation. Nosmot Gbadamosi, "Ghana's Bauxite Boom," *Foreign Policy*, January 28, 2020, <https://foreignpolicy.com/2020/01/28/china-investment-bauxite-mining-ghana-infrastructure/>.

<sup>87</sup> Such was the main conclusion from the IEA's own investigation into the effects of Chinese national oil companies (NOCs) (IEA, "Overseas Investments by Chinese National Oil Companies," February 2011, <https://www.iea.org/reports/overseas-investments-by-chinese-national-oil-companies>). During the same time frame, the author, with others, participated in two World Bank studies of NOCs and value creation that included Chinese NOCs. Their observations were that opportunities and acquisitions tended to be costly, encumbering performance. Like other NOCs in the studies, China's NOCs and, presumably, China's mining and processing companies benefitted from the widespread view in capital markets that China would backstop any financial distress, enabling favorable credit ratings for the companies in spite of risk profiles (Michot Foss et al., "A Citizen's Guide to National Oil Companies," World Bank, 2008, <https://documents1.worldbank.org/curated/en/724511468181483392/pdf/471150WP0v20P11y01P109169101PUBLIC1.pdf>; and Silvana Tordo, "National Oil Companies and Value Creation," World Bank, 2011,

<https://documents1.worldbank.org/curated/en/650771468331276655/pdf/National-oil->

[companies-and-value-creation.pdf](#)). These remain rich resource topics for mining, minerals, and materials.

<sup>88</sup> Harry Dempsey and Euan Healy, “Copper Producers Warn of Lack of Mines to Meet Demand for Metal, *Financial Times*, October 8, 2023, <https://www.ft.com/content/b3ad2631-f8b9-41df-8e2e-b4493738ded8>.

<sup>89</sup> A telling comment from Henry Sanderson’s article: “There is a reasonable slug of evidence,” says one London-based fund manager, “that shows to operate there you need to do things western shareholders do not allow their management teams to do” (“Robert Friedland, China and the Rush for Copper in the Democratic Republic of the Congo,” *Financial Times*, October 29, 2019, <https://www.ft.com/content/2f170b48-eb44-11e9-a240-3b065ef5fc55>).

<sup>90</sup> For more information, see Brandon Zheng, “China’s Risky Regulation of Video Gaming” (Houston: Rice University’s Baker Institute for Public Policy, March 8, 2024), <https://doi.org/10.25613/DAQ9-9E38>.

<sup>91</sup> For more information, see Collins, “The US-China Economic Relationship Needs ‘Robust De-Risking,’ and a Little Strategic ‘Decoupling’” (Houston: Rice University’s Baker Institute for Public Policy, November 13, 2023), <https://doi.org/10.25613/PP4T-M805>.

<sup>92</sup> Based on operations at Brushy Creek, Doe Run Mining Company, which the author visited in August 2023.

<sup>93</sup> Michael S. Moats, “Where Have all the Smelters Gone? America’s Dependency on Foreign Non-Ferrous Metal Production,” presentation at O’Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science and Technology, August 3, 2021, [https://bpb-us-e2.wpmucdn.com/sites.mst.edu/dist/3/535/files/2023/11/Findings-Report\\_Workshop-on-Resilient-Supply-of-Critical-Minerals\\_Locmelis-et-al.-2021.pdf](https://bpb-us-e2.wpmucdn.com/sites.mst.edu/dist/3/535/files/2023/11/Findings-Report_Workshop-on-Resilient-Supply-of-Critical-Minerals_Locmelis-et-al.-2021.pdf).

<sup>94</sup> Yasemin Esmen, “Smelter Closure to Wipe Nearly 30% of US Aluminum Capacity,” *Fastmarkets*, January 25, 2024, <https://www.fastmarkets.com/insights/smelter-closure-to-wipe-nearly-30-of-us-aluminum-capacity/>; Andy Home, “Column: Another US Primary Aluminum Smelter Bites the Dust,” *Reuters*, January 28, 2024, <https://www.reuters.com/markets/europe/another-us-primary-aluminium-smelter-bites-dust-2024-01-26/>. These articles reference Magnitude 7’s New Madrid smelter in Missouri. It happens that natural gas costs for power generators in Missouri skyrocketed from 2021–22, based on data from the U.S. Energy Information Administration. In fact, natural gas prices for power generation in that state were substantially higher in 2022 than the U.S. average, and higher than a slew of states – roughly \$16 per million Btu (MMBtu) in Missouri as compared to \$7 per MMBtu for the United States. Missouri industrial customers, along with everyone else, could ask “what gives?” A possibility is rapid development of wind, which has appeared to pull hard on natural gas for balancing in the face of rapidly declining coal use since 2013. That would paint a similar picture for Missouri electricity customers as that observed by Hartley, Medlock, and Hung.

