August 2024

Critical Minerals for the Clean Energy Transition: Supply, Demand, and Impacts

TABLE OF CONTENTS

The clean energy transition—the accelerated deployment of clean energy technologies in pursuit of local, national, and global electric sector and economy-wide decarbonization goals—will require what the International Energy Agency (IEA) describes as a "shift from a fuel-intensive to a material-intensive energy system" [1]. While technologies such as wind, solar photovoltaics (PV), and batteries do not depend on coal or natural gas like conventional fossil-fired power generation technologies, they rely heavily on "critical minerals"[1] such as copper, lithium, nickel, cobalt, and rare earth elements (REEs) for manufacturing and deployment. Recent studies that have compared the impact of clean energy technology deployment on the demand for these minerals and their potential availability have highlighted that the decarbonization of the electric power and transportation sectors will fundamentally alter the mineral demand and mineral intensity of the energy system [1,4,5,6,7].

Mineral supply and demand for the clean energy transition continues to gain attention due to concern that the supply of minerals for clean energy technologies may fall short of the amount needed to support economy-wide decarbonization, and that the fluctuating cost of needed minerals may limit scaling. Media headlines in recent years have indicated both a potential shortage and a potential abundance of critical minerals.[2] How should this buzz around critical minerals and the energy transition be interpreted? What are the concerns? And what are the impacts on the clean energy transition? This Insight Brief explores some key

1 While several studies have examined the criticality of different minerals, a standard approach or single definition does not exist. The U.S. Geological Survey (USGS) broadly defines a critical material or mineral as one that is important for the "manufacture of high technology devices, national defense applications, and green growth-related industries" and at risk for supply disruption [2], while guidance based on Executive Order 13817 considers critical minerals as "vital to the Nation's security and economic prosperity" where dependency on foreign sources "creates a strategic vulnerability for both its economy and military to adverse foreign government action, natural disaster, and other events that can disrupt supply of these key minerals" [3]. However, critical mineral lists developed under these definitions typically do not include copper, which, as discussed later in this brief, is considered critical to the energy transition and at risk of supply shortfall.

2 Examples of these headlines include "Report: Tesla exec says automaker faces global shortage of EV battery minerals" (Silicon Valley Business Journal) [8], "A shortage of these metals could make the climate crisis worse" (CNN) [9], and "'Dr. Copper' has a worrying message about the energy transition" (Financial Times) [10], while others state "Yes, we have enough materials to power the world with renewable energy" (MIT Technology Review) [11] and "Cobalt, a crucial battery material, is suddenly superabundant" (The Economist) [12].

concepts around the supply, demand, and impacts of the critical minerals of the clean energy transition.

MINERAL SCARCITY VERSUS SUPPLY AND DEMAND FLUCTUATIONS

There are important distinctions to be made between short-run supply-demand fluctuations and typical market adjustments due to changing supply and demand versus the physical unavailability of mineral resources.

Analyses Around Critical Mineral Availability

Studies around the availability of critical minerals for the clean energy transition often focus on a handful of key minerals. Most common among them are:

- copper – used across all clean energy technologies and electricity infrastructure, as well as a wide range of technologies outside of the energy industry,
- lithium, nickel, and cobalt – used in batteries for stationary storage, electric vehicles, micro-mobility, and consumer products, but in different quantities depending on the platform and battery chemistry, and
- REEs – used in permanent magnet generators and motors for wind turbines and electric vehicles, as well as other non-energy strategic sectors, such as defense and space.

Other minerals, such as cadmium, tellurium, and gallium used in thin film solar PV modules and graphite used in battery anodes, are also often analyzed in these types of studies, but to a lesser extent.

EPRI's 2022 white paper *Understanding Generation and Storage Technology Supply Chain Risks and Needs to Support Electric Utility Sector Decarbonization* [7] included a review of studies analyzing future demand and availability of these critical minerals, which are summarized in Figure 1.

These types of studies highlight the significant expected growth in demand for some key minerals, especially those used in lithium ion batteries, and some even conclude that there is a potential for future demand to exceed current reserves and possibly even known resources. However, there are some key caveats to consider when drawing conclusions about this future demand compared to available resources.

One caveat is that all projections of future demand rely on assumptions about the technologies deployed. These can vary by assumptions around policies, technology costs, and the types of technologies deployed (e.g., crystalline silicon vs. thin film PV modules, permanent magnet vs. non-magnet generators and motors, battery chemistries). Future de-

