Research Report

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The Potential Impact of Seabed Mining on Critical Mineral Supply Chains and Global Geopolitics

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About This Report

The potential emergence of a seabed mining industry has important ramifications for the diversification of critical mineral supply chains, revenues for developing nations with substantial terrestrial mining sectors, and global geopolitics. In this report, we present the results of a multipronged examination of each of these issues, exploring the likelihood and magnitude of their impacts to better inform planning and policymaking around seabed mining in particular and critical mineral supply chains more broadly. We conclude with findings and recommendations for the U.S. government. The report is intended for policymakers, but it could also be of interest to readers who are curious about the seabed mining industry.

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Summary

In this report, we present the results of a multi-pronged examination of issues related to seabed mining, including the potential, opportunity, and appetite for diversification of critical mineral supply chains; impacts on revenues for developing nations with substantial terrestrial mining sectors; and global geopolitics. We explore the likelihood and magnitude of these impacts to better inform planning and policymaking around seabed mining in particular and critical mineral supply chains more broadly.

Key Findings

- Interest in seabed mining has rekindled over the past decade as decarbonization of the energy system has increased projected demand for the critical minerals that are contained in seabed resources and as efforts to develop an international regulatory framework for seabed mineral extraction have progressed.
- According to mining company business plans, a global seabed mining industry could feasibly produce amounts of nickel and cobalt—key elements for lithium-ion batteries—that are equal to the projected U.S. demand in 2040.
- For a combination of technical and business reasons, prospective seabed mining companies have expressed a strong interest in establishing new processing and refining capacity for seabed polymetallic nodules outside existing supply chains that are dominated by China, and they have a particular interest in the United States.
    - Seabed mining thus presents an opportunity for the United States and its allies to diversify critical mineral supply chains, bolstering critical mineral supply reliability and security.
        - The U.S. government has yet to develop a clear vision for a potential role of the United States and its allies in an emerging seabed mining industry.
    - Despite companies' desire to operate outside existing supply chains, China is courting these companies to process polymetallic nodules in China and Indonesia; if commercial seabed mining commences and conditions for processing in the United States and its allies are not favorable, companies might ultimately turn to Chinese firms.
- Seabed miners might face fewer barriers to entry into the mining industry than junior terrestrial miners.
- The establishment of a seabed mining industry would be accompanied by geopolitical implications for the United States and the world.
    - The increase in supply from seabed mining would decrease prices, leading to decreased royalty revenue from terrestrial mining; in a case study of cobalt mining in the Democratic

Republic of Congo, even under the most-generous assumptions, royalty sharing and economic assistance from seabed mining would not offset this decrease.

- A seabed mining industry would come with a wide variety of potential global geopolitical implications for the U.S. government, including shifts among relationships within the Indo-Pacific region, concerns related to regulatory enforcement and environmental monitoring, new territorial disputes, increasing demand for maritime domain awareness and security, and new influences on commodity prices and security of supply. Because the U.S. government is not a member of the International Seabed Authority, its influence in some of these areas is limited.

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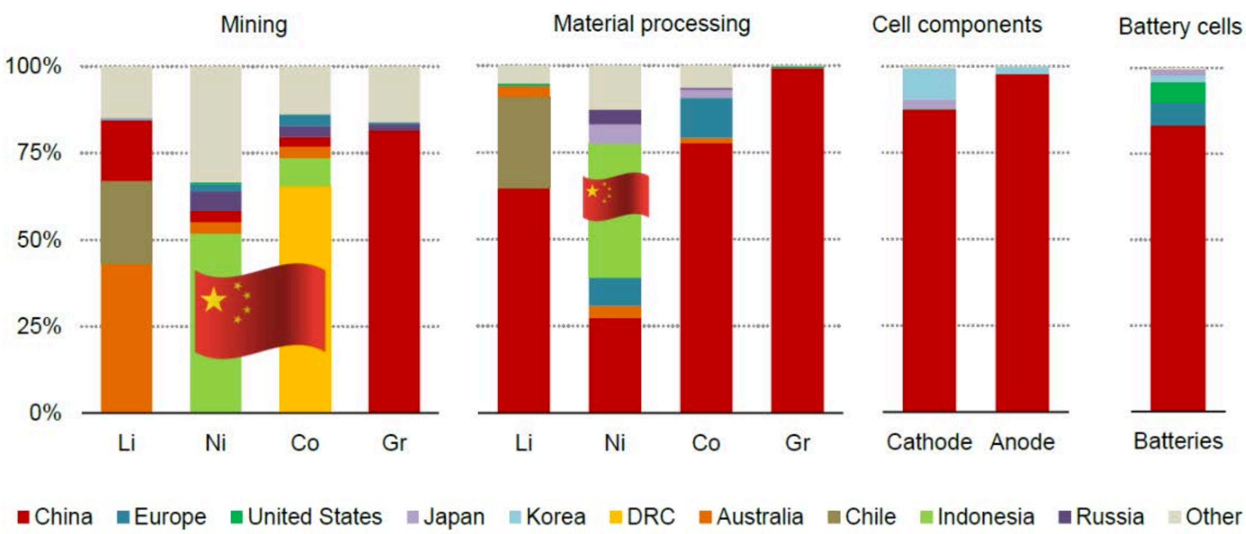
The emergence of a seabed mining industry has important ramifications for the diversification of critical mineral supply chains, revenues for developing nations with substantial terrestrial mining sectors, and global geopolitics. While the industry is still nascent and its future is uncertain, it is worthwhile to consider the likelihood and magnitude of these impacts to better inform planning and policymaking around seabed mining in particular and critical mineral supply chains more broadly.

Critical Mineral Supply Chain Risks and Opportunities

Risks Posed by China's Dominance of Critical Mineral Supply Chains

China's overwhelming dominance over the global supply of critical minerals has fueled substantial concern in the United States and among its allies about the reliability of this supply for Western interests. A single source of supply for a global commodity leaves that supply vulnerable to disruption. When that single source is a state with a history of aggressive and retaliatory manipulation and restrictions on exports, market access, and pricing, there is even more cause for concern that deliberate disruptions could be imposed for political purposes. Furthermore, when the commodities at stake are critical minerals and components that are essential for energy, transportation, defense, and other sectors, these concerns take on even more urgency. As one example, China's dominance over critical mineral supply chains associated with electric vehicle (EV) batteries, from mining to finished components, is illustrated in Figure 1.

Figure 1. Geographical Distribution of the Global Electric Vehicle Battery Supply Chain, 2023



SOURCE: Adapted from International Energy Agency (IEA), 2024, p. 30 (CC BY 4.0).
NOTE: Chinese flags indicate large shares of Chinese ownership of foreign operations. Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of the Congo.

The validity of these concerns has been demonstrated on multiple occasions. In 2010, in response to an altercation between a Chinese fishing vessel and the Japanese Coast Guard, Chinese state-owned enterprises restricted the export of rare earth elements to Japanese customers. Commodity prices rose to six times their average trading value and stayed elevated for four years afterward (Inoue, 2010). In July 2023, China imposed export restrictions on gallium, germanium, and certain graphite products, resulting in a temporary lowering of global supply and a near doubling of prices (Dempsey and White, 2024). In August 2024, China again imposed export restrictions, this time on antimony, citing concerns of national sovereignty, security, and national development (Baskaran and Schwartz, 2024). In October 2024, China blocked the sale of critical battery components to a U.S. drone maker, impeding the company's ability to supply drones to Ukraine in the Russia-Ukraine war (Sevastopulo, Hille, and McMorrow, 2024). In November 2024, China announced tighter export controls on several dual-use specialty materials, including tungsten, graphite, magnesium, and aluminum alloys (McCartney, 2024). And, in December 2024, China fully banned exports of gallium, germanium, antimony, and superhard materials to the United States in response to the Unites States strengthening its export controls to China on advanced semiconductors (Pierson, Bradsher, and Swanson, 2024).

These incidents demonstrate China's willingness and ability to disrupt the global supply of critical minerals. Sustained disruptions could limit production of essential products, affecting essential markets and national security. Concerns about the possibility of further and more-extreme actions by China have led to several efforts by the United States and its allies to secure alternative sources of supply for critical minerals. As of January 2025, these efforts include the Supply Chain Disruptions Task Force (White House, 2021a), the National Science and Technology Council Critical Minerals

Subcommittee (CriticalMinerals.gov, undated), the U.S. Agency for International Development's Supply Chain Integrity and Freedom program (Runde, 2022), the U.S. House of Representatives Select Committee on the Strategic Competition Between the United States and the Chinese Communist Party's Critical Minerals Policy Working Group (Select Committee on the Chinese Communist Party, 2024), the Minerals Security Partnership (U.S. Department of State, undated), the U.S. Inflation Reduction Act (White House, 2023a) and associated critical mineral agreements (U.S. Trade Representative, 2024), and the European Commission's Critical Raw Materials Act (European Parliament, 2024).

Seabed Mining as an Opportunity to Diversify Critical Mineral Supply Chains

Polymetallic nodules, potato-sized concretions that reside on the sea floor at water depths of four to six kilometers, could provide an alternative source for several important critical minerals. The economic and technical potential of extracting these nodules was investigated intently in the 1970s (International Seabed Authority [ISA], undated-f; AMC Consultants, 2021). Research conducted at that time confirmed that polymetallic nodules represent a vast resource of nickel, cobalt, manganese, and copper and demonstrated that harvesting nodules from the sea floor is technically feasible. Current estimates indicate that the amounts of these metals available in seabed resources are several times greater than those on land (S&P Global, 2023). Despite this early work, interest in seabed mining waned in the 1980s for several reasons, including increased costs compared with land-based mining and the absence of a regulatory regime for resource extraction in international waters.

Two significant developments since then, however, have renewed interest in seabed mining. The first is the transition of the world's transportation and energy systems away from fossil fuels in response to climate change. The European Union, for example, has set a goal of having all new vehicles be zero-emission by 2035 (European Commission, undated). Although U.S. policy is in transition in 2025, the Biden administration set targets that half of all new vehicle sales be zero-emission vehicles and 80 percent of energy generation be renewable by 2030 (White House, 2021b; White House, 2021c). Demand for batteries for EVs and energy storage associated with renewable energy generation is increasing demand for nickel, cobalt, manganese, copper, and other critical minerals required to produce those batteries. An unfettered supply of these critical minerals takes on extra significance in the context of energy transitions, and seabed mining has been promoted as an opportunity to introduce new mineral supplies that are independent of Chinese-controlled supply chains (Wittman et al., 2023; Wang, 2024).

The second significant development is the pending implementation of a regulatory regime for seabed mining in international waters. The ISA is an autonomous international organization established in 1994 under the United Nations Convention on the Law of the Sea (UNCLOS) (ISA, undated-a). UNCLOS defines exclusive economic zones (EEZs) for coastal countries and authorizes the ISA to oversee the management of resources in the region beyond any EEZ, known as the *Area*. Most of the attractive polymetallic nodule resources are in the *Area*, particularly in a region between Mexico and Hawaii known as the Clarion-Clipperton Fracture Zone (CCZ) (ISA, undated-b). The ISA controls mineral resource–related activities in the *Area*, including developing exploration and mining regulations, issuing operating contracts to member state–sponsored entities, and overseeing exploration and mining operations.

As of 2024, 169 countries and the European Union are parties to UNCLOS and, hence, members of the ISA (ISA, undated-a). The ISA has established exploration regulations and has issued 31 exploration contracts to 22 entities (ISA, undated-c). It released the first draft exploitation regulations in 2019 (ISA, undated-d) and is, ostensibly, planning to complete them in 2025 (ISA, 2023). Many experts with whom we met expressed doubt that the ISA will meet that date, but most said that they expect that regulations will be completed in due course. Among the issues that the regulations must address are environmental protections and the royalty regime. The United States is not a party to UNCLOS and, therefore, not a member of the ISA, so it cannot sponsor seabed mining operations in the *Area* through the ISA process.

The commercial seabed mining industry does not yet exist, and many aspects of how it will develop have yet to be determined. Most mining companies plan to extract nodules using treaded vehicles tethered to a surface ship. As the vehicle crawls along the seabed, nodules are collected via hydraulic jets and sent up a riser tube to the ship. A competing technology uses untethered vehicles that hover just above the seafloor and pluck individual nodules with robotic arms. When full, the vehicle rises to the surface, and nodules are transferred to a ship. This latter approach has a lower environmental impact because it creates less sediment disturbance. Both technologies have been demonstrated in deep-water conditions, but neither has reached commercial scale. At the surface, nodules are transferred to a transport ship and sent to shore for processing.

Objectives and Approach

In light of increasing interest in proceeding with commercial seabed mining, we conducted an analysis to evaluate (1) the potential for seabed mining to diversify critical mineral supply chains, (2) the opportunity and appetite for doing so, (3) the factors influencing the viability of a seabed mining industry, and (4) the broader implications of establishing a global seabed mining industry. We used several methods to accomplish these objectives, including a literature review, expert interviews, economic modeling, and an expert workshop. Our interviews focused on seabed mining and mineral processing plans, needs, and policy and included several stakeholder groups; specifically, we met with representatives from six seabed mining companies, three mineral processing companies, two terrestrial mining companies, and ten government agencies (including nine U.S. federal agencies and one allied government agency), as well as five subject-matter experts in seabed mining and mineral processing.

The six seabed mining companies that we met with are all active in exploration and technology development and the readiest to begin commercial operations. The status of three Chinese operators is not well known but believed to be advanced as well ("China Is Itching to Mine the Ocean Floor," 2024). Thus, information from the companies that we met with is believed to be representative of the state of the industry outside China.

We also conducted a workshop to elicit potential global geopolitical implications of the emergence of a seabed mining industry. The workshop structure and participants are described in Appendix C.