<sup>95</sup> For information on these developments and others, see U.S. Department of Energy, “Critical Materials Project Search,” <https://www.energy.gov/cmm/critical-materials-project-search>; <https://www.permits.performance.gov/>. The much advertised FAST-41 for infrastructure now extends to mining and minerals (“Permitting Council Announces First-Ever Critical Minerals Mining Project to Gain FAST-41 Coverage,” Permitting Dashboard, Federal Infrastructure Projects, May 8, 2023, <https://www.permits.performance.gov/fpisc-content/permitting-council-announces-first-ever-critical-minerals-mining-project-gain-fast-41>). See <https://www.businessdefense.gov/ibr/mceip/> for information on US Defense Industrial Base support for materials supply chains. See the “News” Section of “CriticalMinerals.gov,”

<https://www.criticalminerals.gov/>. For the most determined, see “USASpending.gov,” <https://www.usaspending.gov/>.

<sup>96</sup> U.S. Department of Defense, “DOD Announces Rare Earth Element Award to Strengthen Domestic Industrial Base,” news release, February 1, 2021, <https://www.defense.gov/News/Releases/Release/Article/2488672/dod-announces-rare-earth-element-award-to-strengthen-domestic-industrial-base/>. The award to Lynas for the Hondo, Texas, facility was the first made under the expanded Defense Production Act.

<sup>97</sup> For information on the graphite processing plant in Vidalia, Louisiana, which takes product from Syrah’s Balama mine in Mozambique, see “Syrah Resources Begins Natural Graphite Active Anode Material Production at Vidalia,” *Green Car Congress*, February 17, 2024, <https://www.greencarcongress.com/2024/02/20240217-syrah.html>. Syrah reached an offtake agreement with Tesla in December 2021 (“Syrah Resources Signs Binding Offtake Agreement With Tesla for Natural Graphite Active Anode Material,” *Green Car Congress*, December 24, 2021, <https://www.greencarcongress.com/2021/12/20211224-syrah.html>). The initial Department of Energy (DOE) \$107 million loan arrangement was made public in April 2022 (U.S. Department of Energy, “LPO Offers First Conditional Commitment for Critical Materials Project for Syrah Vidalia to Support Domestic EV Supply Chain,” April 18, 2022, <https://www.energy.gov/lpo/articles/lpo-offers-first-conditional-commitment-critical-materials-project-syrah-vidalia>). Start-up was achieved in February 2024 (“Syrah Starts Active Anode Material Production in Louisiana,” *Mining.com*, February 9, 2024, <https://www.mining.com/syrah-starts-active-anode-material-production-in-louisiana/>). Start-up occurred after initial troubles in Mozambique in late 2023 (Haydn Black, “Syrah Claims Balama has Unbeatable Graphite Advantage,” *MiningNews.net*, January 31, 2023, <https://www.miningnews.net/energy-minerals/news/1447324/syrah-claims-balama-unbeatable-graphite-advantage/>). In its release on start-up, the company also announced it would seek an additional \$350 million from the DOE. After the Bureau of Mines – established in 1910 and long associated with evolution of the industry – was abolished in 1995, new growth in U.S. government bureaucracy related to minerals and materials has been impressive. For background, see the following sources:

- To find official lists of critical and strategic minerals and materials, see U.S. Department of Energy, “Critical Minerals,” <https://www.criticalminerals.gov/>; Ames National Laboratory, “Critical Materials Innovation Hub,” <https://www.ameslab.gov/index.php/cmj>; and U.S. Department of Energy, “National Laboratories,” <https://www.energy.gov/national-laboratories>.
- For information on the Department of Defense, including background on the Defense Production Act and international partnerships, see Anthony Di Stasio “Manufacturing Capability Expansion & Investments Prioritization (MCEIP) Overview,” U.S. Department of Defense, <https://www.businessdefense.gov/ibr/mceip/docs/ir/MCEIP-Overview-Deck.pdf>.
- U.S. Department of State, “Minerals Security Partnership,” <https://www.state.gov/minerals-security-partnership/>. The Minerals Security Partnership falls under the Bureau of Energy Resources, <https://www.state.gov/bureaus-offices/under-secretary-for-economic-growth-energy-and-the-environment/bureau-of-energy-resources/>. See also ancillary efforts through MINVEST: U.S. Department of State, “MINVEST: Minerals Investment Network for Vital Energy Security and Transition,” <https://www.state.gov/minvest>. MINVEST falls under the Office of Global Partnerships,

<https://www.state.gov/bureaus-offices/under-secretary-for-economic-growth-energy-and-the-environment/office-of-global-partnerships/>.