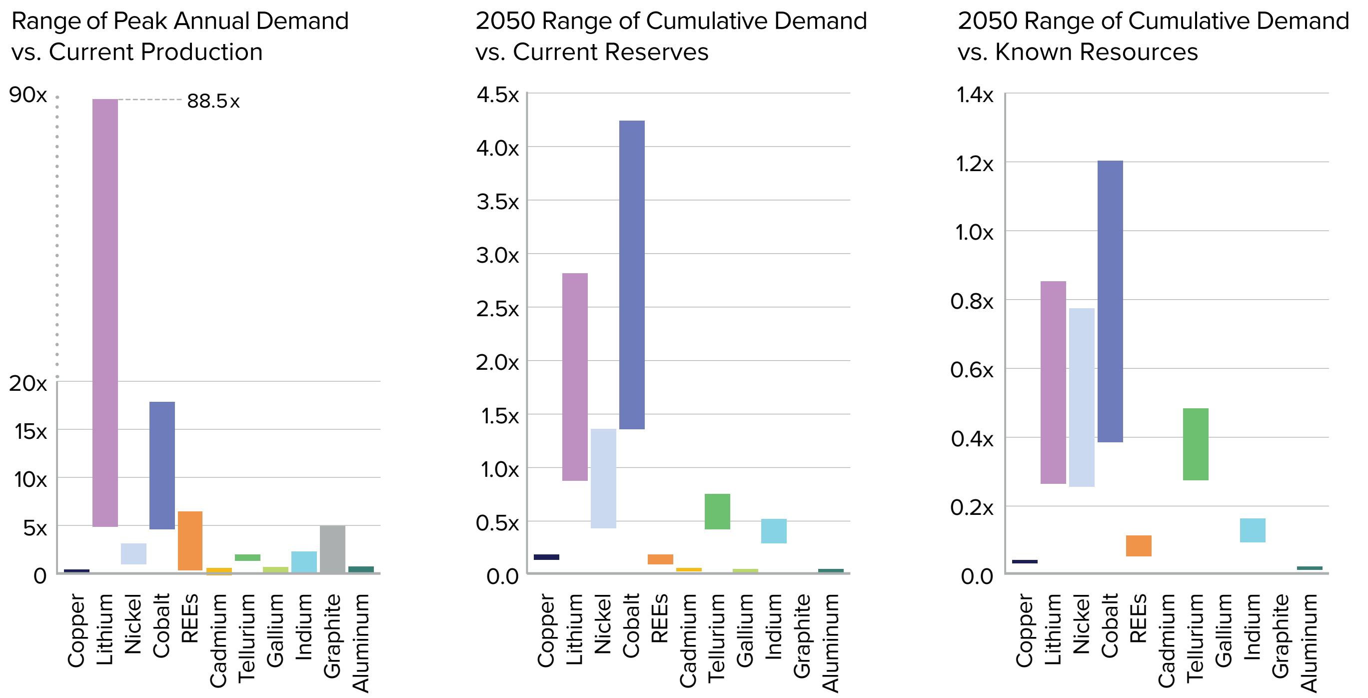


Figure 1: Ranges of projected annual and cumulative demand of key minerals versus current production, reserves, and known resources [7]

mand also depends on assumptions around future technology developments: technology innovation will often reduce the amount of minerals needed for the same technology in the future, while increased lifetimes of a technology can delay the need for new plants and equipment [7]. As such, actual future demand could vary significantly from these estimates depending on both market forces and technology development.

A second important caveat is an understanding the differences between mineral reserves, known resources, and overall availability. *Reserves* are defined as the estimated amount of a mineral that can be economically mined under current conditions, that has been fully evaluated geologically and can be commercially and legally mined; this represents only a fraction of the total resource available. *Known resources* (or *identified resources*) are the total known amount of a mineral for which extraction may potentially be feasible and which may become economic in the future. A *resource base* (not included in the Figure and analyses above) is even broader than the known resources and includes undiscovered or unidentified resources. Ultimately, reliable estimates of the total amount of any mineral that may be available in the earth's crust are not in place [13]. Reserves and resources can both change over time depending on demand strength, changing economic conditions, discovery of new deposits, and technological developments. As such, reserves are dynamic and estimates of reserves at a single point in time are often an unreliable indicator of the long-term availability of these materials. Often, as production has risen, reserves have gone up, but there is little economic incentive to prove out reserves more than twenty to fifty years out [13].

Supply and Demand Fluctuations

While there are likely to be sufficient resources and reserves of the critical materials needed for the clean energy transition such that *scarcity* of a mineral is not a concern, there may be near-term supply challenges, both for mineral extraction and processing capacity, as global production ramps up to meet structural changes in demand. As such, most concerns about the increased demand and availability of certain key minerals used in clean energy technologies (especially the lithium and cobalt used in lithium-ion batteries) are likely short term, and most of the headline-grabbing news around the "availability" of critical minerals is a reflection of supply-demand fluctuations and not indicative of long-term shortages of these minerals. Still, these fluctuations can cause temporary shortfalls and price volatility, which can in turn have impacts on the near-term pace and cost of the energy transition. The remainder of this brief will discuss the causes of supply-demand fluctuations, impacts, and efforts to mitigate concerns.

WHAT CAUSES SUPPLY-DEMAND FLUCTUATION?

Fluctuations in the balance of supply and demand are most prominently reflected in fluctuations in the price of a material: as demand grows and supply gets tighter, prices increase; when prices get high, the market responds with new supply; when sufficient (or surplus) new supply comes online, the price drops. Supply and demand can be influenced by many factors including competitive forces, technology advancements, forecasts and speculation, geopolitics, policies and incentives, and temporary shortfalls.