Seabed Mining's Potential Contribution Toward Projected Critical Mineral Demand

The primary economic mineral resources in polymetallic nodules are nickel, cobalt, copper, and manganese (Kuhn et al., 2017; Kirchain et al., 2019). Historically, nickel, cobalt, and manganese have been used primarily in the production of steel and other metal alloys, while copper has a variety of uses, including in construction, electricity and electronic products, and transportation (Ewing, 2024). However, nickel, cobalt, and manganese are also key ingredients in a common type of cathode in lithium-ion batteries, which is called a nickel-manganese-cobalt (NMC) cathode.[1] As decarbonization policies drive the rapid increase in EV deployment, the distribution of cobalt and nickel consumption has shifted toward battery production. In 2023, 45 percent of global cobalt and 15 percent of global nickel was used in EV batteries (Cobalt Institute, 2024a; Norilsk Nickel, 2024).

We estimated the potential contribution of seabed mining toward cobalt, nickel, and copper demand by comparing demand projections derived from relevant literature with supply estimates from industry business plans. Manganese demand projections were insufficient for including in this computation.

The rapidly rising demand for EV batteries is projected to be the greatest source of demand growth for nickel, cobalt, and copper in the coming decades (Cobalt Institute, 2024b; IEA, 2024b). Current consumption and projected demand in 2040, globally and for the United States, are shown in Tables 1 and 2. Long-term demand is influenced by many factors, and projections are inherently uncertain. Among the uncertainties is the direction of technological evolution, which can influence the relative demand of different minerals. For example, lithium-ion battery technologies are evolving rapidly, and lithium-iron-phosphate (LFP) cathodes, which contain no nickel or cobalt, are increasingly displacing NMC compositions. Projections in Tables 1 and 2 account for this trend and assume a market mix for EV batteries that includes 50 to 60-percent LFP cathode–type batteries by 2040. Note that the demand presented in Table 2 includes only metals used by U.S. manufacturers and does not include the quantity of material included in imported final products.

[1] The percentages of the three metal oxides in the cathode's active material vary. Typically, nickel has the highest percentage, followed by cobalt and manganese. For example, the composition of an NMC 532 oxide is 50-percent nickel, 30-percent manganese, and 20-percent cobalt; NMC 622 is 60-percent nickel, 20-percent manganese, and 20-percent cobalt; and NMC 811 is 80-percent nickel, 10-percent manganese, and 10-percent cobalt.

Table 1. Existing and Projected Global Demand, in Tons

		2040	
Mineral	**2023**	**Low**	**High**
Nickel	3,104,000	5,600,000	6,238,000
Cobalt	215,000	380,000	454,000
Copper	25,855,000	33,500,000	36,379,000

SOURCE: Data are from IEA, 2024b.
NOTE: The numbers in the low column are from the IEA's Stated Policies Scenario, which is a scenario that "reflects today's policy setting," and the numbers in the high column are from the IEA's Announced Pledges Scenario, which is a scenario "that meets all national energy and climate goals in full" (IEA, 2024b, pp. 6–7).

Table 2. Existing and Projected U.S. Demand, in Tons

		2040	
Mineral	**2023**	**Low**	**High**
Nickel	190,000	381,800	1,056,200
Cobalt	6,400	13,500	91,100
Copper	1,800,000	2,532,700	3,609,900

SOURCES: 2023 consumption data are from Ewing, 2024. 2040 consumption data are derived from IEA, 2024b, and Wang, 2024.
NOTE: The low estimates are derived by multiplying the 2023 values by the projected growth in global demand between 2023 and 2040 from Table 1. The high estimates are derived by scaling projected demand for the U.S. power and road transportation sectors to total U.S. demand using global values. This can be expressed as 2040 High = (U.S. $P + T$) / F_{P+T}, in which (U.S. $P + T$) is the 2036–2050 average yearly demand for the U.S. power and road transportation sectors under the Net-Zero America Scenario from Wang (2024), and F_{P+T} is the power and transportation (i.e., the *Cleantech*) portion of the total projected global demand from the 2040 Announced Pledges Scenario (IEA, 2024b, pp. 108–155).

Tables 1 and 2 show mineral demands increasing between 2023 and 2040 by factors ranging from 1.3 for copper globally to more than 14 for cobalt in the United States. This large projected growth in demand for battery materials is one of the key arguments cited in discussions about the need for mining seabed mineral resources (Metals Company, undated; "The World Needs More Battery Metals. Time to Mine the Seabed," 2023).

To provide a sense of the extent to which seabed mining could contribute to projected demand, we developed a notional example of the potential amounts of nickel and cobalt demand that could be provided by seabed mining (see Table 3). Estimates for the nodule recovery rate and metal recovery were provided by representatives of two seabed mining companies with whom we met. For nodule recovery, they indicated that they anticipate using two collectors per vessel, with each collector alternating between operation and maintenance for continuous nodule collection. Under this operational scenario, both representatives estimated a recovery of 3 million tons of nodules per year. This value is consistent with an estimate from Kirchain et al. (2019, 2020) of 1.93 million tons per year for a single collector with a duty cycle of 0.67 (i.e., 18 days of operation followed by 6 days of maintenance).

Table 3. Potential Contributions of Seabed Mining Toward Projected U.S. and Global Demand

Contribution	Nickel	Cobalt
Nodule recovery per vessel, in tons per year	3,000,000	3,000,000
Metal concentration	1.3 percent	0.2 percent
Metal recovery, in matte	95 percent	77 percent
Metal recovery per vessel, in tons per year	37,050	4,620
Number of vessels to meet 2040 low U.S. demand	11	3
Number of vessels to meet 2040 high U.S. demand	29	20
Number of vessels to meet 25 percent of 2040 low global demand	38	21
Number of vessels to meet 25 percent of 2040 high global demand	43	25

SOURCES: Nodule and metal recovery values are estimated from interviews with seabed mining representatives; metal concentration values are from Kirchain et al., 2020; the numbers of vessels are computed from values in Tables 1 and 2 and rounded up to the nearest integer.

Seabed mining would make the greatest contribution toward demand for cobalt; 3 to 20 vessels would be able to supply the entire projected U.S. annual demand in 2040. The projected U.S. annual demand for nickel would require 11 to 29 vessels. Globally, 21 to 43 vessels could supply 25 percent of the projected global annual demand for cobalt and nickel in 2040. For reference, representatives from two of the seabed mining companies with whom we met indicated that they are planning to operate three and eight vessels, respectively. If these values are typical, a relatively modest number of seabed mining operations could make a substantial contribution to the projected U.S. and global demand for nickel and cobalt.

Opportunity for Seabed Mining to Diversify Critical Mineral Supply Chains for the United States and Allied Nations

As with any mineral ore, polymetallic nodules must be processed and refined into compounds useful for manufacturing (e.g., alloys, mattes, sulfates, oxides, metals). In principle, mineral processing can occur anywhere, and extracted raw material is commonly shipped internationally for processing. In fact, much of China's dominance over critical mineral supply chains is built on importing and processing ore from around the globe (IEA, 2024b).

In the case of seabed mining in which collection occurs outside national jurisdictions, nodules necessarily must be shipped across national borders for processing. The ISA has limited authority over the fate of the nodules once they are collected,[2] and contractors are free to partner with whomever they choose for processing. Because the United States is not an ISA member, it cannot be a primary supplier of seabed minerals from the *Area* through the ISA process. Consequently, its opportunity for near-term involvement in seabed mining lies in the processing and refining stages of the supply chain.

Processing and refining minerals mined from the seabed, a topic which has received limited attention in the media and among researchers and decisionmakers, is a major component of mineral supply chains, often comprising more than half of the cost of producing final compounds (CRU Consulting, 2020). A successful seabed mining industry will depend on reliable access to substantial nodule processing and refining capacities. In this section, we analyze the technical, financial, and political considerations and uncertainties that affect decisions about nodule processing.

Perspectives from Industry

A general finding from our interviews with representatives from seabed mining companies is that most companies have not yet developed specific plans for processing polymetallic nodules. The company that is furthest along has engaged with a ferronickel producer that is currently studying the feasibility of processing nodules. Other companies noted that they are examining multiple options and have made no plans. The main reasons cited were that they are still engaged in resource exploration and the development of extraction technology and not yet ready to address processing. They are also weighing trade-offs associated with different technical approaches to processing and dealing with uncertainty about when the ISA will complete its mining regulations.

Despite the absence of fully developed plans for processing, there were a few points of consensus among seabed mining companies and other subject-matter experts. One is that companies plan to retain ownership of collected nodules throughout the processing and refining stages. Furthermore, most stated that they intend to take an active stake as partners or owners in processing and refining rather than rely on toll processing.[3] The reason that they cited for this intention has to do with the fact that seabed polymetallic nodules are a unique resource, and there is no proven processing technology that can recover all four saleable elements contained in them. This means that a significant portion of the financial and intellectual investment required for seabed mining must go toward designing and developing a processing method. The processing stage, thus, represents a substantial portion of the total value of the final compounds derived from the nodules.

Another common tactic that the industry appears to be pursuing is to initially toll process nodules with an established pyrometallurgical nickel processor and then transition to a dedicated processing and refining facility for the long term. Three companies noted this approach explicitly, and a subject-matter expert with whom we met suggested that all companies would likely choose this route.

This choice reflects a trade-off. The benefit is that a seabed mining company that lacks the capital and expertise needed to stand up its own processing capacity can use a toll processing arrangement to generate short-term revenue and experience that it can leverage to finance a dedicated nodule processing

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[2] Current draft regulations require that ISA contractors use only ports in ISA member states (ISA, undated-e), but this does not preclude subsequent transshipment of nodules to non-ISA member states.

[3] *Toll processing* is an agreement in which the supplier of the ore retains ownership of the processed product and pays for processing as a service.

facility in the longer term. The cost is that using existing pyrometallurgical facilities will produce a mixed metal alloy, which is an inferior intermediate product that will be worth less in the market. Specifically, most pyrometallurgical lines (e.g., nearly all those in Indonesia) are designed to produce ferronickel or nickel pig iron (NPI) for use in steelmaking. This product cannot be further refined to the higher-value compounds needed for lithium-ion battery production. And nodules, because they contain so many different metals, are less well suited for steelmaking than abundantly available laterite ores.[4]

Producing compounds for battery manufacturing requires an intermediate product called a *matte*, which can be produced only in a pyrometallurgical line that has been retrofitted with a sulfidation converter. According to a nickel processing expert with whom we met, existing smelters could technically be converted to produce matte, but smelter operators have little incentive to do so until they run out of ore. There might eventually be idle capacity in Indonesia as the refiners there run out of high-grade, cheap ores. But as of this writing, they are still building new NPI facilities. And even a converted pyrometallurgical line would not be designed to recover the cobalt, copper, or manganese in polymetallic nodules; hence, the yields for these elements would be lower than desired.

Thus, although toll processing could be an attractive tactic for a seabed mining company to generate initial revenue, the only option for getting the most value out of the nodules is to invest in dedicated, customized processing and refining operations. Companies, therefore, have an incentive to move to this model as quickly as possible.

Another point of clear consensus among seabed mining companies is that they do not want to work with Chinese firms for processing. The reasoning is multifaceted. First, as described previously, using existing pyrometallurgical lines, of which China owns several in Indonesia and China, is not an effective long-term option from a technical perspective. In addition, companies reported that, in exploring options for partnering, they found that the terms demanded by Chinese firms were unattractive. For example, Chinese firms will not agree to a toll processing arrangement; they will only consider partnerships or buying nodules outright. But even partnering with Chinese firms is unattractive because it requires ceding too much ownership, operational decisionmaking, and intellectual property. As one company representative put it, "China's reach is far—even just buying their equipment comes with the same requirements of an offtake agreement or partnership."

Another important motivation to avoid Chinese firms is the Foreign Entity of Concern exclusion in the Inflation Reduction Act (IRA). Products produced in partnership with a Chinese firm would not be eligible for the critical mineral and EV battery production tax credits in the IRA, which are an important aspect of seabed mining companies' financial planning.

A final reason cited is that partnering with Chinese firms conflicts with important parts of seabed mining companies' missions and networks. One of the central drivers for pursuing seabed mining in the first place is to diversify critical mineral supply chains *away* from Chinese control. Although such global geopolitical considerations do not necessarily affect business decisions, several company representatives nonetheless cited this as an important criterion in their decisionmaking. Company representatives also noted that they are raising money from Western sources, including governments, that support that mission, which deters them from working with China.

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[4] Appendix A provides an overview of processing and refining methods that are relevant to polymetallic nodules and a summary of global operations that use these methods.

Despite all the reasons to avoid Chinese firms, several company representatives and experts noted that one aspect of working with China—its low cost—remains tempting. Some warned that, although no one really wants to work with China, doing so remains a possible option if other avenues fail to materialize. And China has been actively reaching out to seabed mining companies seeking to partner. As one company representative noted to us in an earlier study, "I don't know of a single seabed mining contractor that *hasn't* been approached by the Chinese" (LaTourrette, Helmus, and Chindea, 2022).

Beyond seeking to process other contractors' nodules, China has been aggressively pursuing seabed mining itself, it has more exploration contracts and influence with the ISA than any other nation (ISA, undated-c; Kardon and Camacho, 2023), it explicitly includes seabed mining among its national strategic objectives (LaTourrette, Helmus, and Chindea, 2022), and it is pursuing an aggressive technology development and testing program (Lei, 2023; Tong, 2024). A key motivation for this pursuit is to reduce China's heavy reliance on foreign suppliers of raw material (Lei, 2023). Given China's demonstrated technical expertise in mineral processing, a seabed mining program will inevitably be accompanied by a sophisticated and, ultimately, low-cost nodule processing capacity.

Several companies and experts raised additional observations that could be helpful to understanding industry decisionmaking. One is the capital needed. Some companies confirmed that the IRA production tax credit for refined critical mineral compounds is an incentive to process nodules in the United States or allied countries. But they noted that seabed miners face a more immediate barrier of capital cost. The capital investment required to develop dedicated nodule processing and refining capacities is substantial, and companies noted that they either do not have access to or are reluctant to commit the capital needed.