- Lastly, consider the role of the U.S. Department of Interior and the USGS. In all, as the repository for the former Bureau of Mines collection and the main source of ongoing data and information on resources, including the United States' lists of critical and strategic minerals, questions are being asked about whether the role of the USGS should be expanded (Linda R. Rowan, *Critical Mineral Resources: The U.S. Geological Survey [USGS] Role in Research and Analysis*, CRS Report Prepared for Members and Committees of Congress [Washington, DC: Congressional Research Service, April 5, 2024], <https://crsreports.congress.gov/product/pdf/R/R48005>).

<sup>98</sup> An example is the Missouri Cobalt effort (“US Strategic Metals Secures \$500 Million in Funding for Missouri-Based Cobalt-Nickel Mine,” *Mining.com*, December 18, 2023, <https://www.mining.com/u-s-strategic-metals-secures-500-million-in-funding-for-missouri-based-cobalt-nickel-mine/>).

<sup>99</sup> Home, “US Looks to Reboot Aluminum Sector With a New Smelter,” *Reuters*, March 27, 2024, <https://www.reuters.com/markets/commodities/us-looks-reboot-aluminium-sector-with-new-smelter-2024-03-27/>; Julian Luk and Scheyder, “Exclusive: Grupo Mexico’s Asarco to Reopen U.S. Copper Smelter Amid Surging Prices,” *Reuters*, May 24, 2024, <https://www.reuters.com/markets/commodities/grupo-mexicos-asarco-reopen-us-copper-smelter-amid-surging-prices-2024-05-24/>. And what an icon the smelter was. For historical perspective, see Lauren Villagran, “Before Flint, Before East Chicago, There Was Smelertown,” *Natural Resources Defense Council (NRDC)*, November 26, 2016, <https://www.nrdc.org/stories/flint-east-chicago-there-was-smelertown>. For related views, see Margaret Riddle, “The ASARCO Smokestack — Once the World’s Largest — Is Demolished at the Company’s Old Copper Smelter in Ruston, North of Tacoma, on January 17, 1993,” *HistoryLink.org*, August 26, 2008, <https://www.historylink.org/File/8744>.

<sup>100</sup> An example of a critique is “President Biden’s First Term Minerals Mining Legacy,” *Minerals Make Life* (blog), May 22, 2024, <https://mineralsmakelife.org/blog/president-bidens-first-term-minerals-mining-legacy/>.

<sup>101</sup> Mentioned in “President Biden’s First Term Minerals Mining Legacy,” are Twin Metals in Minnesota and Ambler Road in Alaska, which are particular sore points within the mining industry.

<sup>102</sup> The following text from Alexander Panetta’s article was typical of reactions: “Biden may have triggered some cringes in Canadian political circles when he appeared to suggest the value-added transformation jobs from this future sector would go to the U.S.” (“U.S. Offers Cash to Canadian Critical Minerals Projects During Biden’s Visit,” *CBC News*, March 24, 2023, <https://www.cbc.ca/news/politics/critical-minerals-biden-trudeau-1.6790933>).

<sup>103</sup> For more information, see Meidl and Medlock, “The Pride and Prejudice of Sustainability.”

<sup>104</sup> For references and links to mining sustainability and related issues, see Michot Foss, “Mining, Minerals, and Materials in the Age of Sustainability and Alliances”; and Michot Foss, “Defining the ‘Minerals Heartland’ of the Future — From Africa to Central Asia,” (Houston: Rice University’s Baker Institute for Public Policy, December 20, 2022), <https://www.bakerinstitute.org/research/defining-minerals-heartland-future-africa-central-asia>.

