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PERSPECTIVE ON A TIMELY POLICY ISSUE

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Technology-Driven Opportunities and Risks to Sustainable Development of Critical Minerals in Developing Countries

Consolidated Remarks Delivered to a United Nations Expert Group Meeting

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About This Paper

This paper consolidates the remarks delivered by RAND researchers who attended an expert group meeting (EGM) hosted by the United Nations's Department of Economic and Social Affairs. The EGM, 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development, was organized to support the writing of the United Nations's annual World Economic Situation and Prospects report for 2025. The meeting took place at the United Nations's New York headquarters from May 29 to May 30, 2024.

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Technology-Driven Opportunities and Risks to Sustainable Development of Critical Minerals in Developing Countries

An energy sector transition to support climate change mitigation is underway. This transition is strongly driving increased demand for the critical minerals that are needed for the energy generation and storage technologies that are supplanting fossil fuel use. As a result, developing countries are witnessing an increased demand for mineral resources within their sovereign territories, and many countries are looking to take advantage of opportunities for economic growth.[1] These opportunities entail substantial investment to develop extraction and production capacity, much of which is derived from foreign sources. However, the development of these resources can present developing countries with challenges, such as stresses on transportation, water, energy, and power infrastructure; humanitarian and environmental issues; labor and workforce issues; knowledge and technology gaps; financing concerns; and security issues. The mineral commodities, specialty chemicals, and metal alloys that are required to manufacture energy technologies—broadly termed *critical minerals*—are at the heart of a dilemma developing countries are facing: how to shape a strategy that leverages domestic resources for economic growth without realizing negative externalities.

Low- and middle-income countries, particularly those with significant critical mineral deposits, are implementing policies related to the management of their mineral resources.[2] These policies show a clear desire to avoid the effects of a colonialist past, capture more value, and fuel sustainable and shared growth. Achieving these goals will not be easy—the mining sector presents a unique set of challenges and, when combined with changing demand signals from technology adoption and innovation, it is clear that developing countries are in need of robust strategies.

From May 29 to May 30, 2024, the United Nations's Department of Economic and Social Affairs hosted an expert group meeting (EGM) titled 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development at the United Nations's New York

[1] United Nations Secretary-General's Panel on Critical Energy Transition Minerals, "Background Paper for the UN Secretary-General's Panel on Critical Energy Transition Minerals," May 13, 2024.

[2] The production of mineral and chemical commodities occurs over several stages of the value chain. In this paper, we use the following terminology: *Extraction* is the removal of ore from the site of a mineral deposit. A *resource* is an estimate of the amount of metal contained in naturally occurring ore in a deposit site. *Reserves* are the total amount of resources that have been proven to be economically feasible to produce, regardless of whether extraction is underway. *Processing* refers to the concentration or refining of extracted ore to produce an intermediate or final product, such as a metal or specialty chemical used as an input for manufacturing.

headquarters. The EGM was organized to support the writing of the United Nations's annual World Economic Situation and Prospects report for 2025.[3] In this paper, we consolidate the remarks that we delivered at the EGM and offer general strategic guidance on the technological factors that affect economic development and the mining sector.

In the next section, we discuss the complexity of mineral supply chains. We show that decisionmakers often face dilemmas that require balancing multiple desirable goals alongside uncertainties derived from technological demand and national policies that affect global demand for minerals. We follow that with a description of strategic planning considerations in developing countries. The historical failures of forecasting highlight the limitations of predictions regarding energy technology changes and demonstrate that developing countries should approach energy production and mineral demand estimates cautiously. The use of foresight methods to explore multiple plausible future scenarios, which enable countries to strategically plan for various potential disruptions, provides a more robust alternative. We then highlight five technological factors affecting demand for critical minerals and the implications of those factors to strategic planning in developing countries.