The inability to raise or reluctance to commit investment resources stems, in part, from a perceived ambivalence from the U.S. government. Several company representatives commented that the United States has thus far taken a largely passive attitude toward a potential seabed mining industry. Several seabed mining companies and at least one processing firm have approached U.S. government agencies, including the Defense Production Act Office, the U.S. Department of Energy, and the Supply Chain Integrity and Freedom program, seeking partnership opportunities, grants, and policy support. Their general impression is that the U.S. government has yet organize its thinking about and planning for a potential U.S. role in a seabed mining industry. As one company representative put it, "Whenever we come to D.C., it's never clear who to talk to. If the United States can at least conditionally be favorable to seabed mining, we are willing to look into establishing processing operations there and diversifying supply chains."

Another issue is the extent to which transportation distance influences decisions about choosing a processing site. The CCZ lies in the eastern Pacific, and Mexico and the United States are the closest nations. When asked how important transportation costs are in decisionmaking, companies indicated that transportation is a relatively modest portion of the total cost and, hence, less important than such factors as securing financing and a capable partner. In the words of one company representative, "The nodules will go wherever is open for business; in that context, the U.S. could do some things."

Representatives from two companies raised the issue of the impact of the growing demand for LFP cathodes on future nickel and cobalt demand. One of the reasons that battery manufacturers are shifting from NMC to LFP batteries is because of cobalt's price volatility and lack of supply continuity. But, these representatives argued, seabed mining could alleviate those barriers, and battery manufacturers could focus on producing the best product for a given application. Increased supply of cobalt and nickel can also help lower prices to better compete with LPF cathodes.

Perspectives from Government

Concern about China's dominance over critical mineral supply chains has spurred several federal efforts to diversify supply and lessen dependence on Chinese-controlled sources. These efforts are led by different federal offices, and we met with as many agencies and program representatives as possible. In total, we met with representatives from nine offices.

A central finding from our inquiries is that U.S. government efforts pertaining to seabed mining are still in the early stages of organization and decisionmaking. Specifically, the U.S. government's attention is focused on broad questions related to the merit and feasibility of commercial seabed mining, and it has not yet begun considering any role in such an industry. Representatives noted that they were engaged in the ISA process or monitoring its progress, they had questions about the technical and economic viability of nodule extraction, and they were concerned about the potential environmental impacts of nodule extraction. One representative noted, "By and large, the U.S. government focus is on ensuring the administration's stance is represented in the ISA meetings."

Several respondents confirmed the seabed mining industry's view that having several critical mineral offices spread out across the government causes confusion among industry representatives regarding who to talk to about seabed mining. Representatives of two agencies noted that, because little attention is being paid to seabed mining and activities are spread among many agencies, government positions and activities are strongly driven by individual personalities and opinions.

When asked about visions, strategies, or policies related to capitalizing on nodules as a new source of critical minerals or processing nodules in the United States or allied countries, government representatives had little to offer. One representative noted plainly that "processing nodules is not a major part of the discussion yet." Several respondents conveyed the sentiment that seabed mining is not consciously or explicitly part of an existing critical mineral strategy because there is too much uncertainty about the future of the industry.[5]

We also met with a government representative of an allied nation who had a different view. He told us, "Right now, the debate is whether [seabed mining] should or shouldn't happen. I think it will happen, but looking at the United States and other partners, the governments seem to be sleepwalking." In referring to the potential benefit of taking a more proactive approach toward processing nodules in North America, he noted, "Time is important, too, because while we have a lead now, we won't necessarily have it forever, and there's nothing stopping [seabed mining companies] eventually relenting and setting up processing in China."

[5] As this report was being finalized in early April 2025, Reuters reported that the Trump administration is considering an executive order that would indicate that the U.S. intends to unilaterally pursue seabed mining in the *Area* via the 1980 Deep Seabed Hard Mineral Resources Act (Scheyder and Renshaw, 2025). In the same week, a seabed mining company announced that it had formally initiated the process of applying for an exploration license through this route ("The Metals Company to Apply for Deep Sea Exploration License Under U.S. Legislation," 2025).

Considerations for a Commercial Seabed Mining Industry

For seabed mining to help diversify critical mineral supply chains, it must transition from the exploration stage to a commercial industry. Beyond the promulgation of a regulatory framework, commercialization requires that seabed mining be a viable industry. Although the question of industry viability is beyond our scope, in this section, we use the Five Forces analytical framework (Porter, 1979) to present a preliminary examination of the prospects for seabed mining to meet sharply increasing future demand compared with new terrestrial mining.

To help discern the important factors that firms face in their endeavor to enter the mineral extraction sector and the extent to which seabed mining can exploit opportunities associated with those factors, we use the Five Forces strategic business framework established by Michael E. Porter in 1979 and updated several times since then (Porter, 2008). We take a qualitative approach to this industry analysis based on a review of relevant literature and our interview data. In the following sections, we analyze the mineral extraction industry using each of the five forces: (1) rivalry among existing competitors, (2) threat of new entrants, (3) threat of substitute products or services, (4) bargaining power of suppliers, and (5) bargaining power of buyers.

Rivalry Among Existing Competitors

The critical mineral extraction industry is capital-intensive and characterized by large multinational corporations and state-owned enterprises. For terrestrial mines to be profitable and competitive, firms must invest in large-capacity, specialized operations that typically require significant supporting infrastructure and long lead times. These conditions create entry and exit barriers for existing firms, which prolongs the time that less competitive firms remain in the industry, contributing to downward price pressure.

Although most firms act in accordance with market principles and prioritize profitability, China's state-owned enterprises often act in support of China's industrial policy goals and related incentives, which decrease the profitability of Western firms and create barriers to entry for new firms. These actions and activities distort market information and create issues (such as price volatility) that drive Western firms out of the market or force temporary closures. At the same time, Western countries are also enacting their own industrial policy to diversify supply chains away from China, similarly distorting incentives and market information.

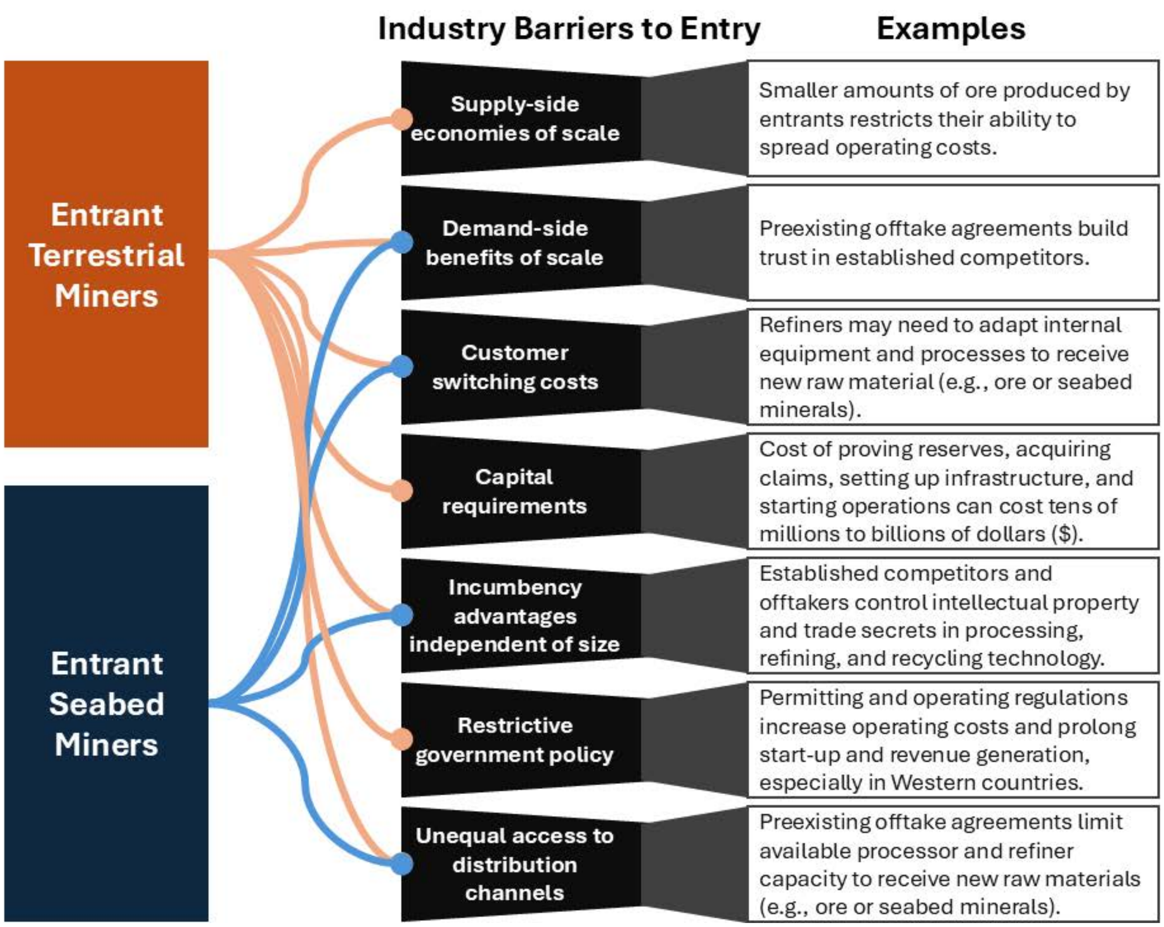
Overall, competition in the critical mineral industry is complicated by goals other than profitability, such as acquiring geopolitical leverage, using tools of economic statecraft and coercion, securing access to key defense industrial base inputs, and building supply chains resilient to disruption. Such goals might provide niches that favor the entrants that support them.

Threat of New Entrants

New entrants have the potential to increase supply, putting downward pressure on prices. A group of existing competitors within an industry necessarily generates barriers to new entrants. These barriers can be grouped into seven categories: (1) supply-side economies of scale, (2) demand-side benefits of scale, (3) customer switching costs, (4) capital requirements, (5) incumbency advantages independent of size, (6) restrictive government policy, and (7) unequal access to distribution channels (Porter, 2008).

Figure 2 provides a general overview of the barriers to entry for new firms by contrasting the barriers affecting terrestrial junior miners, which traditionally take the most risk in developing new resources, with those affecting seabed mining companies. Although both groups face barriers, seabed miners face fewer than their terrestrial mining competitors. For example, a supply-side economy of scale benefit enjoyed by established competitors is the ability to spread costs over a large quantity of product. Because of the higher total metal content of polymetallic nodules, seabed miners need to extract less material than terrestrial miners to produce an equivalent amount of product. A smaller quantity of ore for equivalent revenue theoretically allows seabed mining entrants to spread operating costs over smaller quantities of product and reach profitability more quickly.

Figure 2. Barriers to Entry in the Mineral Extraction Industry



Compared with terrestrial mining companies, seabed mining companies might incur fewer required fixed capital costs to begin producing an equivalent quantity of product. Terrestrial mining companies are, in some ways, like logistics companies; once a reserve is proven, infrastructure and transportation must be developed to transport equipment and labor to the site and move the product to market. This could require millions to billions of dollars in investment. Seabed mining companies must acquire ships with specialized equipment and secure access to existing ports, but, overall, the infrastructure and logistical support requirements for seabed mining are generally much lower than for terrestrial mining.

Finally, seabed and terrestrial mining operations face differing regulatory barriers to project approval and start-up. The time needed to open a mine is notoriously long in Western countries. In the United States, it takes an average of 29 years (Bonakdarpour, Hoffman, and Rajan, 2024). This is because of a combination of permitting requirements at the local, state, and federal levels, which entail environmental impact studies, local stakeholder pushback, and financing barriers. If the ISA or an individual nation establishes seabed mining regulations and begins to accept applications for mining, mining projects would be subject to regulations only at the national level (for mining within EEZs) or the international level (for mining in the *Area*), which might present fewer barriers to approval than those faced by terrestrial mining projects. On the other hand, the prospect of a seabed mining industry, as a whole, faces considerable opposition from nations and organizations concerned about the potential negative environmental impacts (see, for instance, Deep Sea Conservation Coalition, undated-a; Levin, Amon, and Lily, 2020; Filho et al., 2021; Ashford et al., 2024; Crane et al., 2024). This global opposition presents a significant near-term barrier to entry for seabed mining projects that terrestrial mining projects are less susceptible to.

Overall, contingent on the establishment of a regulatory framework and a social license to operate, seabed miners might face fewer barriers to entry than terrestrial junior miners, although large market forces, such as price volatility and poor public perception of extractive industries, are still overarching barriers for all new entrants to the market.

Threat of Substitute Products or Services

Substitute products and services have the potential to decrease demand for products and push prices downward (Porter, 2008). Given the rapid evolution of batteries and other relevant technologies, there is great uncertainty about the future demand for critical minerals. As noted previously, demand projections for nickel and cobalt already account for the widespread adoption of LFP battery chemistries. Substitution is often driven by the availability of raw materials, and new sources could make alternative battery cathode chemistries cost-competitive. For example, new supplies of manganese from seabed nodules could lower the cost of manganese and spur research and development to produce viable alternative cathode chemistries, such as lithium-manganese-phosphate or lithium-nickel-manganese-oxide (Wu, Maier, and Yu, 2020).

Bargaining Power of Suppliers

Suppliers of products or services to firms can increase the cost of fixed assets or operational costs. The shipbuilding sector, for example, is saturated and has also become concentrated over time within a few select countries (Frittelli, 2023). Shipbuilders serve a variety of industries, and the demand for specialized ships for seabed mining is likely to be relatively small, limiting the seabed mining industry's ability to negotiate prices. Producers of specialized seafloor extraction equipment will not enjoy a similar diversity of customers and will be more likely to work with seabed mining companies on pricing.

However, because producers of deep-sea extraction equipment are so entwined with the operations of seabed miners, they might see opportunities to enter the industry themselves as competitors.

Bargaining Power of Buyers

The consumers of products can decrease profitability by negotiating for lower prices from competing firms and demanding special requirements of their products (Porter, 2008). The processors and refiners signing offtake agreements with seabed miners will have sway over seabed mining companies' profitability. There are a limited number of processors and refiners in the world that could theoretically receive nodules, and, according to several of our interviewees, it will require adjustments to operating procedures and equipment to do so. This lowers the incentive for processors and refiners to switch from terrestrial ores to nodules or other seabed minerals. Without the guarantee of offtake, industry entrants find it difficult to raise capital—a recurring theme in our interviews. Hence, seabed miners are seeking offtakers that are struggling to acquire material and, hence, are in a weakened position. These include processors attached to a mine that has played out, processors affected by Indonesia's nickel ore export ban, and, according to one firm, battery recyclers that are suffering from the limited amount of black mass currently available on the market.