<sup>105</sup> An interesting “roar of the crowd” opinion captures well the efforts in Canada to coordinate across internal jurisdictions (Barry Butterfield, “Canada Leads on Critical Minerals While the U.S. Falts,” *Nebraska Examiner*, March 22, 2024,

<https://nebraskaexaminer.com/2024/03/22/canada-leads-on-critical-minerals-while-the-u-s-falters/>).

<sup>106</sup> Erik Els, “Chile, Codelco Face Another Lost Decade of Output Growth,” Mining.com, September 2, 2022, <https://www.mining.com/copper-price-chile-codelco-face-another-lost-decade-of-output-growth/>.

<sup>107</sup> Questions revolve around the ability of smaller companies and juniors to implement digital innovations and measure and report on sustainability, including how well contractors will perform in that regard. Many mines are run by entities contracted by mine owners and operators.

<sup>108</sup> See Nassar, et al. “Rock-to-Metal Ratio,” supplemental information published with journal article.

<sup>109</sup> This first appeared in our nickel case study (Michot Foss and Koelsch, “Need Nickel?”).

<sup>110</sup> “Global Tailings Portal,” <https://tailing.grida.no/about>.

<sup>111</sup> For treatment of the Vale Brumadinho tailings dam collapse in Brazil’s Minas Gerais state and the coordinated response on tailings management through the International Council on Mining and Metals (ICMM), see Michot Foss, “Defining the ‘Minerals Heartland’ of the Future.” (ICMM is now positioning as the leading industry organization on sustainability principles for mining.)

<sup>112</sup> For background on the Superfund, see EPA, “Superfund,” <https://www.epa.gov/superfund>. For information on abandoned mine lands (AMLs), see EPA, “Abandoned Mine Lands,” <https://www.epa.gov/superfund/abandoned-mine-lands>. For an example of lead smelting, see EPA, *EPA Lead Smelter Strategy Summary Report*, September 2017, <https://semspub.epa.gov/work/HQ/100000189.pdf>. For additional background on AMLs, see “Characterization, Cleanup, and Revitalization of Mining Sites,” Contaminated Site Clean-Up Information, [https://clu-in.org/issues/default2.focus/sec/Characterization,\\_Cleanup,\\_and\\_Revitalization\\_of\\_Mining\\_Sites/cat/Overview/](https://clu-in.org/issues/default2.focus/sec/Characterization,_Cleanup,_and_Revitalization_of_Mining_Sites/cat/Overview/).

<sup>113</sup> Kathleen Quirk, the CEO of Freeport-McMoRan, estimated 40 billion pounds to a Houston audience at the Veriten energy conference on June 6, 2024. Daniel Gleeson, “Freeport Furthers its Leading Copper Leaching Excellence,” International Mining, February 7, 2023, <https://im-mining.com/2023/02/07/freeport-furthers-its-leading-copper-leaching-excellence/>.

<sup>114</sup> Freeport-McMoRan, “Freeport Project Selected to Receive \$80 Million from U.S. Department of Energy,” press release, March 22, 2024, <https://www.fcx.com/freeport-features/032224>; Freeport-McMoRan, “Chino Mine Clears the Way for ‘Perfect Stockpile,’” press release, May 30, 2024, <https://www.fcx.com/freeport-features/053024>; and “Copper Leaching Technology Makes Freeport-McMoRan Shares Expensive (For Now),” *Seeking Alpha*, November 7, 2023, <https://seekingalpha.com/article/4648619-copper-leaching-technology-makes-freeport-mcmoran-shares-expensive-for-now>.

<sup>115</sup> Comment made to author by Yet-Ming Chiang of MIT during the U.S. DOE ARPA-E energy summit May 2022 in Denver, Colorado. The U.S. DOE has long sought to utilize coal waste for extraction of metals. See Jeff Postelwait, “Batteries From Coal Waste? DOE Funds Projects to Extract Rare Earth Metals From Coal Byproducts,” *T&D World*, February 20, 2024, <https://www.tdworld.com/electrification/article/21283105/batteries-from-coal-waste-doe-funds-projects-to-extract-rare-earth-metals-from-coal-byproducts>.

<sup>116</sup> Yet-Ming is chief scientist for the Form Energy team developing iron-air battery technology for grid-based energy storage at abandoned steel mill sites. Debra K. Rubin, “Long-Duration

Battery Maker Will Build \$760M First Large US Plant,” *Engineering News Record*, December 23, 2022, <https://www.enr.com/articles/55660-long-duration-battery-maker-will-build-760m-first-large-us-plant>; “Form Energy,” <https://formenergy.com/>.

