THE STATE OF CRITICAL MINERALS REPORT 2023

The Payne Institute for Public Policy
COLORADO SCHOOL OF MINES

FOREWORD

By Morgan D. Bazilian
Director, Payne Institute
Professor of Public Policy, Division of Economics and Business

CHANGING MINDS AND MINING

This is our first State of Critical Minerals Report. It accompanies an extraordinary annual event at the Colorado School of Mines where hundreds of experts from academia, government, and industry come together to identify gaps in knowledge, key challenges, and massive opportunities.

U.S. politics are deeply divided, no question. But amid the rancor and distrust, there's a surprising area of bipartisan agreement over so-called critical minerals – the metals and other raw materials needed to build iPhones, electric cars, solar panels and even ammunition and weapons systems for the military.

The "critical" in critical minerals refers to how much we depend on foreign sources of supply. Right now, our dependence is very high, and they are essential ingredients for modern economies, and especially clean energy technologies. Global markets for many of the minerals we need are dominated by China, and as U.S. relations with China's ruling Communist Party have worsened, the once-obscure field of critical minerals has rapidly become a front-and-center policy issue.

The world is watching. Two of the main international organizations in the energy space, the International Energy Agency, and the International Renewable Energy Agency both released big reports on the topic just this summer.

We need to produce more critical minerals and their associated chemicals here in America and work with friendly nations to build secure international supply chains. That work is just beginning. President Biden and his administration have clearly recognized this imperative. The White House and Congress have plowed billions of dollars into research, resource assessment and workforce development programs focused on critical minerals. And just recently the Department of Interior-led Inter Agency Group came out with a sweeping strategy on the topic.

It seems we mostly agree on the need for critical minerals. But the mines needed to produce them? Not so much.

Mining has garnered a bad reputation, and certainly some of that is understandable. For example: In the U.S., historical mining practices from the 19th Century to the mid-20th Century largely disregarded the environment and human health.   Modern processes, technologies, and community engagement have completely transformed the mining industry since then, but that has failed to sway many of its detractors.

At this point there doesn't seem to be a mine on federal land that isn't facing opposition, delays or rejection.

Clearly, broad agreement on critical minerals isn't enough to get the job done – stakeholders across the spectrum need to take the next step and reach broad agreement on critical *mines.* So, how can stakeholders and policy professionals working in the critical minerals space actually make this agreement happen?

First, making the tradeoffs explicit will be important towards engaging in useful discussions. That is, acknowledging the environmental impacts, whilst also quantifying the benefits to future clean energy, national security, and economic development would be a start.

Second, changing the narrative around mining. The industry has much responsibility for this, but so do lawmakers. It is a once in a lifetime opportunity to recognize how important mining products are to the modern economy—and taking great pains to ensure better community engagement and cutting-edge sustainability technologies and processes are employed.

Third, deepen engagement, analysis and investment with friendly countries who have significant experience with mining, such as Canada and Australia. Over time, this can expand to countries without favored trading status or similar relationships, but where mining can play an important role in economic development, and U.S. engagement can help support good governance. Think Peru, Indonesia, Mozambique, and Tanzania.

Fourth, support the creation of a new institutional landscape of organizations and processes that can provide the money, time and tools needed to expand sustainable mining practices. This will be especially important in relation to Native American lands and Tribes. These institutions could also importantly provide guidance on new ways of expediting permits and implementing those decisions, and bringing the General Mining Act of 1872 into a modern context.

Lastly, take advantage of the slivers of bipartisan light that this area might provide, and build on it politically for the good of the country. Among other things, that means allowing national security concerns – such as materials needed by the Department of Defense – to play a bigger role in the discussion, as opposed to only seeing mining through an environmental lens.

There are no shortcuts to changing the mining industry and perceptions of it overnight. But we desperately need good cases and novel approaches that go well beyond pro-mining political rhetoric on the one hand and environmental protests on the other.

Colorado School of Mines is a key institution in this global discussion. We are problem focused, and solutions oriented. We hope the event and this report make a useful contribution towards our common goals.

Morgan Bazilian

TABLE OF CONTENTS

INTRODUCTION

Energy transitions to clean technologies are taking place globally. The development and deployment of these energy sources, as well as building modern economies, are largely dependent on critical minerals.

This is the inaugural annual State of Critical Minerals Report by the Payne Institute for Public Policy and the Colorado School of Mines. It is aimed at contributing to the important discourse on critical minerals and how to harness them in a more sustainable manner as a catalyst to the energy transition and by extension, climate action. It explores various parts of the critical minerals value chain and the interplay of these segments in driving a successful minerals industry.

The report covers geopolitics and what that means for national security, the demand and supply dynamics of critical minerals markets, financial markets and investments, the future of sustainable mining and the environment, and social governance (ESG) factors confronting the industry. The ESG section explores the environmental impacts of mining, the social issues around artisanal and small-scale mining (ASM), Native/indigenous people and the mining workforce. On the governance aspect, the report looks at the permitting process and the implications for meeting the critical minerals requirements of the future.

The policy implications of the interaction of the various chapters of the report form the basis for the recommendations and conclusions outlined in the report. The scope of the topics covered will be expanded in subsequent annual editions and additional chapters added to align with the fast-paced critical minerals landscape.

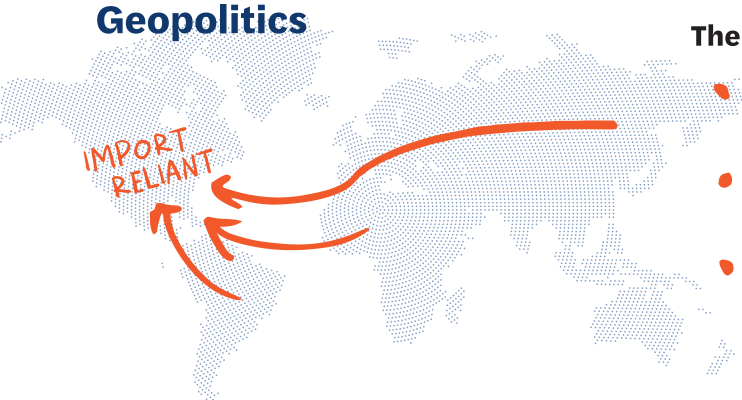
The Payne Institute for Public Policy

COLORADO SCHOOL OF MINES

THE STATE OF CRITICAL MINERALS REPORT 2023

EXECUTIVE SUMMARY

Geopolitics



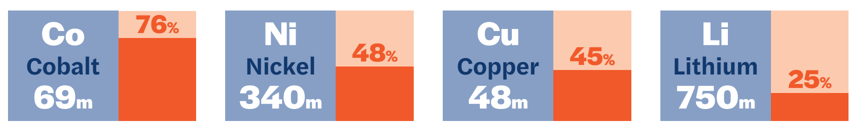
The U.S. relies on China for 16 critical minerals

- Out of the 50 minerals on the U.S. critical minerals list, the U.S. is 100% reliant on imports for 12 of these minerals
- It is more than 50% import dependent for another 31 of them
- China's new export regulations on gallium and germanium has further highlighted US dependence

Supply & Demand

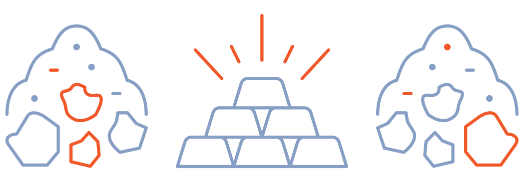
- The U.S. ranks in the top 10 countries with the highest reserves for some critical minerals

U.S. reserves in metric tons and percentage of apparent consumption imported

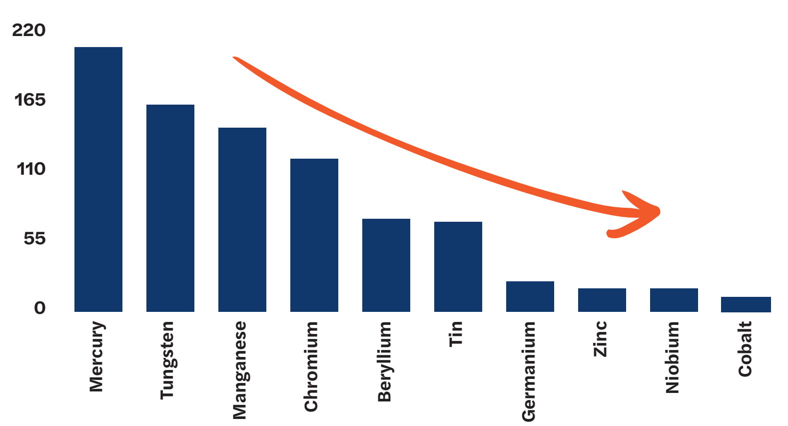


National Security & Defense

- Despite provisions in the Defense Production Act, the critical minerals stockpile has consistently declined
- A more strategic approach is required for critical minerals stockpiles instead of the reactive boosts seen only in times of war



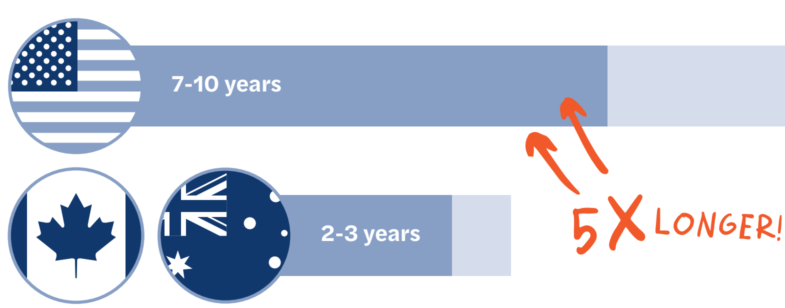
Top 10 Materials in Stockpile—Value (In Millions of USD)



Permitting

- It takes 5X longer to get permitting approvals in the U.S. as compared to countries like Canada and Australia with very similar environmental standards.
- U.S. efforts to improve critical mineral supply chain will not be effective without improvement to mining permitting process

7-10 Years to secure a mine permit in the U.S. vs. 2-3 years in Canada and Australia

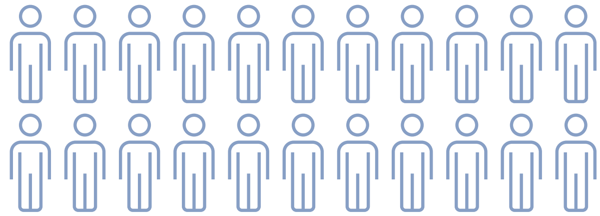


Artisanal & Small-scale Mining (ASM)

ASM accounts for:

- **26%** of global tantalum production
- **25%** of global tin production
- **25%** of global gold production
- **6-8%** estimate of global cobalt production

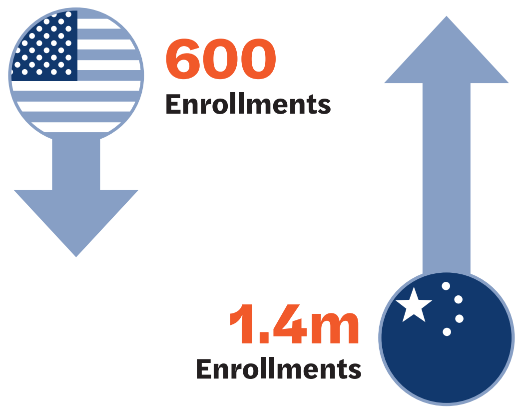
40 million people are estimated to be employed in ASM worldwide



The Workforce

- China has invested strategically in the industry and its workforce—for decades
- This past academic year, across the U.S., there were 600 enrollments in accredited undergraduate and graduate mining engineering and related programs. On the other side—China has over 1.4 million enrollments
- Mining Schools Act of 2023 is an important opportunity to strengthen mining education in the U.S.

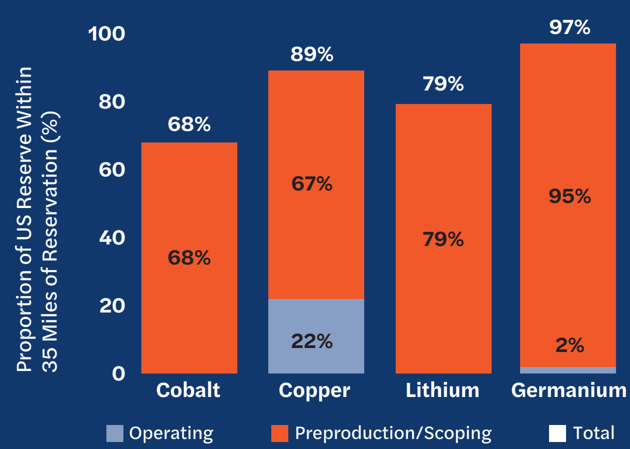
There has been a decline in Mining Engineering Programs and Faculty in the U.S.



Native/Indigenous People

- More than 50% of reserves for critical minerals in the U.S. are within 35 miles of Native American Reservations
- As part of good engagement practice, companies should seek "community benefits agreements" that include job training, local hiring and other benefits

US Transition—Metal Reserves Within 35 Miles of Native American Reservations



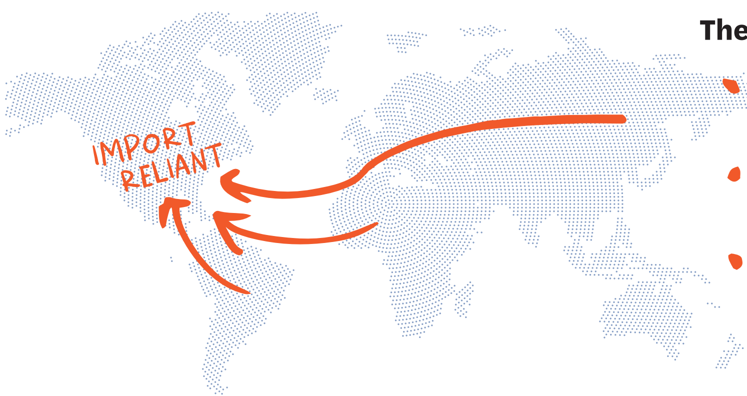
CHAPTER 1

GEOPOLITICS

Critical minerals are geographically concentrated, with a few countries dominating the mining and downstream processing of these minerals and metals. The concentration of these minerals makes these supply chains vulnerable to global events like Russia's invasion of Ukraine and the impacts on Nickel supply and prices. Australia produces more than 40% of Lithium, Chile dominates Copper and ranks second in Lithium production. More than 50% of the world's Cobalt and Nickel production happens in the Democratic Republic of Congo (DRC) and Indonesia respectively. China dominates the production of Rare Earth Elements (REE) and Graphite, while South Africa accounts for more than half of the world's production of Platinum Group Metals (PGMs).

China dominates the downstream minerals value chain, processing and refining as much as 100% of the world's natural graphite and some critical REEs like Dysprosium. China also processes more than 80% of the world's Manganese, about 70% of the world's Cobalt and close to 60% Lithium. In the case of copper, China is the largest processor with current output of about 40%. China already dominates the battery supply chain and now controls 80% of the world's lithium-ion battery production, 77% of the world's battery cell capacity and 60% of the world's battery component manufacturing (BloombergNEF, 2020).

The United States relies on China for 16 critical minerals and 25 other minerals, and this puts the U.S. in a very vulnerable position. It is also more than 50% import reliant for 31 out of the 50 materials on the critical minerals list. Only 9 of the world's 142 lithium-ion battery mega factories are planned for the U.S. while 107 are in China. This has huge implications for the U.S. economy and national security.



The U.S. relies on China for 16 critical minerals

- Out of the 50 minerals on the U.S. critical minerals list, the U.S. is 100% reliant on imports for 12 of these minerals
- It is more than 50% import dependent for another 31 of them
- China's new export regulations on gallium and germanium has further highlighted US dependence

Figure 1: U.S. Import Reliance for Critical Minerals

When U.S. companies build military weapons systems, electric vehicle batteries, satellites and wind turbines, they rely heavily on a few dozen "critical minerals" – many of which are mined and refined almost entirely by other countries. Building a single F-35A fighter jet, for example, requires at least 920 pounds of rare earth elements that come primarily from China. That level of dependence on imports worries the U.S. government. Natural disasters, civil unrest, trade disputes and company failures can all disrupt a mineral supply chain and the many products that depend on it – making many critical minerals a national security priority.

Export restrictions have also been on the increase within the critical minerals space as many producing countries are now requiring downstream processing of these materials and imposing restrictions on raw material exports. Countries like Indonesia, Zimbabwe, Chile, Peru Namibia, Tanzania and Ghana have started making demands for domestic processing and value-add to their natural resources. The levels of restrictions vary from country to country and depend largely on the type of mineral, the downstream processes required and the country's infrastructural readiness in supporting these processes as well as the socio- political agenda of the countries and their interactions with the wider global economy.

The rare earth crisis of 2010 and China's alleged exertion of geopolitical leverage by restricting the export of rare earths to Japan and the subsequent petition of the U.S. and EU to the WTO, highlight the vulnerabilities in accessing these critical minerals. More recently, China imposed new export regulations on Gallium and Germanium, which also highlight the dangers of the U.S. over-dependence for such critical minerals.

Developing countries play a huge role in the geopolitical framework of critical minerals. Some of the world's large resources and reserves are found in these countries. For instance, Bolivia has the world's largest reserves of Lithium even though it currently mines less than 1% of global supply and does not rank in the top five producing countries. The DRC is responsible for producing more than 70% of the world's cobalt, used in almost all rechargeable lithium ion batteries that power everything from cellphones and laptops to electric vehicles, and China has invested heavily in the region. However, countries like the Democratic Republic of Congo, which made headlines in the past due to mineral sales that financed armed conflict, are not particularly appealing partners for U.S. companies.

The United States must secure the sustainable supply of critical minerals and metals to ensure resilience across manufacturing and defense. The ability of the United States to drive demand – but hesitation to get involved with "risky" nations or commit to domestic production – means the U.S. is reliant on countries that are more willing to accept those risks. The recommendations for the U.S. to diversify critical mineral supply while avoiding national security threats include defense stockpiling, mineral security partnerships and increased domestic production.

1.1 National Defense Stockpiles

The concept of stockpiling is not new to governments. The U.S. government operates several stockpiles, and these are managed by different agencies depending on the stockpile's purpose.
For instance, the Department of Health and Human Services manages the Strategic National Stockpile (containing medicines and medical equipment), that is meant to supplement state and local reserves of such items in times of public health emergencies. Similarly, the Department of Energy manages the Strategic Petroleum Reserves for use in times of severe disruption on the international oil market.

The purpose of the National Defense Stockpile (NDS) is to hedge against the uncertainties of supply and demand of some of the critical resources that supply the military, industrial and essential civilian needs of the United States. The stockpile is to be used for national defense purposes only, not for any economic or budgetary purposes (IEA, 2022). The NDS acknowledges the possible supply chain disruptions that could be inevitable in times of a national or global emergency, due to the low national production and reliance on other countries for these critical/strategic minerals. These vulnerabilities were exposed during World War II and the Cold War, prompting additional legislation like the Defense Production Act of 1950. After more than half a century of no major wars, the Covid-19 pandemic was a reminder of the vulnerabilities that still exist in accessing these materials.

Geopolitics and the nature of the global economy further endanger critical material supply chains. Renewed great-power competition between the U.S. and China has elevated the need for strategic NDS and the industrial base that supports it. China is currently in a position of advantage over the U.S. and can leverage that for both economic and military gains. Unlike the Cold War, in which the Soviet Union and the

United States were economically independent of each other, today the United States depends on China for majority of the critical minerals required for defense applications. Even worse, China in some cases is the sole supplier or controls more than 50% of the global supply, limiting the ability of the U.S. to immediately diversify supply sources (Clark, 2022).

Within the defense space, metals and minerals were equally very instrumental during the two most documented seasons of tension/conflict in world history; World War I and II. Materials like steel, iron and tungsten were highly utilized during the Great War for the manufacture of weapons, artillery, warships and tanks. Copper helped to build communication systems, whilst coal was used to power steam engines, locomotives and naval vessels. In addition, aluminum and uranium also heavily impacted the Second World War as they were used in the manufacture of aircrafts and bombs.

There are currently 42 commodities in the NDS, ranging from base metals such as zinc, cobalt, chromium and manganese to the more precious metals such as iridium and platinum. They are stockpiled in six locations across the U.S., with a current market value between $880 million to $1.1 billion. This is very insignificant as compared to the stockpile values during the periods of war. The Korean War was the first major boost to the NDS. The value rose from about $54 million in 1941, to $4.02 billion by 1952. The investments in the NDS continued to rise until 1989, when it peaked at a total value of $9.6 billion. Figure 2 is a graphic presentation of the stockpile value as compared to historic/previous stocks, while Figure 3 gives the top 10 materials in the stockpile in terms of US dollar value.

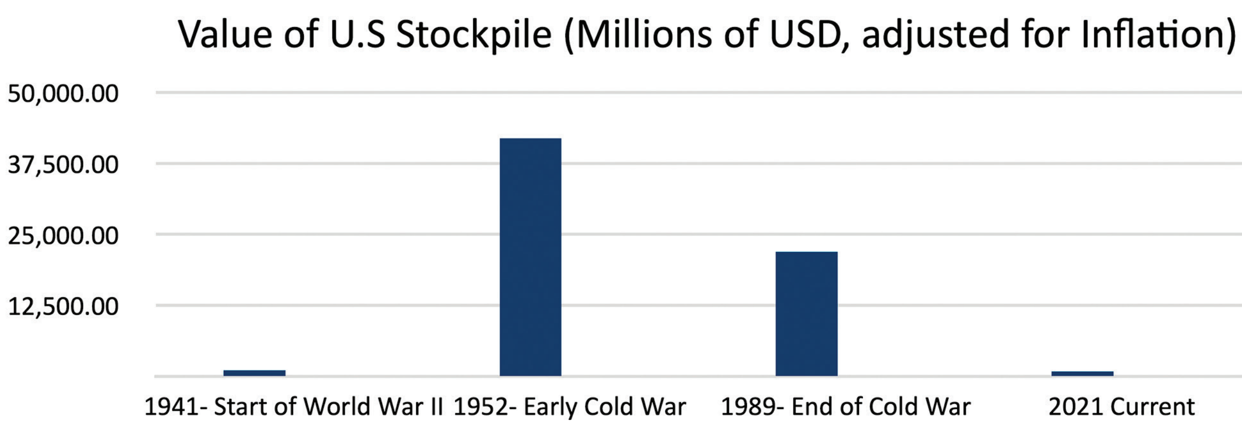


Figure 2: Value of U.S. Stockpile Inventory
Source: Clark, 2022

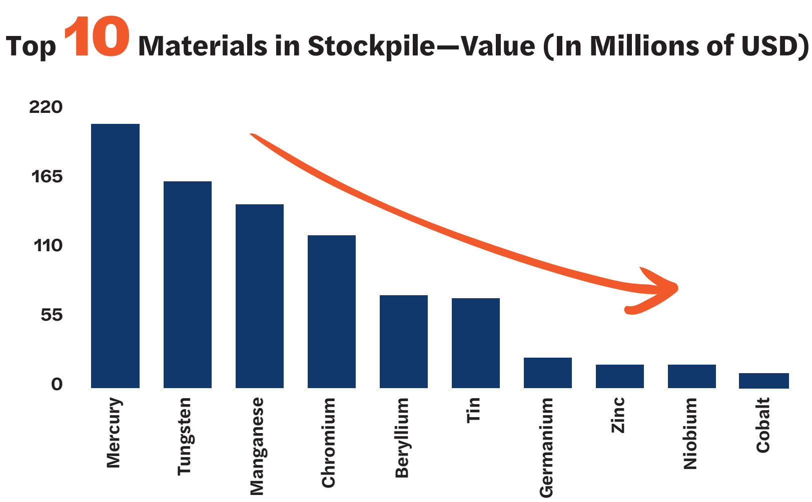


Figure 3: Top 10 Material Value in USD(NDS)
Source: Payne Institute based on data from Clark, 2022

1.2 Mineral Security Partnerships and Allies

The United States and key partner countries - Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom and the European Commission – have announced the establishment of the Minerals Security Partnership (MSP). This partnership will augment critical mineral supply chains by ensuring that these minerals are produced, processed, and recycled responsibly. The partnership will also ensure that countries realize the full economic benefit of their geological endowments.