Broader Implications of Seabed Mining

In addition to the opportunity to diversify global supply chains of critical minerals, the potential emergence of a global seabed mining industry based in international waters brings with it significant geopolitical implications. Because mineral resources in the *Area* are deemed the "common heritage of humankind," benefits from their exploitation must be equitably shared with all member nations (ISA, undated-a). Associated with this stance is a concern that the emergence of a seabed mining industry could negatively affect terrestrial mining revenues in developing nations. UNCLOS, therefore, also provides that a portion of the collected royalties be allocated to an economic assistance fund to compensate affected nations (ISA, 2022b).

More generally, the emergence of a seabed mining industry could create tensions associated with bilateral and multilateral relationships among nations related to forging, complying with, and enforcing international regulations, as well as tensions associated with respecting nations' contract areas, the potential intelligence and military applications of seabed mining technology and programs, and more.

Implications for Terrestrial Mining in Developing Nations

Since the 1970s, when the prospects for seabed mining were first seriously explored, a key question contemplated by both the United Nations and industry has been how an influx of seabed mineral products might affect terrestrial producers, particularly those in developing countries whose economies are heavily reliant on mineral exports (United Nations Secretary-General, 1982; Tilton, 1983). Despite the promise of benefit-sharing schemes in line with the common heritage principle, many developing countries with substantial mining industries have remained staunchly skeptical of seabed mining. In a June 2022 statement on royalty regimes under consideration by the ISA, the United Nations' African Group warned that "if [seabed mining] is such a high cost, risky and inefficient industry that miners cannot afford to fairly compensate mankind, then it would be better if [seabed mining] in the *Area* did not proceed until such a time that adequate compensation is viable" (ISA, 2022d).

Although some studies have qualitatively explored the avenues through which developing countries might be affected by seabed mining,[6] to our knowledge, no recent study has sought to quantify the potential impact of seabed mining on developing countries' mining-related fiscal revenues.

Broadly, an influx of mineral resources from the ocean floor could affect government revenue through two primary mechanisms. Under the first mechanism, an influx of resources could put downward pressure on the price of the minerals contained in seabed nodules. For a terrestrial producer, a drop in price implies a decrease in royalties and export earnings as the value of the mineral commodity falls and miners constrict production to mitigate against revenue losses. A second, counteracting mechanism is a potential new source of revenue for developing countries, specifically ISA seabed mining royalties and the ISA economic assistance fund. Royalties are collected by the ISA from seabed mining contractors and apportioned to all nations per Article 140 of UNCLOS, which states that royalties are to be shared on an "equitable" basis with "particular consideration [to] the interests and needs of developing States" (UNCLOS, 1982, p. 71). Recognizing the potential impact of seabed mining on terrestrial mining incomes in particular, UNCLOS includes a mechanism to compensate developing nations for such losses. Specifically, Part 10 of Article 151 of UNCLOS provides for assistance to "developing countries which suffer serious adverse effects on their export earnings or economies resulting from a reduction in the price of an affected mineral or in the volume of exports of that mineral, to the extent that such reduction is caused by activities in the Area" (UNCLOS, 1982, p. 78). This assistance will be funded through royalty payments to the ISA (ISA, 2022b).

We developed a simple modeling framework to better understand the relative magnitude of the price decrease and ISA royalties and assistance. The goal of this exercise was to determine whether developing countries reliant on terrestrial mining have more to gain or lose from seabed mining and explore conditions under which gains might be amplified and losses mitigated. For simplicity, we examined a single country and nodule mineral as an illustrative case study: the DRC and cobalt. We chose this combination because the DRC is well known for having the world's largest and highest purity cobalt resources and for producing most of the world's cobalt (IEA, 2024b).

Our analysis is limited in scope. We focus specifically on the impact of seabed mining on government revenue and do not explore the broader economic impacts of having a more or less robust land-based mining sector on such factors as employment opportunities or the demand for local inputs and services. Our analysis also relies on several assumptions, perhaps the most significant being that seabed mining operations are able to surmount practical and regulatory hurdles and start production immediately and that the quantity of nodules supplied by seabed miners is independent of existing and future land-based mining production. Despite these limitations, we believe that this exercise is valuable in its potential to illustrate the dynamics driving mining-related revenue gains and losses for developing countries.

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[6] Most notable among these is a study by the ISA that examined the impact of seabed mining in the *Area* on land-based producers of the same metals found in polymetallic nodules (ISA, 2022a).

The box on the next page lays out our simple framework for comparing mining revenues with and without seabed mining. In the scenario without seabed mining, total revenues, TR_{DRC}, consist of the royalties collected by the DRC from domestic terrestrial mining, which can be expressed in terms of the domestic royalty rate, R_{DRC}, the current cobalt price, P, and the quantity of cobalt produced in the DRC at that price, $Q_{DRC}(P)$. In the scenario with seabed mining, total revenues consist of royalties from domestic terrestrial mining, where the cobalt price reflects the effect of seabed mining, P_{SBM} (first term); the DRC's share, X_{DRC}, of seabed mining royalties collected by the ISA at rate R_{ISA} and distributed to all member nations (second term); and the DRC's share, Y_{DRC}, of the ISA economic assistance fund (third term). In the second and third terms, E_{ISA} is the fraction of seabed mining royalties collected by the ISA that is diverted to the economic assistance fund prior to distributing royalties to member nations.

Framework for Comparing Mining Revenues With and Without Seabed Mining

Scenario without seabed mining:

$$TR_{DRC} = Q_{DRC}(P) \times P \times R_{DRC}.$$

Scenario with seabed mining:

$$TR_{DRC} = Q_{DRC}(P_{SBM}) \times P_{SBM} \times R_{DRC} + Q_{SBM}(P_{SBM}) \times P_{SBM} \times R_{ISA} \times (1 - E_{ISA}) \times X_{DRC} + Q_{SBM}(P_{SBM}) \times P_{SBM} \times R_{ISA} \times E_{ISA} \times Y_{DRC}.$$

We drew on several sources to obtain estimates for each of these parameters. The quantity of cobalt supplied by the DRC at current prices uses U.S. Geological Survey (USGS) data for 2023, the latest year for which full-year production data are available (Ewing, 2024). The price of cobalt in the scenario with seabed mining is based on recent examples of cobalt price fluctuations that were associated with a significant increase or decrease in the supply of cobalt (see Table B.2 in Appendix B). We relied on estimates of the metal content of nodules, metal recovery rates, and collector and vessel capacity provided by Kirchain et al. (2019), which were corroborated by our own interviews, to obtain a range of values for seabed cobalt production. We used cobalt price *elasticities*—a measure of how supply and demand change with a given change in price—from academic studies to estimate how much cobalt DRC producers might supply at prices that account for seabed production.[7] We relied on analyses published by the Extractive Industries Transparency Initiative (EITI) and the IEA to obtain information on the DRC's mining royalty rates (IEA, 2022a; IEA, 2022b; EITI, 2023), and we referenced ISA working papers on potential taxation regimes and benefit-sharing schemes for our estimate of royalty rates for seabed mining and the proportion of royalties that could reasonably be allocated to the DRC (ISA, 2022b; ISA, 2022c).

As we were interested in comparing the relative magnitude of (1) the losses in mining revenue from DRC cobalt production resulting from seabed mining and (2) the gains in revenue from ISA benefit sharing, we varied and tested different combinations of the parameters associated with these two dimensions. Specifically, we looked at cases in which the impact on land-based mining was either *low* (meaning only one seabed mining vessel was in operation) or *high* (ten vessels were in operation).

[7] Specifically, we used elasticities estimated by Cavallero (2021) and Shojaeddini, Alonso, and Nassar (2024).

We also looked at cases in which the ISA royalty-sharing regime was either low or high in terms of favoring the DRC, considering such factors as the ISA royalty rate, the proportion of royalties allocated to the DRC, the size of the ISA economic assistance fund, and the proportion of the fund allocated to the DRC.[8]

The resulting two-by-two matrix of these dimensions and the four illustrative cases we examined are shown in Figure 3.

Figure 3. Expectations for the Impact of Seabed Mining on Terrestrial Mining Revenue

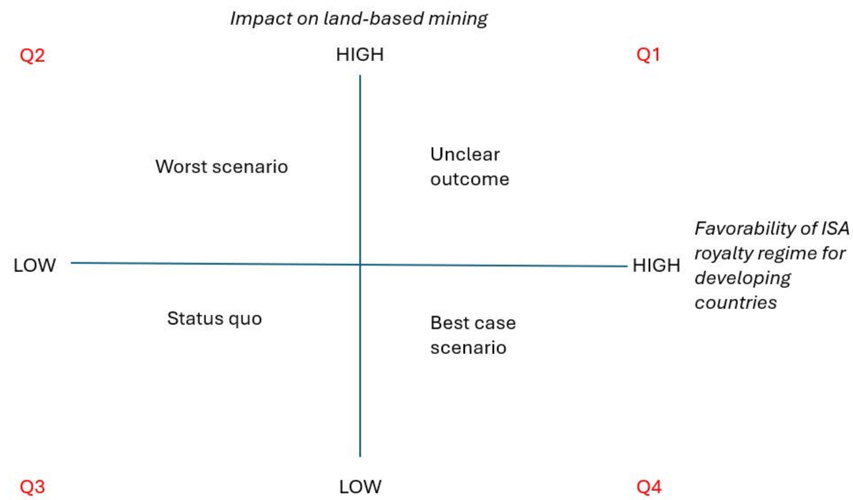
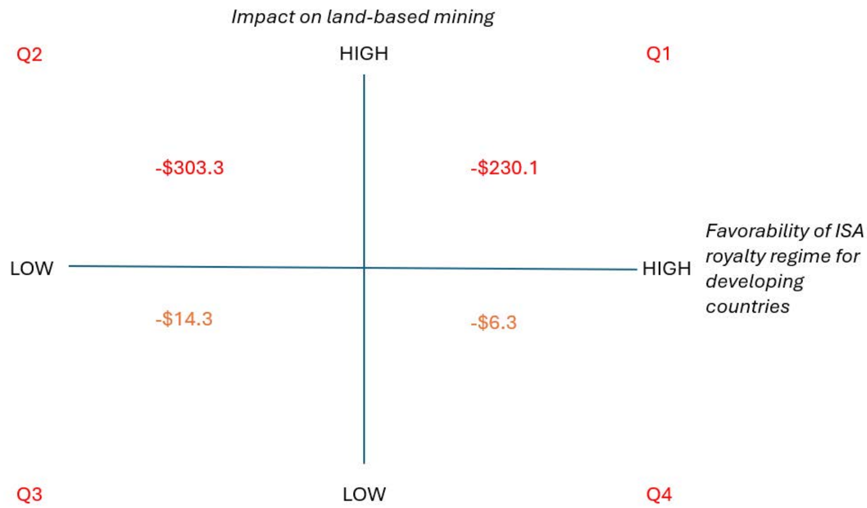


Figure 4 shows the results of our analysis. Across all four cases, the DRC experienced a loss in revenue following the introduction of seabed mining. In the cases with just one seabed mining vessel operating (Q3 and Q4), the corresponding decrease in cobalt price is estimated to be about 2 percent. However, even this small price drop translates to a decrease in terrestrial mining royalties that is greater than the gains in revenue from ISA benefit sharing. Losses associated with the ten-vessel scenarios (Q1 and Q2) are substantially greater, and the extent to which the ISA's royalty-sharing regime favors the DRC has a lesser impact on revenue. In other words, even the marginal change in the price of cobalt resulting from the introduction of seabed mining from just one vessel cannot sufficiently be counteracted by new revenue from the ISA's royalty-sharing program.

[8] The proportion of ISA revenue that is to be set aside for the ISA economic assistance fund has yet to be determined, but comparable programs in terrestrial mining countries suggest that the rate could be somewhere between 10 percent and 30 percent of royalties (see Table B.3 in Appendix B).

Figure 4. Democratic Republic of the Congo Revenue Change with Seabed Mining, in Millions of Dollars Per Year



NOTE: We used the average monthly U.S. spot price of cobalt from January 2024 to September 2024 ($27,011 per metric ton) as our estimate of the current price of cobalt—i.e., the price of cobalt without seabed mining (International Monetary Fund, 2025).

One important factor driving these results is that ISA royalty revenues will be shared with all 170 member states, weighted by population, so an individual country (such as the DRC) receives a small share of total royalties (ISA, 2022b). This arrangement contrasts with terrestrial mining royalties that are fully retained by the DRC. Even under an extremely generous system in which 30 percent of ISA royalties are allocated to the economic assistance fund, and the DRC receives one-third of this funding (Q4 in Figure 4), the seabed mining scenarios still result in lower revenue for the DRC government compared with the scenario without seabed mining.

If we consider nonroyalty revenue received by governments from terrestrial mining companies, the negative impact of seabed mining on revenue is even greater. For the DRC, EITI reporting suggests that royalties represent less than one-fifth of total mining revenue; other major revenue flows are corporate income taxes and taxes on mining-related imports (EITI, 2023). Additionally, ISA royalties could be subject to various deductions—such as ISA administrative costs or repayments to member states for their previous contributions to the ISA—which would reduce the amount of money available for redistribution to member nations (Amadi and Mosnier, 2024a; Amadi and Mosnier, 2024b).

In short, to be unaffected by seabed mining—even under the generous ISA royalty-sharing and economic assistance funding scenario—the price of cobalt would have to remain within 1 to 1.5 percent of current cobalt prices. Our analysis suggests that production from even a single seabed mining operation would decrease prices more than this. Alternatively, if we expect more seabed miners to enter the market (i.e., ten operators in the high scenarios), ISA financial assistance to the DRC would have to be increased substantially to leave the government's revenue on par with its revenue in the scenario without seabed mining. Specifically, the majority of ISA royalties (more than 92 percent) would have to be reallocated to the DRC.