<sup>117</sup> Some good advice from colleague Kwame Awuah-Offei, Missouri S&T.

<sup>118</sup> Lindsay Delevingne et al., “Climate Risk and Decarbonization: What Every Mining CEO Needs to Know,” McKinsey, January 28, 2020, <https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know>.

<sup>119</sup> Michot Foss, “Defining the ‘Minerals Heartland’ of the Future.”

<sup>120</sup> Benigna Cortés Leiss, “Green Hydrogen and Chile’s Energy Transition” (Houston: Rice University’s Baker Institute for Public Policy, April 23, 2021), <https://doi.org/10.25613/ZDEG-WA5>; Cortés Leiss et al., “Paving the Road for Competitive Green Hydrogen Hubs: Does Chile Have a Chance?” (Houston: Rice University’s Baker Institute for Public Policy, May 5, 2023), <https://doi.org/10.25613/42F2-EW17>.

<sup>121</sup> Data on energy use for aluminum smelting based on IEA, “Aluminium,” <https://www.iea.org/reports/aluminium>.

<sup>122</sup> Century Aluminum operates two of the remaining four smelters, one in South Carolina and the other in Kentucky. A second smelter in Kentucky and one in West Virginia are idled and closed, respectively. The company is building a smelter in Iceland, due to enter service in 2024, that will be powered by Iceland’s hydro and geothermal energy base (Century Aluminum, “Century Aluminum Selected by U.S. Department of Energy to Receive \$500 Million Investment to Build New Green Aluminum Smelter to Accelerate Industrial Decarbonization,” press release, March 25, 2024, <https://centuryaluminum.com/investors/press-releases/press-release-details/2024/Century-Aluminum-Selected-by-U.S.-Department-of-Energy-to-Receive-500-Million-Investment-to-Build-New-Green-Aluminum-Smelter-to-Accelerate-Industrial-Decarbonization/default.aspx>).

<sup>123</sup> Binyamin Appelbaum, “American Companies Still Make Aluminum, In Iceland,” *New York Times*, July 1, 2017, <https://www.nytimes.com/2017/07/01/us/politics/american-companies-still-make-aluminum-in-iceland.html>.

<sup>124</sup> For historical context on U.S. electric power, see U.S. Energy Information Administration (EIA), “The Changing Structure of the Electric Power Industry: An Update,” December 1996, [https://inis.iaea.org/collection/NCLCollectionStore/\\_Public/28/057/28057580.pdf](https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/057/28057580.pdf). For information on the current PMAs, see U.S. Department of Energy, Office of Enterprise Assessments, “Power Marketing Administrations,” <https://www.energy.gov/ea/power-marketing-administrations>.

<sup>125</sup> Drawn from work performed by author on graphite and steelmaking as advisor to a NATO study group focused on materials supply chain security for defense industries. For an excellent roundup of issues in deploying hydrogen for steel, see “Hydrogen (H<sub>2</sub>)-Based Ironmaking,” World Steel Association, June 2022, <https://worldsteel.org/wp-content/uploads/Fact-sheet-Hydrogen-H2-based-ironmaking.pdf>. A point of view on what this might all mean for Chinese iron ore imports and steelmaking comes from Clyde Russell, “China Iron Ore Imports Likely at Peak, Demand Composition to Shift,” Reuters, May 16, 2024, <https://www.reuters.com/markets/commodities/china-iron-ore-imports-likely-peak-demand-composition-shift-russell-2024-05-16/>.

<sup>126</sup> “ARCH2 Appalachian Regional Clean Hydrogen Hub,” <https://www.arch2hub.com/>.

<sup>127</sup> International Lead Association, “Lead Batteries: The Most Recycled Consumer Product in the US,” March 16, 2022, <https://ila-lead.org/lead-batteries-the-most-recycled-consumer-product-in-the-us/>.

<sup>128</sup> A place to start on metals recovery from recycling is IEA, “End-of-Life Recycling Rates for Selected Metals,” updated April 30, 2021, <https://www.iea.org/data-and-statistics/charts/end-of-life-recycling-rates-for-selected-metals>; and “Back to the Future: the Rising Role of Metals Recycling in the Energy Transition,” Lombard Odier, May 14, 2024, <https://www.lombardodier.com/contents/corporate-news/ft-rethink/2024/may/back-to-the-future-the-rising-ro.html>.