Other U.S. specific policies including the Infrastructure Investment and Jobs Act (IIJA) and the Inflation reduction Act (IRA) are aimed at developing infrastructure, creating jobs and supporting economic growth. Minerals and Materials will play a very critical role in achieving these goals for both the economic development and national security of the United States. The IRA specifically provides about $369 billion in tax credits and funding to support the production of EVs, renewable energy technologies, and critical minerals. The caveat: U.S. carmakers will get tax credits if they source at least 40% of battery materials domestically or from American free-trade partners.

Africa

Africa is home to some 30% of the world's mineral reserves. The continent produces 40% of the world's gold and up to 80% of the world's chromium and platinum. The largest reserves of cobalt, diamonds, platinum and uranium in the world are in Africa. Africa will play a key role in the energy transition through the provision of its natural resources for clean energy technologies, electric vehicles (EVs) and batteries. Africa is also keen on exploring the opportunities in the mineral supply value chain for the economic prosperity of its people in a sustainable manner.

The U.S. currently has free-trade agreements with twenty countries, and Morocco is the only African country on the list. Albeit the shortcomings of the Belt and Road Initiative, China's principle of combining its economic, strategic and security interests, may offer some useful lessons in formulating a new critical minerals partnership with Africa. Africa's challenges are intertwined and require a more sustainable, rather than a piecemeal approach, to any partnership.

Latin America

Latin America accounts for 40% of global production of copper, led by Chile (27%), Peru (10%) and Mexico (3%). The region also produces 35% of the world's Lithium and it's home to the prolific "Lithium Triangle". The Lithium Triangle is located in the Andean southwest corner of South America, covering Argentina, Bolivia, and Chile. These three countries alone account for more than 50% of the world's lithium resources and reserves. Latin America also has huge potential in graphite, nickel, manganese and rare earth elements production.

Strategic partnerships with Latin America, especially with the Lithium Triangle have great value for the U.S. and the world. This could be in the form of public-private partnerships, investments into technology firms and companies involved in the production of lithium-ion batteries. Building these partnerships will require a lot of tact and trust because of the historically rocky relationship with some of these left-leaning countries, whose governments have been critical of the United States. Despite the challenges with some of these relationships, there is a great opportunity for partnerships with many countries in Latin America.

The challenges with these regions around environmental degradation, conflict minerals, child labor, poor governance structures require support from developed countries like the U.S. to overcome for more sustainable mining and supply chains.

1.3 Promote Domestic Mining

Many countries are trying to restructure supply chains in response to the anticipated obstacles in critical minerals supply, but new mining and processing facilities have long lead times and may not achieve results in the near term. The U.S. has increased its strategic planning and investment in reliable supply chains in recent years, particularly as China has moved to increase control over critical mineral exports, but the United States' own mining and recycling of these minerals is still small (China briefing, 2021). The U.S. doesn't have enough mines to meet the demands of the energy transition—not even close. While the United States also has to work closely with allies to secure the supply chains for these materials, something has to change at home, too. Like many other U.S. industries, mining was largely outsourced to other parts of the world during the late twentieth century. As a result, global markets for most in-demand minerals are now dominated by the Chinese Communist Party. Simply stated, the United States needs to build new mines and expand existing mines in the United States. Rather than stop the digging, the United States needs to start.

An "out of sight, out of mind" approach to metals and other mineral commodities took hold, giving tacit approval to toxic waste dumping, the use of child labor, and other reprehensible mining practices abroad. Today, there is an opportunity to write a new chapter for the U.S. mining sector, in which some of the raw materials for advanced energy technologies are produced here, under close scrutiny, subject to the most protective standards in the world and—above all—with strong public support. The complicated history of mineral extraction in this country must be addressed fully and forthrightly, but it cannot be used as an excuse to keep saying no. At this point, there does not seem to be a mine on federal land that is not facing opposition, delays, or rejection.

One of the greatest challenges confronting domestic production of these critical minerals is the long and tedious permitting process in the U.S. The mine permitting process in the United States is causing challenges that hinder the country's competitiveness in the global mining industry and there is an urgent need to revise and streamline the permitting process to attract investment, foster innovation, and ensure responsible resource extraction.

A major mining project on federal lands could be subject to as many as 30 or more local, state, and federal regulations and programs. Beyond these multiple programs across many agencies, another major challenge is the lack of cross-agency coordination, which sometimes results in duplicitous processes and longer approval times. These delays in the permitting process pose significant threats to mining projects, even in states that have better mining regimes, such as Nevada, West Virginia, and Arizona.

The Department of Defense has been one of the strongest supporters for more resilient supply chains. In the last few years, it has been proactive about strengthening domestic production, especially for rare earth elements. That includes new contracts with rare earth mining and production operations in California, Nebraska and Texas (U.S. Department of Defense, 2021). The U.S. is also a leader in ESG, technology and innovation which, when applied to the mining value chain will make the sector more sustainable globally.

Fortunately, the U.S. has the mineral resources and reserves in some of these minerals. It also has the technology and innovation required for more sustainable mining practices. The expertise and skilled workforce required to drive the value chain also exist. Another very important component for developing domestic mining is the financial capital to support this capital-intensive sector. The U.S. financial markets are deep, mature and sophisticated enough to support the likely upsurge in capital requirements to boost domestic mining.

CHAPTER 2

MINERAL DEMAND AND SUPPLY

2.1 Demand

Up until the middle of the previous decade, the energy sector constituted only a minor portion of the total demand for most critical minerals. However, with the acceleration of clean energy technologies, they have rapidly emerged as the segment with the fastest growth in demand. As an example, projections indicate that by 2030, the demand for copper could potentially increase twofold, while lithium could witness a three to six-fold surge (IRENA, 2023). In a future trajectory aligned with the goals of the UN Paris Agreement, the proportion of total demand accounted for by clean energy technologies significantly rises over the forthcoming two decades, reaching over 40% for copper and rare earth elements, between 60% and 70% for nickel and cobalt, and nearly 90% for lithium (Figure 4). Electric vehicles (EVs) and battery storage technologies have already superseded consumer electronics to become the largest consumers of lithium, and they are projected to surpass stainless steel to become the primary end users of nickel by 2040 (IEA, 2023).

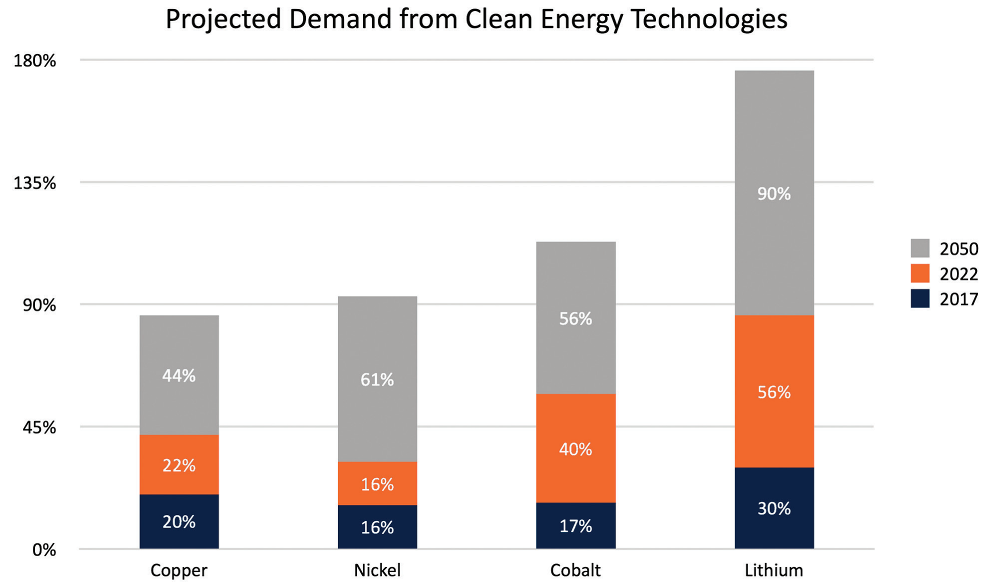


Figure 4: Projected Demand from Clean Energy Technologies
Source: Payne Institute based on data from the IEA

Understanding future critical mineral demand is challenging, with numerous conflicting assumptions, parameters, and models to sort through. The expected increase in critical mineral uses, driven by clean energy technologies and population growth and increase in income has resulted in the creation of many mineral demand models. These quantitative demand models have been developed to help understand the scale of growth, and whether material shortages will become an obstacle to the deployment of clean energy technologies. Understanding the potential mineral demand associated with the clean energy transition is crucial for policymakers, mineral producers, renewable energy developers, and civil society organizations. However, these demand projections are inherently subject to large variations, due to the complexities and uncertainties around forecasting energy scenarios, technology choices and other behavioral factors.

A study of various mineral demand models establishes a point of convergence around escalating mineral demand. The differences in the exact mineral quantities arise around the scenarios and assumptions of the future energy mix, mineral and energy policies, and technological advancements. Most demand models and scenarios unanimously project the intensification of EVs and storage systems, wind, and solar PV technologies, signaling increased demand for materials like lithium, cobalt, and rare earth elements. Efforts to achieve the Paris Accord target of less than 1.5^{0}C climate warming will drive long-term increases in the demand for the top minerals deployed across various low carbon technologies.

Other factors such as cost, energy intensity, and consumer behavior and preferences can shape future markets and sub-technologies. For instance, in the case of solar energy, the potential preference for cadmium telluride (CdTe) solar cells over the currently prevalent technology - crystalline silicon photovoltaic cells - could shift the demand for minerals like cadmium and tellurium. Similarly, the battery chemistry of the future will play a significant role in determining the mineral demand mix. Lithium-ion phosphate (LFP) batteries, which do not require nickel, manganese, or cobalt, are strong competitors to Lithium-ion batteries that do contain manganese, nickel, and cobalt (NMC). Other factors like the supply side dynamics of the various minerals and materials also plays an important role in the technology preference. For instance, ESG concerns around the Cobalt supply chain in the DRC has been a leading factor in the substitution for Cobalt in some technologies and battery chemistries.

However, LFP batteries require more copper than NMC batteries and phosphorus, a key ingredient in large-scale fertilizer production. If not carefully managed, this could lead to a tug-of-war between battery manufacturing and the agricultural sector. In general, NMC cathodes require nearly eight times more cobalt than nickel-cobalt-aluminum oxide (NCA) lithium batteries, but only half the nickel amount. Cathode chemistry preferences are increasingly splitting between high-nickel or LFP, while silicon-doped graphite is gaining traction for anode chemistries. In a recent collaboration between the International Energy Forum (IEF), the Future of Minerals Forum (FMF) and the Payne Institute for Public Policy, a meta review of some energy and technology scenarios proposed by notable institutions were consistent with expectations of higher demand for the critical minerals that will drive these technologies. The report covered eight agencies and organizations across different geographies, spanning from 2019 to 2023.

An illustration of the expected future demand for some of the minerals and metals under different scenarios.

Copper

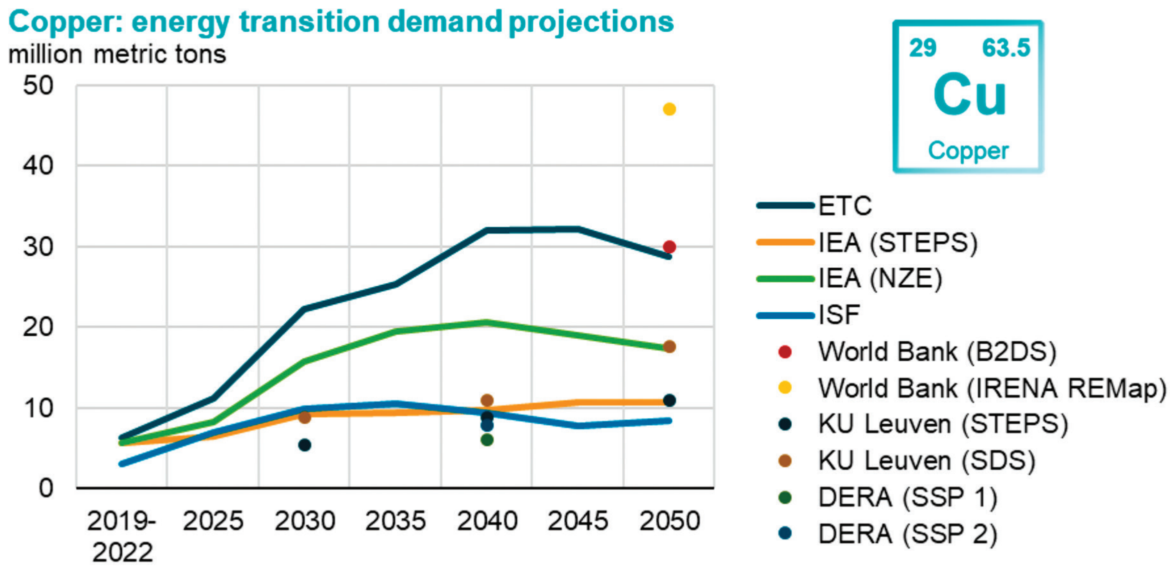


Figure 5: Projected Demand for Copper
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

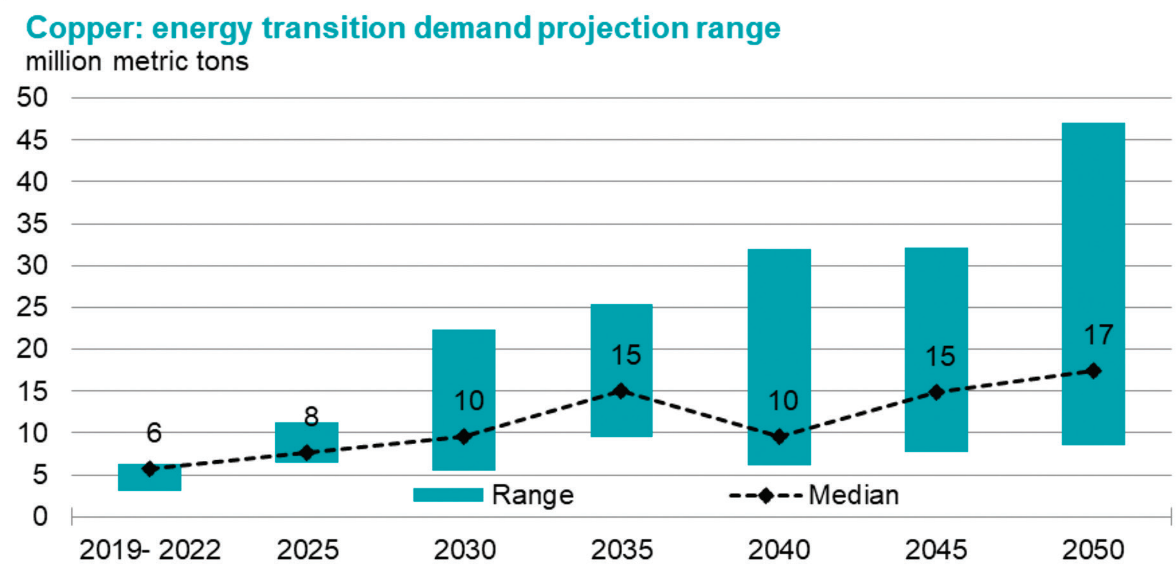


Figure 6: Projected Demand for Copper
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

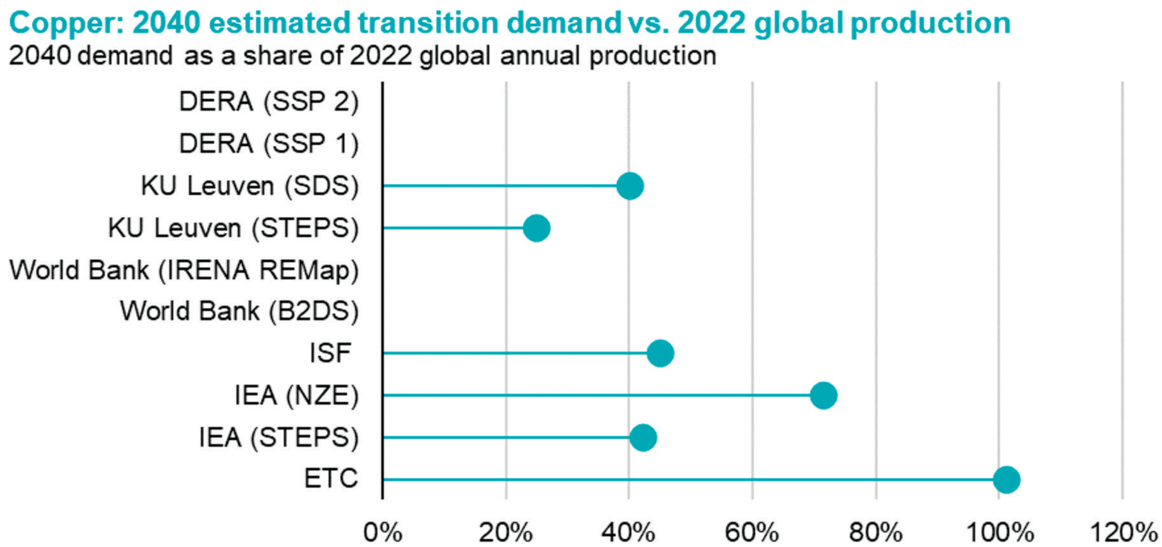


Figure 7: Projected Demand for Copper
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

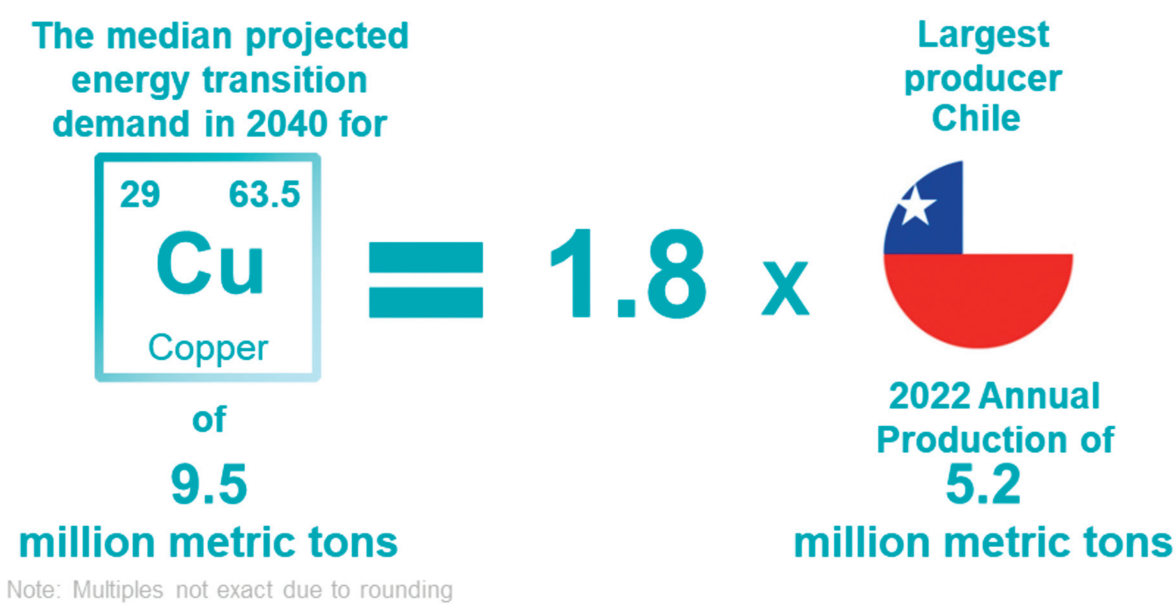


Figure 8: Projected Demand for Copper
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Lithium

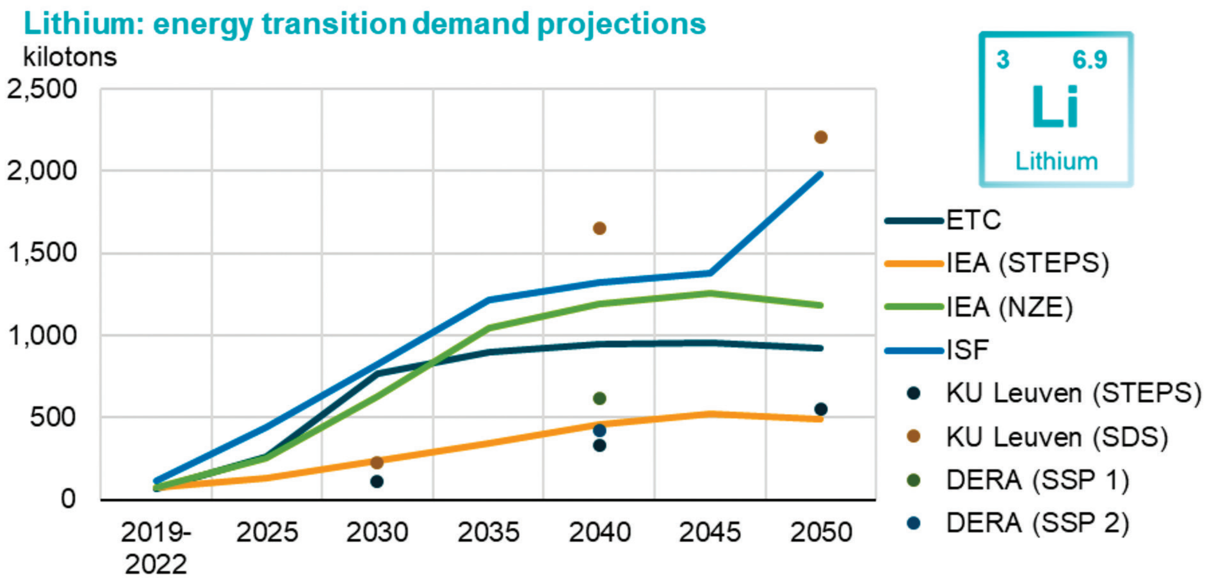


Figure 9: Projected Demand for Lithium
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

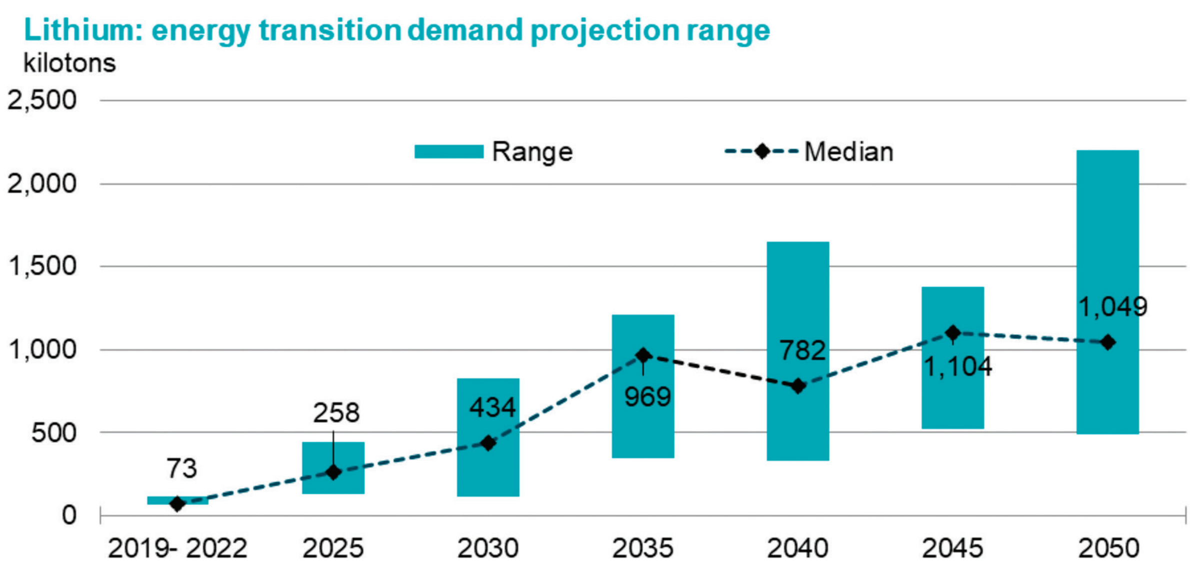


Figure 10: Projected Demand for Lithium
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

