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Geopolitics of Critical Minerals

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EXECUTIVE SUMMARY

This essay finds that the supply chains of critical minerals are highly concentrated by a few countries, creating geopolitical issues amid global clean energy transitions.

MAIN ARGUMENT

Several minerals are indispensable to the production of clean energy equipment, such as solar photovoltaic modules, wind turbines, and batteries, and demand for these minerals is expected to increase substantially in the next few decades as many economies deploy clean energy technologies. A review of supply chains (mining, processing, manufacturing, and end use) of six critical minerals (cobalt, copper, lithium, nickel, rare earth elements, and silicon) suggests that the supply chains of critical minerals are highly concentrated, which creates potential economic, energy, and national security risks. Highly concentrated supply chains will also shape the related downstream industries and the future energy mix of many countries. Technological innovation could reduce this concentration and the associated risks, but game-changing innovation is likely several decades away from commercialization. Given the technological uncertainties, increased investment in diverse supply chains is required to ensure an adequate supply of critical minerals in the coming decades.

POLICY IMPLICATIONS

- The demand for critical minerals is expected to increase drastically in the next few decades to achieve the energy transition and the net-zero emission targets that many countries have already proposed. Under this projection, the highly concentrated critical mineral supply chains will increase the potential economic and security risks that should not be ignored.
- Historical events have shown that an economy with substantial market power in critical mineral supply chains has the potential and ability to shape downstream industries and use them as a political and economic weapon.
- Innovative technologies in the supply chains for critical minerals could mitigate the concentration and the associated risks. However, considering the uncertainty of innovation, investment in diverse supply chains is still indispensable to ensure adequate and affordable critical minerals.

As of June 2022, 137 countries have committed to achieving net zero or carbon neutrality by the middle of this century. The transitional period requires switching from fossil fuel to cleaner energy, in which renewable energy plays a crucial role. The International Energy Agency (IEA) estimates that the share of renewable energy is expected to account for two-thirds of the total energy supply by 2050 in its "net-zero emissions by 2050" scenario.[1] The Asia-Pacific Economic Cooperation (APEC) shows a similar trajectory out to 2050 in its "carbon neutrality" scenario.[2] To facilitate this transition to more sustainable energy systems, there is a correspondingly important role for clean energy technology and critical minerals.

This essay selects critical minerals based on three key criteria: demand growth, supplier concentration, and importance to clean energy technology.[3] Using these criteria, six critical minerals are selected for study: cobalt, copper, lithium, nickel, rare earth elements (REEs), and silicon. Clean energy technologies in this study include solar photovoltaic (PV) panels, wind turbines, electric vehicles (EVs), and electrical grids.[4]

Geographically, in each of the mining, processing, and manufacturing phases, there are three countries responsible for at least around half the global production of each critical material. Although the countries are not the same in each phase, there are notable similarities in the top three, which emphasizes supply limitations. Technologically, China is the global leader in mining REEs and silicon as well as in the processing, manufacturing, and end uses of all six critical minerals. While the Democratic Republic of Congo (DRC) dominates global cobalt ore production, Australia is the largest lithium ore producer in the world. Indonesia has the largest share of global nickel raw materials, and Chile is the largest copper ore producer worldwide. Thus, in the current context, heavy geographic concentration and know-how led by a small number of countries raise serious concerns about supply instability, pricing volatility, and geopolitical risks in the global critical mineral market. This should cause alarm for nations that rely on critical mineral imports or the final products.

This essay begins with an overview of critical minerals and supply chains, followed by a discussion of geopolitical issues. It concludes with an analysis of new technologies that may mitigate some of the geopolitical concerns.

Overview of Critical Minerals and Supply Chains

According to the IEA's "sustainable development" scenario, the consumption of lithium, nickel, and cobalt is expected to drastically rise by 42, 33, and 21 times, respectively, by 2040 compared to 2020, while REEs, copper, and silicon will have relatively less growth of 7, 3, and 2 times, respectively.[5] Based on various sources, shortages and higher prices are expected in almost

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[1] IEA, *World Energy Outlook 2021* (Paris: IEA, 2021), https://www.iea.org/reports/world-energy-outlook-2021.

[2] Asia Pacific Energy Research Centre (APERC), *APEC Energy Demand and Supply Outlook*, 8th ed. (Tokyo: APERC, 2022), https://www.apec.org/publications/2022/09/apec-energy-demand-and-supply-outlook-%288th-edition%29---volume-i.