Opposition to seabed mining among many developing countries suggests that these countries are well aware of the potential losses that they face (ISA, 2022d; Deep Sea Conservation Coalition, undated-b). Although such outcomes do not necessarily preclude the commencement of commercial seabed mining, they do present barriers to the design of a royalty scheme, which is one of the key issues being debated in the finalization of the ISA's seabed mining regulations. Countries with significant revenues from terrestrial mining have expressed concern about the potential of seabed mining to affect revenues and are working collectively with the ISA to ensure that their interests are being considered (ISA, 2022d).

Global Geopolitical Considerations

Beyond its implications for diversifying critical mineral supply chains, a global seabed mining industry would entail commercial activity, regulation, and oversight in international waters governed by an international treaty. Mining within EEZs would be governed by individual countries' policies and norms, adding additional opportunities, constraints, and variability to the sector. For these reasons, the prospect of commercial seabed mining raises several global diplomatic, economic, and security concerns. To elucidate the role of seabed mining in furthering U.S. strategic interests and the potential geopolitical impacts from seabed mining on international relations, we developed various scenario prompts and presented them at a workshop to help participants imagine a future in which seabed mining operations are underway. Participants analyzed the potential impacts of seabed mining operations on stakeholders, U.S. strategic interests, and across the diplomatic, informational, military, and economic (DIME) framework for national instruments of power (Joint Doctrine Note 1-18, 2018). A description of the workshop methods and participants is available in Appendix C.

Seabed Mining and U.S. Strategic Interests

The most common alignment of critical mineral supply chain issues with U.S. strategic interests is in relation to techno-economic competition between the United States and China (Villalobos et al., 2022; Villalobos and Bazilian, 2023). The two nations have employed tools of economic statecraft and technological controls at an increasing rate. This competition has also affected the partners and allies of the two countries and has implications for related bilateral and multilateral cooperation (Kang et al., 2024), including cooperation on defense and security, economic security, economic development, sovereignty and EEZ enforcement, oceanic science, environmental conservation, and supply chain diversification, resiliency, and transparency.

In pursuing the diversification of critical mineral supply chains, participants from the workshop noted the opportunity that seabed mining brings to drive investment into the Indo-Pacific region in support of economic development. In particular, seabed mining could be a vehicle for economic growth for small island nations (e.g., Cook Islands, Nauru) and U.S. territories (e.g., American Samoa). It was also seen by participants as useful in pursuit of the five objectives of the 2022 Indo-Pacific Strategy.[9] Cooperation on diversifying critical mineral supply chains allows the United States to modernize its

[9] The five objectives are to advance a free and open Indo-Pacific, build connections within and beyond the region, drive regional prosperity, bolster Indo-Pacific security, and build regional resilience to transnational threats (White House, 2022).

alliances and strengthen partnerships, such as the Mineral Security Partnership and Mineral Security Partnership Forum and the ongoing trilateral talks between the United States, the Republic of Korea, and Japan (White House, 2023b; White House, 2024).

Deepening economic ties to the region via seabed mining was also noted by participants as a potential pathway to security or military cooperation. In some cases, economic security and territorial sovereignty could be intertwined. For example, the China-Vietnam oil rig crisis of 2014 resulted in a minor conflict between the nations about oil resources that resided in overlapping maritime territorial claims (Green et al., 2017). Both nations saw the development of these resources as key to their economic security and, therefore, found it necessary to protect their claim to the resource. Additionally, in a seabed mining incident, a Chinese vessel entered a seabed mining contract area in Papua New Guinea's EEZ and sampled the seabed without first obtaining permission; the action resulted in the Australian military escorting the ship out of the EEZ (LaTourrette, Helmus, and Chindea, 2022). Participants noted that countries supporting seabed mining operations will require more maritime domain awareness, which could provide opportunities for U.S. Coast Guard cooperation.

More broadly, building diversified supply chains for critical minerals using seabed mining was seen by participants as a way to mitigate the threats posed by climate change and an opportunity for oceanic science cooperation. State revenues from mining were also seen as potentially useful for the development of resilient infrastructure for climate adaptation.

Impacts of Seabed Mining Across Diplomatic, Informational, Military, and Economic Instruments of Power

We also asked workshop participants to examine seabed mining in the context of the DIME framework for understanding geopolitical power. Participants evaluated four aspects of seabed mining impacts across the framework: operations, technology, and infrastructure; governance, legal, and regulatory; industry, market, and supply chains; and social and environmental. Several themes emerged from the workshop discussions, which are summarized in Appendix D and discussed in the following sections.

Diplomacy

Participants noted that seabed mining operations might create cross-boundary impacts in the *Area* or in EEZs, requiring bilateral or multilateral resolutions to manage relations. These impacts could include claim encroachment, environmental concerns, impacts to other maritime industries (e.g., fisheries and tourism), and labor violations.

Clear, strict regulatory frameworks will play a crucial role in the operations of the seabed mining industry. Many topics need to be resolved, most notably the enforcement of ISA regulations, including potential illegal, unreported, and unregulated (IUU) seabed mining that leads to international disputes. These regulatory challenges demand diplomatic engagement to ensure responsible and sustainable exploitation of seabed resources. However, although regulations are being formulated by the ISA, the United States (because it is not a party to UNCLOS) is limited in its ability to influence these international laws and regulations.

If seabed mining were to commence in the absence of ISA regulations—for example, in a country's EEZ or in the *Area* via the Paragraph 15 clause of UNCLOS[10]—bilateral or multilateral agreements would become even more necessary. If mining in the *Area* does not commence, EEZ operations could be the only option left for the industry and countries would need to arrange their own regulatory institutions.

The competition and supply chain dimensions related to critical minerals further complicate the diplomatic landscape. New supply from seabed mining could reduce vulnerability to economic coercion, but seabed mining companies might require subsidies or other government assistance to survive market volatility, or they could face trade barriers from anti-seabed mining countries. China's efforts to dominate the seabed mining industry (by having the most ISA contracts, strongly influencing the ISA proceedings, and pursuing aggressive technology development) might require a strategic response from other nations. Otherwise, the opportunity presented by seabed mining to diversify critical mineral supply chains might be lost as China attempts to dominate yet another dimension of critical mineral supply.

Information

Seabed mining operations warrant enhanced maritime domain awareness, both on the surface and subsurface. In the digital realm, there is a challenge in countering misinformation and disinformation about seabed mining, and doing so might require resources that can provide accurate information or refute false claims.

The potential for inadvertent or clandestine operations and data collection under the guise of seabed mining further accentuates the importance of developing robust mechanisms for information gathering. Such efforts are crucial in identifying IUU mining activities or environmental damage, interactions with undersea telecommunications cables and other seabed infrastructure, and potential threats to security through dual-use tools for data collection and sabotage. In this context, updating information-sharing agreements among the Five Eyes intelligence alliance members could play a role in assisting efforts to monitor seabed mining in the Pacific.[11]

Among participants, there was substantial uncertainty about the potential negative environmental impacts of seabed mining at scale. As the seabed mining sector evolves, the development of methodologies for conducting comprehensive environmental impact assessments will be essential. However, the type and amount of data needed to determine such impacts are still uncertain (González Ortiz et al., 2023).

[10] In Section 1, Paragraph 15 of the Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982 (with annex) (1994), there is a clause that allows an ISA member to announce its intent to submit a mining application before the ISA mining regulations are completed. The clause states that, if the regulations are still not in place two years after the announcement, the ISA must "consider and provisionally approve" any application based on existing draft regulations and other considerations. Nauru initiated the two-year notice in 2021, and now any ISA member may submit an application.

[11] The Five Eyes countries are Australia, Canada, New Zealand, the United Kingdom, and the United States.

Military

Commencement of seabed mining operations could present an array of challenges and considerations for national and international security, including territorial disputes and threats to maritime operations.

Participants highlighted that there is uncertainty about who would be responsible for regulatory enforcement should the ISA's process fail to manifest its desired results. Claims to ISA contract areas will need to be enforced, and, drawing parallels with such issues as IUU fishing, it is conceivable that nation-states could use their militaries to safeguard seabed mining activities. The prospect of mineral piracy, particularly in unstable regions where, in the extreme case, the concentration of the global supply of minerals in just a few ships could render these supply lines more vulnerable to disruption, either intentionally or unintentionally. These prospects highlight the need for a maritime security posture.

Increased shipping activity from seabed mining, coupled with existing sea-lane control challenges in such regions as the Pacific Islands and in the EEZs of the Association of Southeast Asian Nations (ASEAN) member-states, highlights the potential for seabed mining operations to exacerbate or give rise to new maritime security concerns. Moreover, the enforcement of EEZs might necessitate coordinated international responses. It is also conceivable that the protection and enforcement of seabed mining rights might inadvertently cause environmental damage.

Additionally, the application of dual-use technology in the context of seabed mining raises concerns about the potential for monitoring or interfering with submarine vessel and communications operations. For example, one participant raised the question of whether increased noise from seabed mining could interfere with passive detection mechanisms, making it more challenging to detect adversarial movements.

Economic

The possibility of a seabed mining industry presents a mix of industry, market, trade, and environmental considerations. A recurring question for workshop participants was whether seabed mining is an economically viable undertaking. By their own admission, seabed mining companies struggle to attract capital, citing uncertainty associated with a new industry, volatile metals commodity prices, opposition based on potential environmental impacts, and uncertainty about the timeline for ISA regulations. Interviewees claimed that the cost structure of seabed mining operations is straightforward and expressed great confidence and enthusiasm for business prospects, but profitability remains to be seen in practice. As an entirely new industry using new technologies and methods, operational realities could complicate matters. For instance, one workshop participant noted that the reliability of undersea remote-operated vehicles, which are crucial to some seabed mining operations, poses challenges, potentially inflating operational costs for some firms.

An ongoing economic question for potential U.S. nodule processing operations is whether raw material sourced from international waters qualifies for the battery components and critical mineral tax credits that were established or amended by the IRA (Pub. L. 117-169, 2022, Sections 13401 and 13502). The recent final ruling on Section 45X of the U.S. tax code clarified that the cost of extracted raw materials is eligible for the critical mineral credit and this eligibility holds whether the material is mined or purchased and regardless of whether the material is domestically or foreign-sourced

(Internal Revenue Service, 2024). This ruling seems to imply that the cost of nodules procured from the *Area* would qualify toward IRA tax credits.

Participants also noted that the dispersal of plumes and sediment from seabed mining operations could conceivably disrupt adjacent oceanic industries, such as fishing and tourism, posing risks to established economic sectors and local livelihoods, especially in island nations. As noted earlier in this report, price pressure from seabed mining production could decrease revenues in developing countries with substantial terrestrial mining sectors. Secondary or tertiary economic impacts in these countries could include the loss of artisanal and small-scale mining jobs and uncertain effects on civil conflicts and their associated humanitarian suffering.[12]

Operations in EEZs will involve a smaller set of stakeholders and might face fewer barriers to obtain approval. These operations also would not be subject to benefit-sharing schemes in line with the common heritage principle, which makes them attractive for industry. However, few nations have attractive deposits of seabed minerals in their EEZs. Nonetheless, several nations—including, most notably, the Cook Islands and Norway—are pursuing seabed mining industries in their EEZs. The economic implications of operating in the *Area* versus EEZs are unclear but could affect the metals produced, production volumes, and environmental costs.

Geopolitical Priorities for Policymakers

To help U.S. policymakers prioritize potential issues of concern should a global seabed mining industry emerge, participants were asked to select which policy impacts and unresolved policy questions should be prioritized according to their actionability.[13] The top issues selected by participants were as follows:

1. bilateral and multilateral relationships associated with implementing and enforcing rules and regulations for seabed mining operations in international waters absent international mechanisms
2. uncertainties and risks associated with environmental impacts (e.g., seabed ecology, ocean life), safety (e.g., of workers), and marine industries (e.g., fisheries, tourism)
3. lack of clarity regarding the enforcement of international regulations and penalties for violation outside ISA jurisdiction
4. the potential role of military force to protect seabed mining activities (e.g., illegal mining, violation of international agreements, EEZ expansion)
5. challenges with incentivizing nodule processing in the United States or at least outside China
6. the potential of seabed mining to exacerbate sea-lane control issues
7. uncertainty about seabed mining's commercial viability
8. how perceptions of social-environmental impacts will influence demand for critical minerals produced from seabed mining
9. shifting goals and priorities for supply chain resilience as seabed mining changes the availability and accessibility of critical minerals.

[12] Arguments can be made for why conflict and humanitarian impacts could be either net positive or net negative under different circumstances.

[13] See Appendix D for a more detailed breakdown of the policy questions and impacts discussed during the workshop.

Summary and Recommendations

Our analysis revealed several insights related to the potential, opportunity, and appetite for seabed mining to diversify critical mineral supply chains and other insights related to the viability of commercial seabed mining and some broader implications of a global seabed mining industry. We conclude with a summary of these insights and recommendations for the U.S. government.

Implications of Seabed Mining for Critical Mineral Supply Chains

Global supplies of a wide array of critical minerals, including nickel and cobalt, are heavily dominated by Chinese-owned and -operated firms. China leverages this dominance by repeatedly imposing export restrictions, manipulating pricing, and limiting market access. Numerous recent examples of these actions demonstrate the risk of remaining reliant on Chinese-dominated supply chains for critical minerals that are essential for energy, defense, space, electronics, and other sectors.

If a seabed mining industry emerges, it would introduce a new source of supply for nickel, cobalt, copper, and manganese, all of which are key elements for lithium-ion batteries and other energy transition and defense technologies. Production rate estimates from seabed mining companies suggest that the amount of nickel and cobalt supplied by seabed mining could exceed the entire projected U.S. annual demand in 2040.

Because the United States is not an ISA member, it cannot directly sponsor any seabed mining contracts in the *Area* through the ISA process. U.S. companies could, nonetheless, play a role in the industry as processors and refiners of seabed mineral resources. Several seabed mining companies indicated that they are considering or even targeting the United States for processing seabed polymetallic nodules. Proximity to the CCZ and the availability of low-cost and low-emission electricity, deep-water ports, metallurgical expertise, financial incentives (such as the IRA production tax credits and other grant and loan programs), as well as a desire among investors to help diversify supply chains away from China, were all cited by industry representatives as attractions to processing nodules in the United States.