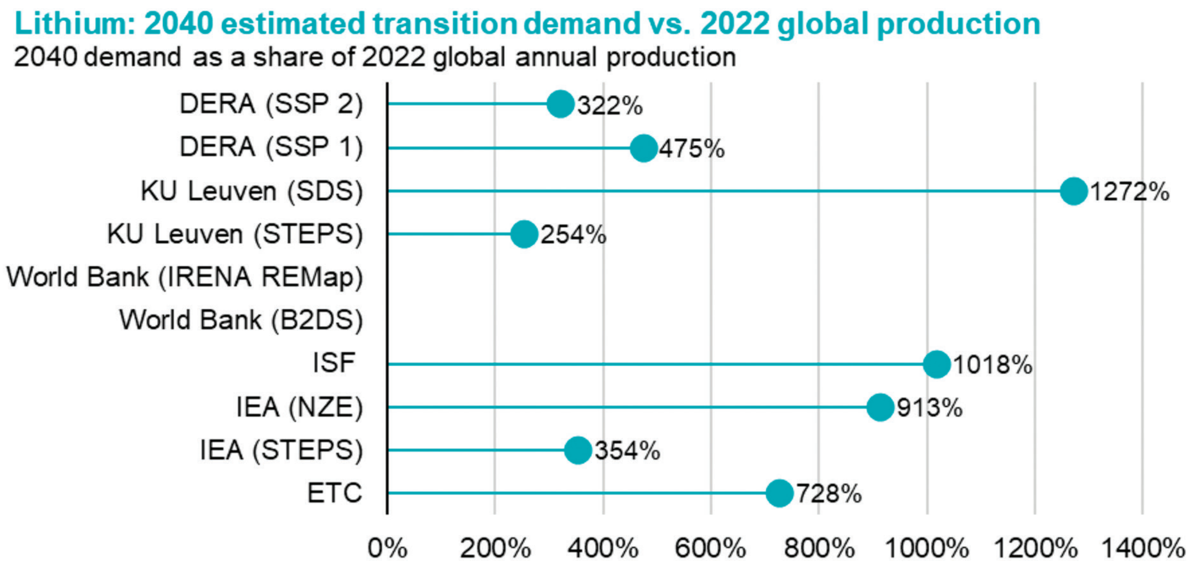


Figure 11: Projected Demand for Lithium
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

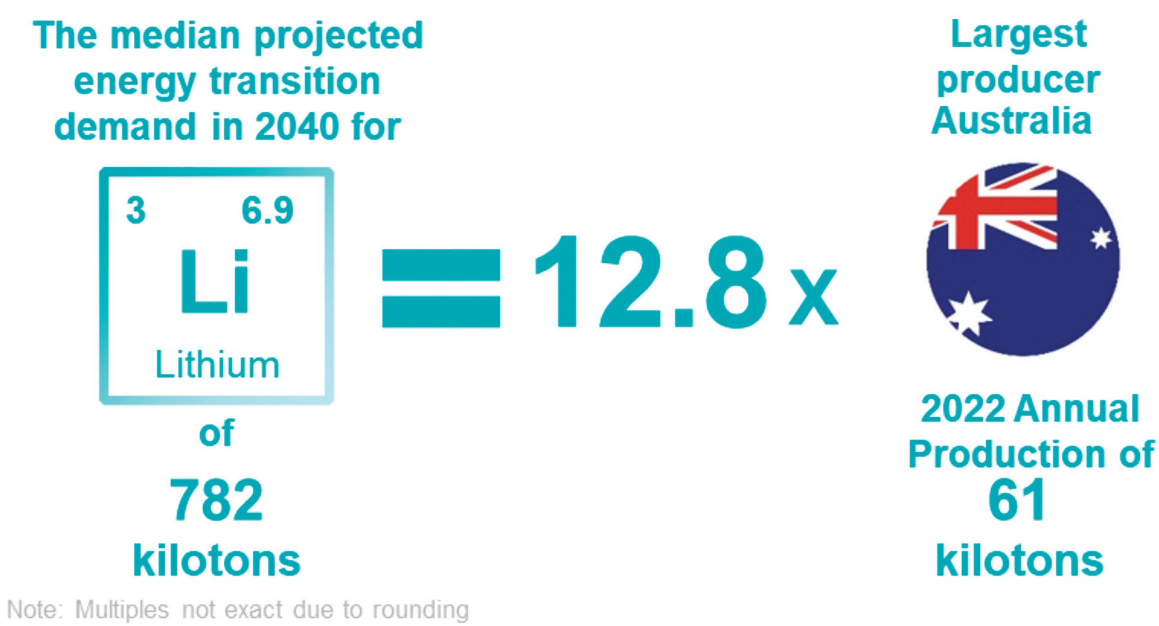


Figure 12: Projected Demand for Lithium
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Nickel

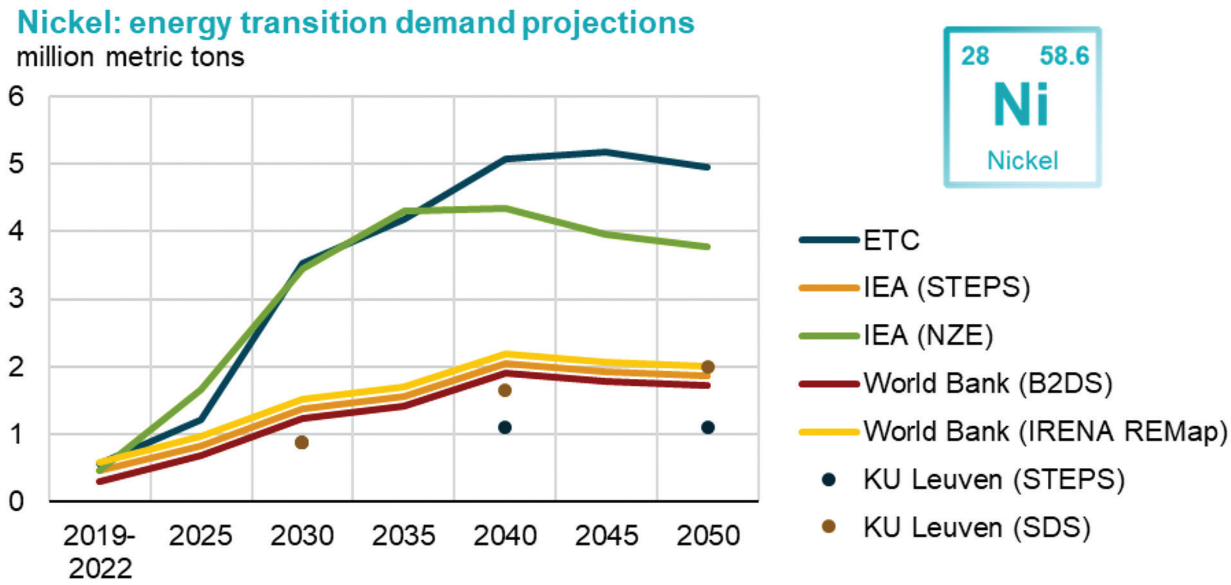


Figure 13: Projected Demand for Nickel
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

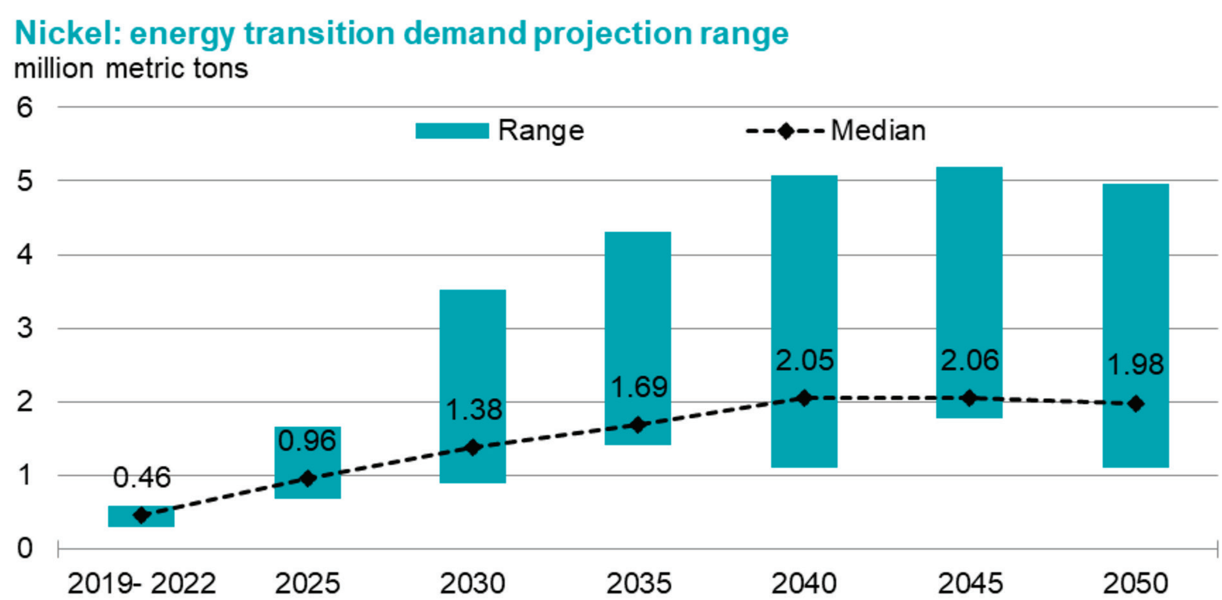


Figure 14: Projected Demand for Nickel
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

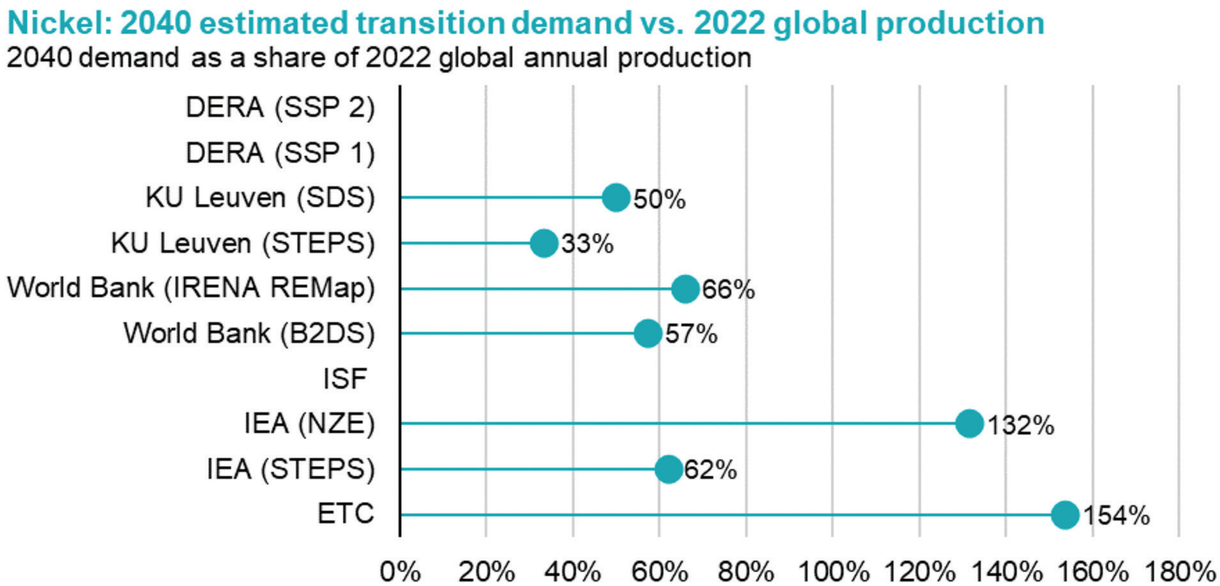


Figure 15: Projected Demand for Nickel
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

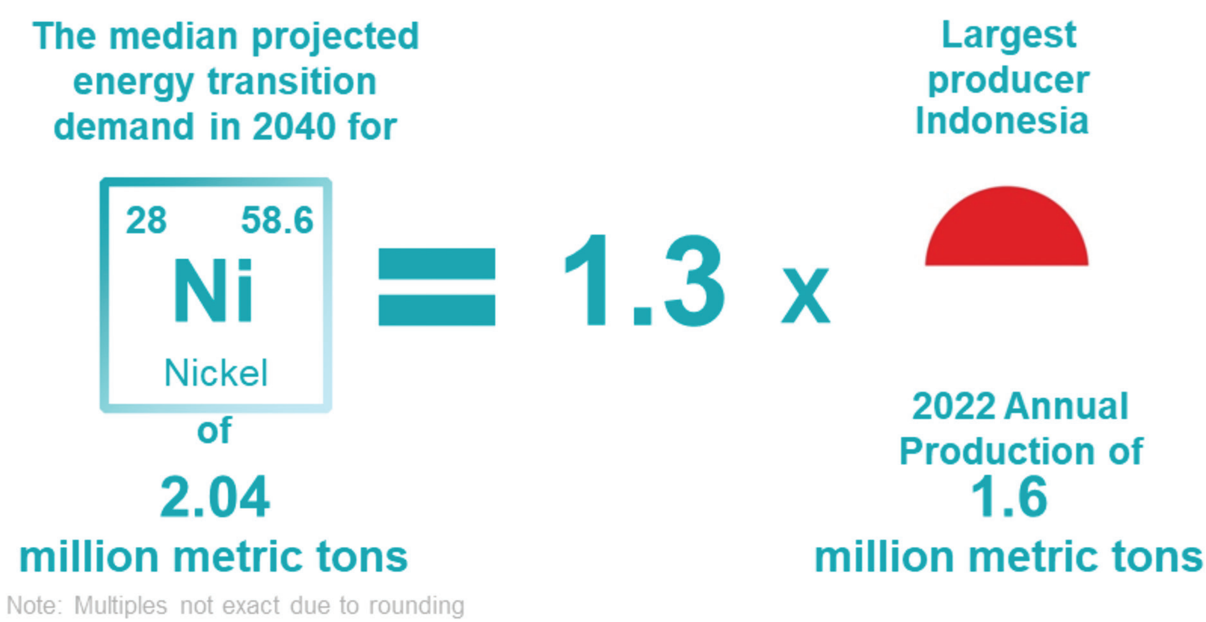


Figure 16: Projected Demand for Nickel
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

2.2 Supply

Countries that extract and possess large mineral reserves have considerable impacts on the price of raw materials, especially due to the cost of extracting these minerals for further processing. Mining has always had a major influence on the global economy. If we consider the supply and demand of minerals, the alteration of the market can influence the price of these raw materials. For example, in countries such as Chile and Peru, a notable influence on the market can be found because their production is large enough to influence prices in the short term, but it should also be considered that a higher than competitive price can encourage production in other countries in the long term, and demand is inelastic to price in the short term but not in the long term.

Country politics also have a major influence on the price, whether it involves country environmental policies, mining regulations or government instability. For example, in January 2020, the authorities in Jakarta banned exports of nickel ore, a key raw material in the manufacture of stainless steel or lithium batteries, with the goal of forcing companies to invest in and develop processing capacity in the country, rather than exporting raw ore. While this policy change was oriented toward domestic development, it has large implications for international markets.

Another very important issue is when countries are not able to develop mining efficiently, the quality and size of deposits with ample reserves of high-quality ore can improve and supply global demand; however, not being able to maintain an adequate infrastructure can increase the cost of ore production.

In mining, the cost of production and the relationship between supply and demand is indispensable in determining the market price of minerals. Many mineral-producing countries may have an advantage in the extraction of their minerals due to good production policies and adequate infrastructure and this helps to influence the price of metals. The minerals analyzed for this report are Bauxite and Nickel.

Bauxite

Bauxite is the primary ore used for the extraction of aluminum. The process is efficient in terms of yield and cost. The largest bauxite resource is found in Guinea and the lowest cost of extraction is in India.

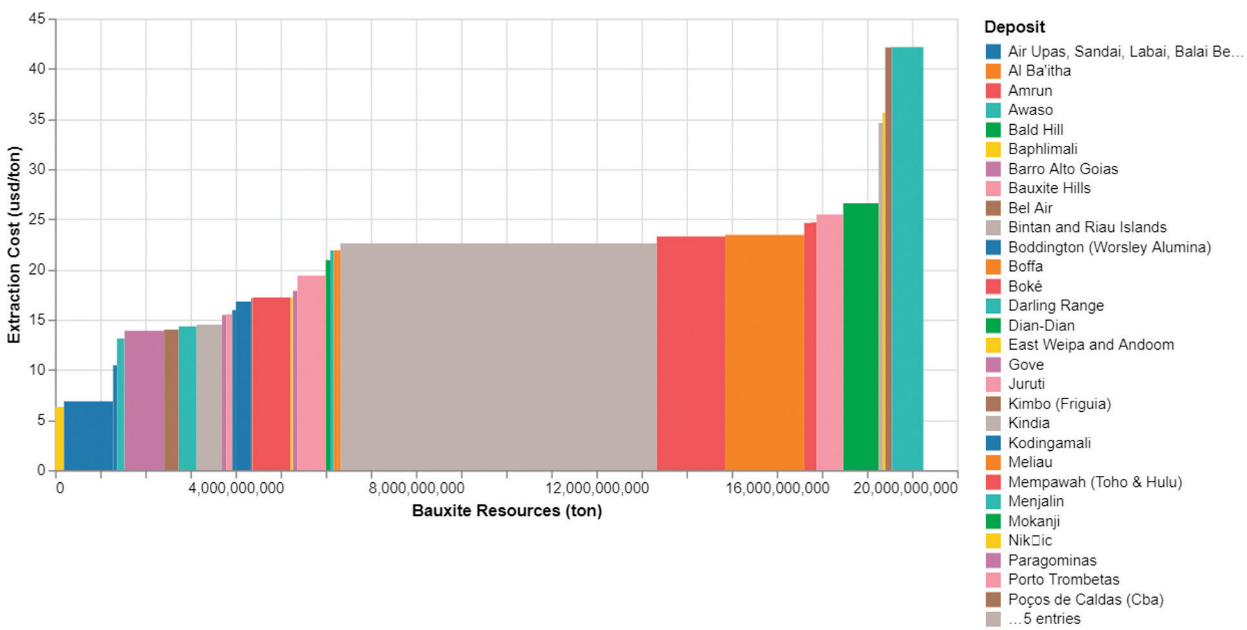


Figure 17: Cumulative Availability Curve for Bauxite
Source: Payne Institute

Main Bauxite Deposits (in tons) :

1. Sangarédi (Guinea) - 7,014,000,000
2. Boké (Guinea) - 1,518,800,000
3. Boffa (Guinea) - 1,750,000,000,000

Bauxite deposits with lower extraction cost (usd/ton):

1. Baphlimali (India) - 6.3
2. Boddington (Worsley Alumina, Australia) - 6.86
3. Schwallenburgh / Windalco (Ewarton, Jamaica) - 10.45

Nickel

Nickel is one of the important metals used in various industries because of its corrosion resistance. One of its main uses is in the production of stainless steel and rechargeable batteries. The largest Nickel resource is found in Russia and the lowest cost of extraction is in Turkey.

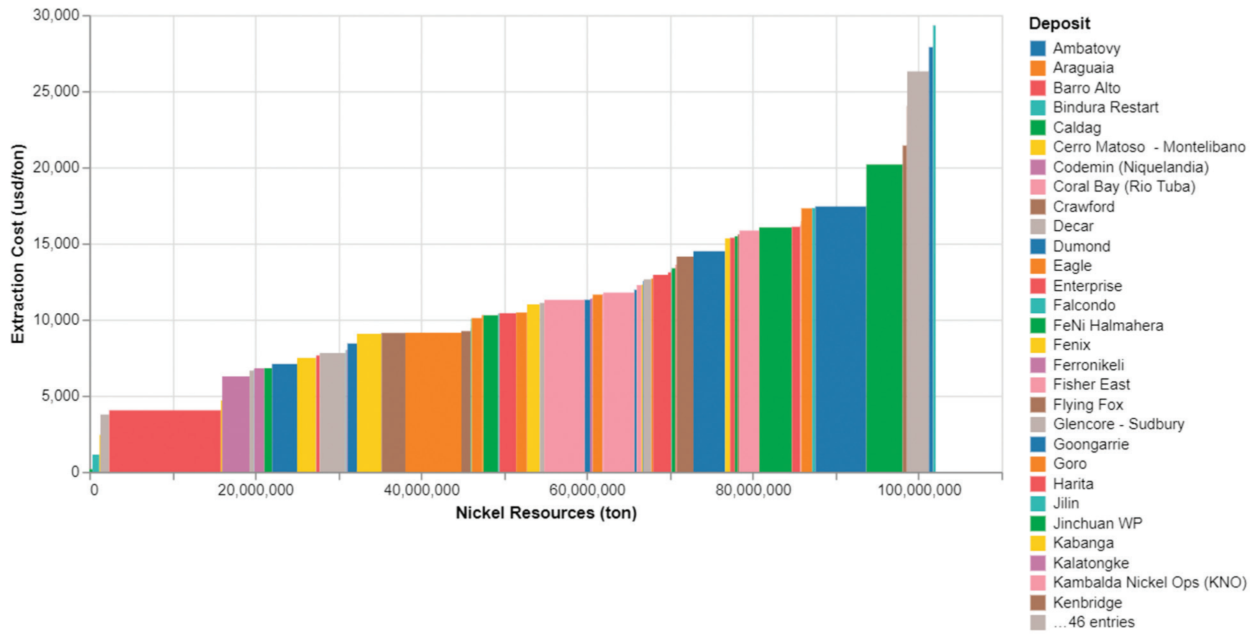


Figure 18: Cumulative Availability Curve for Nickel
Source: Payne Institute

Main Nickel Deposits (in tons):

1. Norilsk (Russia) - 13,456,000
2. PT Vale (Soroako, Indonesia) - 6,134,063.185
3. Weda Bay (Indonesia) - 6,725,250

Nickel deposits with lower extraction cost (usd/ton):

1. Caldag (Turkey) - 167.19
2. Eagle (United States) - 534.42
3. Raglan (Canada) - 1130.96

2.3 Recycling and Reuse

It takes a long time to bring new mines into production, therefore, recycling and reuse has the potential to improve secondary supply. Recycling rates, both for new scrap and old scrap (end-of-life) vary greatly across minerals and has great potential to augment critical minerals' supply. Recycling is a very useful tool in managing critical materials supply, but it should be seen as part of a broader strategy that includes responsible mining, substitution, and other measures to ensure a sustainable and secure supply of critical materials. There are also opportunities to improve the recycling and reuse of critical minerals through research and development, policy incentives, and public-private partnerships.

Aluminum is one of the most recycled—and recyclable—materials in use today. Aluminum products are particularly designed with circularity in mind and this can happen with less energy intensity. A recycled aluminum beverage can, car door or window frame is often recycled directly back into itself with only about 5% of the energy needed to make new aluminum. It is estimated that about 75% of all aluminum ever produced is still in use today and about 90% of Aluminum in industrial use is recycled.

Copper and nickel are also highlighted as minerals currently being recycled to a significant extent with around 8.5 million tons of copper scrap recycled in 2018 and about one-third of global nickel supply derived from recycling (IRENA (2021). Lithium and cobalt demand is expected to increase significantly relative to their 2018 production levels, driven largely by EVs and storage technologies. At the current trajectory, demand for lithium, cobalt and rare earths from renewable energy exceeds current production rates by 2022. Therefore, without recycling, the annual demand for these minerals could surpass existing production rates.

While recycling can increase mineral supply and help reduce the demand for new mining and processing, studies indicate it is not a silver bullet solution to the problem of access to critical materials. There are both economic and environmental challenges associated with recycling. Recycling processes can be complex and expensive, and the quality of the recycled material may not be as high as that of newly mined material. There are also high costs associated with recycling involving energy intensity and collection plus storage costs for some materials.

Policy support to incentivize recycling, including standardizing battery design with recycling in mind and regulating the transportation of end-of-life EV batteries are necessary to support critical mineral supply. New policy measures have recently been taken in this direction by China, Europe, and the United States.