[3] The authors are aware that the supply chain of "clean energy" may not be as clean as its name suggests. This is especially true in the mining, processing, and manufacturing stages, which can be energy-consuming processes. However, there seems to be no well-accepted term to replace "clean energy technology." Hence, in this essay, we use "clean energy technology" to refer to solar, wind, EV and battery storage, and electricity networks.

[4] REEs are a family of seventeen elements (fifteen elements in the lanthanide group, along with scandium and yttrium). Neodymium is one of the most important elements for the clean energy transition and is a key ingredient in producing the powerful permanent magnets used for motors in EVs and wind turbines.

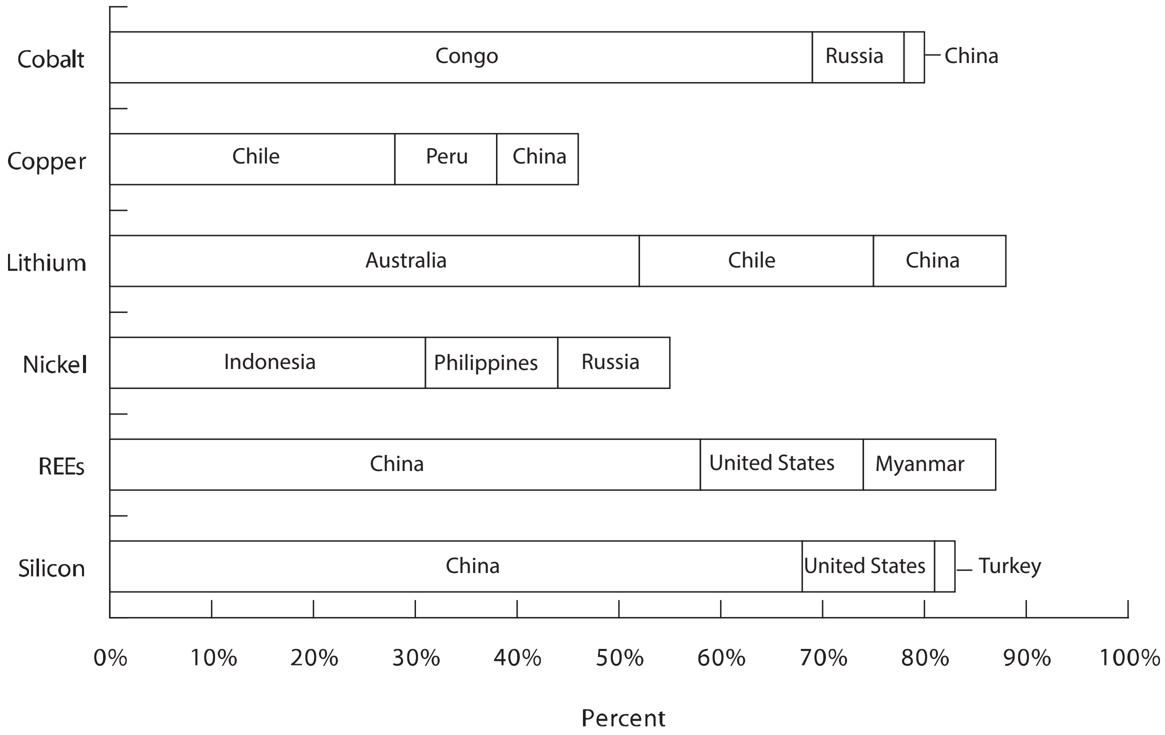
[5] IEA, "The Role of Critical Minerals in Clean Energy Transitions," May 2021, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

all critical mineral markets.[6] In the following sections, the supply chain (mining, processing, manufacturing, and end uses) for six selected critical minerals is discussed to provide broad insights into the main countries with concentrated stakes in each phase.[7]

Mining

The top-three countries' total share of global mining production for each critical mineral is between 47% and 88%, suggesting a concentrated mining market (see **Figure 1**).[8] The DRC has an

FIGURE 1 Top-three producers in the critical mineral mining market



SOURCE U.S. Geological Survey (USGS), *Mineral Commodity Summaries 2022* (Reston: USGS, 2022), https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf; IEA, "The Role of Critical Minerals in Clean Energy Transitions," May 2021, https://www.iea.org/reports/the-role-of-critical-minerals-inclean-energy-transitions.; and "World—Silica Sands (Quartz Sands or Industrial Sands)—Market Analysis, Forecast, Size, Trends and Insights," IndexBox, August 13, 2022, https://www.indexbox.io/store/world-silica-sands-quartz-sands-or-industrial-sands-market-analysis-forecast-size-trends-and-insights.