Although industry is eager to pursue nodule processing in the United States, it is seeking signs of support from the U.S. government, which representatives claim is important for attracting the capital needed to proceed. The U.S. government, on the other hand, is taking a cautious approach and has thus far given little consideration to attracting any processing business. At the same time, mounting external forces (such as the accelerating imposition of Chinese export controls, the industry's requests for action, and the ISA nearing completion of its mining regulations) are creating pressure for a response.

Industry representatives and one foreign government representative expressed concern that, if the United States and allied governments do not act more decisively, the industry might be tempted by the low costs and well-established infrastructure in Indonesia and China and opt to send nodules there for processing.

Recommendations

- U.S. government: Establish an executive branch interagency working group to develop a unified vision for what the United States' role in a seabed mining and nodule processing industry would be and work with allies to align such a vision so that all nations are working toward common goals. The U.S. position on critical mineral supply chains is clear, yet the U.S. position on seabed mining is underdeveloped. This creates uncertainty for the industry and its investors about whether nodule mining and processing will be embraced as an element of broader critical mineral policy goals. The working group should include the White House Office of Science and Technology Policy, U.S. Department of State, National Security Council, Defense Production Act Office, National Oceanic and Atmospheric Administration (NOAA), USGS, and the U.S. Department of Energy.
  - Support the working group, as needed, with research on the environmental impacts and commercial viability of seabed mining conducted by NOAA, USGS, the National Science Foundation, and the U.S. Department of Commerce's Office of Critical Minerals and Metals.
  - Determine whether the unified vision is consistent with and adequately supported by existing programs, policies, and partnerships promoting critical mineral development or whether additional policy actions specifically targeting seabed mining are needed.
- U.S. Department of the Treasury: Clarify whether the cost of purchasing polymetallic nodules extracted from the *Area* is eligible for the battery materials and critical mineral tax credits outlined in the IRA.
- U.S. Bureau of Oceans and Energy Management, NOAA, and USGS: Accelerate efforts to map seabed mineral resources in U.S. and U.S.-territory EEZs and determine whether seabed mining in these areas is a feasible alternative or addition to mining in the *Area*.

Broader Implications of a Global Seabed Mining Industry

Although there is uncertainty about whether a commercial seabed mining industry will be established and when it might arrive, rising demand for critical minerals and increasing economic tensions between the United States and China are likely to continue to incentivize the exploration and development of new critical mineral supplies. This could have a myriad of ramifications on international relations and geopolitics.

Opponents of seabed mining stress its potential to displace terrestrial mining, negatively affecting developing countries whose fiscal revenues are heavily reliant on mineral extraction. In our analysis of the impact of seabed mining on DRC government revenue, we found that government revenue from terrestrial mining was always higher in the scenario without seabed mining compared with any scenario that included seabed mining.

At the same time, China has been actively seeking to shore up support among developing countries for its preferred direction for the ISA's future regulatory system. China is the ISA's primary source of funding and regularly hosts ISA technical experts from developing countries at its deep seaport in Qingdao (Kardon and Camacho, 2023). Meanwhile, the U.S. government has not taken any steps to engage developing countries on matters related to seabed mining.

Additionally, the new supply of critical minerals from seabed mining will affect policy areas across the DIME framework. The ISA's role in managing and regulating mineral operations in international waters is inherently a matter of diplomacy. With the United States absent from the deliberation process because of its lack of membership in the ISA, its ability to influence a potential new supply chain of strategic interest is limited. The U.S. government's lack of focus on the topic also limits the resources available to shape the environment. Should the United States wish to take a firm stance on whether it supports seabed mining, it will need to work with allied and partner signatories to UNCLOS to help shape regulations, increase or decrease the speed of regulations, or incentivize markets and industry.

If operations commence, new territorial disputes could arise in ISA contract areas and EEZs, maritime domain awareness might be affected, and the concentration of large portions of the global supply of strategically relevant resources in a small number of ships might warrant an increased maritime security posture. The economic ramifications are difficult to predict but could include impacts to global commodity prices and terrestrial mining operations (including domestic efforts), environmental damage, impacts on such oceanic industries as fishing and tourism, the growth of Pacific Island nation economies, and a rebalancing of China's outsized influence in strategically relevant markets. Within this context, the information space is likely primed for information operations and the spread of misinformation. More scientific research will be needed to clarify the potential environmental impacts of seabed mining operations and combat misinformation. Maritime domain intelligence collection in strategically relevant areas could also be affected by industry operations.

Recommendations

- U.S. government: Via the working group proposed previously, consider the impacts to developing countries and how developing countries could be integrated into the industry in such a way that creates economic opportunities beyond ISA royalty transfers—for example, by setting up nodule processing and refining capacities in affected terrestrial mining countries, such as the DRC. Such steps could help to mitigate against revenue losses while supporting U.S. economic and security objectives and building credible soft power.[14]
- U.S. Department of State: Working through the ISA, the Minerals Security Partnership, and other channels, should prepare for the start of seabed mining operations with or without U.S. participation by initiating discussions with allies and partners on strategic priorities. The discussions should cover the type of information and quality of scientific data needed to make strategic decisions, the resources needed to gather and share data, the barriers to cooperation, and the pathways that might exist to get past those barriers.

[14] Value addition is currently one of the pillars of the United States' investment strategy in critical mineral projects in developing countries. In a 2022 memorandum of understanding signed between the United States, the DRC, and Zambia, for example, the United States pledged to support the two countries in developing a supply chain for EV batteries "from mine to assembly line" (U.S. Department of State, 2024).

- U.S. Department of State and intelligence community: Monitor seabed mining activity and policy, as well as the influence that foreign entities of concern have on the ISA, and share this information with allies and partners.
- U.S. Department of State: Lead efforts on behalf of the administration to continue to communicate to Congress the limitations of not ratifying UNCLOS and not being a member of the ISA.
- Congress and the executive branch: Enlist federally funded research and development centers, academia, and the private sector to conduct studies to elucidate the potential impacts of seabed mining operations on domestic and international efforts to increase mining capacity outside China, on operations in strategically relevant areas, and on other oceanic industries, as well as ways to counter misinformation and disinformation surrounding the industry.

Appendix A

Processing and Refining Options for Polymetallic Nodules

The absence of extant deep-sea mining operations has precluded the development of processing and refining infrastructure that specifically caters to polymetallic nodules. However, these nodules are often compared geologically with terrestrial nickel laterite ores because of their similar nickel content and the presence of other metals (Su et al., 2022). Laterite ore can be processed and converted to nickel using three types of processes:

- **Pyrometallurgical.** A process in which the ore undergoes heat treatment in a kiln and furnace. Common technologies include rotary kiln electric furnaces and electric arc furnaces. This process is energy-intensive but can be used to produce lower-purity products, such as ferronickel for stainless steel production (Trytten, 2024).
- **Hydrometallurgical.** A process that involves leaching with chemicals, such as sulfuric acid or ammonia. The most common process uses high-pressure acid leaching (HPAL). HPAL produces high-purity Class I nickel (i.e., greater than 99-percent pure nickel) that can be used in battery manufacturing, but the high capital costs and negative environmental impacts have thus far precluded its widespread use for lower-grade ores, such as laterites (Ribeiro, Holman, and Tang, 2021).
- **Caron process.** A process that involves both heat treatment and leaching. In the first step, the ore is dried and roasted under reducing conditions. The metals are then extracted using a series of ammoniacal leaching and calcining steps. The Caron process suffers from high energy costs, the need for chemical reagents, and relatively low metal recovery (Djouani, 2022; Pandey et al., 2023).

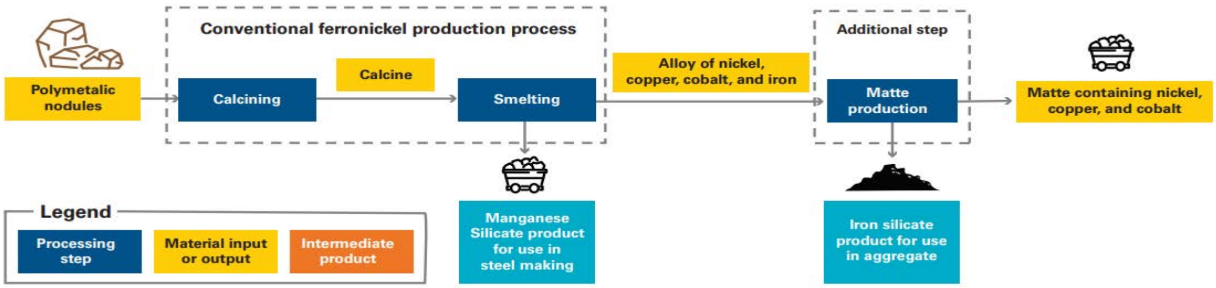
Although existing nickel processing infrastructure is designed to cater to terrestrially mined nickel ores, some prospective miners and research institutions have released theoretical process flowsheets for the processing and refining of nodules. One method, described by Jabbar et al. (2022) as being the closest to commercialization, consists of a two-stage process with both pyrometallurgical and hydrometallurgical steps that borrows heavily from existing techniques used to obtain battery-grade materials from terrestrially mined laterite ore. Some metal processors and recyclers also use methods that are capable of handling different types of feedstock, and these processes could, theoretically, be adapted to process nodules (Altilium, undated).

In the rest of this appendix, we provide a brief overview of the two-stage process described by Jabbar et al. (2022) and discuss the existing global distribution of nickel processing and refining infrastructure.

Processing

Figure A.1 displays the steps in a hypothetical pyrometallurgical nodule processing line.

Figure A.1. Flowsheet for the Hypothetical Processing of Nodules



SOURCE: This figure from Rifat Jabbar et al., *Polymetallic Nodules and the Critical Minerals Supply Chain: A North American Approach*, 2022, p. 6, is used with permission by the Wilson Center.

Nodules are heated in a series of kilns and furnaces, producing a suite of intermediate products, including manganese silicate, iron silicate, and a nickel-copper-cobalt matte that can be refined further to obtain battery-grade materials. The process consists of three steps:

1. **Calcining.** The nodules are heated in a kiln and reduced with a carbon source, such as coke or coal, to remove oxygen. The reduced material is called calcine.
2. **Smelting.** The calcine is heated further in an electric furnace. At this stage, the manganese content can be separated in the form of manganese silicate. The remaining material is a molten mixture of nickel, cobalt, iron, and copper.
3. **Matte production.** The molten mixture is fed to a converter and reacted with sulfur. The iron in the mixture is converted to iron silicate and can be separated. The remaining mixture containing nickel, cobalt, and copper is converted into a sulfide form called matte.

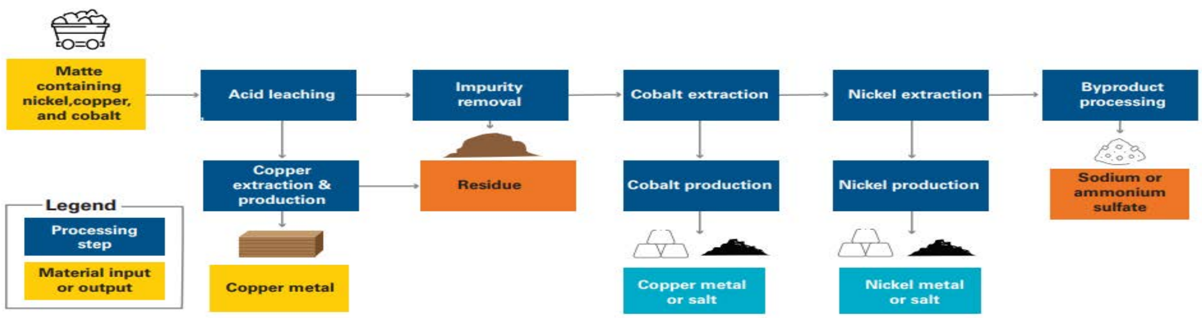
Refining

Figure A.2 outlines the refining stage, during which the matte is reacted with various reagents to obtain copper, nickel, and cobalt compounds used as inputs to battery manufacturing.
There are three major steps:

1. **Leaching.** The matte is introduced to an acidic medium, such as sulfuric acid. The nickel and cobalt content dissolves in the acid while the copper does not. Leaching can be carried out at different temperatures and pressures and with different chemicals; a process flowsheet from one prospective miner makes reference to atmospheric leaching with sulfuric acid.
2. **Copper extraction.** Because copper does not dissolve in the acidic medium, it can be separated by filtration. The filtered copper is further processed to remove such impurities as iron, and the final copper product is typically obtained in the form of copper cathodes.

3. **Nickel and cobalt extraction.** The remaining acid solution is reacted with other chemicals, such as ammonia, to extract the cobalt and nickel. This is typically a multistep process; cobalt is extracted first, and the remaining acid solution is then passed through a second stage that yields nickel. Both cobalt and nickel can be produced in metal or salt form (Jabbar et al., 2022).

Figure A.2. Flowsheet for the Hypothetical Refining of Matte Derived from Nodule Processing



SOURCE: This figure from Rifat Jabbar et al., *Polymetallic Nodules and the Critical Minerals Supply Chain: A North American Approach*, 2022, p. 8, is used with permission by the Wilson Center.

The nickel and cobalt compounds produced by refining are high-purity (greater than 99-percent pure) and are suitable for the manufacture of precursor cathode active materials and cathode active materials that form the cathode-side of lithium-ion batteries.

Distribution of Existing Infrastructure

As with many other critical materials, the processing and refining infrastructure of nickel is highly concentrated in a few countries. The bulk of nickel processing infrastructure is located in Indonesia and China. One processor that we met with estimated that Indonesia and China account for 90 percent of global nickel processing and that this percentage is increasing as non-Indonesian operations are closed because of cost pressures. China also controls a dominant share of nickel refining infrastructure and capacity.