CHAPTER 3

ENVIRONMENT, SOCIAL AND GOVERNANCE (ESG)

3.1 Environmental Implications of Mining

Given the escalating demand for minerals like lithium, cobalt, and rare earth elements—indispensable in today's tech-driven and increasingly renewable-energy-based economies—the scale of mining operations and, correspondingly, their potential environmental footprint, are on an upward trajectory (World Bank, 2020). It's not just about localized impacts such as air pollution or water contamination; the ramifications extend to global challenges like climate change and biodiversity loss. For example, the extraction of a single ton of rare earth minerals produces approximately 2,000 tons of toxic waste, including harmful greenhouse gases like sulfur hexafluoride, which has a global warming potential 23,900 times that of carbon dioxide (Massachusetts Institute of Technology, 2019).

Moreover, industry practitioners and analysts must note that these environmental costs are not externalities to be discounted; they reverberate back into the economic sphere. Companies not attuned to sustainable practices risk not just regulatory backlash but also reputational damage, affecting investor relations and market performance (Deloitte, 2021). This creates a cascade effect impacting job security and working conditions within the mining workforce. Hence, scrutinizing the environmental implications is not an adjunct to our understanding of critical mineral mining; it is a fundamental prerequisite for any stakeholder concerned with long-term sustainability, workforce stability, and economic resilience. A holistic, informed perspective can offer actionable insights for mitigating environmental impacts, thereby creating an equilibrium between our economic ambitions and ecological responsibilities.

3.1.1 Emissions

In the advent of critical mineral mining, emissions generated during extraction and processing are a paramount concern for both environmental and occupational health. These emissions are not monolithic; they are a composite of various pollutants, including but not limited to sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs) (EPA, 2019). The seriousness of the issue is accentuated when we consider the quantifiable data; for instance, a single rare earth mining and processing operation can emit approximately 75,000 tons of SO2 and 38,000 tons of NOx annually (Nuss & Eckelman, 2014).

These emissions have a far-reaching impact beyond the immediate vicinity of the mining operations. SO2 and NOx are precursors to acid rain, which devastates aquatic ecosystems and damages soil, thereby affecting both natural habitats and agriculture (Likens et al., 1996). PM emissions contribute to air quality degradation, with health consequences that can lead to respiratory diseases and cardiovascular problems (Pope et al., 2002). On a global scale, the greenhouse gases emitted contribute to climate change, presenting an existential challenge that further complicates the ecological landscape.

To mitigate these substantial impacts, cleaner alternatives are not just advisable; they are imperative for long-term industry sustainability. Emission reduction technologies such as flue-gas desulfurization and selective catalytic reduction are being incorporated into modern facilities to curb SO2 and NOx emissions (Kumar et al., 2018). Additionally, companies are investing in carbon capture and storage (CCS) to reduce the carbon footprint of mining operations (Global CCS Institute, 2021). In the economic calculus of mining, these investments are becoming increasingly justified as regulatory bodies intensify scrutiny and investors become wary of environmental risks (Deloitte, 2021).

For industry professionals and analysts, understanding the intricate details of emissions in critical mineral mining is not a peripheral concern but a central issue intricately linked to workforce well-being, regulatory compliance, and sustainable profitability. As we progress into an era where environmental responsibility converges with economic viability, it is vital that all stakeholders are acutely aware of the emissions generated, their real-world impacts, and the technological alternatives that can attenuate these issues.

3.1.2 Biodiversity

Biodiversity stands as a silent victim in the unfolding narrative of critical mineral mining. Often overlooked in economic analyses, the toll on both land and aquatic ecosystems presents an urgent call for immediate action. Consider, for example, the mining of rare earth elements, which frequently results in habitat destruction, soil erosion, and water pollution (Ali et al., 2017). These adverse environmental impacts manifest not merely as abstract ecological data points but have cascading effects on entire ecosystems. Studies indicate that for every ton of rare earth minerals extracted, approximately 75 cubic meters of acidic wastewater and one ton of radioactive waste residue are generated (Wang et al., 2013). These waste materials have severe consequences for aquatic ecosystems, disrupting the natural pH levels of water bodies, killing off sensitive species, and thereby derailing the ecological balance (Eisler, 2004).

The repercussions are not confined to flora and fauna. Communities that reside in proximity to mining sites often find themselves on the front lines of this ecological crisis. Cases of fish depletion in regions affected by cobalt and lithium mining, for instance, have compromised local livelihoods that depend on fishing (Sonter et al., 2018). The ripple effects are felt not only through immediate economic loss but also in the form of long-term health issues, especially for communities that rely on contaminated water sources for drinking and agriculture (WHO, 2001). So, the pertinent question arises: can we reverse the damage? Mitigation measures do exist but they require concerted efforts that integrate both technological innovation and governance mechanisms.

Strategic Environmental Assessments (SEA) that anticipate the environmental effects of mining can guide the industry towards more sustainable practices (Jay et al., 2007). Alongside this, the implementation of biodiverse land management strategies, which include reforestation and the creation of protective buffers around aquatic ecosystems, offer some hope for the restoration of impacted habitats (TEEB, 2010).

For industry professionals, analysts, and other stakeholders, it is imperative to recognize that the environmental implications of critical mineral mining are not mere externalities. They are inextricable from the long-term viability of the mining workforce and, by extension, the industry itself. As we strive to reconcile our growing mineral demands with the finite resources of our planet, the conservation of biodiversity cannot be a sidelined issue; it must be at the core of our collective responsibility.

3.1.3 Water

Water stands as an often-overlooked resource in the calculus of environmental implications arising from critical mineral mining. Despite being indispensable for both life and industrial operations, its management presents a dichotomy between utility and potential for long-term environmental damage. Specifically, water pollution and overuse have become synonymous with various mining activities. In rare earth element mining, for instance, large quantities of water are often contaminated with heavy metals, radioactive materials, and toxic chemicals (Mudd & Jowitt, 2018). Moreover, such operations have been known to consume up to 2,000 liters of water per ton of extracted ore (Northey et al., 2013). This not only strains local water supplies but also engenders a cascade of adverse ecological impacts, disrupting aquatic ecosystems and exacerbating water scarcity.

As this stark reality imposes itself, there is a corresponding surge in the implementation of water-saving technologies and practices within the industry. Closed-loop water systems, which recycle and reuse water in mining operations, stand as one of the more promising technological innovations (Molchanov & Laplante, 2020). Additionally, real-time monitoring systems enable precise control over water use, reducing both consumption and the likelihood of accidental discharges into local waterways (Brown et al., 2017). Such efforts indicate that while the challenges are manifold, solutions that marry economic logic with environmental stewardship are within reach. Understanding these water-related implications is far from an academic exercise; it forms the crux of sustainable operational frameworks that the mining industry must adopt. For analysts, policymakers, and other stakeholders, these issues should not be peripheral concerns but integral to any comprehensive evaluation of the long-term sustainability and ethical conduct of the critical mineral mining sector.

3.1.4 Land Degradation

Land degradation, albeit frequently overshadowed by more immediate concerns such as emissions and water pollution, remains a grave environmental implication of critical mineral mining. The effects often manifest in the form of soil erosion and land disturbance, where the removal of topsoil and vegetation can alter the landscape irreversibly. For instance, in mining lithium, a crucial mineral for the burgeoning renewable energy industry, up to 500,000 gallons of water per ton of lithium can be consumed, leaving the land barren and unsuitable for agriculture (Swain, 2020). Furthermore, in the quest for metals like cobalt, significant tracts of forests are being disturbed, inducing soil erosion that alters watershed hydrology (Young, 2019). Yet, as grim as the landscape may appear, there are initiatives and technological advancements that offer a glimmer of hope.

A case example is the Eden Project in the UK, which turned a disused china clay pit into a flourishing ecological park (Eden Project, 2021). Here, comprehensive soil management and innovative land use planning were instrumental in reviving the land post-mining, showcasing that it's possible to reclaim land in a sustainable manner. Companies and regulatory bodies are taking note, and policies are slowly shifting towards obligating mining firms to commit to land reclamation as part of their operating licenses (Schaetzl et al., 2019).

The topic of land degradation and its eventual reclamation is not one that can be relegated to the periphery of industry discussions. It must be brought to the fore, given its ramifications not just on the environment but also on the social and economic fabric of communities living in proximity to mining sites. Analysts, policymakers, and industry stakeholders must therefore prioritize this issue in their evaluations and decision-making processes.

Sustainable Alternatives

Amidst the complex panorama of environmental impacts that critical mineral mining imposes, sustainable alternatives are not just aspirational goals but imperative pathways to a viable future. One beacon of promise is the burgeoning field of green mining technologies. For instance, bio-mining leverages natural bacteria to leach valuable minerals from ores, thereby reducing the need for hazardous chemicals (Johnson & Hallberg, 2009). Another striking innovation is the application of machine learning and big data analytics to optimize resource extraction, reducing waste and energy consumption (Samanta et al., 2018). Policy frameworks are also evolving in tandem with these technological strides. The European Union's Raw Materials Initiative and Canada's Green Mining Initiative are examples of concerted efforts to promote sustainable mining practices (European Commission, 2020; Natural Resources Canada, 2019). Such policies typically advocate for the 'circular economy' approach, emphasizing the need for reusing, recycling, and substituting materials to reduce the extraction of new raw materials.

For the average reader pondering what can be done to catalyze change, the options are surprisingly abundant and accessible. Conscious consumerism stands as a powerful tool; opting for products made from recycled or sustainably sourced materials sends a strong market signal. Moreover, public opinion significantly shapes policy direction. Therefore, engaging in public discourse and advocating for responsible mining practices can wield considerable influence over legislative change. Sustainable alternatives in critical mineral mining are not utopian visions but realistic objectives underpinned by ongoing innovations and progressively responsive policy frameworks. As this narrative moves from the margin to the mainstream, every stakeholder, from industry leaders to the average citizen, has a part to play in this transitional journey towards a more sustainable future.

However, as the data elucidates, the current trajectory is fraught with considerable environmental repercussions ranging from water consumption (Swain, 2020) to carbon emissions (World Aluminium, 2020). In an era defined by climate change and resource scarcity, it is no longer feasible to prioritize economic gains in isolation from ecological concerns. The numbers tell a compelling story: Lithium mining consumes up to 500,000 gallons of water per ton of lithium extracted; Cobalt mining in the Democratic Republic of Congo disturbed 1,100 square kilometers of forested land in a single year; and 12 million tons of the total 22 million tons of soil eroded annually in China are directly attributed to rare earth mining (Hurst, 2010). This is not merely an environmental issue but a multi-faceted challenge that has social, economic, and geopolitical ramifications.

While emerging technologies such as bio-mining and machine learning offer some hope in mitigating these effects (Johnson & Hallberg, 2009; Samanta et al., 2018), they are but pieces of a larger puzzle that requires a multi-stakeholder approach. Policy initiatives like the European Union's Raw Materials Initiative aim to certify up to 40 new sustainable mining operations by 2030 (European Commission, 2020). However, such policies need to be adopted globally and backed by stringent regulations to make a meaningful impact. This analysis underscores a clarion call for industry leaders, analysts, and stakeholders to urgently reimagine the methods governing critical mineral extraction, as it is both an economic necessity and an environmental imperative.

With the global demand for responsible practices and long-term resource viability, the responsibility for change lies with both public and private sectors to innovate collaboratively. Passive awareness is insufficient; active engagement across all stakeholders is vital. Thus, this is not merely an endpoint but an urgent invitation for sustained dialogue and actionable change, for the ecological and economic costs of inaction are too substantial to dismiss.

Table 1: Some Key Environmental Metrics in Critical Mineral Mining

Key Environmental Metrics in Critical Mineral Mining: A Comparative Overview				
Environmental Metrics	Simple Explanation	Quantity & Unit	Mineral/Country	Source
Water Consumption	Gallons of water used	Up to 500,000 gallons per ton	Lithium / General	Swain, 2020
Deforestation	Forest land disturbed	1,100 square km	Cobalt / Democratic Republic of Congo	Young, 2019
Emissions	CO2 emitted	1.1 billion tons	Aluminum / General	World Aluminium, 2020
Energy Use	Energy consumed	2.5x more than common metals	Rare Earth Elements / General	Alonso et al., 2012
Soil Erosion	Soil lost	12 million of 22 million tons	Rare Earth Elements / China	Hurst, 2010
Bio-mining	Hazardous chemicals avoided	Up to 80% reduction	General	Johnson & Hallberg, 2009
Sustainable Policy	New sustainable mines certifie	Up to 40 by 2030	General / European Union	European Commission, 2020
Technological Innovation	Waste reduced	Estimated 40% reduction	General	Samanta et al., 2018

However, as the data elucidates, the current trajectory is fraught with considerable environmental repercussions ranging from water consumption (Swain, 2020) to carbon emissions (World Aluminium, 2020). In an era defined by climate change and resource scarcity, it is no longer feasible to prioritize economic gains in isolation from ecological concerns. The numbers tell a compelling story: Lithium mining consumes up to 500,000 gallons of water per ton of lithium extracted; Cobalt mining in the Democratic Republic of Congo disturbed 1,100 square kilometers of forested land in a single year; and 12 million tons of the total 22 million tons of soil eroded annually in China are directly attributed to rare earth mining (Hurst, 2010). This is not merely an environmental issue but a multi-faceted challenge that has social, economic, and geopolitical ramifications.

While emerging technologies such as bio-mining and machine learning offer some hope in mitigating these effects (Johnson & Hallberg, 2009; Samanta et al., 2018), they are but pieces of a larger puzzle that requires a multi-stakeholder approach. Policy initiatives like the European Union's Raw Materials Initiative aim to certify up to 40 new sustainable mining operations by 2030 (European Commission, 2020). However, such policies need to be adopted globally and backed by stringent regulations to make a meaningful impact. This analysis underscores a clarion call for industry leaders, analysts, and stakeholders

to urgently reimagine the methods governing critical mineral extraction, as it is both an economic necessity and an environmental imperative.

With the global demand for responsible practices and long-term resource viability, the responsibility for change lies with both public and private sectors to innovate collaboratively. Passive awareness is insufficient; active engagement across all stakeholders is vital. Thus, this is not merely an endpoint but an urgent invitation for sustained dialogue and actionable change, for the ecological and economic costs of inaction are too substantial to dismiss.

3.2 Social Implications of Mining

3.2.1 Native/Indigenous people

Native/Indigenous groups in the US have complicated histories with mining, and the race for critical minerals opens yet another chapter. A recent analysis showed that a large majority of reserves for many transition metals are in close proximity to reservations, underscoring the continued salience of indigenous interests and perspectives (MSCI Research, 2021). Already, tensions have emerged between Native/Indigenous groups and projects to mine critical minerals, raising the important question of whether the historical pattern of injustices and conflicts will recur or if new outcomes can be forged.

From the colonial period well into the 20th century, many indigenous groups in the U.S. were expelled from their historic homelands during gold rushes and mining expansions. Even where native people were not expelled, mining often saddled them with environmental injustices, such as the uranium industry's toxic legacy for Southwestern tribes (Ingram et al 2020).

Many proposals for new critical mineral mines in the US have faced opposition from indigenous communities and tribal governments. Among others, this includes proposed mines for lithium in Nevada, copper in Arizona, and copper and nickel in Minnesota. Opposition centers on protection of sacred sites and cultural practices, and concerns over water contamination and environment.

Native/Indigenous People

- More than 50% of reserves for critical minerals in the U.S. are within 35 miles of Native American Reservations
- As part of good engagement practice, companies should seek "community benefits agreements" that include job training, local hiring and other benefits

US Transition—Metal Reserves Within 35 Miles of Native American Reservations

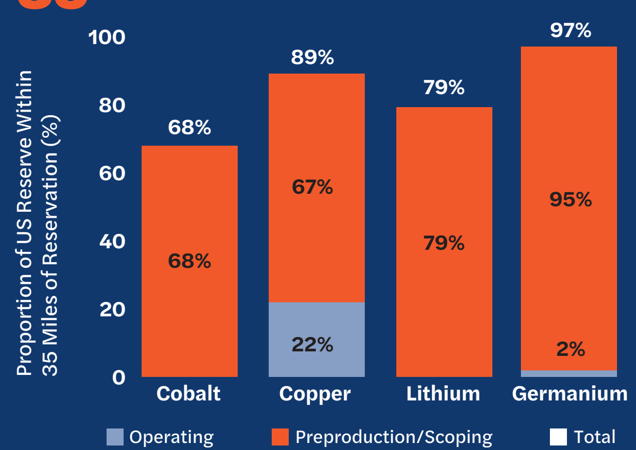


Figure 19: Metal Reserves within 35 Miles of Native American Reservations

Source: MSCI ESG Research, U.S. Census Bureau's MAF/TIGER, S&P Global Market Intelligence

On the other hand, in some native communities mining has become an economic pillar. Coal mining on and near the Navajo Nation provided significant employment and tribal government income, though the decline of coal is raising difficult challenges (Curley 2023). In Alaska, NANA, an Alaska Native regional corporation, is a partner in the world's largest zinc mine, Red Dog. Researchers from Colorado School of Mines are working with NANA and Teck, the mine operator, to explore potential for further mineral recovery from old tailings. Two examples demonstrate the issues, both historically and at present;

Navajo Nation and Uranium

The Navajo Nation, with 400,000 enrolled members, has experienced profound impacts from the legacy of uranium mining. Geologic resources are abundant on the than 27,000 square mile reservation in the Four Corners area including parts of Arizona, New Mexico, and Utah. The 1940s saw surge of uranium mining activities both on and adjacent to the Navajo Nation and other Native American lands, led to the extraction of approximately 30 million tons of uranium ore between 1944 and 1989. Although uranium mining and milling activities have ceased, the Navajo Nation is still grappling with the consequences, including abandoned uranium mines, old mill sites, and houses built with mine and mill waste. The health effects of exposure to these elements have been widespread, with numerous claims awarded on behalf of Navajo uranium workers for illnesses traced back to occupational radiation exposure.

Native American workers, especially those from the Navajo Nation, have disproportionately suffered from the environmental and health consequences of this industry. Exposure to uranium and the related radioactive materials have caused several health issues, such as lung cancer, bone cancer, kidney disease, and physical defects. The contamination of water sources and soil has further exacerbated the health crisis since the communities in the region rely on these resources for drinking, agriculture, and livestock.

These issues are ongoing, given the persistent nature of radioactive material. Tribal and Federal agencies continue to engage in evaluations of cancer cases, health status assessments of descendants of uranium workers, and longitudinal human health impact studies. By pursuing these objectives, the involved organizations aim to address the health impacts of uranium exposure, support affected communities, and ensure that future generations can better understand and manage the long-lasting consequences of the uranium mining industry.

In the past, the legal roadblocks diminished the Navajo government's ability to protect its people and the environment. Jurisdictional complexities arising from the overlapping authority of federal, state, and tribal governments further complicate matters. Laws such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) have not adequately addressed the concerns of the Navajo Nation, especially in relation to the impacts of uranium mining on their land and people. One way to address these challenges could be through passage of federal legislation that caters to the Navajo Nation's unique needs and provides the resources and authority for their protection.

While uranium pollution has been a long-term environmental justice problem on the Navajo Nation and surrounding areas, some see opportunity in cleanup efforts that could address historic injustices. A recent report from the University of New Mexico presents 12 key recommendations for state agencies to systematically tackle the economic and environmental consequences of mining cleanup (Rohrer et al 2020). It emphasizes the importance of collaboration among all stakeholders, including federal, state, and local governments, Native nations, private landowners, private sector firms, educational institutions, and community organizations, in addressing these challenges.

Navajo leaders and scholars emphasize the importance of sovereignty over resource management and the incorporation of traditional knowledge (Rock and Ingram 2020)

Thacker Pass Lithium

The Thacker Pass lithium mine is a proposed mining project in northern Nevada, USA. The project is owned by Lithium Nevada Corporation, a subsidiary of Canadian mining company Lithium Americas.

Construction began in 2023, with production projected to begin in 2026. The project is expected to receive funding from the Department of Energy's Advanced Technology Vehicles Manufacturing Loan Program. General Motors has also announced investment of $650 million in the project, to secure lithium for one million electric vehicles annually (Burmeister 2023).

The project is on traditional Paiute Shoshone lands, located about 40 miles from the present Fort McDermitt Reservation. The site has cultural and religious significance, as well as being historically important to commemorate the massacre of Paiute people on the site in 1865. For these reasons, tribal governments and indigenous groups oppose the project. There is also environmental opposition from the tribe and other groups, largely focusing on the site's value as habitat for sage grouse and pronghorn. Opponents' legal actions against the project were denied by a federal appeals court in 2023, clearing the way for construction to begin.

Legal wrangling over the project raises difficult questions around critical minerals and energy transition on one hand, and indigenous sovereignty and localized environmental concerns on the other. Opponents claim corners are being cut to expedite critical mineral production – what they describe as sacrificing the environment in the name of energy transition. Proponents counter that challenges are frivolous and insist that the project has met all the applicable standards and requirements (Angueira 2023).

The transition to renewable energy and the demand for rapid expansion of critical minerals raises difficult questions and challenges. Leading scholars have highlighted tensions between the desire for a just energy transition – one that fairly distributes costs and benefits and does not repeat or deepen environmental injustices – and a rapid energy transition – one that can prevent the worst effects of climate change before it's too late (Newell et al 2022).

Indigenous communities are at the center of these challenges, as demonstrated by the proximity of critical mineral deposits to reservations and indigenous lands. History is replete with examples of environmental injustices, of tribal lands being treated as sacrifice zones while the benefits of development bypass those communities. Can this time be different? Companies and governments have tools to avoid repeating those abuses – models like free prior and informed consent, or community benefit agreements – but will they be enough?

3.2.2 Artisanal & Small-scale Mining (ASM)

Although the term "artisanal mining" might be unfamiliar to American readers, it is estimated that 80% or more of the global mining workforce are artisanal miners (Fritz et al 2018). The ASM sector (artisanal and small-scale mining) exists in over 80 countries, with greatest presence in Asia, Africa, and South America. It encompasses a wide range of practices, from rudimentary digging with hand tools, to dredging and sluicing in rivers, to organized underground mining with dozens or hundreds of workers. In most cases, ASM is informal, meaning it is not regulated or monitored by governments. Informality often goes hand-in-hand with poor working conditions and environmental standards, though it is also important to recognize that ASM provides income for tens of millions of people, mostly in rural areas with few other opportunities.

ASM accounts for:

26% of global tantalum production

25% of global tin production

25% of global gold production

6-8% estimate of global cobalt production

40 million people are estimated to be employed in ASM worldwide

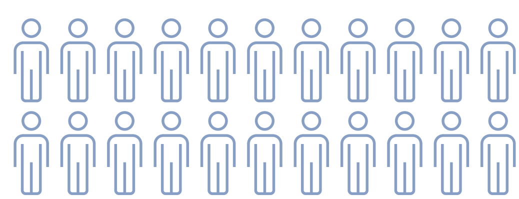


Figure 20: Artisanal and Small-scale Mining Contribution

ASM contrasts sharply to conventional mining – it is labor-intensive and low-tech, compared to the capital-intensive, mechanized nature of modern conventional mines – but it is important to recognize that the two versions of mining are not as cleanly divided as one might assume. Research in numerous contexts has shown that ASM output eventually makes its way into formal value chains and markets, becoming indistinguishable by the time it reaches end users (Smith et al 2023). Artisanal mining also frequently overlaps or borders conventional mining sites or occupies former conventional mines. The two are frequent neighbors throughout the Global South.

As mining is projected to rapidly expand during the transition to renewable energy systems, this raises two important questions related to artisanal mining: (1) Does ASM have any role to play in producing critical minerals for the energy transition? And (2) How will the transition affect the livelihoods of the millions of current artisanal miners?

An important starting point is to recognize that more than half of current ASM activity centers on gold, followed by diamonds and gemstones (Fritz et al 2018). This production is largely irrelevant to the energy transition or development more broadly. Except for some 8% of annual gold demand that goes into technology applications, the rest is used for jewelry and to be held as investments (Lezak et al 2023). A wholesale shift away from gold would be necessary for ASM to become a major part of critical mineral production. This raises the question, what do we already know about non-gold ASM. Two examples stand out, demonstrating challenges and opportunities.