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[6] Silicon may be the only exception. An excess of the mineral in the markets is forecast by 2030, owing to an overcapacity issue in China's silicon industry, according to some sources. The capacity in China alone is expected to be large enough to cover the global demand for silicon metal. Although more studies are needed to understand this overcapacity issue, it may result from a shortage of energy and China's unique "market mechanism." See U.S. International Trade Commission, "Silicon Metal from China," May 2018, https://www.usitc.gov/publications/701_731/pub4783.pdf; and Liesbet Gregoir et al., "Metals for Clean Energy: Pathways to Solving Europe's Raw Materials Challenge," KU Leuven and Eurometaux, April 2022, https://eurometaux.eu/media/jmxf2qm0/metals-for-clean-energy.pdf.

[7] Definitions for different stages of the supply chains are provided in the following sections. However, due to the limited availability of data, the definitions for different critical minerals in the same stage may not be identical.

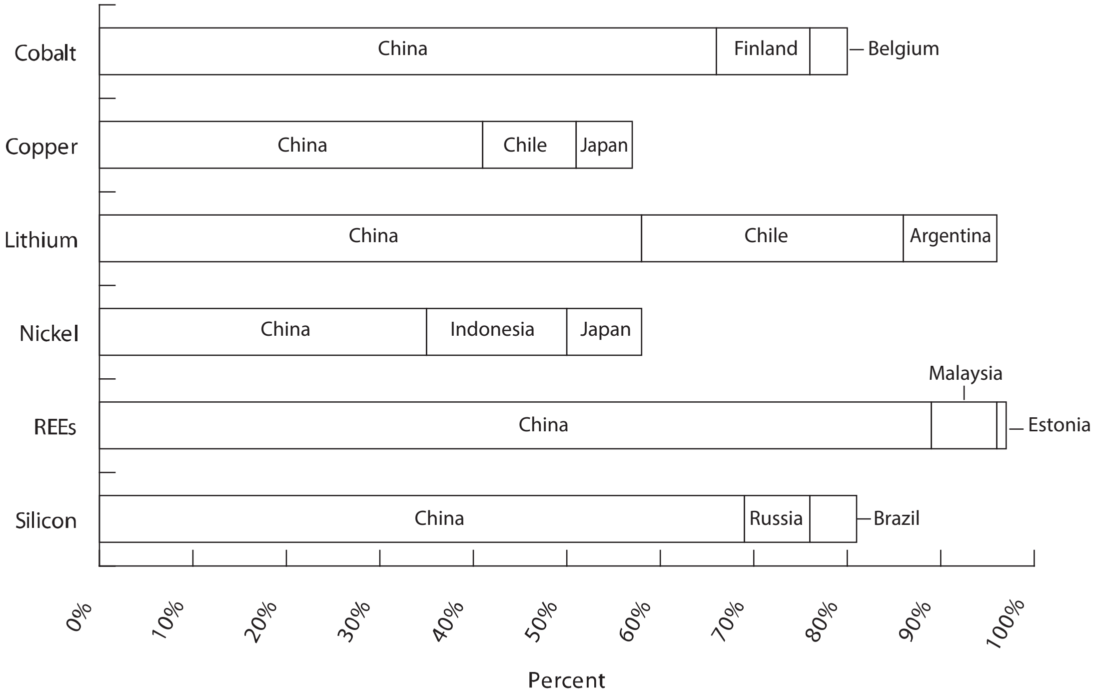
[8] Mining is defined as the activity of extracting targeted raw ores (e.g., sulfide ore and oxide ore) from the Earth's crust, and mining production is defined as the production of the targeted raw ores. The production of silica is regarded as silicon mining production.

overwhelming share of cobalt extraction, accounting for approximately 70% of global production. Chile is the largest copper mine producer (28%) and the second-largest lithium mine producer (23%), while Australia is the principal producer of lithium mine products (52%). Indonesia is the largest nickel producer, accounting for 31% of the world's nickel mining. China dominates REE (58%) and silicon (68%) mining production and ranks third in global mining production of cobalt (2%), copper (8%), and lithium (13%).