The Complexity of Critical Mineral Supply Chains

In complex systems, there are often no "right" answers.[4] A series of dilemmas in a complex system puts the decisionmaker in the position of weighing multiple desirable goals that require policy actions that may undermine one another. In critical minerals supply chains (CMSCs), trade-offs abound. Should a policymaker maximize the positive economic impact of a mining project at the expense of scarce water supply? Should a strict regulation be enacted that might deter foreign direct investment? What is the proper balance of financial incentives for development and rents collected for the state?[5] Should a mining company invest in developing a mine site when price volatility could undermine profitability? These dilemmas and others illustrate the complexity of decisionmaking in the mining sector and CMSCs generally. In this paper, we highlight the basic uncertainties stemming from technological demand and the policies enacted by countries that create complexity.

The energy technologies that are in demand include stationary and mobile battery storage (e.g., lithium-ion batteries [LIBs] used in grid storage and electric vehicles [EVs]); polysilicon solar photovoltaics [PVs]; concentrating solar cells; rare-earth, magnet-driven wind turbines and electric motors; hydroelectric turbines; biofuels; geothermal technologies; nuclear technologies; and hydrogen fuel cells.[6]

Several operational steps need to take place in CMSCs; generally, those steps are mineral exploration, extraction, transportation, refining and processing, more transportation, component

[3] For more information, see United Nations, Department of Economic and Social Affairs, "2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development," webpage, May 16, 2024.

[4] Theodore Kinni, "The Critical Difference Between Complex and Complicated," *MIT Sloan Management Review*, June 21, 2017.

[5] Mineral rents are payments received by a landowner (i.e., developing country) from a licensee (i.e., mining company) who has leased the mineral rights to the land and is producing ore or concentrate for sale.

[6] Tae-Yoon Kim, *The Role of Critical Minerals in Clean Energy Transitions*, International Energy Agency, revised March 2022.

manufacturing, more transportation, systems integration into a final product, and more transportation. These operational steps intersect both the value chain (the manufacturing nodes) and the supply chain (the logistical and transportation nodes comprising international trade). The technologies that are in demand are the output of the final manufacturing step. Many of these products contain substitutable components and thus increase the number of technical iterations available, each with an associated mineral demand. There is a deep uncertainty as to the overall demand for multiple minerals because many, if not all, of the technologies we listed are likely to play some role in producing or storing energy in the future.

The growth of new energy technology markets has been limited by the supply of minerals and associated national policies enacted to navigate the varying abundance of those minerals. The heterogeneous geographic distribution of minerals imbues certain countries with a comparative advantage at the extraction node of CMSCs. Some countries have leveraged this advantage to secure market share and move into other parts of the technology value chain. One of the most notable examples of this is China leveraging its rich endowment of rare-earth elements to become the world's leading producer of rare-earth element compounds and rare-earth magnets and other components. Such countries as Indonesia and others are following suit by executing policies and leveraging advantages to enter or expand into processing and refining component production.

The critical mineral policies being implemented by mineral-rich countries can broadly be classified into four categories on the basis of their objectives: (1) national-level strategies or plans, (2) construction of domestic capability and capacity, (3) protection of environments and people, and (4) financial incentives and foreign agreements.[7]

National-level critical mineral strategies or plans, such as Chile's 2023 National Lithium Strategy and Malaysia's 2021 Mineral Industry Transformation Plan, outline broad goals for a country's critical minerals sector in relation to sustainability and economic growth, clarify the role of the government versus the private sector in developing mineral resources, and some set aside funding to identify and map national resources.

The second category—construction of domestic capability and capacity—includes policies aimed at building CMSC capacity through mineral processing and downstream manufacturing. Indonesia's ban on raw nickel exports, implemented through a series of policies from 2009 to 2019, is largely seen as a successful example of building a domestic processing sector for nickel.[8] Other examples include such initiatives as the Centre of Excellence for Advanced Battery Research at the University of Lubumbashi in the Democratic Republic of the Congo (DRC),[9] a training and research and development (R&D) program launched by the DRC's Minister of Industry in 2022, or policies that redirect some portion of mining royalties to R&D activities.