Front of mind for many is the infamous example of cobalt mining in the Democratic Republic of Congo (DRC), popularized in Siddharth Kara's bestselling exposé Cobalt Red. Cobalt is used in batteries for electric vehicles and other electronics. 73% of mined cobalt comes from the DRC, an unknown share of which is artisanal in origin, while 76% of refining capacity is concentrated in China (Cobalt Institute 2023).

Kara's book shows that abject poverty, environmental degradation, health impacts, child labor, and forced labor are endemic in DRC cobalt mining, and that the conventional and artisanal sectors are tightly intertwined. DRC cobalt production stands as a worst-case scenario for an ASM role in producing critical minerals.

Tech and automotive companies that are major users of cobalt are involved in efforts to improve the human and environmental standards of cobalt supply chains, but impacts have been limited. Some companies are focusing on substitution, using alternative battery chemistries, with the goal of eliminating cobalt given its negative associations and entrenched problems in the supply chain.

While the situation with cobalt from the DRC is sobering in its dimensions and gravity, not all examples of energy transition-relevant artisanal production are negative. ASM copper production in Chile demonstrates the potential contributions.

Chile is the leading global copper producer and has succeeded in fostering growth in both large-scale and ASM copper. The latter has come through a hands-on approach by the state entity ENAMI, which buys ore directly from ASM and handles refining and marketing, creating stable market conditions and avoiding environmental problems that often emerge from self-processing of ore by artisanal miners. ENAMI also helps ASM access loans and technical support. All of this has created a successful niche for ASM and has brought important local development benefits (Atienza et al 2023). However, efforts to export the model have found limited success (Hilson 2020), suggesting that more work is needed to understand which elements are replicable and which are context-dependent.

Finally, returning to the earlier note that most ASM globally focuses on gold, any suggestion of reorienting artisanal miners to more transition-relevant production raises complex geological, technical, and socio-economic questions. Where are there deposits of critical minerals in proximity to existing ASM? Which critical minerals are well suited to artisanal mining techniques? How would ASM ores be responsibly processed and incorporated into value chains? And perhaps most importantly, what would it take to convince artisanal miners to shift away from gold and what sorts of technical, economic, and logistic supports would be needed? These questions should give pause to anyone suggesting a top-down reorientation of ASM from gold to critical mineral production.

More likely, any expansion of ASM production of critical minerals will emerge organically. In many countries ASM is a poverty-driven activity, a last resort or least-bad option for marginalized rural populations. Climate change promises to disproportionately impact the world's most vulnerable, including farmers and rural communities in the Global South. The well-worn pathways from poverty-level agriculture to ASM are only likely to grow as livelihoods are disrupted. Well-crafted policy responses like Chile's ENAMI could help catalyze the emergence of an ASM sector that could provide meaningful work while also producing meaningful quantities of critical minerals for the energy transition. On the other hand, the abuses and degradation of cobalt in the DRC could be repeated in new settings. The direction of ASM's role in the energy transition stands at a crossroads.

3.2.3 Workforce

The mining industry is a pillar of global economic stability, particularly in the domain of essential minerals such as lithium, cobalt, and rare-earth elements. These minerals are essential to the development of our contemporary world, with applications ranging from renewable energy systems to advanced defense technologies. While the significance of these minerals is widely acknowledged, the importance of the mining workforce is frequently overlooked. As of 2019, the U.S. Geological Survey and the International Labour Organization estimate that the mining sector directly employs more than 40 million people worldwide and contributes significantly to national GDPs, especially in developing nations (USGS, 2018; ILO, 2019). Nonetheless, the industry's dependence on its workforce is not limited to mere numbers; it also affects global supply chains and geopolitical stability. For instance, disruptions in the mining workforce in the Democratic Republic of the Congo have historically affected the global price and availability of cobalt, a crucial mineral (World Bank, 2020). Such occurrences emphasize the strategic significance of labor at a time when nations are increasingly competing for resource control.

This vital sector is influenced by a complex matrix of factors, including the demographics of its workforce and the gender dynamics of its workforce. According to data from the International Council on Mining and Metals (ICMM, 2020), the age distribution of a mining workforce can have implications spanning from workplace safety to technological adaptability. Gender representation plays an important factor as well. Emerging studies, including a 2019 report from the World Bank, point to the multifaceted advantages of a more gender-balanced workforce, including safety and operational efficiency. Understanding these internal dynamics is not merely an academic endeavor; it also has practical applications. The Human Development Index (HDI), which considers factors such as health, education, and living standards, can serve as a useful indicator of mining communities' well-being. There is evidence to suggest that balanced workforce demographics and gender representation can positively impact a region's HDI, indicating that the pursuit of diversity and inclusion in the mining workforce is not only a moral but also an economic and social imperative.

Demographics

The global mining industry is a complex tapestry of human skill and effort. Lithium, cobalt, and rare earth elements, among other critical minerals, are the lifeblood of modern industries spanning from renewable energy to defense. According to a 2019 report by the International Council on Mining and Metals, large-scale mining operations employ over 1.2 million people directly, not including innumerable others in auxiliary and support positions (ICMM, 2019). The distribution of this vast labor force reveals intriguing patterns. For example, the 'Lithium Triangle' encompassing Argentina, Bolivia, and Chile, a region wealthy in lithium reserves essential for battery technologies, has experienced a substantial increase in specialized labor. In 2020, lithium extraction accounted for approximately 17,600 direct jobs in Chile (U.S. Geological Survey, 2020). In contrast, the Democratic Republic of the Congo (DRC) is home to a sizeable population of artisanal miners who contribute to the extraction of cobalt, which comprises over 60% of the world's reserves (Cobalt Institute, 2020). As the dominant producer of rare earth elements, China adds yet another layer of specialized labor to this landscape.

In addition to geographical distribution, the diversity of the workforce also encompasses the roles individuals play within the sector. This complexity requires a vast array of skills. Exploration geologists identify possible mineral deposits at the outset of every mining endeavor. Then, mining engineers assume control, ensuring the safe and effective extraction of minerals. Metallurgical engineers then refine and process the unprocessed minerals, while environmental consultants assess the operations' ecological impact. Professionals in mine safety, operational managers, and even human resource administrators play crucial roles in expediting the mining process, upholding safety standards, and ensuring the well-being of the workforce. In addition, artisanal miners and market analysts make substantial contributions (World Mining Congress, 2018; Society for Mining, Metallurgy, & Exploration, 2020; Environmental Protection Agency, 2019; Mining Safety and Health Administration, 2020; World Bank, 2019; U.S. Geological Survey, 2020). Due to the typical locations of mineral deposits, this workforce distribution is significantly biased towards rural areas, which poses unique challenges for infrastructure, housing, and regional economic development. It becomes clear that the mining workforce for essential minerals consists of a mixture of regional specializations, a broad variety of roles, and a discernible urban-rural divide.

Gender in Mining

The mining industry's historical landscape has long been male-dominated, influenced by cultural, economic, and sometimes policy-driven factors that relegated women to the margins. Early mining relied heavily on manual labor and transient lifestyles, effectively sidelining women due to traditional gender role views and superstitions that associated them with bad luck in mines (Lahiri-Dutt, 2012; Jenkins, 2014). However, with the advent of technology, the industry's skill requirements have evolved to include geology, metallurgy, and management. Although this change could theoretically open doors for more women, multiple barriers, such as biases and lack of mentorship opportunities, continue to hinder their participation (International Labour Organization, 2017). Yet, a slow but positive transition is evident, with women now making up 5 to 10% of the global mining workforce (World Bank, 2019). Organizations like Women in Mining (WIM) actively champion for gender diversity, contributing to this slight uptick (WIM, 2020).

Within this broader picture, the challenges faced by women are numerous and often exacerbated by the mining sector's male-dominated culture. Safety concerns for women, particularly in remote mining locations, include risks of gender-based violence and harassment (World Bank, 2019). Systemic discrimination manifests in various ways, including relegation to lower-paying roles and underrepresentation at decision-making levels (Jenkins, 2015; Eftimova et al., 2020). Additionally, cultural norms and economic vulnerabilities, especially in informal and artisanal mining sectors, make women susceptible to exploitation (Lahiri-Dutt, 2012; Hinton et al., 2003).

Despite these challenges, strides are being made to foster a more inclusive environment. Internationally, organizations like the International Women in Mining (IWiM) work to create a gender-inclusive culture through mentorship, scholarships, and advocacy (International Women in Mining, 2020). Major corporations like Rio Tinto and BHP have also set gender equality targets and implemented inclusive policies like flexible work arrangements (BHP, 2018). On a legislative front, some countries, like South Africa, have even set quotas to ensure a minimum percentage of female workforce in mining (Department of Mineral Resources, South Africa, 2018). Other initiatives include capacity-building programs, awareness campaigns, and the institution of women-specific health programs and strict anti-harassment policies (African Minerals Development Centre, 2017; Women in Mining Canada, 2019; Eftimova et al., 2020).

Education and Skills Development

The mining industry in both the United States and globally is at a crucial juncture, increasingly characterized by a transformative blend of technical innovations, surging demand for critical minerals,

and a pressing need for a highly skilled workforce. While China has been strategically proactive—investing significantly in mining-specific education, thus generating over 1.4 million enrollments in relevant courses—the United States finds itself in a precarious position, grappling with acute labor shortages and escalating costs that imperil its competitiveness (Colorado School of Mines). In the last academic year alone, U.S. enrollment figures for accredited undergraduate and graduate mining engineering and related programs languished at just 600, a stark contrast to China's proactive educational strategy.
This "war for talent," as it's been dubbed, presents immediate challenges that ripple through the supply chain and ultimately risk making American mining products uncompetitive both domestically and globally. As labor costs swell and product prices increase, the ramifications are not confined to economics but extend to national security and the reliability of critical materials essential for modern technologies.

There has been a decline in Mining Engineering Programs and Faculty in the U.S.

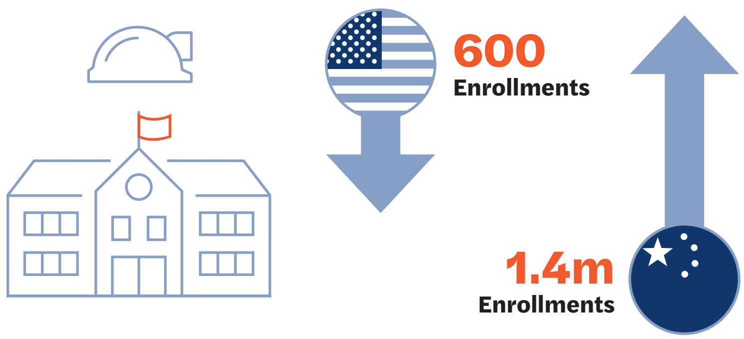


Figure 21: Mining Enrollments in the U.S. and China

However, efforts like the proposed Mining Schools Act aim to inject new life into the industry by preparing the next generation of mining leaders, fostering interdisciplinary education that embraces not just technological innovation but also environmental stewardship and social responsibility (U.S. Geological Survey).

The Colorado School of Mines serves as a pioneering example in this regard, fusing mining engineering with diverse fields like hydrology, geosciences, and even the humanities. However, to scale these models of excellence across the nation, a sweeping rebranding of the mining industry is necessary. For too long, the sector has been saddled with an outdated image that reflects neither its contemporary challenges nor its opportunities. The sector needs to project itself as a cutting-edge, impactful field that appeals to the aspirations of today's youth, who seek to blend economic rewards with positive global impact. To facilitate this transformation, the industry's marketing and communications strategies need a significant overhaul, one that disseminates a new, optimistic, and socially responsible vision of mining. Universities and community colleges must join forces with government agencies and industry associations to elevate the profile of mining, illuminating the raft of exciting job opportunities it presents. Transparency in environmental, social, and governance (ESG) practices will not just be an added bonus but a fundamental requirement to build credibility and trust among prospective students and the wider public.

Simultaneously, as labor shortages become increasingly global, impacting even reliable trading partners like Canada, Australia, and countries in Europe and Latin America, international collaboration will be pivotal. Opening the doors of U.S. educational institutions to foreign students can serve dual purposes: it could mitigate domestic labor shortages and build international networks of expertise and cooperation.

Well-being Measured by HDI

The Human Development Index (HDI) is an essential tool for understanding human well-being, encompassing life expectancy, education, and income per capita. Yet, the well-being of mining workforces extracting critical minerals like lithium, nickel, gold, cobalt, and copper tends to be overshadowed by other economic metrics. To truly grasp the well-being of these vital workers, examining the HDI scores of nations with significant mining activities provides key insights (United Nations Development Programme, 2020).

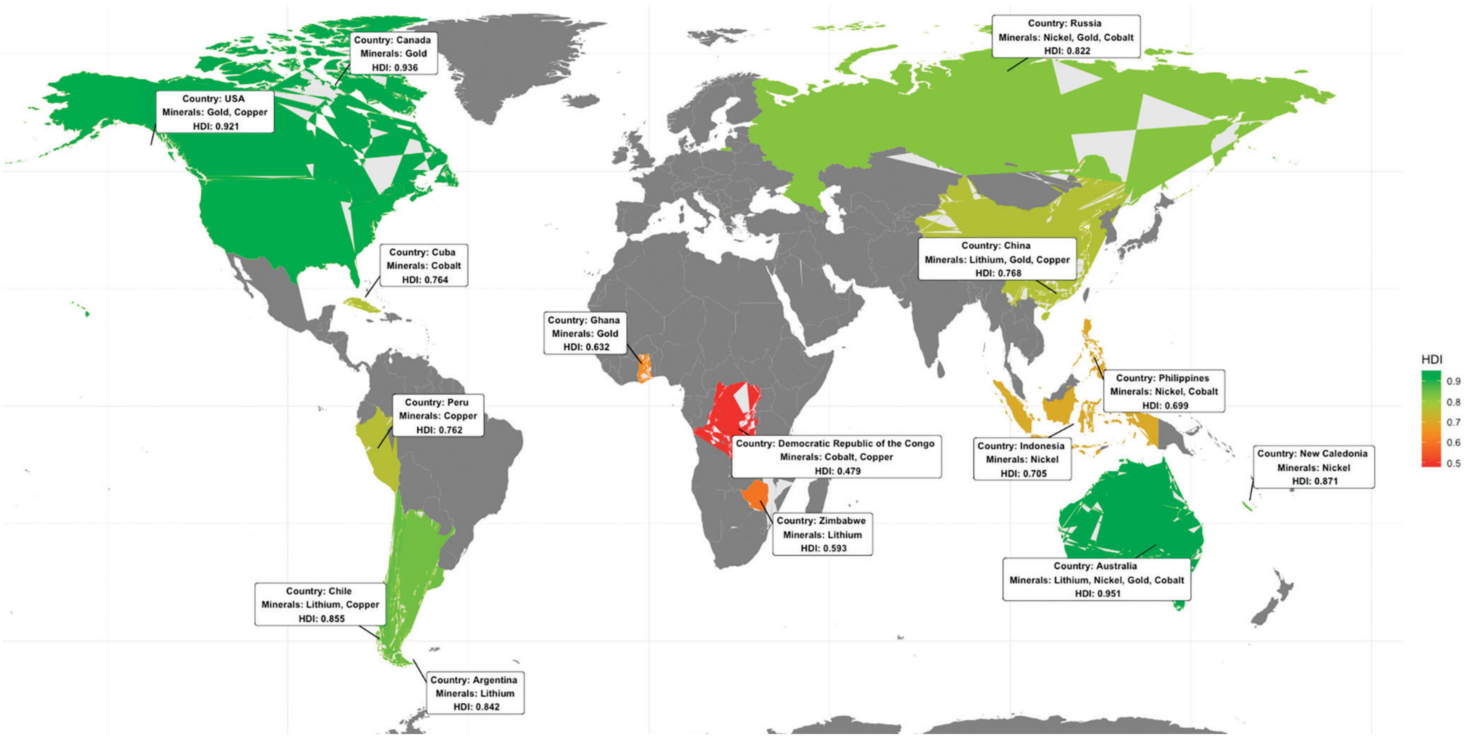


Figure 22: HDI for Top Mining Countries

Australia and Canada, with high HDI scores of 0.951 and 0.936, suggest a superior standard of living for their mining workforces, complete with better working conditions, healthcare, and educational opportunities. These favorable conditions generally correlate with more secure jobs, safety measures, and social benefits for workers in high-HDI countries. On the flip side, nations like the Democratic Republic of Congo (DR Congo), with a low HDI of 0.479, present a starker reality. The poor living conditions, lack of access to quality education, and inadequate healthcare provisions reflect significantly more challenging working conditions for miners, including greater occupational risks (World Bank, 2017). Countries with middle-range HDI scores, like Russia (0.822) and Chile (0.855), offer a mixed bag of conditions for their mining workforce. While workers in these nations fare better than those in low-HDI countries, the mid-range scores indicate areas for potential improvement, particularly when compared to higher-ranking countries (Ul Haq, 1995).

A notable aspect is the apparent inequality in well-being across the global mining workforce. A lithium miner in Australia, for instance, lives a significantly different life from a cobalt miner in DR Congo, despite both being cogs in the same global supply chain. This underscores the need for a nuanced, multipronged approach that acknowledges the unique socio-political contexts of each mining region. Further complexity arises when countries with similar HDI scores, such as China (0.768) and Peru (0.762), show marked differences in mining workforce conditions. These disparities may arise due to variations in governance, industrial regulation, and social policies. Consequently, while HDI offers valuable foundational data, it doesn't paint a complete picture of workforce well-being in the critical minerals sector. Therefore, as the global demand for these minerals escalates, it's imperative to include HDI alongside other sector-specific indicators and qualitative assessments for a more rounded understanding of workforce well-being. This multi-faceted approach is not just beneficial but essential for crafting targeted strategies that contribute to a sustainable and equitable future in mining.

Economic Impacts on Workforce Well-being

The mining sector, especially in the extraction of critical minerals, has emerged as a cornerstone of economic stability, contributing significantly to the GDP of resource-rich nations. This robust economic contribution isn't isolated to the extraction process alone but trickles down to myriad ancillary services, from logistics to maintenance, thereby amplifying employment opportunities and overall economic health (World Bank, 2017; ICMM, 2012). Alongside, miners often enjoy higher-than-average wages and additional benefits, like health and educational perks, leading to an enhanced standard of living (PWC, 2018). However, this prosperity can be cyclical, influenced by the volatile nature of global commodity prices, which may lead to workforce reductions or operational changes (Humphreys, 2015).

Simultaneously, wage disparities, particularly along gender lines, present a challenge to workforce well-being and overall economic growth. Men, who traditionally dominate the sector, often receive 15-20% higher wages than their female counterparts, resulting in not only an imbalanced earning structure but also discouraging women from joining the sector (ILO, 2018). Such disparities resonate far beyond paychecks, influencing the HDI metrics like Gross National Income (GNI) per capita, educational achievements, and health outcomes (Doane, 2017; World Bank, 2015; Sen, 2001).

Moreover, the mining sector is no stranger to risks. While it offers lucrative pay, particularly in the extraction of critical minerals and in remote locations (PWC, 2020), the nature of the work comes with significant occupational hazards ranging from exposure to dangerous chemicals to long-term health conditions (ICMM, 2019). The sector also brings challenges to mental health due to periods of extended separation from families. Furthermore, the industry's cyclical and volatile nature creates an oscillating sense of job security, exacerbated by the increasing adoption of automation technologies that could potentially reduce manual jobs (World Bank, 2017; EY, 2019). Notwithstanding, as the sector increasingly leans towards sustainable practices, there's a concurrent focus on elevating its economic contributions while ensuring consistent workforce security (Hilson & Murck, 2000). The economic landscape of the mining sector is, therefore, a tapestry of potent contributions, risks, and disparities, each of which has far-reaching impacts on the workforce's overall well-being. The growing focus on gender equality and sustainability heralds a gradual shift, aligning the industry more closely with broader human development goals, but there remains considerable work to be done to navigate the complexities of economic and social sustainability.

3.3 Governance & Regulatory Framework

3.3.1 Permitting

Mining permits ensure responsible and sustainable extraction of mineral resources while safeguarding the environment and protecting public interests. The global shift towards clean energy has increased the demand for metals used in battery production, such as lithium, cobalt, and nickel. This demand has prompted the need for new mines to meet the growing requirements. Balancing the pursuit of clean energy with responsible mining practices is crucial for environmental sustainability and efficient resource management. This increased demand for mining activity and the production of batteries, if not properly regulated, may increase the release of greenhouse emissions. Therefore, the clean energy transition has necessitated sustainable mining practices and increased mining activity to meet the rising demand for battery metals.

In addition to battery manufacturing, there is an increase in demand for mined metals that can be attributed to the post COVID era market revival and the need for increased activity. In 2021, The United States produced about $ 90.4 billion in mineral commodities as against $80.7 billion in 2020 (Burton, 2022). This represents a 12% increase over the previous year. Despite this increase, the United States is more than 50% net reliant on foreign sources for raw and processed mineral materials in 2021. (U.S. Geological Survey, 2022).

It takes five times (5X) longer to permit mines in U.S. as compared to Canada and Australia- jurisdictions with similar environmental, social and governance requirements. The mine permitting practices of Canada and Australia present compelling evidence that the United States must take immediate action to reform, revitalize its mining sector, and secure its position in the global market.

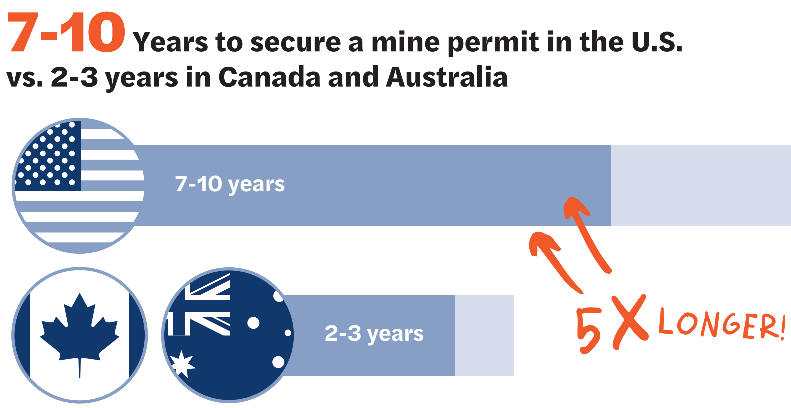


Figure 23: Permitting Times in the U.S. vs. Canada and Australia
Source: Payne Institute, based on data from the National Mining Association

A study of the production in tons of four important metals (gold, aluminum, silver and copper) from 1900 to 2018 revealed that the US produced less silver in 2018 than it did in 1900. For copper, production for 2018 was 30,000 tons less than it was 100 years ago. In terms of aluminum production, the United States produced about 19% of what it produced at its production peak in 1980. Gold production has been generally high since the US is among the world's top five gold producers (Goldhub, 2023). However, when recent production statistics for gold is compared to historical data, it is clear the US is under-performing. For instance, gold production peaked in 1998 with 366 tons. However, since then, production has dropped with 2018, 2019, 2020, 2021 and 2022 producing 62%, 54.6%, 52.7%, 51.1%, and 46.4% respectively of the tonnage it poured in 1998. (Ceic, 2023).