Processing

The processing markets for the six critical minerals are also concentrated.[9] The total share of the top-three producers exceeds 50% of global processing of the selected critical minerals (see **Figure 2**). China owns the largest share of the processing of all selected critical minerals: cobalt

FIGURE 2 Top-three producers in the critical mineral processing market



SOURCE "Global Cobalt Supply Chain: Limited Number of Players, China and the DRC to Maintain Their Dominance," Fitch Solutions, September 22, 2021, https://www.fitchsolutions.com/mining/global-cobalt-supply-chain-limited-number-players-china-and-drc-maintain-their-dominance-22-09-2021; IEA, "The Role of Critical Minerals in Clean Energy Transitions"; U.S. Department of Energy, *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment* (Washington, D.C., February 2022), https://www.energy.gov/sites/default/files/2022-02/Neodymium%20Magnets%20Supply%20Chain%20Report%20-%20Final.pdf; and USGS, *Mineral Commodity Summaries 2022*.

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[9] Processing is defined as the activity of the preliminary separating of the targeted minerals from the raw ores (e.g., pyrometallurgy and hydrometallurgy). Metallurgical-grade silicon production is regarded as silicon processing production.

(66%), copper (41%), lithium (58%), nickel (35%), REEs (89%), and silicon (69%). Chile ranks second in copper and lithium processing, accounting for 10% and 28%, respectively. Indonesia, the largest nickel mining country, ranks second in the nickel processing market (15%). The rest of the countries in the top-three processing markets are not listed in the mining market, which implies that the processing stage does not depend on the origin of raw critical mineral resources.[10]

Manufacturing

The manufacturing markets for the six critical minerals also remain concentrated.[11] The total share of the top-three manufacturers accounts for over half the global manufacturing products (see **Figure 3**). China dominates all manufacturing markets, namely cobalt (67%), copper (41%), lithium (55%), nickel (25%), REEs (92%), and silicon (76%). Chile ranks second in copper (10%) and lithium (27%) manufacturing products. Chile seems to take advantage of mineral resources in the copper and lithium markets to develop the upstream and midstream mineral industries. Japan is listed in the top-three processing and manufacturing countries for copper and nickel as well as in the top-three cobalt and REE manufacturers. Finland ranks second in cobalt processing and manufacturing markets, while Argentina ranks third in lithium processing and manufacturing markets. The market shares for these two countries are around 10% in both the processing and manufacturing stages. Overall, the market shares and ranks suggest a close relationship between the processing and manufacturing markets.[12]

End Uses

The end-use markets for the selected critical minerals are concentrated much like the previous three steps in the supply chain.[13] The total share of the top-three producers exceeds 70% of the global end use of selected critical minerals (see **Figure 4**). There are, however, two caveats. First, except for silicon and lithium, the top-three end users of other critical minerals are aggregated partly by regions instead of countries. The different aggregation makes the comparison of concentration between end-use markets and other markets problematic. Second, the end-use data here refers to the shares of end-use products or the critical mineral consumption in the end-use sectors. However, China's dominance in all end-use markets is undisputed, with cobalt (32%), copper (54%), lithium (39%), nickel (59%), REEs (68%), and silicon (70%). South Korea ranks second in lithium (20%) and silicon (5%) end-use production, while Japan ranks third in lithium (18%) end-use production.

Summary

The market shares of various critical minerals in different stages of the supply chain suggest that the supply chains are highly concentrated and shaped by many factors, including