An Example: Lithium Supply and Demand

The price fluctuation over the last several years (as shown in Figure 2) for battery-grade lithium provides tangible examples of many of these factors. While lithium reserves and mining are generally considered geographically diverse, lithium processing and lithium chemical production are currently highly concentrated in a smaller number of regions. China alone accounts for 60% of global lithium chemical processing and over 75% of global lithium ion battery cell production [14]. As such, as seen in the discussion below, shifts in China can have a significant impact on global supply and demand fluctuations as well.

In the years leading up to 2015, lithium prices were relatively stable. An early boom/bust cycle occurred in the mid-2010s as electric vehicles (EVs), which require lithium ion batteries for production and operation, first began to gain traction and demand increased rapidly. This was followed by some stabilization and decline in late-2018 and 2019 with increased mining and production investments and entering the COVID-19 pandemic. However, as the global economy came out of the COVID-19 pandemic, commodities across all sectors of the economy faced supply challenges as demand increased faster than production was able to ramp back up and logistics disruptions around the workforce and transportation lingered. The lithium market was no exception, and prices began to rise due to supply bottlenecks and global inflation. Furthermore, policies and incentives around the world drove forecasts of increased EV adoption and increased demand for the lithium ion batteries needed to produce these vehicles. This drove speculation around persistent lithium shortfalls, leading to a rapid increase in prices, accompanied by increased production and increased investment in mining. Extensive subsidies were put in place in China and elsewhere in 2021 and 2022, further spurring increases in production and inventories of both lithium material and lithium ion batteries [15,16].

Then in late-2022 and the first quarter of 2023, demand and prices for lithium plummeted. This was the result of a significant oversupply of lithium and lithium ion batteries as producers in China used government subsidies, consumer tax breaks, and production incentives that ended in 2022, creating unsustainably high inventory levels. This was coupled with concerns about poor demand for electric vehicle sales in early-2023, which reduced forecasts and sustained high inventory levels. During the second quarter of 2023, lithium prices began to rise again as EV sales once again increased and expectations for long-term demand rose based on government incentives across the globe to switch to EVs [17]. Mid-2023 saw additional efforts by the Chinese government to boost lithium ion material production to reduce shortage risks, leading to decreased pressures and, therefore, decreased prices [18]. By early-2024, lithium prices were back to levels not seen since mid-2021 "as the market somewhat found an equilibrium of ample supply and muted demand" [16]. Reduced optimism around EV sales combined with high inventories following the supply glut spurred by subsidies in 2021 and 2022 reduced demand for new lithium ion batteries. As of January 2024, forecasts projected that the next lithium deficit would not return until 2028, while investments made prior to the drop in prices may further drive supply to increase by as much as 40% in 2024, further increasing the current surplus [16].