[7] This section sources heavily from the International Energy Agency's Critical Minerals Policy Tracker (International Energy Agency, Office of Legal Counsel, *Introducing the Critical Minerals Policy Tracker*, November 2022).

[8] However, it should be noted that Indonesia's attempts at developing a domestic alumina/aluminum industry via bauxite export bans has not enjoyed the same level of success (Gracelin Baskaran, "Diversifying Investment in Indonesia's Mining Sector," Center for Strategic and International Studies, July 11, 2024).

[9] United Nations, Economic Commission for Africa, "Centre of Excellence for Advanced Battery Research in DRC Officially Launched," April 22, 2022.

The third category aims to protect environments and communities, particularly historically marginalized groups, such as indigenous populations and women. Examples include a 2021 Argentinian resolution to promote the inclusion of women in the mining industry on a more equal basis and Article 297 of Bolivia's 2014 Mining and Metallurgy Law, which requires consulting indigenous communities for any aspirational mining projects.

The final category—financial incentives and foreign agreements—includes policies aimed at attracting private investment into local mining sectors. Such policies include such measures as tax breaks and fiscal stability guarantees for private mining companies. They also include agreements with downstream producing and consumer countries, such as the various memoranda of understanding aimed at supporting investment in local mineral sectors signed between the United States and several developing counties or the much earlier "infrastructure for minerals" deal between China and the Congolese government, through which Chinese firms built roads and hospitals in exchange for a majority stake in a major copper/cobalt mine.[10]

These policies demonstrate a clear desire to avoid the resource curse dynamics of the past by leveraging mineral resources to fuel economic development in a way that is shared and sustainable.[11] However, achieving these goals will require significant amounts of direct investment, capacity-building, and knowledge and technical transfers—areas in which developing countries tend to be more constrained.

For developing countries, industrial and innovation policy packages help not only to facilitate the creation of productive links and foster diversification but also to shape those policies and links. Yet these policies must be strategic, well designed, coordinated, and tailored to the specific characteristics of each country. Also, these policies require sustained political commitment, adequate financing frameworks, and rigorous evaluations that reinforce institutional learning. The strategic use of conditionalities may also play a key role in aligning firm performance with promoting technological capabilities. These conditionalities may encompass product accessibility (ensuring a share of production is accessible to third-party firms for refining), inputs (mandating local content requirements[12]), and reinvestment (allocating a share of earnings to fund R&D investments or benefit local communities).

The uncertainties associated with the effects of national policies on the mining and processing sectors and on the broader economy, as well as conditions that are outside the control of government (such as market changes that could lead to price volatility or human or natural events that cause supply disruptions), have led to deep uncertainty about the ability to secure access to supply at fair

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[10] U.S. Department of State, Office of the Spokesperson, "The United States Releases Signed Memorandum of Understanding with the Democratic Republic of Congo and Zambia to Strengthen Electric Vehicle Battery Value Chain," press release, January 18, 2023; Karin Strohecker and Jorgelina Do Rosario, "Congo Sees Deal on $6 Billion China Mining Contract Overhaul This Year—Finance Minister," Reuters, January 19, 2023.

[11] Michael Ross defines *resource* as "the claim that natural resource wealth tends to adversely affect a country's governance" (Michael L. Ross, "What Have We Learned About the Resource Curse?" *Annual Review of Political Science*, Vol. 18, May 2015, p. 239). See also Zhenqian Huang and Sebastian Vergara, "Harnessing the Potential of Critical Minerals for Sustainable Development," background paper, United Nations, Department of Economic and Social Affairs, May 2024.

[12] Local content requirements are generally inconsistent with World Trade Organization law, but there are emerging arguments for a legal basis for local content requirements for the purposes of development (Natália De Lima Figueiredo, *Local Content Requirements in WTO Law: Between Free Trade and the Right to Development*, dissertation, Maastricht University, September 14, 2022).

market prices. Consequently, considerable uncertainty and complexity characterize the critical mineral problem.