Indonesia is the global leader in nickel processing, with 17 operating nickel smelters as of 2023 (Jabbar et al., 2022). Indonesia's leading position reflects tremendous growth in recent years; as recently as 2014, the country had only three operating nickel processing facilities (Guberman, 2021). However, a series of regulations restricting the export of nickel ore, culminating in a full export ban in 2020, provided the impetus for the development of new nickel processing capacity within Indonesia (IEA, 2024a). Chinese investment has been critical for the development of this new capacity; the Tsingshan Holding Group was the first company to invest in Indonesia's nickel reserves and has since developed a vertically integrated network of mines and processing plants in Sulawesi (Michot Foss and Koelsch, 2022). One source suggests that Tsingshan alone controls or owns majority stakes in 55 percent of Indonesia's NPI production capacity (Jabbar et al., 2022).

Indonesia currently has a minimal presence in the nickel refining sector, with only one operational nickel refinery as of 2023 (Jabbar et al., 2022). The primary nickel ore mined in Indonesia is laterite, which has historically been considered unsuitable for the production of battery-grade material. Therefore, most Indonesian processing capacity is oriented toward the production of feedstocks for stainless steel manufacture, such as ferronickel or NPI (Guberman, 2021). Although these products could be upgraded to Class I nickel for battery manufacturing, firms have tended to be wary of the high capital cost associated with adding sulfidation converters and building the HPAL refineries that would be required for this process. However, this sentiment is slowly changing; Chinese firms are spearheading the development of at least seven HPAL projects in Indonesia (Wood Mackenzie, 2023).

China plays a major role in nickel processing and refining through its control of infrastructure both within China and in such countries as Indonesia. It is the second-largest nickel processor and largest nickel refiner in the world, with 12 operating smelters and 9 refineries (Jabbar et al., 2022). Previously, China was the dominant player in both nickel processing and refining; however, since the imposition of Indonesia's nickel export ban, Chinese producers of ferronickel and NPI developed smelters within Indonesia. More recently, Chinese processing companies have also begun to produce matte in Indonesia as an input for nickel refining in China (Home, 2024). One Chinese refinery, located at Beihai, produces nickel, cobalt, copper, and manganese (Wood Mackenzie, 2022); these outputs are comparable to the products from nodule refining, implying that China might already have infrastructure capable of handling nodules.

The remainder of global nickel processing and refining capacity is distributed across several countries. In terms of processing, Japan and Brazil are tied for a distant third behind Indonesia and China with three smelters each. New Caledonia, a major producer of nickel ore, is fourth with two smelters, while several other countries, such as South Korea and the Dominican Republic, have a single operating smelter. And, although the output from these countries is small relative to Indonesia and China, it is getting even smaller as operations dependent on imported ore suffer from Indonesia's nickel export ban. One processor in that situation relayed to us in an interview that it is operating at a capacity utilization of 15 percent and estimated that other such processors have been similarly affected.

Japan also plays a major role in nickel refining, possessing two refineries, as do South Africa and Canada. Although China possesses a greater number of refineries and refinery capacity than other countries, most Chinese refineries tend to produce a single type of product, such as nickel sulfate or nickel metal. Facilities capable of producing additional products (such as cobalt and copper) appear to be more common outside China, with at least five such refineries distributed across South Africa, Canada, and Japan (Jabbar et al., 2022).

Appendix B

Calculations and Assumptions of Financial Modeling

This appendix includes information about cobalt pricing and supply, as well as existing and potential royalty distribution structures related to mining. Table B.1 details the parameters that we used to estimate the DRC's revenue changes in scenarios with and without seabed mining. Table B.2 lists several examples from the past decade of how changes in cobalt supply affected cobalt prices. Table B.3 lists several examples of existing land-based royalty redistribution mechanisms.

Table B.1. Description of the Parameters Used to Compare Democratic Republic of the Congo Cobalt Royalties With and Without Seabed Mining

Measure	Description	Formula Used	Source(s)	Value(s)
P	Baseline cobalt price in the absence of an influx of supply from seabed mining	Average monthly U.S. spot price of cobalt from January 2024 to September 2024	International Monetary Fund, 2025	$27,011 per metric ton
$Q_{DRC}(P)$	Quantity of cobalt supplied by the DRC at baseline price, P	None	USGS 2023 DRC cobalt production (Ewing, 2024)	170 kt per year
R_{DRC}	DRC mining royalty rate	None	DRC mining code, EITI reports (IEA, 2022a; IEA 2022b; EITI, 2023)	10 percent of production value; royalties represent 17 percent of mining-related financial flows to the DRC government
Q_{SBM}	Quantity of cobalt supplied by seabed mining	One vehicle: 2-percent increase in supply from 2023 baseline Ten vehicles: 21-percent increase in supply from 2023 baseline	Our estimate from interviews with seabed mining representatives and concentrations and metal recovery from Kirchain et al. (2020); global production estimates from Cobalt Institute (2024b)	Low production value (one vehicle): 4,620 tons High production value (ten vehicles): 46,200 tons
P_{SBM}	Price of cobalt with an influx of supply from seabed mining[a]	One vehicle: 2-percent increase in supply from 2023 baseline is associated with a 2-percent decrease in price Ten vehicles: 21-percent increase in supply from 2023 baseline is associated with a 19- to 54-percent change in price	Recent examples of changes in cobalt supply affecting price (see Table B.2)	Low production value (one vehicle): $26,471 High production value (ten vehicles): $12,425
ηs	Price elasticity of supply for cobalt		Cavallero, 2021	0.136
ηd	Price elasticity of demand for cobalt		Shojaeddini, Alonso, and Nassar, 2024	−0.45

Measure	Description	Formula Used	Source(s)	Value(s)
$Q_{DRC}(P_{SBM})$	Quantity of cobalt supplied by the DRC with seabed mining	$\%\Delta Q$(supplied) = $(\eta s - \eta d) \times \%\Delta P$	Hutchinson, 2016	Low production value (one vehicle): 168,008 kt per year High production value (ten vehicles): 124,175 kt per year
R_{ISA}	ISA royalty rate	None	ISA working papers (ISA, 2022c)[b]	Low value: 2 percent High value: 9 percent
E_{ISA}	Proportion of ISA royalties allocated to the ISA economic assistance fund	None	Equivalent programs currently administered by terrestrial mining countries (see Table B.3)	Low value: 10 percent High value: 30 percent
X_{DRC}	Proportion of ISA royalties for equitable sharing allocated to the DRC	None	ISA-sponsored studies (ISA, 2022b)	Low value: 0.1 percent High value: 3.5 percent
Y_{DRC}	Proportion of ISA economic assistance funding allocated to the DRC	None	Authors' estimate	Low value: 10 percent High value: 30 percent

NOTE: kt = kilotonnes.

[a] In our modeling, we estimated ISA's tax base using the estimates of nodule production and associated mineral products, as well as the initial price estimate for the four nodule minerals from Kirchain et al. (2019). We benchmarked the changes in noncobalt prices to our computed changes in cobalt prices (i.e., price multipliers of 0.98 and 0.46 per ton in the low and high cases, respectively).

[b] There are two royalty options under consideration by ISA. Option 1 is a two-stage time-varying ad valorem–only royalty (royalty rates of 2 percent or 6 percent, depending on the production stage). Option 2 is a two-stage progressive or variable price-varying ad valorem–only royalty (royalty rates of 2 percent or 5 to 9 percent, depending on the production stage).

Table B.2. Recent Examples of Changes in Cobalt Supply and Associated Impacts on Price

Example	Quantity	Global Production Change (from Prior Year Level)	Price Change	Time Frame for Price Change Comparison	Other Factors Affecting Price
2023 opening of CMOC's Kisanfu mine (Cobalt Institute, 2024b)	32.5 kt	16.3 percent (increase from 2022 production of 198.6 kt, not accounting for other changes in production in 2023)	34-percent decrease (hydroxide)	2022–2023 (full-year comparison)	End of Chinese EV subsidies in late 2022 (weakened demand); trucking delays in the DRC (price relief)

Example	Quantity	Global Production Change (from Prior Year Level)	Price Change	Time Frame for Price Change Comparison	Other Factors Affecting Price
CMOC surpasses expected production in H1 2024 (Cook and Shi, 2024)	26 kt (above 2023 H1 levels)	22.4 percent (above expected production for 2024 H1 based on 2023 production)	18.8-percent decrease (hydroxide)	Average price in H1 2024 vs. average price H1 2023	Weak demand for cobalt sulfate used in traction batteries (L., 2024)
Mutanda mine shutdown in 2019 (Prvulovic, 2019)	25 kt	17.9 percent (value of Mutanda production relative to 2019 global production)	20-percent increase (metal)	Immediately before and after shutdown announcement	Low price environment
2018 cobalt price crash (Larsen, 2019; USGS, 2020; Shedd, 2022)	24 kt	20 percent (increase from 2017 production)	54-percent decrease (metal)	2018–2019 (full-year comparison	Lower than anticipated demand for EVs; Chinese firms stop stockpiling cobalt

NOTE: H1 = first half (includes the first and second fiscal quarters).

Table B.3. Examples of Existing Land-Based Royalty Redistribution Mechanisms

Country	Program	Rate
Ghana	Minerals and Mining Act of 2006	Requires that 10 percent of all mining royalties paid to the central government be given to the communities affected by mining (Adebayo and Werker, 2021)
Chile	Mining Royalty Bill of 2023	Requires that 18 percent of estimated royalties be allocated to mitigating the negative effects of mining and to the lowest-income communities in the country (IEA, 2023b)
Colombia	Law 2056 to regulate the organization and functioning of the general system of royalties	Requires that 15 percent of royalties be allocated to the poorest municipalities in the country (IEA, 2023a)
Senegal	Decree number 2009-1334	Requires that 20 percent of mining revenue be used to create a national equalization fund (Wall and Pelon, 2011)
Australia (Northern Territory)	Aboriginal Land Rights Act of 1976, Section 64	Requires that 30 percent of mining royalties be set aside for aboriginal people affected by mining on their land (National Indigenous Australians Agency, undated)

Appendix C

Workshop Method and Materials

To provide a useful forum in which to explore the potential geopolitical impacts of seabed mining operations, we conducted a virtual workshop, taking inspiration from previous RAND workshops on critical minerals (Tingstad et al., 2024). Participants were led through a series of exercises designed to elucidate which stakeholders might be involved or affected, how U.S. foreign policy in the Indo-Pacific might be affected, what policy impacts or unresolved questions might arise in the context of the DIME framework, and what policymakers and decisionmakers should prioritize, primarily from a U.S. perspective (although takeaways could be relevant to other nations).

The workshop included participants with expertise in maritime military operations (U.S. Navy and U.S. Coast Guard), maritime commerce and law, ISA activity and bylaws, critical mineral supply chains, economic security, Chinese foreign policy and industrial policy, and the People's Liberation Army. A total of ten participants from the U.S. government and RAND took part in the workshop on October 11, 2024.

The workshop was conducted virtually using the Mural platform to create an online whiteboard. A subsequent workshop survey was delivered to participants to recover comments and suggestions to define goals for identified policymakers and other decisionmakers. Figure C.1 summarizes the different facets of the workshop and survey.

Figure C.1. Overview of Workshop and Survey Activities

The workshop began with an introduction to a scenario in which seabed mining operations were already underway in 2035. The scenario included prompts and a fictional newspaper's front page with headlines and articles from July 2035 that highlighted issues affecting technology and demand, supply chains, firms, infrastructure, mineral exploration and mapping, and more (Figure C.2). The timeline prompts and market activity prompts are summarized in the boxes on page 39.

Figure C.2. Newspaper Scenario

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Issue
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RIVIAN CLOSES ITS DOORS AS CHINESE EVS CONTINUE TO MAKE GAINS

By SAM O'WA

IRVINE, CALIFORNIA – A somber mood fell over the last remaining staff at Rivian's Irvine, California facilities. After showing strong performance in the 2020's with its suite of stylish EV models, underlying debt and ballooning costs from transitioning its production lines to cater to new battery chemistries made possible by metal rocks on the sea floor proved to be too much for the company.

Indeed, the proliferation of seabed mining created a glut of supply that help fuel its demise. Most analysts spent the 2020s worrying about nickel and cobalt and the price volatility that kept new market entrants from diversifying supply outside of Chinese-owned mines, smelters, and gigafactories. But following the International Seabed Authority's finalization of deep-sea mining (DSM) regulations, companies like GSR found that their poly-metallic nodules presented new opportunities. Initially, they disregarded the manganese that made up large portions of the nodule in favor of nickel and cobalt demand stemming from traditional battery cathode chemistries for fear of flooding the manganese market. But battery startups in Silicon Valley pursuing little known manganese-dependent chemistries like lithium nickel manganese oxide and lithium manganese phosphate suddenly found themselves with a cheap, abundant source and commercially viable products. They quickly entered into partnerships.

Chinese battery manufacturers found their established processes for producing lithium iron phosphate could be adapted to lithium manganese phosphate to capture its superior electrochemical performance. Chinese EV firms like BYD quickly secured offtake and were able to increase their vehicles' range and power to present cheaper alternatives to American OEMs like Rivian.

Above: Deep sea crawler prepares to comb the ocean floor for nodules.
Photo credit: Global Sea Mineral Resources (www.deme-gsr.com)

COOK ISLAND DOUBLES ITS GDP THANKS TO DSM

By CLIP ARTON

AVARUA – During the past 10 years, the Cook Islands has made great strides in its economic development. In the early 2020's, the small island nation suffered major setbacks during and after the COVID-19 pandemic. But following the signing of a Memorandum of Understanding between Japan, then the lead for the multi-lateral Minerals Security Partnership (MSP), and the island in 2026, the nation was able to become eligible for inclusion in the MSP. With the increased attention, the island attracted financing to build out a new suite of ports catering to the emerging deep-sea mining (DSM) industry. This early investment, along with subsequent expansions and upgrades, provided the Cook Islands with the stable footing required to support DSM companies' operations while increasing state revenue.

While other DSM companies needed to wait until the International Seabed Authority finalized their regulations for extraction of poly-metallic nodules, the Cook Islands allowed companies operating in its EEZ to refine their operational procedures and gain a lead on companies with tracks in the Clarion Clipperton Zone (CCZ). They were later able to expand operations in Japan, Norway, and elsewhere.