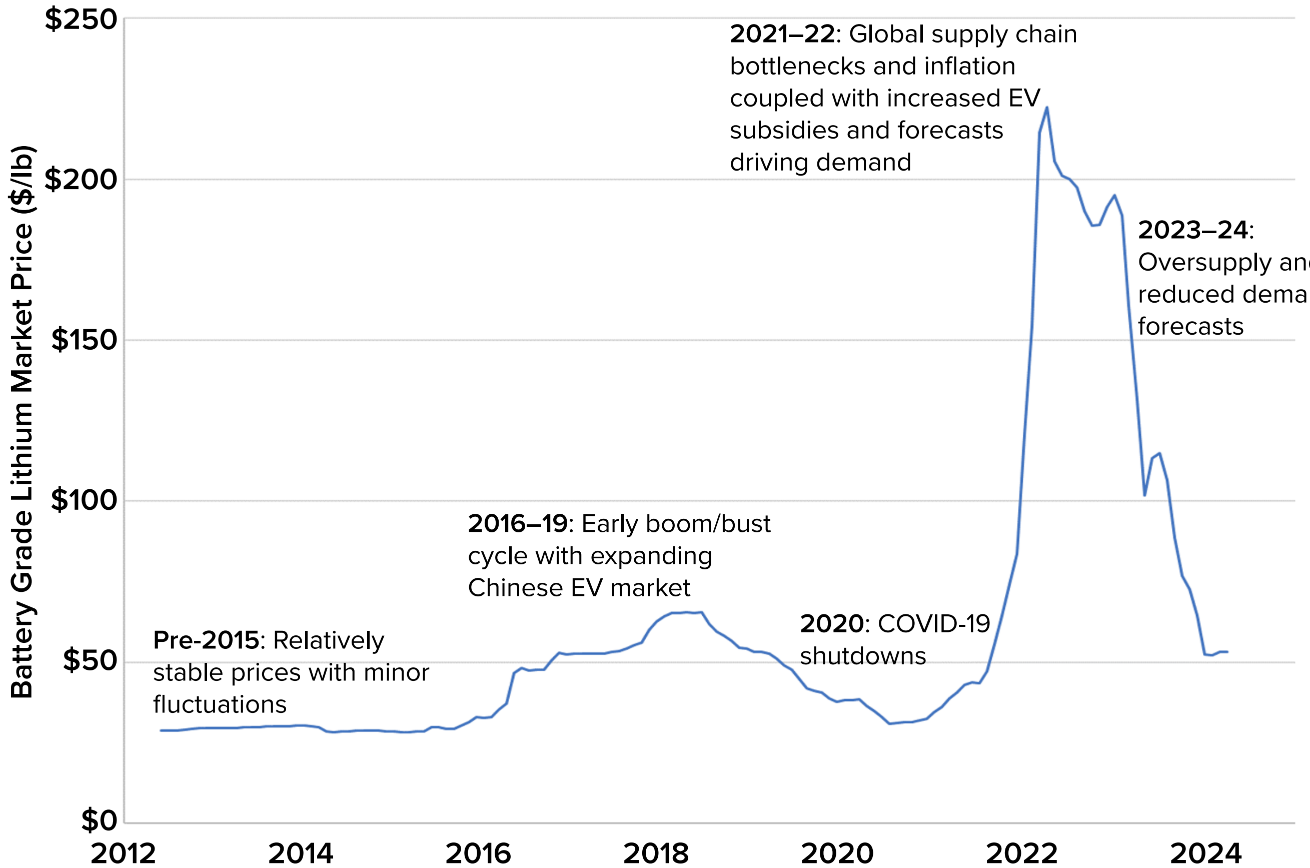


Figure 2: Volatility in lithium prices observed from 2012 through mid-2024 [19]

Challenges in Matching Supply and Demand

One of the biggest challenges around matching the supply and demand for many minerals is that supply increases typically lag market signals. While already established mines and processing facilities may be able to ramp production up and down depending on market signals, bringing new mines online for production can be a time intensive process, and there may be temporary supply issues as global production ramps up to meet structural changes in demand. In addition, supply chains for some materials are currently dependent on a small number of mines and processing facilities and may not be immediately resilient to a supply shock. For example, if a particular mine were shut down or a materials processing facility were to go offline, the supply chain could take several years to recover.

Mining is a capital-intensive industry that typically has long lead times, with IEA analyses indicating that on average it can take over 16 years to move from discovery to first production [1]. Notably, lead times for mines containing key minerals like copper, nickel, and lithium, are trending upward, with the average duration for mines coming online in 2020-2023 reaching 17.9 years [20]. Developing a new mine requires environmental assessments, permitting, and forging relationships and agreements with local communities before construction can begin. Concerns about labor rights, public health impacts, and environmental impacts can raise public opposition to new mines, and these concerns can delay both permitting and development/construction for long periods and create unpredictable delays or cancellations [7,13,21,22,23]. The recent uptick in mine lead times is largely attributable to greater time spent to obtain financing and permits [20].

A further challenge is determining that a project is viable and securing funding given the uncertainty around future prices in the face of long lead times. Recent dynamics around investments in copper mining have highlighted this challenge. A highly publicized July 2022 analysis by S&P Global, *The Future of Copper: Will the looming supply gap short-circuit the energy transition?*, did a deep dive into the expected future demand of copper, which it described as "the metal of electrification" due to the its significant role in clean energy and electrification technologies, including renewable technologies, EVs, and the grid infrastructure needed to support the clean energy transition (in addition to considerable demand from non-energy markets, such as building construction, appliances, electrical equipment, and communications). The 2022 analysis projected that demand for copper could double over the next 10 to 15 years. While small in terms of a percentage increase compared to that of other critical minerals in the energy transition, as shown earlier in Figure 1, this represents a significantly larger increase in total volume of material expected in the coming years due to the already prolific demand for copper in both the energy and non-energy sectors [24]. However, while the report indicates that the significant rise in demand for copper will require near-term investments to avoid future shortfalls, there is currently a reluctance to invest in new mines due to currently low copper prices, with companies saying that they "are waiting for higher prices before committing to big new investments" and want "to deliver copper to the world when it is needed and not before" [25].

WHAT ARE THE IMPACTS OF SUPPLY-DEMAND FLUCTUATIONS?

While analyses indicate that there are likely sufficient reserves of minerals and materials to meet the growing demand of clean energy technology deployment [7], temporary shortfalls and price volatility can have impacts on the near-term pace and cost of the energy transition. Higher costs for raw materials, coupled with a supply-demand imbalance for the final products, led to increases in the cost of lithium ion batteries, PV modules, and wind turbines in 2021 and 2022 after years of cost declines [26]. Project delays and cancellations were also observed as equipment was slow to arrive and, in some cases, contracts needed to be renegotiated to account for cost increases. These fluctuating and increased equipment costs, contract renegotiations, and project delays and cancellations could ultimately increase the cost and/or delay the achievement of local, national, and/or global electric sector and economy-wide decarbonization goals [27,28]. But with forethought, incentives, and technology innovation, the clean energy transition can still be achieved.