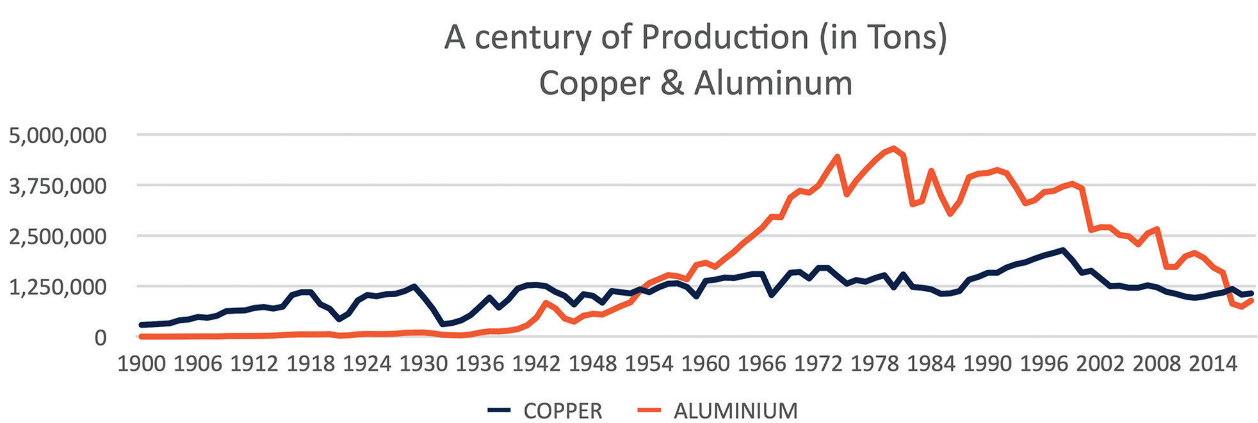


Figure 24: U.S. Copper & Aluminum Historical Production
Source: Payne Institute, based on data from USGS

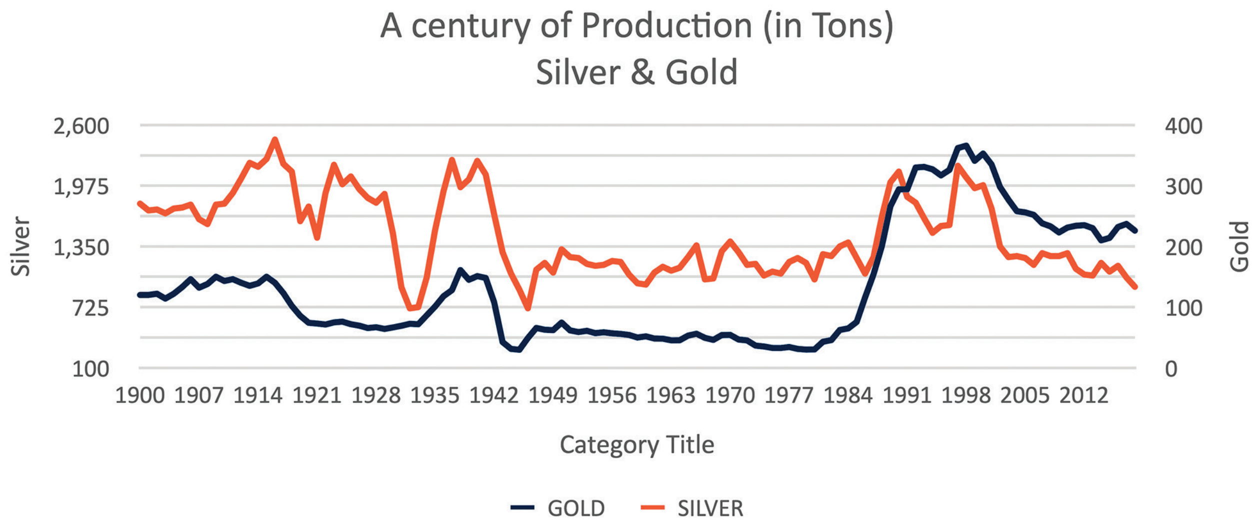


Figure 25: U.S. Silver & Gold Historical Production
Source: Payne Institute, based on data from USGS

The lower production is not a result of a lack of resources or reserves in the U.S. over the century. In contrast, the U.S. is an important player in the mineral's commodity markets due to its vast mineral endowment, advanced technology, highly skilled workforce, deeper and more mature financial markets and good infrastructure and networks. In fact, at the beginning of the century, the U.S. produced enough minerals and metals to meet its domestic consumption. Domestic production met more than 100% of domestic consumption for Copper, Gold, Aluminum, REEs and Lithium. Globally, the U.S. accounted for more than 50% of the total world production for Copper, more than 30% of Global Aluminum and Gold production and about 20% of the production of REEs by the early 1900s.

Contrary to assumptions that the U.S. has less resources and reserves for most minerals, the U.S. ranks in the top 10 countries with the highest reserves for some of the critical minerals including Copper, Lithium, Cobalt and REEs.

U.S. reserves in metric tons and percentage of apparent consumption imported

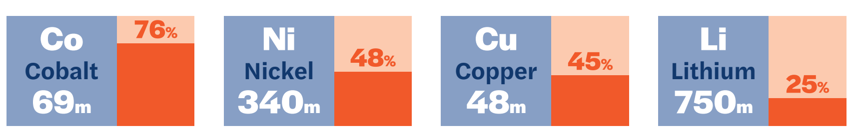


Figure 26: U.S. Reserves of some Critical Minerals
Source: National Mining Association

Advancement in technology in mining has always been driven by the need to increase productivity and safety. Over the past century, the mining industry has undergone significant technological advancements that have revolutionized various aspects of mining operations, leading to increased production levels, safety improvements, and efficiency gains. There are now many technologies that improve all aspects of mining and they include: mechanization and heavy machinery, blasthole drilling with rigs, open-pit mining and strip mining, underground mining technologies, advanced surveying and mapping, remote sensing and satellite imagery, automation and robotics, digitalization and data analytics, advanced material handling, environmental and safety technologies.

The Permitting Process

The mine permitting process in the USA involves a series of regulatory steps and requirements that mining companies must follow to obtain permission to develop and operate a mine. The process aims to balance the economic benefits of mining with environmental protection and public health considerations. Here is a summarized overview of the mine permitting process:

- **Exploration and Site Identification:** Mining companies identify potential mineral resources and evaluate the feasibility of mining in a specific location. This involves geological surveys and initial environmental assessments.

- **Pre-Application and Planning:** Before formally applying for permits, companies engage with relevant federal, state, and local agencies, as well as stakeholders such as communities, tribes, and environmental groups. They develop a mining plan that outlines the project's scope, methods, and potential environmental impacts.

- **Application Submission:** The mining company submits permit applications to the appropriate regulatory agencies, which can include federal agencies like the U.S. Army Corps of Engineers and the Environmental Protection Agency (EPA), as well as state and local agencies. These applications typically include details about the mine's design, operation, environmental impact assessment, and mitigation plans.

- **Environmental Review and Impact Assessment:** Agencies conduct environmental reviews to assess potential impacts on air, water, soil, wildlife, cultural resources, and nearby communities. This process often includes an Environmental Impact Statement (EIS) or Environmental Assessment (EA), depending on the significance of the project's potential impacts.

- **Public Comment and Hearings:** Agencies provide opportunities for public input and hold public hearings to gather feedback from communities, environmental organizations, and other stakeholders. Public concerns and expert opinions are considered during the permitting process.

- **Agency Coordination and Consultation:** Various federal, state, and local agencies collaborate to ensure that all relevant laws and regulations are being addressed. This can include compliance with the Clean Water Act, Clean Air Act, National Environmental Policy Act (NEPA), and other relevant laws.

- **Permitting Decision:** Regulatory agencies review all information, public input, and environmental assessments to make a decision on whether to grant permits. They may approve the permit application as submitted, approve with modifications or conditions, or deny the application based on environmental, social, or economic considerations.

- **Mitigation and Monitoring Plans:** If permits are granted, mining companies often need to implement mitigation measures to minimize environmental impacts. They are also required to develop monitoring plans to track and report on environmental conditions throughout the mine's lifecycle.

- **Construction and Operation:** Once permits are obtained, the mining company can proceed with construction and mine operation in accordance with the approved plans and regulations.

- **Post-Closure Responsibilities:** After mining operations cease, companies are often required to carry out reclamation and restoration activities to rehabilitate the site to a condition that is compatible with its surroundings.

It's important to note that the mine permitting process can vary depending on the specific type of mine, the jurisdiction (federal, state, or local), and the nature of the environmental and social considerations involved. The process seeks to strike a balance between economic development and environmental protection, ensuring that mining operations are conducted responsibly and sustainably.

Reasons for Delays

The mine permitting process in the USA can be exceptionally long and tedious compared to countries like Canada and Australia due to a combination of factors:

- **Regulatory Complexity:** The regulatory framework in the USA involves multiple layers of federal, state, and local regulations. Each level of government has its own permitting requirements, which can lead to duplication of efforts and a more complex process. In contrast, countries like Canada and Australia often have more streamlined and centralized regulatory structures.

- **Environmental Impact Assessments:** The USA places a significant emphasis on comprehensive environmental impact assessments (EIAs) under the National Environmental Policy Act (NEPA). These assessments can be expensive and time-consuming, involving in-depth studies of potential impacts on air, water, wildlife, cultural resources, and communities. While Canada and Australia also have environmental assessment processes, the USA's NEPA process can be more rigorous and subject to legal challenges.

- **Public Participation and Litigation:** The USA places a strong emphasis on public participation and allows for legal challenges to the permitting process. While public input is important for transparency and democratic decision-making, it can also lead to delays as stakeholders raise concerns and legal challenges that need to be addressed.

- **Interagency Coordination:** Coordinating among various federal, state, and local agencies in the USA can be complex and time-consuming. In countries like Canada and Australia, there might be more centralized oversight and coordination, leading to a smoother process.

- **Environmental Protection Standards:** The USA often has stringent environmental protection standards and requirements, which can lead to more thorough reviews and additional mitigation measures. This can prolong the permitting process, as mining companies need to meet higher standards and demonstrate robust environmental protection plans.

- **Public Opposition and Advocacy:** The USA has a history of active environmental advocacy and opposition to mining projects, which can lead to longer permitting processes as companies must address concerns and seek to address potential impacts.

- **Indigenous Rights and Consultation:** In the USA, consultation with indigenous communities is a crucial part of the permitting process, as tribal sovereignty and rights are protected by law. This can add additional steps and considerations to the process.

- **Litigation Risk:** Due to the complexity of the permitting process and the involvement of multiple stakeholders, there's a higher risk of legal challenges in the USA. Legal disputes can significantly prolong the permitting timeline.

It is important to note that the comparisons between countries are not absolute, and factors can vary depending on specific projects, jurisdictions, and changes in regulations. While the USA's permitting process might be perceived as longer and more complex, it also reflects a commitment to robust environmental protection, public involvement, and responsible resource development.

Impact of Delays

The permitting process in the US can have significant impacts on the mining industry, influencing its operations, development, and competitiveness. Here are some ways in which the permitting process affects the US mining industry:

- **Project Delays and Costs:** The lengthy and complex permitting process can lead to substantial delays in project timelines. Delays can increase costs due to prolonged pre-production phases, regulatory compliance expenses, legal fees, and the need for additional studies and assessments. The National Mining Association (NMA) estimates the prolonged permitting process can cut the expected value of a mine by half before production even begins.

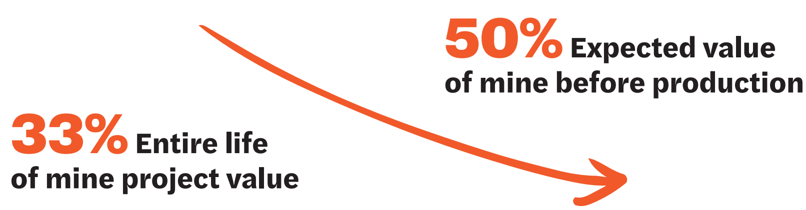


Figure 27: Financial Costs of Delays in Permitting
Source: Payne Institute, based on data from the National Mining Association

- **Investment Uncertainty:** The uncertainty caused by lengthy permitting timelines and potential for regulatory changes can discourage investment in the mining sector. Investors might opt for jurisdictions with more predictable and efficient permitting processes. The result is shown by the level of investments in exploration. Canada, Australia and Latin America are attracting more investments in mineral exploration, a key requirement for long-term sustainable mineral development.

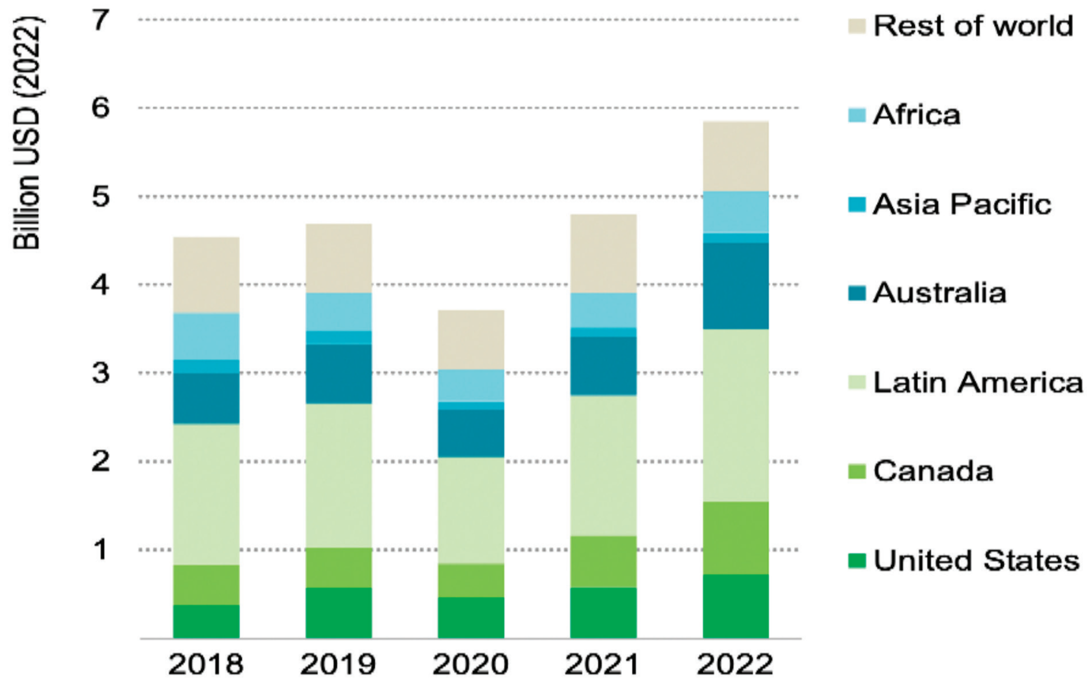


Figure 28: Exploration spending led by Australia, Canada and Latin America Region
Source: IEA

- **Competitiveness:** Countries with higher mining competitiveness will tend to attract larger amounts of exploration investments. The US mining industry's global competitiveness can be impacted if other countries offer more streamlined and efficient permitting processes. Lengthy delays might lead to missed opportunities and hinder the industry's ability to respond to market demand.

- **Resource Availability:** Prolonged permitting can delay the availability of important mineral resources for various industries, including manufacturing, electronics, and renewable energy. This can impact domestic supply chains and economic growth.

- **Environmental Considerations:** While the permitting process's stringency aims to protect the environment, it can also impact the industry's ability to access resources responsibly. Balancing environmental protection with resource development is a challenge the industry faces.

- **Innovation and Technology:** Lengthy permitting can slow the adoption of new technologies and innovations in mining. Companies might be hesitant to invest in research and development if regulatory uncertainties delay their ability to implement new practices.

- **Job Creation and Economic Impact:** The mining industry contributes to local economies through job creation and revenue generation. Delays in permitting can postpone the creation of these economic benefits for communities.

- **Regulatory Compliance:** Companies must allocate resources to navigate the complex regulatory landscape, including hiring experts, conducting studies, and engaging in public consultation. This diverts resources from actual mining operations.

- **Small and Medium Enterprises (SMEs):** Lengthy permitting processes can disproportionately affect smaller mining companies with limited resources. These companies might struggle to manage the financial and administrative burden of prolonged permitting.

- **Community and Stakeholder Relations:** The engagement required during the permitting process can foster positive relationships with local communities and stakeholders. However, conflicts and disputes can also arise if communities are concerned about environmental impacts or other issues related to mining.

- **Global Supply Chains:** In a globally connected economy, delays in the US mining sector can impact international supply chains for various industries, which might turn to other countries for their resource needs.

- **Litigation Risk:** The potential for legal challenges during the permitting process can add uncertainty to projects and increase the risk of costly legal disputes.

Overall, while the permitting process aims to strike a balance between resource development and environmental protection, its complexity and length can impact the US mining industry's ability to compete, innovate, and contribute to economic growth. Striking a balance between regulatory rigor and efficiency is essential for ensuring a sustainable and competitive mining sector.

Recommendations

Permitting Reforms:
New regulatory requirements or environmental reviews are unnecessary. U.S. minerals mines are already subject to over three dozen federal and state laws and regulations with no comprehensive law that provides clear direction for permitting hard rock mines. The General Mining Law of 1872 is the primary statute governing hard rock mining on public federal lands. It has not been significantly revised for more than the past 150 years of its existence.

Inter-agency Collaboration:
Collaboration and Coordination of both federal and state agencies will improve the permitting process and reduce duplication of processes. These agencies must also work together, perhaps through a shared information system, to reduce the time and financial costs of these duplicitous submissions. Agencies must also approach the permitting process with a sense of duty, adhering to schedules for permit reviews, transparently tracking progress to providing accountability.

Communication: 'Mined-In-America' Messaging
America needs a new relationship with mining and the messaging must be at all levels. The over-reliance of countries like China for critical minerals has dire economic and national security risks. Fortunately, the U.S. is home to an estimated $6.2 trillion of mineral reserves that will help ensure the success of future energy technologies and both economic and national security. The U.S. also has the people and technology to make mining safer and more sustainable, so it is better to mine in 'our backyard' to ensure compliance with the best ESG standards.

Education and Training:
Invest in new technologies and human capital through grant programs to become an innovation hub to develop smart mining practices that are cleaner, faster and cheaper. Reintroduce earth science and mining related programs in early-stage curricula and continuously encourage innovation and clean technology development. There is also the need to train other key stakeholders, including civil society and federal agencies on mining and material science.

CHAPTER 4

INVESTMENTS AND MARKETS

With the demand for critical minerals poised to grow dramatically, investment in mine development is imperative. The visible investment horizon points to continued dominance by Chinese firms and continued high concentration (i.e., sourcing from a few countries) for specific minerals. Meanwhile, one barrier to investment by large, publicly traded mining firms domiciled in North America and Europe appears to be investor pressure for these firms to be more "disciplined" in their capital expenditures. This constraint may be partially offset by capital injections from "downstream" users of the minerals, which are being used to fund advanced purchase commitments and take equity stakes in mining companies.

The critical minerals market is estimated to have been USD ($) 320 Billion (B) in 2022, doubling from the cyclical trough of 2017 and 2018. For purposes of this discussion, critical minerals are defined to include copper (Cu), which was ~$195B of the total, followed by nickel (Ni, $60B) and lithium (Li, $40B). See Exhibit 1. Expressed in volume, production of Li led growth of critical minerals over the period, rising 4x to ~130 Kilotons (Kt). Cobalt (Co) rose 1.5x to ~170 Kt and Nickel rose 1.4x to ~3,000 Kt.

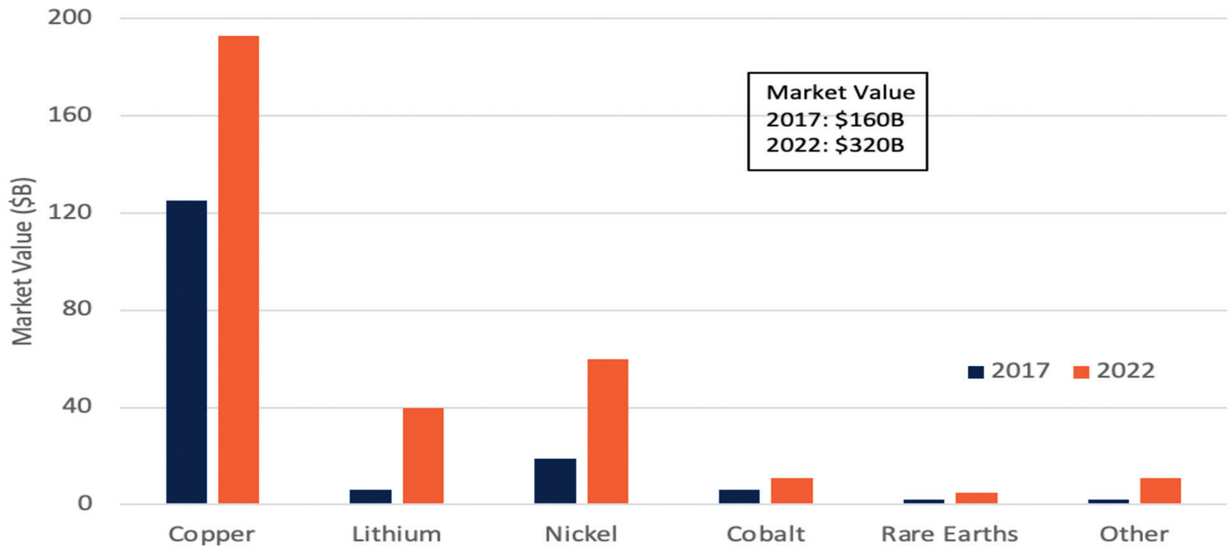
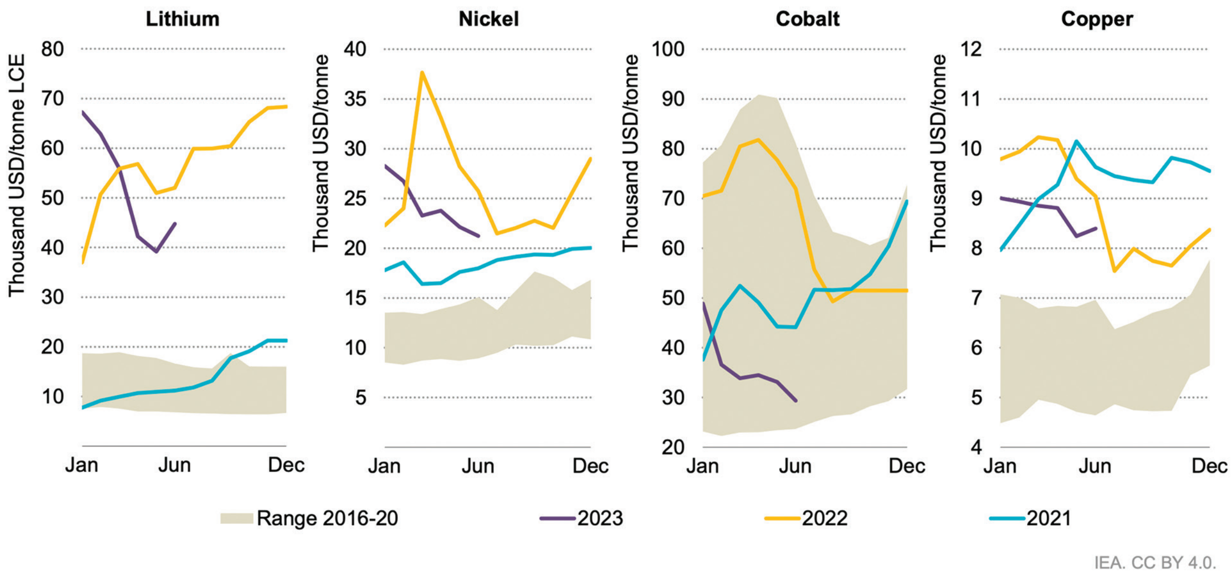


Figure 29: Market Value, Raw critical Minerals Market,2017 and 2022
Source: IEA based on S&P Global data

The market value growth also reflects consistently higher prices across critical minerals, although there has been considerable volatility over the last two and half years. See Figure 30.



Notes: LCE = lithium carbonate equivalent. Assessment based on LME Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices (nominal).

Figure 30: Price History, Select Critical Minerals, 2016 – 1H2023
Source: IEA based on S&P Global data

The growth in minerals production volume over the last five years has done little to change the concentration of that production as measured by country. Over 85% of various raw critical mineral production remains concentrated in its three top producing countries. See Figure 31.