General Considerations for Strategic Planning in Developing Countries

Before delving into the technological factors affecting strategic planning in CMSCs, a review of generic considerations for long-term decisionmaking is appropriate. These considerations include risk, the limits of forecasting, and scenario-planning.

Risk

Investing in mining projects and related infrastructure can require hundreds of millions to billions of dollars. With such high capital costs, risk cannot be overlooked. We review four sources of risk:[13] the challenges of mining for economic development, shifting technological demand, international competition, and the governance of international trade and investment flows.

Challenges to the Use of Mining for Development

The mining sector poses unique challenges to leveraging mineral resources for sustainable economic growth, including investment in infrastructure. In many ways, mining companies are logistics companies—they require reliable and integrated transportation to move bulk products across vast distances. In developing countries, however, transportation infrastructure is often lacking and otherwise limited. Mineral deposits tend to be located in remote and hard-to-access areas, which further complicates logistical planning. Mineral processing also poses infrastructural challenges because of the significant amounts of water, energy, and power required to turn ore and brine into useful commodities and specialty chemicals. Many countries are not equipped to provide the level of reliable electricity that is needed to power refining and processing facilities.

The extent to which the mining sector can support local employment opportunities is limited. Large-scale mining projects tend to function as economic enclaves—they are capital intensive and often require imported technology, limiting opportunities for establishing backward linkages with the rest of the economy.[14] Studies that have looked at the local employment and economic effects of large-scale mining operations have had mixed findings, which suggests that new mining projects do not automatically result in positive local spillover effects.

In many developing countries, the biggest employers are not necessarily large, industrial-scale mines but the artisanal and small-scale mining (ASM) sector, which employs around 41 million

[13] We note that these are not the only sources of risk for developing countries hoping to leverage domestic mineral resources for development. However, these four categories best reflect the remarks made by our team at the United Nations EGM.

[14] Tim Wegenast, Mario Krauser, Georg Strüver, and Juliane Giesen, "At Africa's Expense? Disaggregating the Employment Effects of Chinese Mining Operations in Sub-Saharan Africa," *World Development*, Vol. 118, June 2019.

people worldwide, many of whom are women.[15] Unfortunately, the ASM sector is rife with challenges and misinformation that deter downstream manufacturers and consumers from engaging meaningfully. BMW, for example, stopped sourcing cobalt from the DRC because of perceived human and environmental risks, even though only about 8 percent of Congolese cobalt is sourced via ASM.[16] Mineral processing has its own limitations. Processing tends to be less labor intensive than mining but requires more technically complex skill sets. For countries with a limited skilled workforce, this might encourage companies to source skilled labor from abroad, undermining local employment opportunities.

An additional challenge is gaps in national and international regulatory systems. For example, initiatives aimed at formalizing the ASM sector require a trained workforce that is empowered to inspect sites and monitor for compliance, but these staff are often under-resourced. International finance also creates gaps, making it possible for multinationals to minimize potential payouts to host countries. For example, when Freeport-McMoRan sold a large cobalt mine in the DRC in 2016, the DRC government did not receive any tax revenue from the sale because what was technically sold were shares in a company incorporated in Bermuda.[17]

Finally, the negative ecological and environmental impacts of mining are well documented. Processing and refining involve an array of chemical waste streams that pollute. Extremely high energy requirements can also result in higher carbon footprints if local utilities rely on fossil fuels for electricity generation.

Shifting Demand from Technological Competition and Innovation

The energy transition that is underway is inherently a disruption of fossil fuel technology markets. In this period of disruption, a portfolio of clean energy technologies is receiving investment from both the public and private sectors with the expectation that some technologies may not gain traction. There is, therefore, a risk that investing in a particular mine to support the demand for one technology may see that demand evaporate when a competing technology surpasses its utility in the form of performance or cost-benefit trade-offs. This competition among substitutable technologies can occur at the final product stage or between components and even subcomponents.