DEVELOPMENTS IN MINERAL SUPPLY TO MEET DEMAND

The expected increase in critical mineral demand has received significant attention in recent years through academic analyses, industry reports, government studies, and the lay press. As such, there is a general recognition in the industry that investment is needed now to ensure that supplies are available when they are needed. While the lengthy process of developing and commencing operation of new mines will still need to be balanced with the commodity price market signals that most commonly trigger investment, government incentives and venture capital investments are helping to motivate development. Furthermore, there are innovations beyond the development of new mines that can increase the supply and/or reduce the demand of certain minerals. While it is difficult to rapidly reconfigure global supply chains, particularly in the short-term, actions are underway to potentially reduce the probability and potential impacts of supply chain disruptions over time.

Government Policies

Several government policies and initiatives over the past few years have focused on diversifying and expanding critical mineral supplies, including the U.S. Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA), the European Union's Critical Raw Materials Act, Australia's Critical Minerals Strategy, and Canada's Critical Minerals Strategy. Most aim to diversify current supply chains, some by further developing domestic mineral resources when available (for example, Canada's 30% Critical Mineral Exploration Tax Credit), and others focused on increasing refining capacity, technology innovation, and recycling [26]. The U.S. IIJA includes funding for refining key materials for EVs and battery manufacturing and recycling [26]. The IRA has spurred billions in investments in mineral extraction due to a tax credit for EVs that requires that at least 40% of the value of the critical minerals contained in the vehicle's battery be sourced from the U.S. or a country with free trade agreements or are recycled in the U.S. [29]. Similar strategies have been used in Australia, Canada, and France [25]. As a result, there have been increased bilateral and multinational agreements to develop projects and improve access to mineral supplies. There has also been an increased focus on enhancing environmental, social, and governance policies around raw materials [26], though such policies can cause supply challenges, as exemplified in the U.S., where regulators rejected development of a large copper mine in Alaska due to anticipated impacts to an important salmon fishery [30].

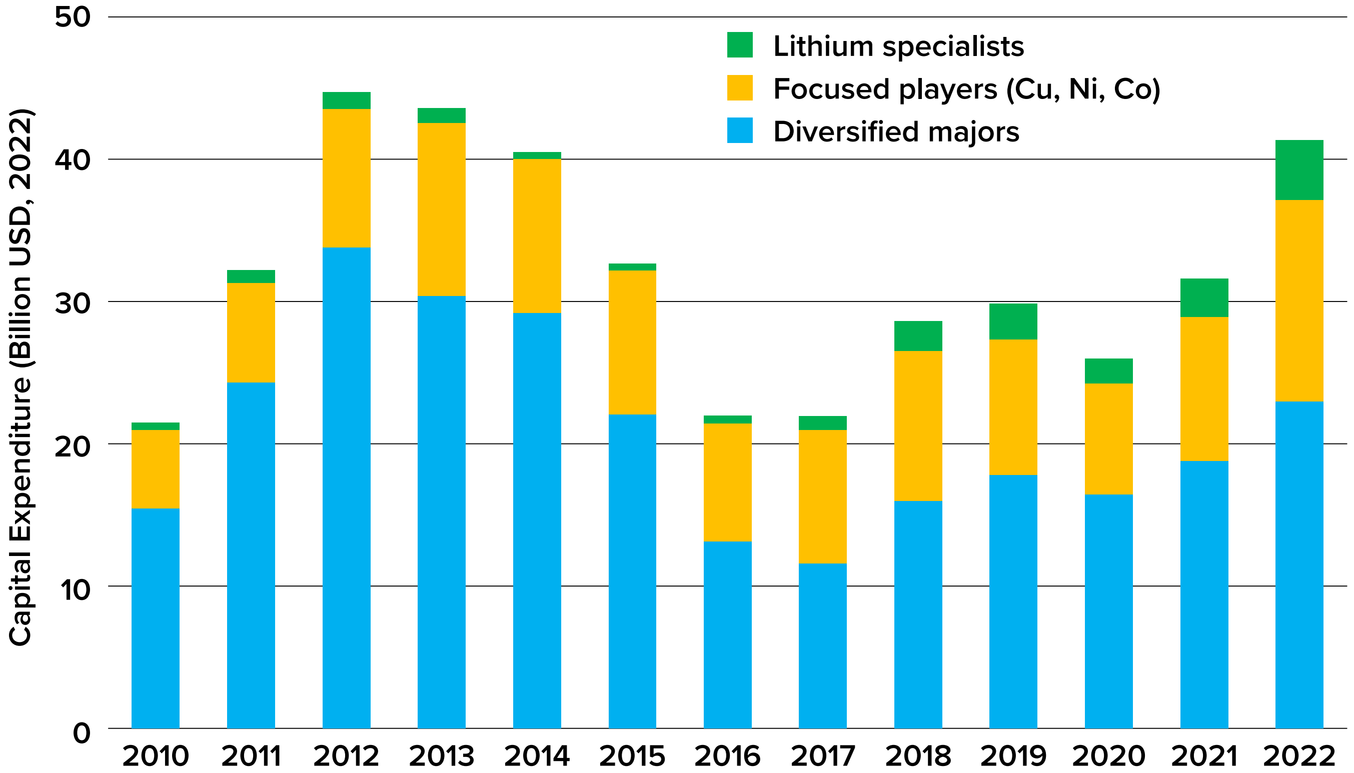
Investments in Critical Mineral Extraction

IEA's *Critical Minerals Market Review 2023* noted that the high commodity prices observed in 2021 and 2022, coupled with government incentives and policies, resulted in elevated profitability and cash flows in the mining industry that led to increased investment in exploration and reinvestment in new production. Figure 3 shows trends in investment in critical mineral mining by major mining companies, including a 30% increase in 2022, while Figure 4 highlights trends in exploration investment, both by region and commodity, in recent years [26].