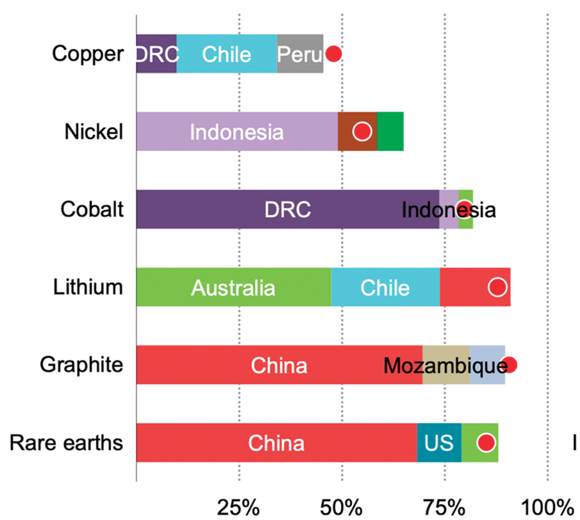
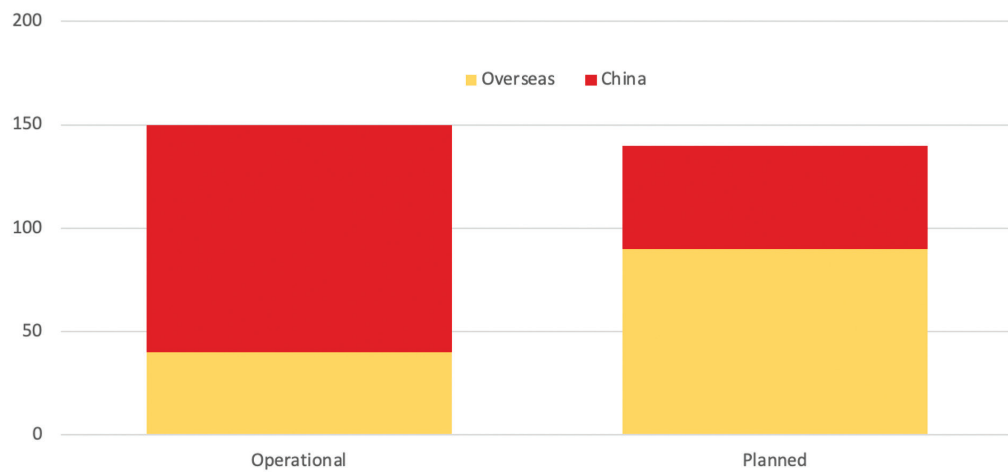


Figure 31: Country Concentration (% of Total), Select Critical Minerals Extraction Sources, 2022
Note: The red dot indicates estimated % concentration in the three largest countries in 2019
Source: IEA based on S&P Global data

The above does not reflect the far greater role and influence that Chinese-owned entities have in critical minerals markets. For example, Chinese companies/investors have a 70% share in The Democratic Republic of the Congo. Further, it does not reflect the dominant position that China has built in processing critical minerals including Co, Li, graphite and rare earths.

The growth outlook for critical minerals demand is dependent on the pace of the Energy Transition. Yet analysis by the IEA and others suggests that even countries' announced pledges to decarbonize imply a doubling of demand collectively for the larger-volume minerals by 2030 vs. 2022 and more than a tripling of demand by 2050.

Chinese entities continue to lead efforts at expansion. To wit, Chinese companies spent $4.3 billion between 2018 and the first half of 2021 acquiring lithium assets, twice the amount spent by companies from the United States, Australia, and Canada combined. In addition, China nearly doubled its investment spending in critical minerals in 2022, with a focus on lithium, copper, and nickel. The 2021 merger of three state-owned companies to form China Rare Earth Group, which accounts for over 60% of China's heavy rare earth supply, may reflect a pooling of financial resources to allow for further expansion. And there is evidence to suggest that Chinese-controlled entities are planning to develop 89 critical minerals mines outside of China (Energy monitor, 2023) as compared to 40 in operation currently. See Figure 32.



*Mines containing either of the following minerals as a primary commodity: chromim, cobalt, copper, graphite, iron ore, lead, lithium, mnganese, vanadium and zinc

Figure 32: Operating and Planned Critical Minerals Mines Majority-Owned by Chinese Companies
Source: Energy Monitor with data from GlobalData

Western mining companies have responded to the opportunity to some degree as well. Capital expenditures (capex), excluding for mergers & acquisitions, for a set of 22 miners, which reflects capital put to mining exploration and development, were $53B in 2022 vs. $31B in 2017 (71% higher). Yet there is evidence of a collective hesitancy to pursue growth more aggressively. First, the same group's capital expenditures in the mining industry's prior upturn (in 2011-2013) averaged $78B per year. Second, a subset of the total that includes the largest mining companies, which produce a diversified set of minerals, grew their capex 61% in 2022 from 2017 (the "diversifieds'" aggregate capex was 59% of the combined capex of the 22 companies in 2022) but reinvested only 25% of their cash flow (defined as Free Cash Flow plus dividends plus capex) into mining development, down from a 67% reinvestment rate in the prior upcycle.

The diversifieds appear to be planning further constraint in the near term. They are targeting 11% higher capex in 2024 (per FactSet Consensus analyst estimates, which are generally informed by company commentary to some degree), which translates to a reinvestment rate of 35% on 2024 cash flow estimates. In exercising capital discipline, these diversified mining companies appear to be following the behavior of other natural resources sectors. It should be noted, however, that investors are not obviously rewarding the diversifieds for their "capital discipline" with a higher value for their shares.
Given that mining is a cyclical industry, one can expect investors to accord less value to higher earnings periods than lower earnings periods in a cycle; in other words, one can expect multiples on earnings reflected in share prices to compress during higher earnings periods and expand during lower earnings

periods. However, the diversifieds are currently trading at lower multiples than the last cycle's peak earnings, even with plausible prospects that there can be significant earnings expansion for some time. To wit, the price-to-12-months-forward-earnings estimates (a forward P/E ratio) averaged 7.7x from 2021 through the first half of 2023 (1H2023) for this diversifieds group as compared to an average of 8.6x during the prior cycle peak (2011-2012). The lower earnings multiples may reflect several investor concerns, including:

- Volatility in the commodities pricing, as noted earlier
- Uncertainty regarding demand (e.g. if Energy Transition spending will meet levels that models suggest are needed to mitigate against global warming reaching certain levels
- Environmental, Social & Governance concerns
- Permitting challenges across countries

Recent capital discipline has been exhibited as well by publicly traded Cu miners. This group spent only 46% more on capex in 2022 than it did in 2017 and are targeting 31% growth by 2024 (again per FactSet consensus estimates). Like the diversifieds, Cu miners are spending well within their cash flow. This group reinvested 37% in 2021-2022 and 2024 estimates imply an expected reinvestment rate of free cash flow of 51%. This compares to a reinvestment 52% during the prior cycle peak earnings period (2011-2013), although reinvestment rates exceeded 100%, even as the miners cut their capex in half, as the cycle rolled over in 2014-16.

Li-targeted companies have, in contrast to the diversified and Cu miners, increased capex aggressively, raising it by 370% in 2022 vs. 2017 (on an apples-to-apples basis, i.e. only companies that were public in both 2017 and 2022). The Li companies intend to raise their capex another 65% by 2024. Yet with the dramatic increase in cash flow for this group, their spending implies a similarly conservative reinvestment rate of 44% compared with 48% from 2011-2020 (although the reinvestment rate did average 90% in 2019-2021). See Figure 33.

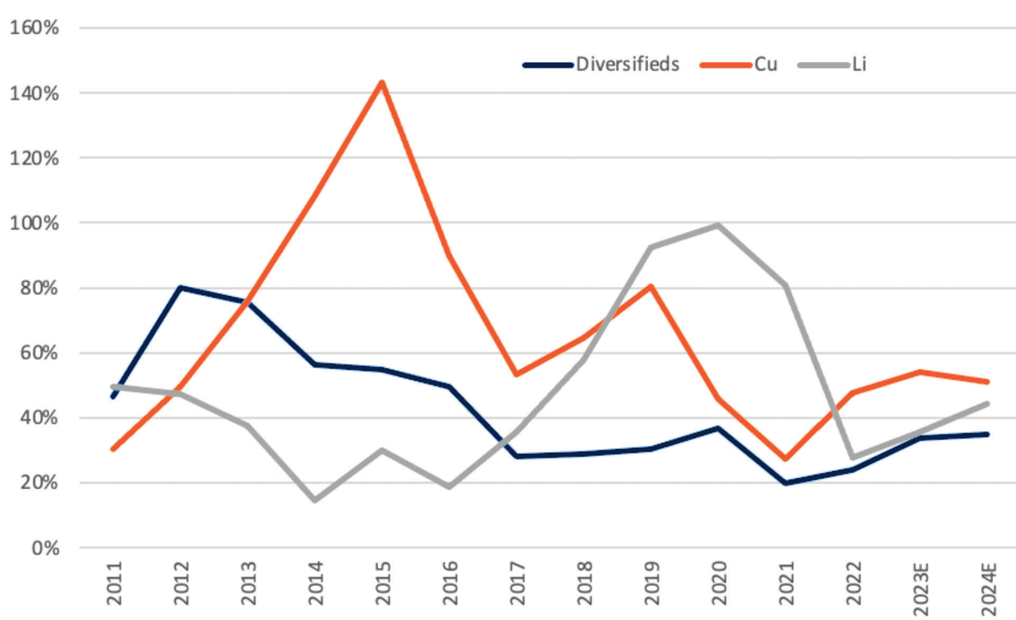


Figure 33: Mining Segment Reinvestment (Capex as % of Cash Flow) Rates, 2011-2024E
Source: Factset, Payne Institute

Investors appear to be encouraging these critical minerals companies to pursue growth, at least to some degree. The Cu group traded at an average forward P/E multiple of 15.9x from 2021 through 1H2023 vs. a prior peak earnings period multiple of 12.3x. And the Li group has traded at 34.3x in 2021-1H2023 vs. an average of 19.7x in 2011-2020. However, given the apparent dramatic growth prospects, it would still appear that investors harbor uncertainty. To wit, earnings estimates for the Li companies are 5x what they were a decade ago and yet the forward P/E multiple is less than 2x what it was then.

The public equity markets have provided modest support for new investment through initial public offerings (IPOs) as well. Some examples include; Lifezone Metals, which was taken public through a Special Purpose Acquisition Company (SPAC) GoGreen Investments which raised $318 million (NS Energy, 2022); 12 mining Canadian IPOs, with 11 on the Canadian Security Exchange (CSE) completed for a combined $157 million and Lithium Royalty Corporation's $150 million IPO (Bloomberg, 2023) on the Toronto Stock Exchange (TSX). Australia, too, saw investors pump A$1.6 billion into 104 metals and mining IPOs (S&P Global, 2022).

Supplementing public markets, industrial investors have also stepped in to provide capital. These investors are companies that are "downstream" of the minerals producers, i.e. are either processors, battery manufacturers, or, increasingly, EV manufacturers. These downstream companies have approached the investments in mining companies in two ways. The first, and most prevalent, approach is to make long term commitments to the mining company to take product. To offer just a few examples of contracts signed since the beginning of 2022 (IEA, 2023):

- Tesla secured a five-year contract with Australia's Liontown Resources for lithium spodumene concentrate, starting with 100,000 tons in 2024 and scaling to 150,000 tons. It also has signed a long-term cooperation agreement with Ganfeng Lithium and established five-year contracts with nickel processing firms in Indonesia valued at $5 billion.

- General Motors (GM) signed a long-term offtake agreement with Vale Canada for 25,000 tons per year of battery-grade nickel sulphate beginning in the second half of 2026

- BMW Group secured a $335 million offtake agreement with Livent for lithium hydroxide from Australia. It also has signed a long-term supply agreement with Ganfeng Lithium.

- Renault signed a seven-year deal with Managem Group for 5,000 tons per year of cobalt sulphate from Morocco. It also established a five-year agreement with Vulcan Energy to procure 6,000-17,000 tons of lithium per year.

The second approach is for the downstream company is to provide capital to the miner in exchange for an equity stake, or to simply acquire the miner. Some examples include:

- CATL, the largest manufacturer of electric vehicle (EV) batteries globally, acquired Millennial Lithium based in Canada. CATL also obtained stakes in an Australian lithium mining company and in copper-cobalt mines located in the Democratic Republic of the Congo (DRC).

- Suzhou CATH Energy Technologies entered an agreement to invest US$240 million for a 24% equity stake in the Manono lithium and tin project in the DRC, forming a joint venture with AVZ Minerals.

- SK On is set to acquire a 10% stake in Lake Resources, an Australian lithium developer, with the rights to secure up to 230,000 tons for ten years starting from the fourth quarter of 2024.

- General Motors announced a $650 Million investment in Lithium Americas to develop Nevada's Thacker Pass lithium mining project. GM would become Lithium Americas' largest stakeholder and would buy all of the early production from the project.

In principle, both forms of downstream "investment" are not ideal in terms of sources of capital for mining companies as they come at a higher cost relative to public sources of capital. Yet with their baseload commitments, these investments allow the mining companies to de-risk development such that public equity and debt markets become more available to them. This is particularly important given that futures markets in most critical minerals remains thin, i.e. the miners have limited opportunities to obtain financial hedges for future production. Thus, the downstream commitments, plus the increasing understanding of the degree of future demand and supportive government policies, likely all contribute to spurring greater investor support for critical minerals mining over the medium term.

CHAPTER 5

THE FUTURE OF MINING

5.1 Innovation & Optimization

The commodity super-cycle of the early 2000s (just like previous versions) was ignited by factors such as global economic growth, supply chain constraints etc., resulting in the obvious; the increase/inflation in commodity prices. Realizing this, Mining companies took advantage of this boom, to rack in more cash by expanding most of their operations. Even though this led to an increase in profit, productivity eventually decreased, as most companies struggled to manage these expanded/new operations which was largely profit-driven, without proper planning or workforce readiness (Clifford *et al,* 2018).

Sustained decline in commodity price, (after the most recent super cycle), has drawn the attention of the industry, on how to improve upon productivity. With declining high grade easy-to-access ore reserves, increased cost of critical mining inputs like water and electricity, increased scrutiny by community and governments (social license, ESG), are key to solving or at least, mitigating these increasing operational constraints is innovation (Steen *et al,* 2018).

Over the years, processes such as solvent extraction electrowinning (SXEW; hydrometallurgical processing rather than smelting) and computerization of operations has reduced close to 70% in operational cost. There has, however, been mounting pressure in recent times to improve upon innovation in the industry (Tilton and Landsberg, 1997).

The mining industry (for the most part) largely thrives on process innovation, rather than other forms of innovation. This is mostly because of how mining operations are set up. Mining operations are not simple isolated activities, but rather a system of connected technologies (drilling, blasting, loading/excavation, haulage/conveyance, processing etc.), working together to produce a finished product. This set-up puts the industry to heavily rely on Mining Equipment, Technology and Services (METS), for solutions/ new technologies, making mining companies a net consumer of innovation. This has resulted in the current trend where technological innovation enters a mining operation as part of an already existing, deeply connected, social, technical and organizational framework, making it difficult to quantify mining innovation in a more traditional sense like other businesses/industries.

5.2 Sustainable Mining Technologies

5.2.1 Exploration

TerraCore's Core Imaging Spectrometer™ (CIS™) can scan up to 1500 meters of core per day, keeping pace with most drilling programs. Interpretation of spectra is semi-automated when project geology is identified, allowing fast turnaround on results relevant to your exploration or resource project. Completed mineral maps and abundance data are uploaded to ALS CoreViewer™, allowing online examination of core photography and hyperspectral mineralogy at site, office, or anywhere your geologists might be located via secure web-based distribution.

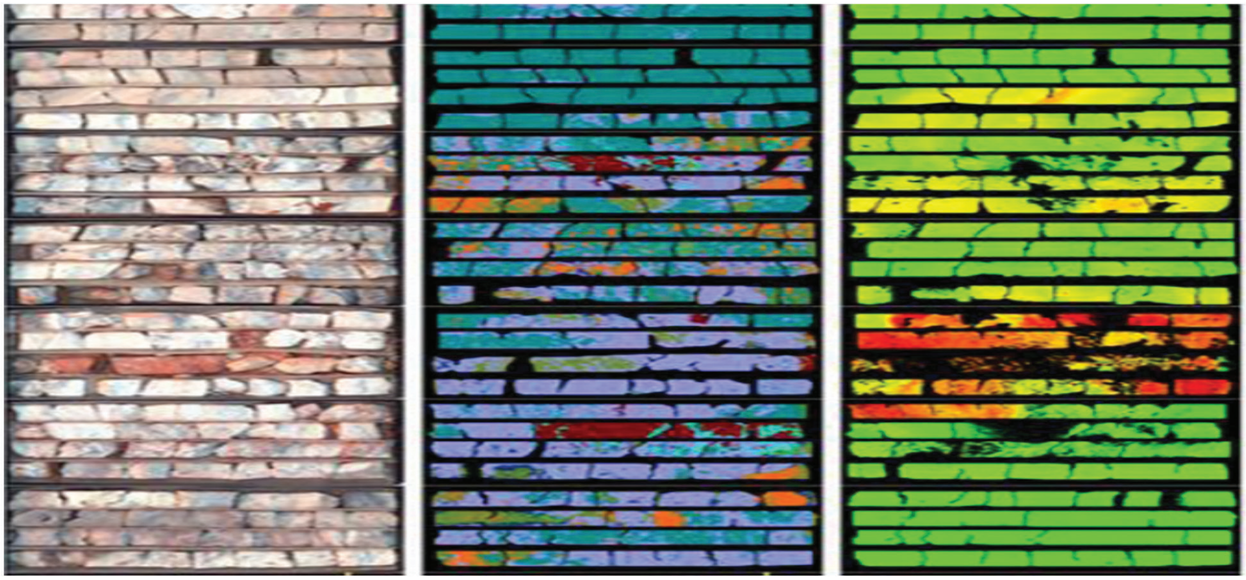


Figure 34: Core Imaging Spectrometer
Source:TerraCore, 2015

In 2018, the Red Lake Gold mine fed IBM's Watson, 80 years of geological data to help geologists identify the next best area for exploration. Processing data became 97 % more efficient for geologists after using IBM Canada's Watson cognitive technology at the site for a year.

5.2.2 Mine Planning and Production

In response to labor availability challenges, Rio Tinto introduced their future mine concept to make their operations at Pilbara much safer and more efficient. Two basic features of this mine plan/operations program were the use of autonomous drilling and haulage. The haulage trucks were estimated to have operated on average 700 hours more than conventional haul trucks, with 15% lower costs, delivering clear productivity benefits. Autonomous trains (AutoHaul™) became the world's first heavy-haul, long-distance autonomous rail operation, transporting iron ore from the Pilbara region of Western Australia. This network includes about 200 locomotives on more than 1,700 kilometers of track in the Pilbara. With 26 autonomous drills, Rio Tinto operates one of the largest autonomous drilling fleet in the world for safe and accurate drilling of blast-holes from a remote location (Rio Tinto, 2019).

Several other mining operations, mining software companies and mining support services/equipment companies have since then introduced or entered into partnerships on drilling, blasting and haulage technologies for safer and more efficient operations. Some of them include, Orica's BlastIQ, Newtrax cap lamp technology, HxGN MineOperate UG Pro, Caterpillar MineStar™ Solutions and battery electric trucks; Sandvik's AutoMine and OptiMine as well as its battery electric trucks, Newmont Mining partnership with Caterpillar for zero emission mining, and Syama Gold Mine partnership with Sandvik, making it Africa's first fully automated underground mine etc.

5.2.3 Mineral Processing and Metallurgy

Advanced Ore Sorting
Using sensors and AI, ore sorting technology can identify and separate valuable minerals from waste material early in the production process. A typical example is TOMRA Mining's X-Ray Transmission (XRT) which has been very helpful in delivering value across various operations. The use of this equipment at Australia's Mt Carbine mine helps to achieve high purity tungsten for the processing plant, resulting in significant cost savings. TOMRA XRT in 2015 recovered one of the largest diamonds in recorded history at Lucara's Karowe Mine in Botswana.

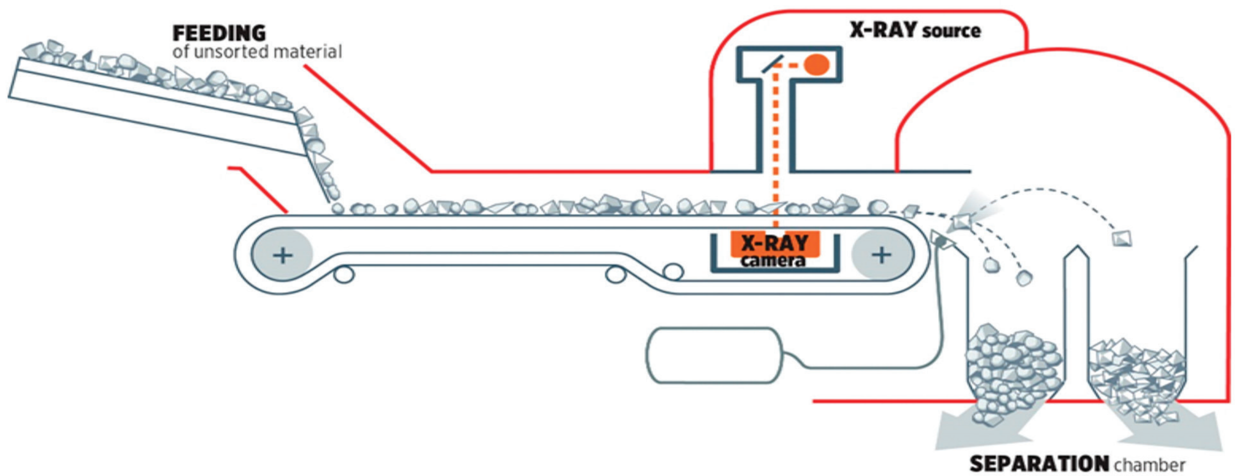


Figure 35: Simple layout of TOMRA Mining's X-Ray Transmission Machine
Source: TOMRA

Advancements in Metallurgy

Most extractive metallurgy processes use hydrometallurgy, pyrometallurgy or a combination of both. Clean mining's metallurgical process of replacing cyanide with thiosulphate represents an advancement in hydrometallurgy (CSIRO, 2021). Similarly, Metso Outotec's flash smelting process is one of the world's most commonly used processes for the production of primary copper and nickel. The process utilizes the internal energy of the feed material for smelting, minimizing the need for external fuel and making the process very energy efficient.

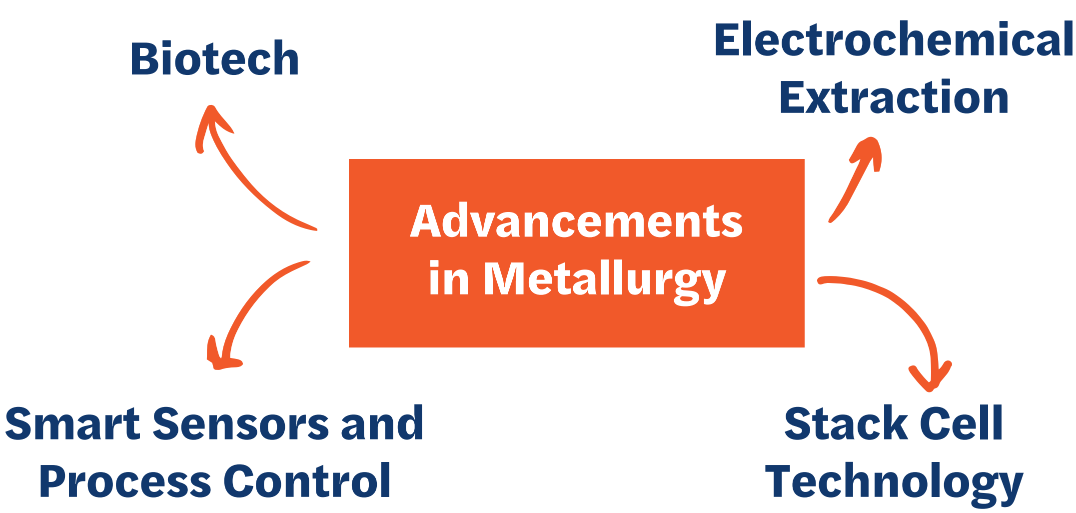


Figure 36: Examples of some Advancements in Metallurgy

5.2.4 Predictive Maintenance

Several predictive maintenance technologies exist for improved equipment health and maintenance practices within the industry. An example is ABB's Belt Conditioning Monitoring. This is an advanced digital service tailor made for predictive maintenance of conveyor belts, helping to reduce unplanned activities by 30 %. It does so by collecting and tracking data from the conveyor belt to provide information about failure potential, thus enabling planned and timely action.