For instance, LIBs are one type of energy storage technology used in EV production. Subcomponents of LIBs include cathodes and anodes. However, there is a variety of cathodes, each with a unique chemistry and associated mineral demand. Some cathode chemistries overlap in their mineral inputs and others do not.[18] Meanwhile, scientists and engineers are hard at work conducting R&D to produce novel chemistries that can substitute for existing cathode chemistries; others are

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[15] Fitsum Weldegiorgis, Lynda Lawson, and Hannelore Verbrugge, *Women in Artisanal and Small-Scale Mining: Challenges and Opportunities for Greater Participation*, International Institute for Sustainable Development, 2018.

[16] William Clowes, "BMW to Source Cobalt Directly from Australia, Morocco Mines," Bloomberg, April 24, 2019. See also Andrew L. Gulley, "China, the Democratic Republic of the Congo, and Artisanal Cobalt Mining from 2000 Through 2020," *Proceedings of the National Academy of Sciences*, Vol. 120, No. 26, June 2023.

[17] Thomas Wilson, "Congo Government Will Investigate, Tax Freeport Mine Sale," Bloomberg, May 13, 2016.

[18] Cathode chemistries with overlapping demand include lithium nickel manganese cobalt (NMC) oxide and lithium nickel cobalt aluminum (NCA) oxide. In this case, lithium, nickel, and cobalt are required for each. To complicate matters further, the NMC chemistry has several options, wherein the percentage of each chemical element varies. The lithium iron phosphate cathode chemistry does not require any nickel, cobalt, manganese, or aluminum. The only consistent chemical element is lithium.

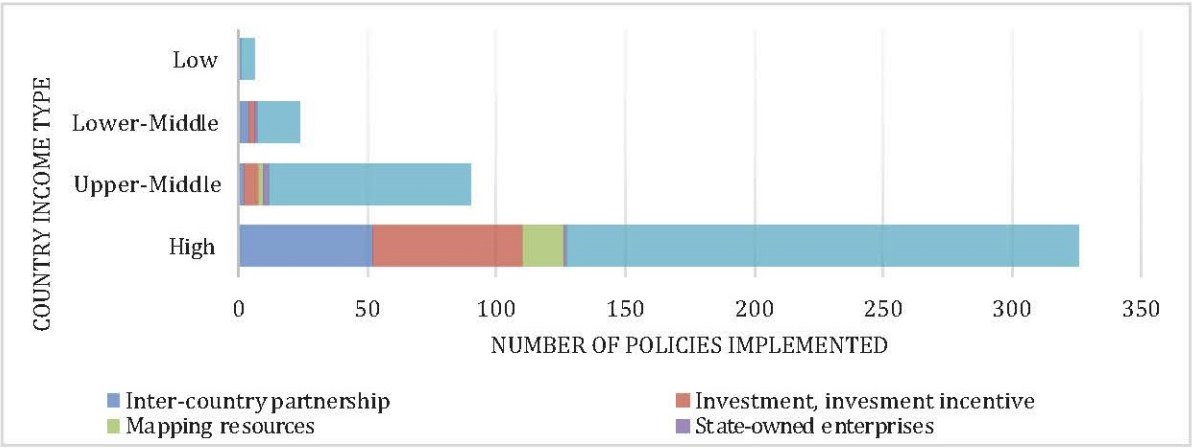
working to supplant LIBs altogether with new battery systems or alternative ways to store energy, such as compressed air or gravity storage. There is, therefore, a technological source for the deep uncertainty of long-term demand for some critical minerals, such as cobalt, manganese, or even lithium. This problem of substitutability will be the subject of more scrutiny later in this paper.

International Competition and the Desire for Market Share

The economies of many upper-middle–income and high-income countries participate in the auto and energy sectors. As a result, these countries are sensitive to changes in consumption that may affect their ability to compete effectively in global markets. Expectedly, these countries are also enacting legislation and policies to help maintain their economic competitiveness; an example of how Western countries are reacting is illustrated by the United States's Inflation Reduction Act.

Figure 1 indicates a correlation between country income and critical mineral policy activity. This pattern persists even when adjusting for the number of countries in each of the income categories. In other words, countries with the highest need for government support to build out their critical minerals sectors via industrial policies are also those with the lowest levels of government involvement in CMSCs.