EPRI's *Recent U.S. Development in Lithium Ion Battery Critical Material Extraction* report highlights several projects under development in the U.S. to bolster domestic production of battery materials as a result of IRA incentives, including a dozen lithium projects, a handful of cobalt and nickel projects, and several graphite projects focused on both extraction and production of synthetic graphite [29].

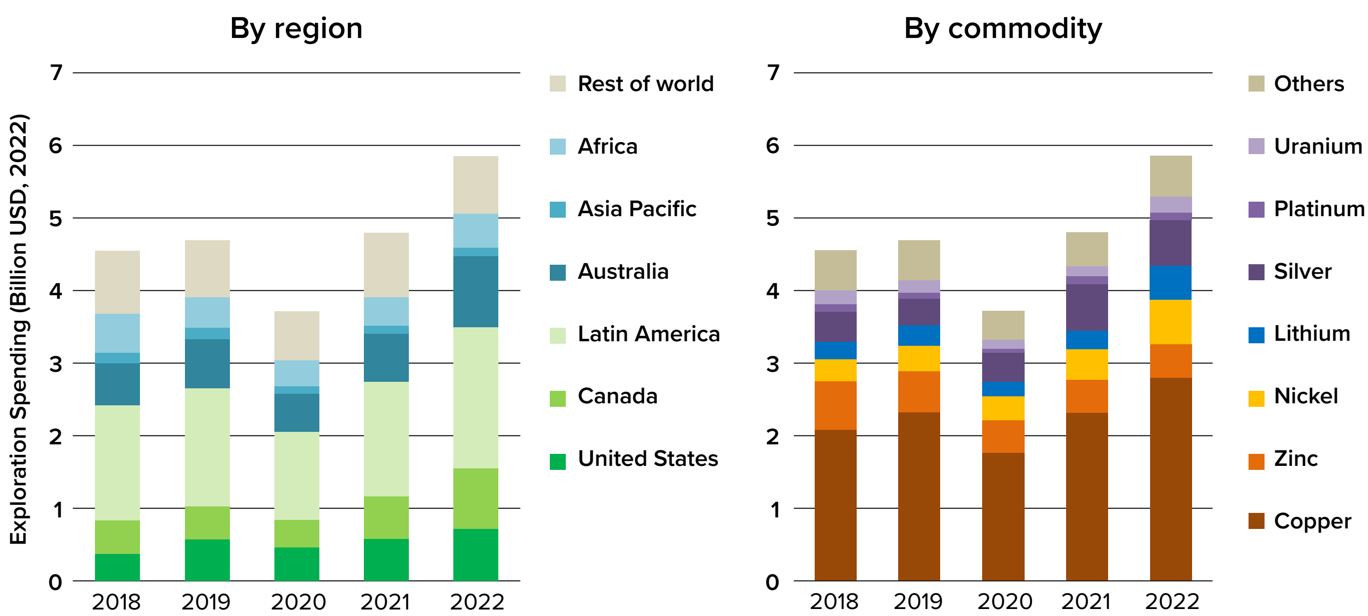
Furthermore, EV makers and battery cell makers have begun to strategically invest in the raw material sector, from long-term offtake agreements to investing in mining and refining activities to reduce exposure to longer-term market risks [26].

Beyond investments in new mining, there are efforts underway to expand the use of enhanced metal recovery from mining and processing waste to increase supply and reduce dependence on imported materials. This can include projects to extract copper, lithium, cobalt, nickel, and REEs from mine tailings [11], research to extract REEs and other critical minerals from domestic coal, coal ash, and other waste streams and byproducts from coal-based resources [31,32,33], and development of methods to extract lithium from seawater [34] and from geothermal brines [35].



Notes: Co = cobalt; Cu = copper; Ni = nickel. For diversified majors, capex on the production of iron ore, coal and other energy products was excluded.
Source: IEA (2023), *Critical Minerals Market Review 2023*, IEA, Paris, License: CC BY 4.0.

Figure 3: Recent investments in critical mineral production by major mining companies [25]



Notes: Excludes budgets for iron ore, coal, aluminium, gold and diamonds. Others comprise rare earth elements, potash/phosphate and many other minor metals.
Source: IEA (2023), *Critical Minerals Market Review 2023*, IEA, Paris, License: CC BY 4.0.