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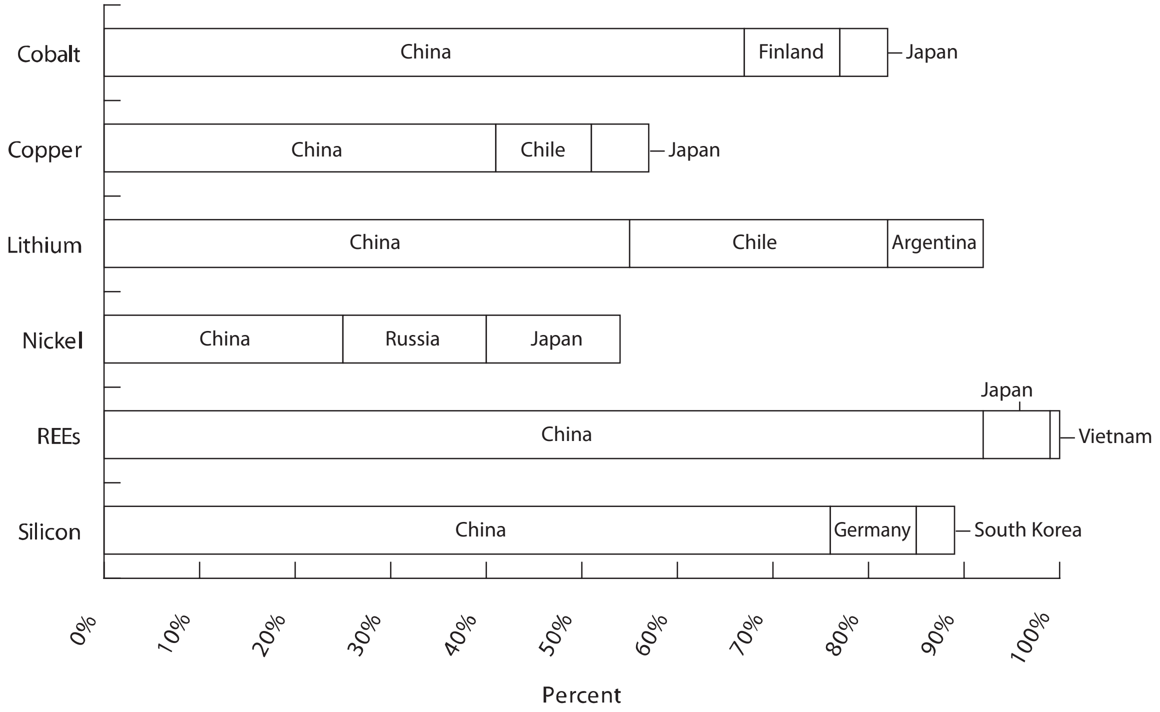
[10] The development of processing industries in countries without raw resources may result from their comparative advantages in separation or refinery technology and the investment needed. The cooperation of China and Myanmar in REEs is one example: the former possessed the needed capital and technological know-how, and the latter offered the raw materials.

[11] Manufacturing is defined as the activity of further refining the targeted minerals from the processed products. Lithium chemical production, Class 1 nickel production, sintered neodymium magnet production, and polysilicon production are regarded as manufacturing productions.

[12] The relationships may result from the similar definitions we made for the stages and critical minerals. The close relationships between processing and manufacturing may imply that economies with a comparative advantage in one stage can naturally have a comparative advantage in the other. However, further studies are needed to understand the relationships between these two stages.

[13] End uses are defined as the amounts of critical minerals consumed to produce the final product. Solar PV module production is regarded as a silicon end-use product.