<sup>129</sup> IEA estimate, as reported by Joseph Hoppe, “Green Transition Set to Face Critical Minerals Shortfall, IEA Says,” WSJ Pro Sustainable Business, May 17, 2024, <https://www.wsj.com/articles/green-transition-set-to-face-critical-minerals-shortfall-iea-says-cc89acf0>. Comment during a private roundtable on metals recycling and EVs held by the CES Energy, Minerals, and Materials and Energy and Environment programs on May 24, 2022.

<sup>130</sup> Meidl, Michot Foss, and Ju Li, “Waste Management of Alternative Energy Supply Chains” (Houston: Rice University’s Baker Institute for Public Policy, March 2, 2022), <https://doi.org/10.25613/BB1T-4K23>.

<sup>131</sup> News stories from which public domain images were accessed: Spencer McKee, “Homes Damaged as Likely EF3 Tornado With 150 MPH Winds Touches Down in Colorado,” Denver Gazette, August 10, 2023, [https://denvergazette.com/outtherecolorado/news/homes-damaged-as-likely-ef3-tornado-with-150-mph-winds-touches-down-in-colorado/article\\_a68f8ed0-3798-11ee-8ffa-4f567984f6ec.html](https://denvergazette.com/outtherecolorado/news/homes-damaged-as-likely-ef3-tornado-with-150-mph-winds-touches-down-in-colorado/article_a68f8ed0-3798-11ee-8ffa-4f567984f6ec.html); Sean Murphy, “Wind Towers Crumpled After Iowa Wind Farm Suffers Rare Direct Hit From Powerful Twister,” AP News, May 23, 2024, <https://apnews.com/article/tornado-iowa-wind-farm-turbines-feb9913c3d53915ffa420e277af4bb6d>; and “Baseball-Sized Hail Smashing Into Panels At 150 MPH Destroys Scottsbluff Solar Farm,” Cowboy State Daily, June 28, 2023, <https://cowboystatedaily.com/2023/06/27/baseball-sized-hail-smashing-into-panels-at-150-mph-destroys-scottsbluff-solar-farm/>.

<sup>132</sup> Comments were made to that affect during the 2022 roundtable on metals recycling and EVs mentioned previously. See also a related event, “The Future of Electric Vehicles: The EV Ecosystem and Society,” Rice University’s Baker Institute for Public Policy, May 24, 2022, <https://www.bakerinstitute.org/event/future-electric-vehicles-ev-ecosystem-and-society>.

<sup>133</sup> The EPA, Pipeline and Hazardous Materials Safety Administration (PHMSA, U.S. Department of Transportation), U.S. Postal Service (USPS), and Federal Aviation Administration (FAA) are coordinating on ways to transport lithium-ion battery (LIB) products, which are banned from passenger air cargo and must be labeled and packaged for USPS and other shipping. U.S. agencies and those in other countries are coordinating with the UN on international movements of goods with LIBs. For a glimpse into the process at the EPA, see EPA, “Battery Collection Best Practices and Battery Labeling Guidelines,” <https://www.epa.gov/infrastructure/battery-collection-best-practices-and-battery-labeling-guidelines>.

<sup>134</sup> In private discussions about proposed 30% premiums for green hydrogen steel made in Europe, an American auto industry representative indicated that their company would not partake. Any price premiums would be directed toward “shoes for Indonesian nickel miners.”

<sup>135</sup> A suggestion from a congressional staff member.

<sup>136</sup> World Bank Group, “Commodity Markets,” <https://www.worldbank.org/en/research/commodity-markets>.