While DSM companies needed to ship their nodules elsewhere for smelting and refining, the Cook Islands quickly attracted increased attention from the People's Republic of China (PRC). The PRC provided foreign direct investment to build the infrastructure needed to support undersea research laboratories. Since these laboratories began operations, a wealth of knowledge has birthed the new seabed-products and tourism sector.

This growth has not been without tension. A U.S.-based undersea research group believes it has found evidence of damage to local biodiversity due to DSM, especially near sea floor tracks owned and exploited by Chinese firms. They claim these tracks may even be host to equipment used to monitor the activity of undersea operations. These accusations come just one year after one Chinese firm was found to be illegally harvesting nodules outside of its tack and had to be ousted with the help of the New Zealand Coast Guard. The Chinese embassy refutes the claim, speculating that U.S. researchers are simply jealous of China's scientific leadership.

USGS completes map of mineral reserves in Guam's EEZ

After Alaska, the West coast, American Samoa, Puerto Rico and the U.S. Virgin Islands, the USGS has completed mapping Guam's EEZ for nodules and sulfide crusts.

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Port in Baja, Mexico crumbling under stress from DSM usage

Mexico's Western ports have seen increased usage from offloading nodules thanks to demand from processing, battery, and EV production. Now, structural issues are causing port shutdowns and disruption.

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DRC sees declining state revenues as nodules fail to deliver on promises

Mineral rich developing nations thought they'd share in the wealth generated from DSM, but it isn't adding up. Countries like the DRC have failed to recoup losses from declining demand for terrestrial minerals.

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SOURCE: Deep sea crawler image is used with permission by Global Sea Mineral Resources.

Summary of Timeline Prompts

2026: Countries like the Cook Islands and Norway approve deep-sea mining operations in their EEZs.

2027: ISA finalizes and adopts regulations regarding seabed mining, clearing the way for mining operations.

2035: Eight years later, polymetallic nodules are the dominant output of seabed mining as sulfide crust extraction was found to be too ecologically damaging.

Summary of Market Activity Prompts

Companies like The Metals Company have two vessels operating while others have vertically integrated to produce battery precursor materials. Western and Chinese firms are exploiting EEZs and the Western Pacific. Some governments like India are in the process of establishing deep-sea mining state-owned enterprises.

Deep-sea mining companies have entered agreements to refine nodules in Mexico, Indonesia, Japan, Europe, and elsewhere. BYD and Tesla are the first major EV manufacturers to sign an offtake agreement to supply precursor cathode active material.

Seabed miners release data comparing emissions, energy use, etc. with terrestrial operations and claim that seabed mining is the environmentally responsible path for the energy transition. Consequently, developing nations see decline in demand for their minerals.

Following the ISA adoption of regulations, oceanographers and other scientists have rushed in to conduct as much seabed research as possible before more tracks of the seafloor are developed.

Growth in EV demand has remained steady post-2030 as more EV models have become available and cheap, but capable Chinese EVs have proven popular and gained market share. New battery chemistries have become commercially viable, contesting the traditional dominance of lithium nickel manganese cobalt oxide and lithium iron phosphate cathode chemistries.

Ports in the Pacific Rim (e.g., Mexico, Canada, Philippines, Indonesia) are catering to demand for nodule offload sites near processing plants, gigafactories, and battery recycling plants.

The prompts presented participants with assumptions about which seabed mineral resource is in demand (i.e., nodules), where commercial operations were taking place (the CCZ and some EEZs), how market dynamics and demand for minerals have shifted, initial environmental impact assessments, stakeholders, and impacts to terrestrial mining.

The purpose of the newspaper cover page was not to predict a future or a pathway to its realization; instead, its purpose was to provide participants with enough fodder to frame their thinking and analysis for the exercises to come. Participants were encouraged to share their thoughts on the scenario's plausibility and provide other reactions.

The participants were then presented with a set of seabed mining operation stakeholders identified by the project team throughout the study from our review of the literature and our interviews; these stakeholders included seabed mining companies, the ISA, countries with operations in their EEZs, countries opposed to seabed mining, and nongovernmental organizations. Participants were asked to suggest additional stakeholders that might have been omitted from our list. Participants were encouraged to discuss the potential relationships between stakeholders and how seabed mining operations might affect them.

Participants were then asked to reflect on the role of critical minerals and seabed mining in geopolitics from the United States' perspective, specifically in the context of the U.S. Indo-Pacific Strategy. Participants reviewed the five objectives of the strategy along with the ten lines of effort supporting its implementation.[15] Participants were then asked how critical minerals and seabed mining could help advance U.S. strategic goals. Facilitators encouraged participants to share and discuss their opinions.

Participants were then guided through a policy mapping exercise using the DIME framework. Participants were asked to generate policy issues that might arise from future seabed mining operations within the context of each pillar of the DIME framework and across four policy areas: (1) seabed mining operations, technology, and infrastructure; (2) governance, legal, and regulatory; (3) industry, market, and supply chains; and (4) social and environmental. After generating policy issues across the four DIME pillars, participants were asked to select one policy issue for each intersection, generating a set of 16 policy issues. Participants were then asked to rank the 16 policy issues according to their actionability by policymakers or other decisionmakers. Facilitators used pair-wise comparison to help participants rank the 16 policy issues. The top ten policy issues were then selected for the final round of input.

[15] The five objectives are to (1) advance a free and open Indo-Pacific, (2) build connections within and beyond the region, (3) drive regional prosperity, (4) bolster Indo-Pacific security, and (5) build regional resilience to transnational threats. The ten lines of effort are (1) drive new resources to the Indo-Pacific, (2) lead an Indo-Pacific economic framework, (3) reinforce deterrence, (4) strengthen an empowered and unified ASEAN, (5) support India's continued rise and regional leadership, (6) deliver on the Quadrilateral Security Dialogue between the United States, Australia, India, and Japan, (7) expand U.S.-Japan-Republic of Korea cooperation, (8) partner to build resilience in the Pacific Islands, (9) support good governance and accountability, and (10) support open, resilient, secure, and trustworthy technologies (White House, 2022).

Appendix D

Workshop Findings

Table D.1 presents the results of the workshop exercise to generate policy issues at the intersection of each pillar of the DIME framework and four policy impact areas. The box on page 45 presents the prioritized list of policy issues that emerged from winnowing the original list down to the top ten (two choices had overlapping remits and, thus, were consolidated to produce a total of nine policy issues or questions).

Table D.1. Potential Impacts of Seabed Mining Across the Diplomatic, Information, Military, and Economic Framework

Policy Impact Areas	Diplomatic	Information	Military	Economic
Seabed mining operations, technology, and infrastructure	• EEZ encroachment or IUU seabed mining harvesting might cause international disputes. • Absent ISA regulations and guidance, bilateral and multilateral agreements will be needed. • China's lead on seabed mining plots and commercial readiness might require working with partners and allies to catch up and protect non-Chinese firms in the future.	• More information on deep-sea worker and environmental safety might be needed. • There might be more opportunity for clandestine operations and data collection. • The United States and its partners might need to improve maritime domain awareness on the surface and subsurface. • Seabed mining companies will need to be cognizant of seabed infrastructure or risk disrupting communication lines. • What information is needed to determine whether IUU mining or environmental damage is occurring? • Can U.S. technology be leveraged for seabed mineral extraction, processing, or refining?	• Supply of seabed minerals would be concentrated to a few ships and could make disruptions easier. • Use of dual-use technology might provide adversaries with the opportunity to monitor or interfere with submarines and undersea cables. • Seabed mining operations could increase ambient noise and make marine domain awareness harder as passive detection of adversarial activities becomes more difficult. • Existing sea-lane control issues in ASEAN and Pacific Island nations might be exacerbated or arise in new locations. • EEZ enforcement of countries with seabed minerals in their EEZs will need to be addressed. • Will existing U.S. government offices or organizations need to expand their remit, or will new organizations need to be created?	• Dispersal of plumes and sediment might disrupt other industries, such as fishing or tourism. • The reliability of undersea remote-operated vehicles will likely be challenging and could affect firms' operational costs. • Ownership of port and processing infrastructure might be of concern. • Non-ISA countries might be prohibited from offloading nodules derived from ISA-regulated areas.

Policy Impact Areas	Diplomatic	Information	Military	Economic
Governance, legal, and regulatory	• Clear, strict operational regulations are crucial for the industry to operate effectively. • Outside UNCLOS, the United States is severely limited in its ability to influence international laws and regulations. • What will the penalties be for bad behavior in ISA-regulated plots and who will enforce them?	• An information resource might be needed to refute seabed mining misinformation and disinformation. • Information-sharing agreements among the Five Eyes might need to be updated to monitor seabed mining activity. • Does the National Environmental Policy Act apply to U.S.-based seabed mining?	• Similar to the case for IUU fishing, navies and coast guards might need to provide freedom of navigation and EEZ enforcement. • Mineral piracy could become an issue if seabed mining operations occur near unstable regional waters. • Who is designated responsibility for the enforcement of claims to ISA plots?	• Anti–seabed mining nations might impose tariffs on seabed minerals. • There is a potential need for regulatory and sanctions cooperation should mineral piracy become rampant. • ISA royalties for developing nations might not meet revenue displacement. • Who will enforce ISA revenue sharing? • Do seabed minerals qualify for IRA tax credits?
Industry, market, and supply chain	• Seabed mining supply might reduce vulnerability to economic coercion. • Subsidies and trade barriers will affect industry competitiveness. • Is demand for seabed mining sustainable amid technological uncertainty? • Could seabed mining projects be included in the Mineral Security Partnership? • Could seabed mining in the U.S. EEZ improve supply chain resilience? • Where will seabed minerals be processed and refined?	• Price volatility and market information might be improved by additional supply from seabed minerals. • Supply chain information might move more slowly for seabed mining. • Transparency from seabed mining companies is disincentivized. • How will market information be made available?	• U.S. goals and priorities for supply chain resilience could shift as the supply of nodules changes estimates of availability of and accessibility to critical minerals. • Information-sharing is needed if commercial and defense industries cooperate on downstream operations. • Small demand from the defense industrial base might not support demand for seabed minerals. • Would the United States pursue seabed mining outside an international framework for security reasons? • Does seabed mining qualify for MCEIP funding?[a]	• Barriers exist to investing in Pacific Island nations because of ineligibility for developing-country foreign direct investment benefits. • Is seabed mining economically viable and will it be cheaper than terrestrial mining? If so, when? • Does a domestic market exist for seabed minerals, and how long will it persist? • How could nodule processing be incentivized outside China and in the United States? • Will there be a market for partially depleted seabed mineral plots? • Should the United States invest in partners with access to seabed minerals?

Policy Impact Areas	Diplomatic	Information	Military	Economic
Social and environmental	• Cross-boundary environmental impacts in high seas or EEZs will require bilateral or multilateral resolutions. • Labor violations might be a concern. • Offshore environmental issues might not receive adequate attention. • Could anti–seabed mining countries prevent commercial operations with the Biological Diversity of Areas Beyond National Jurisdiction agreement?	• Environmental concerns fuel narratives in the information space. • How much information is needed to determine whether seabed mining operations can proceed? • Can seafloor technologies be used to help monitor and detect environmental impact? • To what extent can environmental impact be measured or recorded?	• Nation-states might use military force to protect seabed mining–related activity. • Less demand for terrestrially mined minerals could reduce mineral conflicts and human rights abuses. • Protection and enforcement of seabed mining rights might create environmental damage. • Who is designated responsibility to enforce environmental cleanup in ISA plots?	• Low- or middle-income countries with access to seabed minerals in their EEZs might experience a variant of the resource curse.[b] • Demand for seabed minerals is very sensitive to social acceptance. • There is uncertainty regarding the trade-off between national and economic security and environmental impacts. • How could developing countries and artisanal and small mine jobs be affected? • How could fisheries be affected?

NOTE: MCEIP = Manufacturing, Capability Expansion, and Investment Prioritization program.

[a] MCEIP administers the Defense Production Act Title III and the Industrial Base Analysis and Sustainment funding programs.

[b] Michael Ross defines the *resource curse* as the “adverse effects of a country’s natural resource wealth on its economic, social, or political well-being” (2015, p. 240).

Geopolitical Priority Areas for the United States Associated with Seabed Mining

1. Bilateral and multilateral relationships will be needed to set rules and regulations for seabed mining operations and enforcement absent guidance from the ISA or other international authorities and absent international enforcement mechanisms.
2. Greater understanding is needed regarding uncertainties and risks associated with seabed mining operations as they pertain to environmental impacts (e.g., seabed ecology, ocean life), safety (e.g., of workers), and marine industries (e.g., fisheries or tourism).
3. Better understanding and clarity are needed regarding the enforcement of international regulations and penalties for violations outside ISA jurisdiction.
4. Consideration is needed of the potential for nation-states to use military force to protect seabed mining–related activity (e.g., illegal mining, violation of international agreements, establishment and claims of such territories as islands, and EEZ expansion).
5. There is a need to explore how to incentivize nodule processing in the United States or at least outside China.
6. A better understanding is needed of how seabed mining could exacerbate sea-lane control issues (e.g., in Asian territorial waters).
7. More clarity is needed regarding uncertainties about seabed mining's commercial viability.
8. Perceptions of social-environmental impacts of seabed mining can influence the demand for nodules.
9. Goals and priorities for supply chain resilience might shift as the supply of nodules changes estimates of availability of and accessibility to critical minerals.

Abbreviations

ASEAN	Association of Southeast Asian Nations
CCZ	Clarion-Clipperton Fracture Zone
DIME	diplomatic, informational, military, and economic
DRC	Democratic Republic of the Congo
EEZ	exclusive economic zone
EITI	Extractive Industries Transparency Initiative
EV	electric vehicle
HPAL	high-pressure acid leaching
IEA	International Energy Agency
IRA	Inflation Reduction Act
ISA	International Seabed Authority
IUU	illegal, unreported, and unregulated
LFP	lithium-iron-phosphate
NMC	nickel-manganese-cobalt
NPI	nickel pig iron
UNCLOS	United Nations Convention on the Law of the Sea
USGS	U.S. Geological Survey

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