FIGURE 3 Top-three producers in the critical mineral manufacturing market

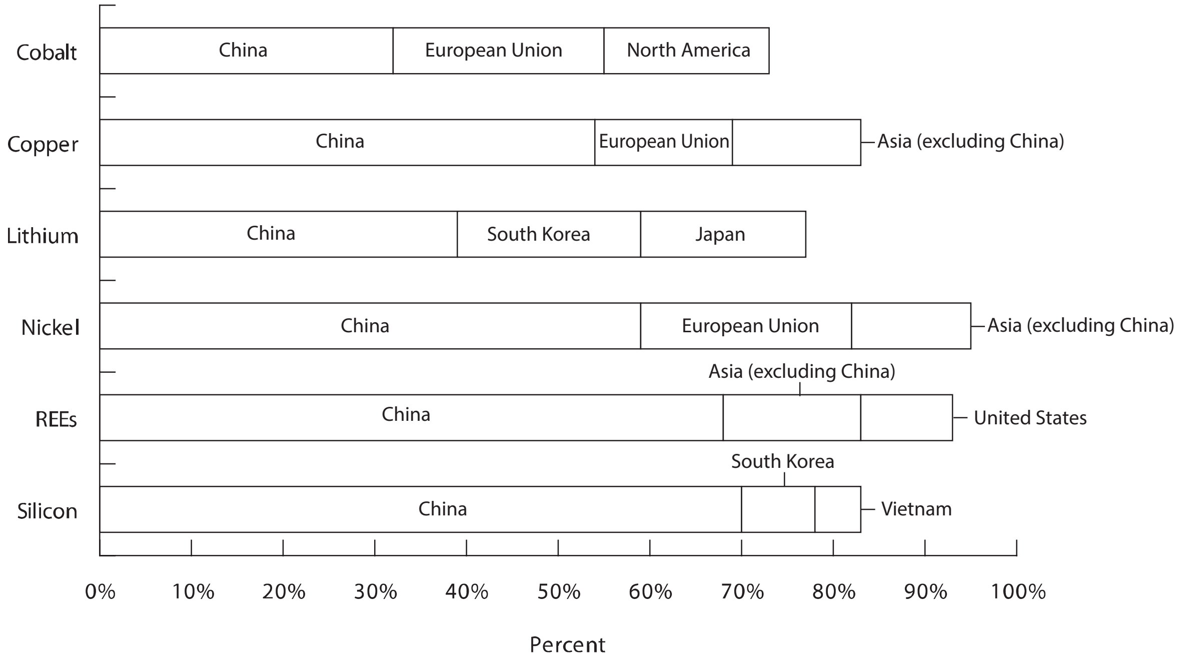


SOURCE: "'State of the Cobalt Market' Report," Cobalt Institute, May 17, 2021, https://www.cobaltinstitute.org/wp-content/uploads/2021/05/CobaltInstitute_Market_Report_2020_1.pdf; International Copper Study Group, *The World Copper Factbook 2021* (Lisbon: International Copper Study Group, 2021), https://icsg.org/wp-content/uploads/2021/11/ICSG-Factbook-2021.pdf; "Europe's Lithium Challenge on the Road to Electrification," Rock Tech Lithium, June 4, 2021, available at https://elements.visualcapitalist.com/europes-lithium-supply-challenge-on-the-road-to-electrification; Marcelo Azevedo, Nicolas Goffaux, and Ken Hoffman, "How Clean Can the Nickel Industry Become?" McKinsey & Company, September 11, 2020, https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become; U.S. Department of Energy, *Rare Earth Permanent Magnets*; Johannes Bernreuter, "Background and Ranking of the Top Ten Polysilicon Producers," Bernreuter Research, June 29, 2020, https://www.bernreuter.com/polysilicon/manufacturers; and Kelly Pickerel, "China's Share of World's Polysilicon Production Grows from 30% to 80% in Just One Decade," Solar Power World, April 27, 2022, https://www.solarpowerworldonline.com/2022/04/chinas-share-of-worlds-polysilicon-production-grows-from-30-to-80-in-just-one-decade.

endowments (e.g., distribution of mineral reserve and labor cost), economic structure, energy policy, technology, and environmental regulations of each country. An abundant mineral reserve alone does not necessarily imply dominance of the entire supply chain. The best example of this is in the world's largest cobalt miner, the DRC, which does not play any significant role in the processing, manufacturing, or end-use stage. In addition, China dominates the entire supply chain of REEs and silicon and ranks first in the processing, manufacturing, and end use of the other critical minerals discussed in this section. China's leadership might result from its early and abundant investment in the critical mineral supply chain.

The following section discusses the geopolitical aspects of highly concentrated supply chains.

FIGURE 4 Top-three users (producers) in the critical mineral end-use market



SOURCE "Global Cobalt Supply Chain"; IEA, "The Role of Critical Minerals in Clean Energy Transitions"; U.S. Department of Energy, *Rare Earth Permanent Magnets*; and USGS, *Mineral Commodity Summaries 2022*.

Geopolitical Aspects

The critical mineral market is expected to be more complicated and volatile than the oil market given its highly concentrated supply chains. Under the global energy transition trend, it will be essential to pay equal or even greater attention to supply chains. The concentrated supply chains in critical minerals could be problematic or trigger disputes because intentional disruptions could affect a country's industrial competitiveness and provide economic and political leverage to suppliers with market power.

For the industry's competitiveness, a country that dominates upstream production may enjoy ease of access to the feedstock. For example, China dominates the entire supply chain of solar PV modules. Its cost advantage is generally recognized as the result of cheap labor, an economy of scale, and ease of access to the feedstocks. It is also worth noting that economies of scale in solar PV module production further reinforce the profitability of those with market power in upstream production. China's solar PV supply chain dominance has raised concerns in several countries, including the United States. According to the U.S. Department of Energy, it would be risky for the United States to continue to rely on China's silicon production, and it would be beneficial for the U.S. economy to develop and secure its own solar PV supply chain.[14]

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[14] U.S. Department of Energy, "Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment," February 2022, https://www.energy.gov/sites/default/files/2022-02/Neodymium%20Magnets%20Supply%20Chain%20Report%20-%20Final.pdf.