Figure 1. Critical Mineral Policies, by Country Income Level



SOURCE: Adapts data from the International Energy Agency's Critical Mineral Policy Tracker (2022).

Many policies in high-income countries are oriented internally and aim to build domestic capacity, including upstream nodes of CMSCs, an area in which low- and middle-income, mineral-rich countries have historically held a comparative advantage (i.e., mining and processing). The investment policies of high-income countries—in the form of grants, loans, and credits—tend to focus on domestic rather than international capacity and capability development.[19] In the United States, for

[19] A number of agreements have been signed between high-income countries—particularly China, the United States, and the European Union—and developing countries. Some agreements discuss supporting local value addition, but it remains to be seen whether these partnerships will lead to positive development outcomes or perpetuate old patterns of resource exploitation.

example, the U.S. Department of Energy has invested billions of dollars in the form of loans and tax credits to support domestic critical mineral mining and processing.[20] These investments may compete directly with mineral-rich, low- and middle-income countries, affecting prices and, ultimately, the long-term profitability of mines.

Governance of International Trade and Investment Flows

There is an emerging view that the global, regional, and bilateral regime of international agreements and treaties governing cross-border trade and investment flows, cooperation in R&D, and transfers of technology needs to be modified to incorporate standards that are related to the United Nations Sustainable Development Goals (SDGs) regarding the extraction and processing of critical minerals in developing countries.[21]

It has been a practice for decades for parties to such instruments to update their terms for consistency with changes in the structure and conditions of the global economy. That is why, for example, several countries have in place model bilateral investment treaties that serve as templates for negotiation. It is in this context that modifications to the extant regime of international trade and investment agreements could be called for. What has yet to be articulated, however, are the most salient components that should be the focus of such modifications. To that end, the following questions should receive great attention:

- What specific institutional mechanisms or standards, for example the SDGs, should the parties to international trade and investment agreements employ to determine and modify the objectives of such agreements in light of prospective technological changes?
- Inasmuch as most cross-border investment agreements are *bilateral* and trade agreements tend to be *plurilateral*, how should such differences be factored into agreements to ensure consistency with such standards as the SDGs, which are *global* in nature?
- How can such agreements provide for robust frameworks that effectively transmit changes in demand for and supply of such minerals, so as to reduce sharp changes in prices and thus smooth out investment decisions over time?
- What governance regimes can be established among the parties to such agreements to mitigate, on a continual basis, ex ante disruptions and disagreements and what mechanisms should be employed to provide compensation when damages occur?
- How should such agreements support co-investments in production, R&D and technological advancements, storage, waste disposal, and the assessment of prospective changes in demand and supply in global markets?
- What process should be followed when new parties seek to become signatories or current parties wish to exit from agreements?

[20] U.S. Department of Energy, "Biden-Harris Administration Announces $4 Billion in Tax Credits to Build Clean Energy Supply Chain, Drive Investments, and Lower Costs in Energy Communities," March 29, 2024; U.S. Department of Energy, "Biden-Harris Administration Announces $15.5 Billion to Support a Strong and Just Transition to Electric Vehicles, Retooling Existing Plants, and Rehiring Existing Workers," August 31, 2023.

[21] Harry G. Broadman, Bruce R. Guile, David T. Delpy, and Albert P. Pisano, "Capitalizing on the G7 Research Compact," *Science*, Vol. 374, No. 6571, November 2021.

- Should the parties establish a panel of international independent experts to whom they can turn when seeking advice on changes to such agreements?

Forecasting Failures and Uncertainty in the Clean Energy Transition

Analysts have developed increasingly sophisticated energy models that incorporate uncertainty and explicitly account for a variety of possible futures.[22] These models also include deliberate methods to calibrate expert assessments because of well-known tendencies toward overconfidence.[23] Despite this progress, forecasts of energy technology changes remain projections of possible futures and not predictions. A brief history of energy forecasting failures provides implications for the sustainable development potential of critical minerals.