Figure 4: Exploration spending for key mineral resources, 2018-2022 [25]

Recycling

Recycling serves more as a long-term option to improve mineral supply rather than to mitigate near-term fluctuations and does not change the demand curve associated with near-term deployment. Lithium ion battery recycling would relieve demand for new critical materials in the long term but is not a panacea as mining would still be needed. Reaching something like 50% of new material demand will require near 95% battery collection and retrieval for recycling from all platforms, as well as geographically dispersed recycling centers [36]. Instead, recycling may mostly affect peak and cumulative demand as components and equipment reach the end of their useful life and are replaced by new equipment [7]. Still, a significant amount of battery recycling capacity is being developed, mainly in China, Europe, and the United States, with investments from government incentives and venture capitalists alike [7,26].

Technology Innovation and Substitution

The price fluctuations associated with supply and demand can drive technology innovation and substitution, as producers and consumers look for less expensive options. As one commodities analyst stated, “We don’t run out of anything in commodity markets, we engineer out” [37].

There are already several examples of technology innovation leading to reduced material usage in PV modules and wind turbines: the amount of silver used per cell in a crystalline silicon PV module decreased by 75% between 2009 and 2020 and is expected to be halved again by 2030 [38], while innovations in wind turbines that have led to taller towers, larger rotors, lighter drivetrains, and higher capacity turbines have increased electricity generated by new onshore wind projects and decreased material intensity [1]. Increasing the efficiency and output of a technology decreases the overall requirement for materials to produce the same amount of energy, and increasing the lifespan of a technology will decrease the need for replacement, further reducing the overall material requirement [7].

There are also differences in the level of mineral demand for solar PV, wind, and battery technologies depending on the sub-technologies deployed. For example, the mineral needs of lithium ion batteries vary considerably depending on the chemistries of the cathodes and anodes, especially with variations in the use of nickel, manganese, and cobalt: widely deployed nickel manganese cobalt oxide (NMC)-111 batteries require more than three times the cobalt as the more recently developed NMC-811 batteries; nickel cobalt aluminum oxide (NCA) batteries require about twice as much nickel but only a third of the cobalt of NMC-111 batteries; and lithium iron phosphate (LFP) batteries do not require nickel, cobalt, or manganese, but need about 50% more copper than NMC batteries [1,22]. Tradeoffs in mineral intensity must typically be balanced against other considerations, such as cost, efficiency, maturity, and recyclability, but diversifying technology selection may help relieve supply chain pressures and reduce risk [7].

CONCLUSIONS

As the energy system transforms and clean energy technologies are deployed at increasing levels, there will be an increased demand for the critical minerals needed to manufacture those technologies. As the industry responds to these shifts in demand, it is likely that there will be near-term supply and demand fluctuations in the market for some of the minerals that will see the largest increases in demand. This could result in short-term price spikes and possible project delays as production is ramped up to meet demand. Long-term shortage in material availability or resource scarcity is unlikely. Although some entities foresee potential gaps in long-term supply of materials like copper [24, 39], investments and innovation both in mineral extraction and processing, as well as in the energy technologies themselves are expected to allow the industry to adapt and meet the demands of the clean energy transition into the future.

REFERENCES

1. *The Role of Critical Minerals in Clean Energy Transitions*. International Energy Agency (IEA), 2021. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

2. U.S. Geological Survey (USGS), Critical Minerals. https://www.usgs.gov/science/critical-minerals

3. *Executive Order 13817: A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals*, December 20, 2017. https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals

4. Dominish, E., Florin, N., and Teske, S., *Responsible Minerals Sourcing for Renewable Energy*. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney. 2019.

5. *The Mineral Intensity of the Clean Energy Transition*. The World Bank, Washington, D.C., 2020.

6. *Critical Raw Materials for Strategic Technologies and Sectors in the EU*. European Union, 2020.

7. *Understanding Generation and Storage Technology Supply Chain Risks and Needs to Support Electric Utility Sector Decarbonization*. EPRI, Palo Alto, CA: 2022. 3002023228

8. "Report: Tesla exec says automaker faces global shortage of EV battery minerals" *Silicon Valley Business Journal*. (May 2, 2019): https://www.bizjournals.com/sanjose/news/2019/05/02/tesla-ev-battery-mineral-copper-shortage-tsla.html

9. "A shortage of these metals could make the climate crisis worse" *CNN*. (May 5, 2021): https://www.cnn.com/2021/05/05/business/climate-crisis-metals-shortage/index.html

10. "'Dr. Copper' has a worrying message about the energy transition" *Financial Times*. (July 13, 2022): https://www.ft.com/content/f199cd8e-a5aa-4202-9965-3c71748401eb

11. "Yes, we have enough materials to power the world with renewable energy" *MIT Technology Review*. (January 31, 2023): https://www.technologyreview.com/2023/01/31/1067444/we-have-enough-materials-to-power-world-with-renewables

12. "Cobalt, a crucial battery material, is suddenly superabundant" *The Economist*. (February 16, 2023): https://www.economist.com/finance-and-economics/2023/02/16/cobalt-a-crucial-battery-material-is-suddenly-superabundant

13. *Critical Metals Handbook*. Edited by Gus Gunn, British Geological Survey, Keyworth, Nottingham, UK. 2014.