- <sup>137</sup> CME Group, “CME Group All Products – Codes and Slate,” <https://www.cmegroup.com/markets/products.html#sortDirection=desc&sortField=vol>.
- <sup>138</sup> “Silver Thursday” was noted in the passing of Herbert Hunt on April 9, 2024, who, with his brother Bunker, hatched the trading strategy (Chris Kornelis, “Herbert Hunt, Billionaire Who Tried to Corner the Silver Market, Dies at 95,” Wall Street Journal, May 3, 2024, <https://www.wsj.com/finance/commodities-futures/herbert-hunt-billionaire-silver-market-dies-at-95-4d73913a>).
- <sup>139</sup> Nicole Goodkind, “How a Chinese Metal Tycoon Imploded the Nickel Market – and Walked Away With Billions,” CNN Business, July 12, 2022, <https://www.cnn.com/2022/07/12/economy/nickel-tycoon-lme/index.html>. See the report of investigation, London Metal Exchange (LME), “Independent Nickel Market Review,” January 10, 2023, <https://www.lme.com/en/trading/initiatives/nickel-market-independent-review>.
- <sup>140</sup> Michot Foss and Koelsch, “Need Nickel?”
- <sup>141</sup> All based on numerous interviews and discussions held by author following the nickel trading incident. For information on China’s emerging rules to contain fraud in raw materials trading, see “China Mulls Tougher Rules on Commodity Trading For Key Firms,” Bloomberg News, September 4, 2023, <https://www.bloomberg.com/news/articles/2023-09-04/china-mulls-tougher-rules-on-commodity-trading-for-key-firms?sref=OKIHH2Pn>.
- <sup>142</sup> Those comments and more (e.g., “it’s dirty and has social baggage”) come from one of the more experienced observers on commodities businesses, Jeff Currie of the Carlyle Group. The comments were made during a plenary at the Future Minerals Forum in Riyadh on January 10, 2024. The industry has its work cut out.
- <sup>143</sup> Michot Foss, “A TGIF Post With Observations From [CERAWeek 2024](#),” LinkedIn post, March 23, 2024, <https://www.linkedin.com/feed/update/urn:li:activity:7177073859823640576/>.
- <sup>144</sup> Michot Foss et al., “A Citizen’s Guide to National Oil Companies” and Tordo, “National Oil Companies and Value Creation.” Research conducted by author and colleagues included many details on NOC privatizations and related issues.
- <sup>145</sup> The author was a participant in Washington Consensus implementation as a U.S. Agency for International Development (USAID) contractor in Central and South Asia, Africa, Mexico, and related initiatives. Moise Naim, “Fads and Fashion in Economic Reforms: Washington Consensus or Washington Confusion?” Working Draft of a Paper Prepared for the IMF Conference on Second Generation Reforms, Washington, D.C., October 26, 1999, <https://www.imf.org/external/pubs/ft/seminar/1999/reforms/naim.htm#l>.
- <sup>146</sup> For information on treatment of Grasberg, see Michot Foss and Koelsch, “Need Nickel?”
- <sup>147</sup> For more information, see Monaldi, [“The Cyclical Phenomenon of Resource Nationalism in Latin America.”](#) Oxford Research Encyclopedia of Politics (March 31, 2020), <https://doi.org/10.1093/acrefore/9780190228637.013.1523>.
- <sup>148</sup> As of publication, talks were continuing, but impacts rippled to other mining assets in Canada operated by First Quantum Minerals. For the Cobre mine incident, see “First Quantum’s Shut Panama Copper Mine to Present Initial Preservation Plan,” Reuters, January 10, 2024, <https://www.reuters.com/markets/commodities/first-quantums-shut-panama-copper-mine-present-initial-preservation-plan-2024-01-10/>.
- <sup>149</sup> See author publications related to Heartland super region developments: Michot Foss, “Defining the ‘Minerals Heartland’ of the Future”; and Michot Foss, “Mining, Minerals, and Materials in the Age of Sustainability and Alliances.”

<sup>150</sup> Clare Church and Alec Crawford, “Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-Carbon Economy,” International Institute for Sustainable Development, August 13, 2018, <https://www.iisd.org/publications/report/green-conflict-minerals-fuels-conflict-transition-low-carbon-economy?q=library/green-conflict-minerals-fuels-conflict-transition-low-carbon-economy>.

<sup>151</sup> Michot Foss, “Mining, Minerals, and Materials in the Age of Sustainability and Alliances.”

<sup>152</sup> See Michot Foss, Moats, and Kwame Awuah-Offei, “Framing Energy and Minerals for Future Pathways,” T20 Policy Brief, <https://www.bakerinstitute.org/research/climate-and-environment-t20-saudi-arabia>.

<sup>153</sup> For a notable, attention-grabbing treatment of the June 9, 2024, EU voting, see Ruy Teixeira, “‘Greenlash’ is Here,” The Liberal Patriot, June 20, 2024, <https://www.liberalpatriot.com/p/greenlash-is-here>.

<sup>154</sup> Or, for that matter, how would an advanced CNTF materials hypercar compare with the original idea? Amory Lovins, “Hypercars FAQ,” RMI, 1997, <https://rmi.org/insight/hypercars-faq/>.



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