5.2.5 Tailings Management

Tailings management/engineering has seen a lot of developments/improvements over the years amidst backlash from the public and various regulators of the industry. Some of the resulting technologies include dry stack tailings, paste and thickened tailings, tailings reprocessing, geochemical stabilization, cover systems, bioremediation, remote sensing and monitoring, numerical modeling and simulation, integrated water management etc. The Rosh Pinah zinc-lead mine opted for dry stack tailings to manage tailings generated during its operations. The dry stacking approach aligned with the mine's commitment to responsible environmental stewardship and helped reduce the potential impact on surrounding ecosystems, reducing water consumption and the risk of tailings dam failures while allowing for faster reclamation of the site after the closure of the mining operations.

5.3 Space/Asteroid Mining

Space exploration is a scientific activity that has been going on for decades. The possibility of extracting water from the moon and certain asteroids has been a focal point in recent times as this will significantly reduce and possibly eliminate the need to transport water from earth to space, thereby enhancing future human exploration of space.

Minerals such as iron, nickel, iridium, palladium, platinum, gold and magnesium have been discovered in asteroids with an estimated value of over $100 billion. Quite recently, researchers have uncovered to-metal rich near earth asteroids containing 85% iron, nickel and cobalt that exceeds global reserves of these minerals (Carter, 2021). Technical challenges, however, still exist in terms of developing efficient technologies that can safely extract these deposits without causing potential environmental impacts like altering celestial bodies and creating space debris.

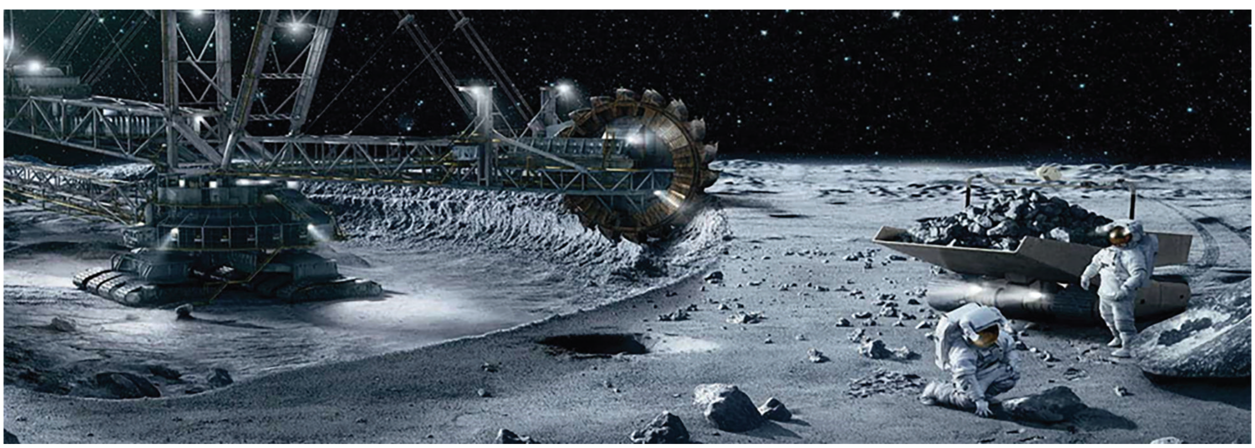


Figure 37: An artistic impression of space mining
Source: Dassault Systemés, 2022

The legal framework involved in space mining is still quite complex, involving several international space treaties and agreements. The primary governing treaty remains the Outer Space Treaty of 1967, which prohibits the appropriation of celestial bodies such as the moon or asteroids, by individual nations. Experts are still unsure whether space mining should be allowed under this treaty or a new one should be developed.

5.4 Deep Sea Mining

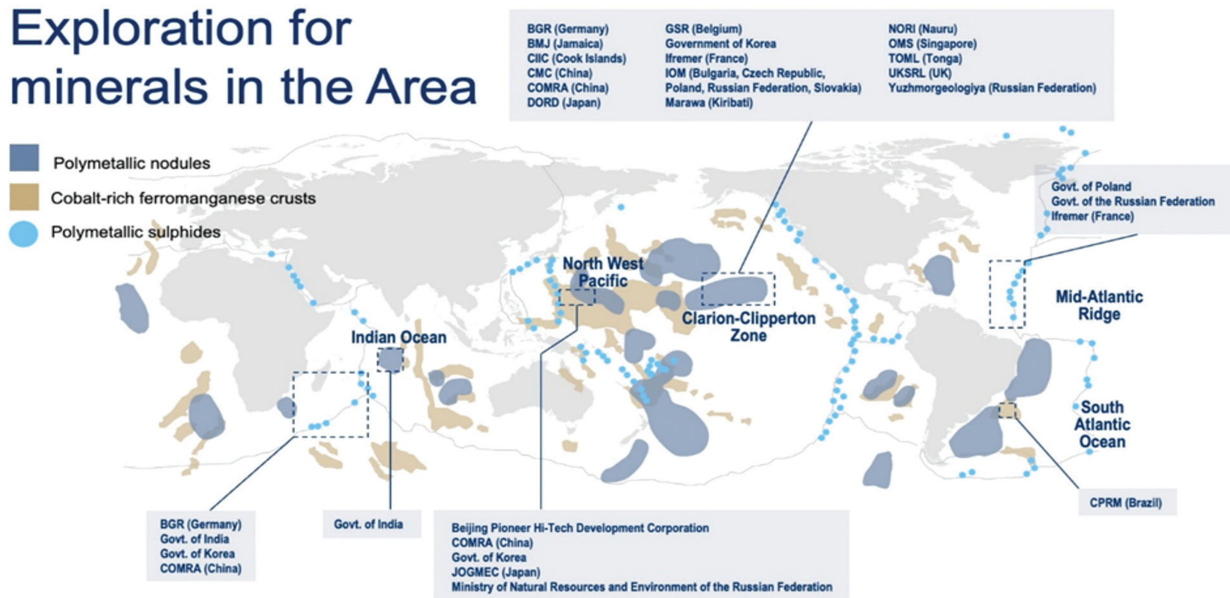


Figure 38: Seabed exploration
Source: International Seabed Authority, 2021

Exploration of the deeper sea floor since the 1970s has given the impression of wide-spread metallic mineral commodities, spread across various sections of the Pacific regions, offshore eastern Africa, the Atlantic Ocean etc. The seabed potential includes polymetallic sulphides/Seafloor massive sulphides (copper, gold with lead, zinc and silver by-products); manganese/polymetallic nodules with metals of great economic interest being nickel, copper, cobalt and manganese; and cobalt-rich ferromanganese crusts. Research however suggest that deep-sea mining could severely harm marine biodiversity and ecosystem. This is because the deep sea remains understudied and poorly understood, resulting in gaps in our understanding of its biodiversity and ecosystems. As at May 2022, the International Seabed Authority (ISA), which regulates activities in the seabed beyond national jurisdiction ('the Area'), had issued 31 contracts to explore deep-sea mineral deposits. More than 1.5 million km2 of international seabed has been set aside for mineral exploration. Only exploration contracts have been issued by the ISA as it is still developing regulations to aid in the transition from exploration to exploitation. Mining in international waters could commence as soon as 2026; even though vital research and work to adopt the required regulations, standards and guidelines to manage deep-sea mining sustainably is far from complete.

ACKNOWLEDGEMENTS

This inaugural state of critical minerals report was prepared by the Payne Institute for Public Policy at the Colorado School of Mines under the vision and leadership of the Director of the Institute, **Morgan Bazilian. Gregory Clough,** the Deputy Director of the Payne Institute, supervised this work. **Juliet Akamboe,** a Critical Minerals Demand Researcher at the Colorado School of Mines, was the lead author and coordinator of this work.

The chapters were written and led by various subject-matter experts.
The authors in order of appearance on the report are;

Aaron Malone — Associate Professor, Colorado School of Mines

Macdonald Amoah — Researcher, Payne Institute for Public Policy

Ian Lange — Associate Professor, Colorado School of Mines

Yasmin Marin Alvarez — Graduate Student, Colorado School of Mines

Ebenezer Manful-Sam — Graduate Student, Colorado School of Mines

Brad Handler — Sustainable Finance Lab Lead, Payne Institute for Public Policy

Felix Ayaburi — Graduate Student, Colorado School of Mines

The report also relied on publications, reports, and testimonies
from the following experts in the Colorado School of Mines.

Elizabeth Holley, Rod Eggert and **Walt Copan.**

REFERENCES

African Minerals Development Centre. (2017). Gender Sensitivity Training Manual. AMDC.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., ... & Humphreys, D. (2017). 'Mineral supply for sustainable development requires resource governance.' Nature, 543(7645), 367-372. doi:10.1038/nature21359

Alonso, E., et al. (2012). 'Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies.' Environmental Science & Technology.

Australian Bureau of Statistics. (2018). Mineral and Petroleum Exploration, Australia. ABS.

BGS (British Geological Survey). (2020) World Mineral Production.

BHP. (2018). Inclusion and Diversity Report. BHP.

Bindman, P. (2023, August 21). Weekly data: China seeks to extend its critical minerals dominance with overseas investment surge. Energy Monitor.

Bindman, P. (2023, August 21). Weekly data: China seeks to extend its critical minerals dominance with overseas investment surge. Energy Monitor.

Brown, E., Mudd, G. M., & McLellan, B. (2017). 'A review of water re-use in flotation.' Minerals Engineering, 108, 83-93. doi:10.1016/j.mineng.2017.01.007

Carbon Sovereignty | UAPress. (2023, September 19). UAPress. https://uapress.arizona.edu/book/carbon-sovereignty

Carter J, 2021. "Space Mining: Scientists Discover Two Asteroids Whose Precious Metals Would Exceed Global Reserves". Forbes.com

Clark, M., 2022. "Revitalizing the National Defense Stockpile for an Era of Great-Power Competition". Heritage Foundation.

Clifford, M.J., Perrons, R.K., Ali, S.H. and Grice, T.A. eds., 2018. "Extracting innovations: Mining, Energy, and Technological Change in the Digital Age". CRC Press.

Cobalt Institute. (2020). Cobalt in the DRC: Blessing or curse?. Cobalt Institute.

Deloitte Insights. (2021) The Future of Work in Mining.

Deloitte. (2021). 'Tracking the Trends 2021: The Top 10 Issues Transforming the Future of Mining.'

Deloitte. (2021). 'Tracking the Trends 2021.' Available at: https://www2.deloitte.com/global/en/pages/energy-and-resources/articles/tracking-the-trends.html

Department of Mineral Resources, South Africa. (2018). Mining Charter. DMR.

Doane, D.L. (2017) Economic Inequality and the Human Development Index: A Comparative Study.

Eftimova, B., & Schwarzkopf, S. (2020). Gender and the mining industry: Micro, meso or macro? Extractive Industries and Society, 7(2), 456-463.

Eftimova, B., & Schwarzkopf, S. (2020). Gender and the mining industry: Micro, meso or macro? Extractive Industries and Society, 7(2), 456-463.

Eisler, R. (2004). 'Health risks of gold miners: a synoptic review.' Environmental Geochemistry and Health, 25(3), 325-345. doi:10.1023/B:EGAH.0000028471.43190.8a

Environmental Protection Agency. (2019). Environmental considerations of active and abandoned mine lands. EPA.

EPA. (2019). 'Environmental Impacts of Mining and Smelting.' U.S. Environmental Protection Agency. Available at: https://www.epa.gov/report-environment/what-are-environmental-impacts-mining-and-smelting

European Commission. (2020). 'Raw Materials Initiative.' Retrieved from: https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en

EY. (2019) Digital Mining: The Next Wave of Business Transformation.

Global CCS Institute. (2021). 'The Global Status of CCS: Targeting Climate Change.' Available at: https://www.globalccsinstitute.com/resources/global-status-report/

Hilson, G. & Murck, B. (2000) Sustainable development in the mining industry: clarifying the corporate perspective.

Hinton, J.J., Veiga, M.M., & Beinhoff, C. (2003). Women and artisanal mining: Gender roles and the road ahead. The Socio-Economic Impacts of Artisanal and Small-Scale Mining in Developing Countries, 2, 161-203.

Historical demand and supply. (2023, August 1). World Gold Council. https://www.gold.org/goldhub/data/gold-demand-by-country

Humphreys, D. (2015) The remaking of the mining industry.

Hurst, C. (2010). 'China's Rare Earth Elements Industry: What Can the West Learn?'

ICMM (2012) The role of mining in national economies.

ICMM. (2019) Health and Safety Performance Indicators.

ICMM. (2019). Mining's contribution to people: An update. International Council on Mining and Metals.

ICMM. (2020). Mining's contribution to sustainable development. International Council on Mining and Metals.

IEF Critical Minerals Outlooks Comparison. (n.d.). International Energy Forum. https://www.ief.org/focus/ief-reports/critical-minerals-outlooks-comparison

ILO. (2018) Women and Men in the Informal Economy: A Statistical Picture.

ILO. (2019). Mining: a brief overview. International Labour Organization.

Ingram, J. C., Jones, L., Credo, J., & Rock, T. (2020, March 20). Uranium and arsenic unregulated water issues on Navajo lands. Journal of Vacuum Science & Technology; American Institute of Physics. https://doi.org/10.1116/1.5142283

International Council on Mining and Metals (ICMM). (2020) Innovations in the Mining Industry.
International Energy Agency (2023). Critical Minerals Market Review 2023. International Energy Agency.

International Energy Agency, 2022. "Strategic and Critical Materials Stockpiling Act".

International Labour Organization. (2017). Women and Men in the Informal Economy: A Statistical Picture. ILO.

International Renewable Energy Agency (2023). Geopolitics of the energy transition: Critical materials. International Renewable Energy Agency, Abu Dhabi.

International Renewable Energy Agency (2023). World Energy Transitions Outlook 2023: 1.5°C Pathway, Volume 1. International Renewable Energy Agency, Abu Dhabi.

International Women in Mining. (2020). Annual Report. IWiM.

Jay, S., Jones, C., Slinn, P., & Wood, C. (2007). 'Environmental impact assessment: Retrospect and prospect.' Environmental Impact Assessment Review, 27(4), 287-300. doi:10.1016/j.eiar.2006.12.001

Jenkins, K. (2014). Women and Work Culture: Britain c.1850-1950. Ashgate Publishing.

Jenkins, K. (2015). Women and Work Culture: Britain c.1850-1950. Ashgate Publishing.

Johnson, D. B., & Hallberg, K. B. (2009). 'Acid mine drainage remediation options: A review.' Science of the Total Environment, 338(1-2), 3-14. doi:10.1016/j.scitotenv.2004.09.002

Johnson, D.B. & Hallberg, K.B. (2009). 'Biological manganese removal from acid mine drainage in constructed wetlands and prototype bioreactors.'

Kumar, P., Golchha, M., & De, S. (2018). 'Recent Advances in Emission Control Technologies in Coal Combustion.' Journal of Environmental Management, 231, 1298-1310. doi:10.1016/j.jenvman.2018.11.030

Lahiri-Dutt, K. (2012). Gendering the Field: Towards Sustainable Livelihoods for Mining Communities. ANU Press.

Lahiri-Dutt, K. (2012). Gendering the Field: Towards Sustainable Livelihoods for Mining Communities. ANU Press.

Laplonge, D. (2014). Dealing with gender diversity in the resources industry: The experience of male workers. Emerald Group Publishing.

Likens, G. E., Driscoll, C. T., & Buso, D. C. (1996). 'Long-Term Effects of Acid Rain: Response and Recovery of a Forest Ecosystem.' Science, 272(5259), 244-246. doi:10.1126/science.272.5259.244

Markets, I. E. (n.d.). Foresight 2023 Report. https://info.ceicdata.com/foresight-2023-report
Massachusetts Institute of Technology. (2019). 'The Cost of Clean Coal.' MIT Technology Review.

McKinsey & Company. (2020) How Technology is Reshaping Supply and Demand for Natural Resources.

McKinsey & Company. (2020) The Future of Mining: Four Trends for Tomorrow's Success.

Mining Energy-Transition Metals: National Aims, Local Conflicts. (n.d.). MSCI. https://www.msci.com/www/blog-posts/mining-energy-transition-metals/02531033947

Mining Safety and Health Administration. (2020). Annual mining safety data report. MSHA.

Mining Weekly. (2018) The Benefits of Legal Mining Operations.

Mining, Minerals, and Sustainable Development Project. (2002). Breaking New Ground: Mining, Minerals, and Sustainable Development. Earthscan Publications Ltd.

Molchanov, S., & Laplante, A. (2020). 'Closed-loop water recycling systems in the mining industry: A review.' Journal of Cleaner Production, 257, 120539. doi:10.1016/j.jclepro.2020.120539

Mudd, G. M., & Jowitt, S. M. (2018). 'A detailed assessment of global rare earth element resources: Opportunities and challenges.' Economic Geology, 113(3), 593-626. doi:10.2113/econgeo.113.3.593

National Mining Association - The National Mining Association is the ... (n.d.-a). https://www.nma.org/wpcontent/uploads/2016/09/NMA_Report_Mines_to_Market_FINAL.pdf

Natural Resources Canada. (2019). 'Green Mining Innovation.' Retrieved from: https://www.nrcan.gc.ca/science-data/research-centres-offices/office-energy-efficiency/green-mining-innovation/20064

Newell, P. J., Geels, F. W., & Sovacool, B. K. (2022, April 1). Navigating tensions between rapid and just low-carbon transitions. Environmental Research Letters, 17(4), 041006. https://doi.org/10.1088/1748-9326/ac622a

Nuss, P., & Eckelman, M. J. (2014). 'Life Cycle Assessment of Metals: A Scientific Synthesis.' PLoS ONE, 9(7), e101298. doi:10.1371/journal.pone.0101298

Odeh, L., & Lorinc, J. (2023, March 9). Lithium Royalty Raises $109 Million in Biggest Canadian IPO Since May. Bloomberg.com.

Odeh, L., & Lorinc, J. (2023, March 9). Lithium Royalty Raises $109 Million in Biggest Canadian IPO Since May. Bloomberg.com.

Permitting, Economic Value and Mining in the United States. (n.d.) https://www.nma.org/wp-content/uploads/2016/09/SNL_Permitting_Delay_Report-Online.pdf

Permitting, Economic Value and Mining in the United States. (n.d.-b). https://www.nma.org/wp-content/uploads/2016/09/SNL_Permitting_Delay_Report-Online.pdf

Pope, C. A., Burnett, R. T., Thurston, G. D., Thun, M. J., Calle, E. E., Krewski, D., & Godleski, J. J. (2002). 'Cardiovascular Mortality and Long-Term Exposure to Particulate Air Pollution.' Circulation, 109(1), 71-77. doi:10.1161/01.CIR.0000041946.49104.CB

PWC. (2018) Mine 2018: Tempting Times.

PWC. (2020) Mine 2020: Resilient and Resourceful.

Raw Materials Group. (2018) Global Trends in the Mining Industry.

Rio Tinto, 2019. "Pioneering Automation And Robotics In Mining"

Samanta, B., Alinia-ziazi, A., & Szymanski, J. (2018). 'Role of Data Analytics in Decision Making: A Mining Industry Perspective.' Decision Analytics, 5(1), 1-19. doi:10.1186/s40165-018-0059-2

Samanta, B., et al. (2018). 'A review of machine learning algorithms for text-documents classification.'

Schaetzl, R. J., Burns, S. F., Johnson, D. L., & Lapen, T. J. (2019). 'Soils, landforms, and landform history: The foundation of soil geography.' In Soils: Genesis and Geomorphology (pp. 19-70). Cambridge: Cambridge University Press. doi:10.1017/CBO9781139171304.002

Sen, A. (2001) The many faces of gender inequality. New Republic.

Society for Mining, Metallurgy, & Exploration. (2020). Minerals exploration and exploitation. SME.

Sonter, L. J., Ali, S. H., & Watson, J. E. M. (2018). 'Mining and biodiversity: key issues and research needs in conservation science.' Proceedings of the Royal Society B: Biological Sciences, 285(1892). doi:10.1098/rspb.2018.1926

Steen, J., Macaulay, S., Kunz, N. and Jackson, J., 2018. "Understanding the Innovation Ecosystem In Mining And What The Digital Revolution Means For It" (pp. 3-26). New York: CRC Press.

Swain, E. (2020). 'Lithium Mining and Environmental Impact.'

Swain, E. (2020). 'The lithium triangle: The case for post-extractivism in Chile, Argentina, and Bolivia.' Journal of Latin American Geography, 19(3), 111-135. doi:10.1353/lag.2020.0061

TEEB. (2010). 'The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations.' Pushpam Kumar (Ed.), Earthscan, London and Washington. Available at: http://teebweb.org/our-publications/teeb-study-reports/ecological-and-economic-foundations/

Tharayil, R. (2022, December 14). Lifezone Metals to go public through $1bn SPAC deal with GoGreen. NS Energy. https://www.nsenergybusiness.com/news/lifezone-metals-to-go-public-through-1bn-spac-deal-with-gogreen/

Tharayil, R. (2022, December 14). Lifezone Metals to go public through $1bn SPAC deal with GoGreen. NS Energy. https://www.nsenergybusiness.com/news/lifezone-metals-to-go-public-through-1bn-spac-deal-with-gogreen/

Tilton, J.E. and Landsberg, H.H., 1997. "Productivity Growth and the Survival of the US Copper Industry'. Resources for the Future.

U.S. Geological Survey. (2020). Mineral Commodity Summaries 2020. U.S. Department of the Interior.

U.S. Geological Survey. (2020). Mineral Commodity Summaries 2020. U.S. Department of the Interior.

UNDP. (1990) Human Development Report 1990: Concept and Measurement of human development.

United Nations Development Programme (UNDP). (2018) Sustainable Management of Mineral Resources.

USGS. (2018). Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply. U.S. Geological Survey Professional Paper 1802.

Wang, S., Ang, H. M., & Tadé, M. O. (2013). 'Novel applications of red mud as coagulant, adsorbent and catalyst for environmentally benign processes.' Chemosphere, 92(6), 681-689. doi:10.1016/j.chemosphere.2013.03.009

WHO. (2001). ‘Arsenic and arsenic compounds.’ Environmental Health Criteria, 224. Available at: https://www.who.int/ipcs/publications/ehc/ehc_224/en/

Women in Mining (WIM). (2020). Annual Review 2020. WIM UK.

Women in Mining Canada. (2019). The Role of Women in the Mining Sector. WiM Canada.

World Aluminium. (2020). ‘Aluminium Industry Greenhouse Gas Emissions Data.’

World Bank. (2015) World Development Report 2015: Mind, Society, and Behavior.

World Bank. (2017) The Growing Role of Minerals and Metals for a Low Carbon Future.

World Bank. (2019) Gender Inclusivity in Mining: A Path to Development.

World Bank. (2019). Extractive Industries for Development Series. World Bank Publications.

World Bank. (2019). Gender in the Mining Industry. The World Bank Group.

World Bank. (2019). The role of artisanal and small-scale mining in the global economy. World Bank.

World Bank. (2020). ‘Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.’

World Bank. (2020). The Growing Role of Minerals and Metals for a Low Carbon Future. The World Bank Group.

World Economic Forum. (2019) Gender Gap in the Mining Sector.

World Mining Congress. (2018). Innovations in the mining industry. WMC.

Young, S. (2019). ‘Environmental Consequences of Cobalt Mining in the Democratic Republic of Congo.’ Environmental Policy Review, 33(1), 45-57.

THANK YOU TO OUR SPONSORS

ALFRED P. SLOAN FOUNDATION

Baker Hughes

BHP

BQ ENERGY, llc

FREEPORT-MCMORAN

IEF INTERNATIONAL ENERGY FORUM

KAPSARC
مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

Newmont™

The Payne Institute for Public Policy
COLORADO SCHOOL OF MINES

tinyurl.com/payne-critical-minerals-report