14. *Global Supply Chains of EV Batteries*. International Energy Agency (IEA), 2022. https://www.iea.org/reports/global-supply-chains-of-ev-batteries

15. "Understanding Lithium Prices: Past, Present, and Future" *Carbon Credits*. (May 29, 2024) https://carboncredits.com/understanding-lithium-prices-past-present-and-future/

16. *Trading Economics – Lithium*. https://tradingeconomics.com/commodity/lithium Data and insights accessed 1/23/24.

17. *Trading Economics – Lithium*. https://tradingeconomics.com/commodity/lithium Data and insights accessed 5/17/23.

18. *Trading Economics – Lithium*. https://tradingeconomics.com/commodity/lithium Data and insights accessed 7/28/23.

19. Data from *International Monetary Fund*, Primary Commodity Prices, Indices and Market Prices, Excel Database, Lithium Metal =99%, Battery Grade. https://www.imf.org/en/Research/commodity-prices Last updated June 5, 2024, accessed June 24, 2024.

20. *Average lead time almost 18 years for mines started in 2020–23*. S&P Global. (April 2024).

21. *Sustainability Aspects of the Lithium Ion Battery Supply Chain*. EPRI, Palo Alto, CA: 2021. 3002029811.

22. "Serbia wants talks with Rio Tinto over Jadar lithium project" *Reuters*. (January 17, 2024): https://www.reuters.com/markets/commodities/serbia-wants-talks-with-rio-tinto-over-jadar-lithium-project-2024-01-17/

23. "Closure of First Quantum's Panama copper mine

threatens e-transition" *Financial Post*. (February 2, 2024): https://financialpost.com/opinion/closure-first-quantum-panama-copper-mine-threatens-e-transition

24. *The Future of Copper: Will the looming supply gap short-circuit the energy transition?* S&P Global, 2022.
25. "Copper Market Slump Threatens Shift to Wind Power, Electric Cars: Green-energy transition requires increasing supplies, but demand is waning" *The Wall Street Journal*. (November 11, 2023).
26. *Critical Minerals Market Review 2023*. International Energy Agency (IEA), 2023. https://www.iea.org/reports/critical-minerals-market-review-2023
27. "Today in Energy: Utility-scale solar projects report delays." Energy Information Administration (EIA). (August 11, 2022): https://www.eia.gov/todayinenergy/detail.php?id=53400#
28. "Rising power costs spark fears of clean energy slowdown" *E&ENews*. (September 13, 2023): https://www.eenews.net/articles/rising-power-costs-spark-fears-of-clean-energy-slowdown/
29. *Recent U.S. Development in Lithium Ion Battery Critical Material Extraction*. EPRI, Palo Alto, CA: 2022. 3002024174.
30. *Final Determination for Pebble Deposit Area*. Environmental Protection Agency. (January 2023). https://www.epa.gov/bristolbay/final-determination-pebble-deposit-area
31. *Program on Technology Innovation: Recovery of Strategic and Rare-Earth Elements from Coal Ash: State of the Technology*. EPRI, Palo Alto, CA: 2018. 3002013916.
32. U.S. Geological Survey (USGS): Rare Earth Elements in Coal and Coal Fly Ash (September 2019): https://pubs.usgs.gov/fs/2019/3048/fs20193048.pdf
33. National Energy Technology Laboratory (NETL): Rare Earth Elements and Critical Minerals (September 2021): https://netl.doe.gov/sites/default/files/2021-09/Program-141_0.pdf
34. "Can seawater give us the lithium to meet our battery needs?" *Chemical & Engineering News*. (September 28, 2021): https://cen.acs.org/materials/inorganic-chemistry/Can-seawater-give-us-lithium-to-meet-our-battery-needs/99/i36
35. California Energy Commission, Lithium Valley Commission: https://www.energy.ca.gov/data-reports/california-power-generation-and-power-sources/geothermal-energy/lithium-valley
36. Dunn, J., Slattery, M., Kendall, A., Ambrose, H., and Shen S., Circularity of Lithium-ion Battery Materials in Electric Vehicles, pp. 1-30, (2021). 10.1021/acs.est.0c07030.
37. "'The basic metal of electrification': Why famed energy analyst Daniel Yergin sees a copper crunch looming" *Financial Post*. (July 14, 2022): https://financialpost.com/commodities/the-basic-metal-of-electrification-why-famed-energy-analyst-daniel-yergin-sees-a-copper-crunch-looming
38. *International Technology Roadmap for Photovoltaic (ITRPV) 12th Edition*. VDMA, 2021.
39. *Copper Mining and Vehicle Electrification*. International Energy Forum. (May 2024). https://www.ief.org/focus/ief-reports/copper-mining-and-vehicle-electrification

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

EPRI CONTACT

ROBIN BEDILION, *Principal Team Lead*
509.714.1766, rbedilion@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002030639 **August 2024**

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com