Consequently, the United States has implemented several policies to encourage domestic solar PV and the upstream industries and imposed restrictions on specific solar PV products or feedstocks from China.

Some countries with abundant critical mineral resources have imposed restrictions on the export of raw materials to stimulate domestic investment and production of higher value-added products. Indonesia, the world's largest nickel miner and second-largest nickel processor, started restricting raw nickel exports in 2014. According to the Indonesian government, the restriction stimulated investment in nickel refineries and nickel-based products.[15] This case shows a country's attempt to develop an entire supply chain, increase economic profits, and improve economic structures. Not surprisingly, the restrictions on exports resulted in complaints from other economies. The European Union, for example, claimed that the restrictions were illegal and harmful to its stainless steel producers.[16]

The security risks involved with critical mineral supply disruption are more disquieting. A supply disruption can be caused by natural disasters, political turmoil, international conflicts, or anything that can affect the production and export of critical minerals. One well-known example is the export restrictions on REEs that China imposed on Japan in 2010 after Japan seized a trawler it said was fishing illegally in its waters. The effectiveness of these restrictions was demonstrated by the speed with which Japan released the boat captain without receiving any concessions. This example highlights how market power in the supply chains of critical materials can be used as both a political and an economic weapon.[17]

A more recent example of a critical mineral supply disruption occurred in Myanmar. In 2021, REE exports from Myanmar to China were affected by the military coup and the border closure to limit the spread of Covid-19. Although China is the world's leading REE producer and consumer, it relies on the (heavy) REE feedstock from Myanmar. The disruption is believed to be one of the reasons that the price of REEs rose significantly in 2021.[18] This example shows that domestic political turmoil or a natural disaster can cause a global supply issue if it happens in a country that dominates, or partially dominates, certain critical minerals.

These economic and security aspects of geopolitical issues suggest that participants in a supply chain should pay attention to the movements of major suppliers of critical minerals because of their potential ability to reshape the related industries. The following section discusses the potential of innovative technologies along with their uncertainties.

Innovative Technologies

The foregoing analysis of the geographic concentration of critical minerals and the resulting geopolitical issues has revealed the fragility of global supply chains. This situation underscores

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[15] Krisna Gupta, "Indonesia's Claim That Banning Nickel Exports Spurs Downstreaming Is Questionable," Conversation, March 30, 2022, https://theconversation.com/indonesias-claim-that-banning-nickel-exports-spurs-downstreaming-is-questionable-180229.

[16] "Indonesia Says 'Ready to Fight' EU at WTO over Nickel Export Curbs," Reuters, February 26, 2021, https://www.reuters.com/article/us-eu-indonesia-trade-idUSKBN2AQ0GO.

[17] Under China's REE export restrictions in 2010, Japan used its REE stockpile to fill the gap, sought different REE sources, and invested in related technologies (e.g., seabed mining and recycling). There were short-term shocks resulting from China's restrictions on Japan, but the restrictions did not tremendously harm the Japanese economy. Instead, the restrictions raised Japan's awareness of its import dependency on critical minerals.

[18] The strong demand for wind power and electric vehicles is another reason for the increasing price of REEs.

the need for innovative technologies at all stages in the supply chain to provide more stable and affordable mineral sources for future clean energy development.

In mining, deep-seabed mineral extraction is one potentially innovative technology that several countries are interested in exploring—particularly countries located in the Pacific Ocean's Ring of Fire. Japan, for example, plans to create mining technology and select a mining location in its exclusive economic zone by the end of 2028.[19] In Europe, Norway plans to start seabed mining exploration on its continental shelf as early as 2023. However, deep-seabed mining still carries uncertainties due to technological and marine environmental hurdles. First, a pilot project on deep-sea mining was conducted by the Japan Oil, Gas and Metals National Corporation in 2017, but it still needs further technical investigations to become commercially feasible. Second, impacts on ecosystems and biodiversity remain poorly understood, despite several rigorous studies. The International Seabed Authority, a UN body, is drawing up regulatory frameworks for the international seabed—areas outside any national jurisdiction—aiming to promote deep-sea mining while minimizing damage to the marine environment.[20]

In processing, various research projects have been conducted in the United States, including several pilot-scale tests and demonstrations. The West Virginia University Research Corporation has implemented a project called "Development and Testing of an Integrated Acid Mine Drainage (AMD) Treatment and Rare Earth/Critical Mineral Plant." If successful, the plant will generate around one thousand tons per year of REE and critical material oxides from coal and other ore bodies, with an estimated contained value of $237 per kilogram.[21] Additionally, the United States is conducting a feasibility study to assess the potential of REE recovery from coal, coal byproducts, and waste materials to support the U.S. domestic supply of REEs for clean energy. The target is to produce one to three tons of REEs per day by 2026.

In manufacturing and end use, innovative technologies in efficiency and design are vital to reduce material intensity. In the case of wind turbines, a larger size contributes to higher capacity, leading to a reduction in the material intensity of minerals. For instance, on a kilogram per megawatt (MW) basis, a 3.45 MW turbine contains around 50% less copper than a 2 MW turbine.[22]

Although innovative technologies are being developed at various stages of critical mineral supply chains to reduce dependency on primary supply, these innovations reveal uncertainties due to technological and environmental obstacles. Therefore, investment in mineral production is imperative to ensure a supply of critical minerals for clean energy technologies in the coming decades.[23]

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[19] "JOGMEC Conducts World's First Successful Excavation of Cobalt-Rich Seabed in the Deep Ocean; Excavation Test Seeks to Identify Best Practices to Access Essential Green Technology Ingredients While Minimizing Environmental Impact," Japan Oil, Gas and Metals National Corporation, August 21, 2020, https://www.jogmec.go.jp/english/news/release/news_01_000033.html; "Japan to Commercialize Mining of Rare Metals on Seabed," Eleven Media Group, January 19, 2021, https://elevenmyanmar.com/news/japan-to-commercialize-mining-of-rare-metals-on-seabed; and IEA, "The Role of Critical Minerals in Clean Energy Transitions."

[20] "G-7 Countries Say Strict Environmental Rules Needed for Deep-sea Mining," Reuters, May 27, 2022, https://www.reuters.com/world/g7-countries-say-strict-environmental-rules-needed-deep-sea-mining-2022-05-27.

[21] U.S. National Energy Technology Laboratory, "2020–2021 Critical Minerals Sustainability Program Project Portfolio," May 2021, 18, https://www.netl.doe.gov/sites/default/files/2021-05/2020-2021-REE-Portfolio.pdf.

[22] Alessia Elia et al., "Wind Turbine Cost Reduction: A Detailed Bottom-Up Analysis of Innovation Drivers," *Energy Policy*, no. 147 (2020).

[23] IEA, "The Role of Critical Minerals in Clean Energy Transitions."

Conclusion

Demand for critical minerals is expected to rise rapidly in the coming decades, given their significant role in the manufacture of clean energy equipment. The geopolitics of critical mineral supply chains have become an issue for many governments, particularly in import-dependent countries. The following are the main takeaways from this study:

- The demand for six materials critical to the manufacture of clean energy equipment is expected to triple by 2030 and quadruple by 2040 as the world transitions toward clean energy technologies. By 2040, lithium has the highest expected growth in demand relative to 2020 levels (42-fold), followed by nickel (33-fold) and cobalt (21-fold), while demand for REEs, copper, and silicon will grow at a slower pace.
- Processing and manufacturing are mostly concentrated in the top-three countries, accounting for over half of the global production of each critical mineral (although the top three are different for different materials). China is the global leader in mining REEs and silicon and currently dominates the processing to end-use segments for all six critical minerals.
- Critical mineral supply chains are much more concentrated than the oil and gas supply chains on which the world currently relies. Geopolitical issues suggest that participants should pay attention to the potential economic, energy, and national security risks associated with critical mineral supply chains to ensure affordable and available critical minerals for economic development and decarbonization.
- In the long term, technological innovations, such as deep-seabed mining, provide potential solutions to reduce dependency on concentrated supplies and secure material supply in several countries. However, various uncertainties exist due to technological constraints and environmental impacts. As a result, increased investment in diverse supply chains is required to ensure an adequate supply of critical minerals in the coming decades.