In 2000, Vaclav Smil reflected on decades of energy analysis and observed that "long-range energy forecasts show a remarkable extent of individual and collective failure."[24] Table 1 summarizes some examples of these failures, including several noted by Smil. For example, although the U.S. Energy Information Administration's (EIA) Annual Energy Outlook gives a range of primary U.S. energy consumption forecasts, its reference case scenario has until very recently been systematically high. As a case in point, in 2000, the EIA projected U.S. energy consumption in 2020 to be more than 120 quadrillion British thermal units (BTUs), while actual consumption has remained relatively constant since 2000 at near 100 quadrillion BTUs.[25]

[22] Leon Clarke, Yi-Ming Wei, Angel De La Vega Navarro, Amit Garg, Andrea N. Hahmann, Smail Khennas, Inês Margarida Lima de Azevedo, Andreas Löschel, Ajay Kumar Singh, Linda Steg, Goran Strbac, and Kenichi Wada, "Energy Systems," in Priyadarshi R. Shukla, Jim Skea, Raphael Slade, Alaa Al Khourdajie, Apoorva Hasija, Juliette Malley, Roger Fradera, Malek Belkacemi, Géninha Lisboa, David McCollum, Purvi Vyas, Minal Pathak, Renée van Diemen, Sigourney Luz, and Shreya Some, eds., *Climate Change 2022: Mitigation of Climate Change*, Intergovernmental Panel on Climate Change, 2022.

[23] Tamara Savage, Alex Davis, Baruch Fischhoff, and M. Granger Morgan. "A Strategy to Improve Expert Technology Forecasts," *Proceedings of the National Academy of Sciences*, Vol. 118, No. 21, May 2021.

[24] Vaclav Smil, "Perils of Long-Range Energy Forecasting: Reflections on Looking Far Ahead," *Technological Forecasting and Social Change*, Vol. 65, No. 3, November 2000, p. 251.

[25] EIA, *Annual Energy Outlook 2000 with Projections to 2020*, 1999, p. 3; EIA, "U.S. Energy Facts Explained," webpage, last updated July 15, 2024.

Table 1. Failures in Forecasting Future Energy Technology, Prices, and Supply

Year of Projection	Statement or Estimated Value(s) and Anticipated Year of Outcome	Too Optimistic or Too Pessimistic? Actual Outcome or Value(s)
1954	In an unspecified future year, "[i]t is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter"[a]	Too optimistic: Units 3 and 4 of Georgia Power's four-unit nuclear power plant—Plant Vogtle—came online in late 2023 and early 2024, respectively, at an estimated cost of $35 billion.[b]
1976	Primary energy derived from renewables globally in 2000: ~35 quadrillion BTUs per year[c]	Too optimistic: ~7 quadrillion BTUs per year[c]
1977	Global peak oil between 1990 and 2004: ~80 million barrels per day[c]	Too optimistic: 101.4 million barrels per day in 2023[c]
2003	"The [United States] is 'running out of [natural] gas.'"[d]	Too pessimistic: Domestic production of natural gas nearly doubles from early 2000s to 2023[e]

NOTE: ~ = approximately.

[a] This statement has been described as "a prediction for a fission utopia in the foreseeable future" rather than a reference to nuclear fusion technologies that obviously remain quite expensive, especially in the United States, where new plants have not come online in many decades. The author noted that this statement was a personal prediction and not the official statement of the U.S. Nuclear Regulatory Commission (Lewis L. Strauss, "Remarks Prepared by Lewis L. Strauss, Chairman, United States Atomic Energy Commission, for Delivery at the Founders' Day Dinner, National Association of Science Writers, on Thursday, September 16, 1954, New York, New York," September 16, 1954; Thomas Wellock, "'Too Cheap to Meter': A History of the Phrase," U.S. Nuclear Regulatory Commission, September 24, 2021).

[b] Units 3 and 4 were originally expected to cost $14 billion and be completed by 2017 (Amy, 2023).

[c] Smil, 2000.

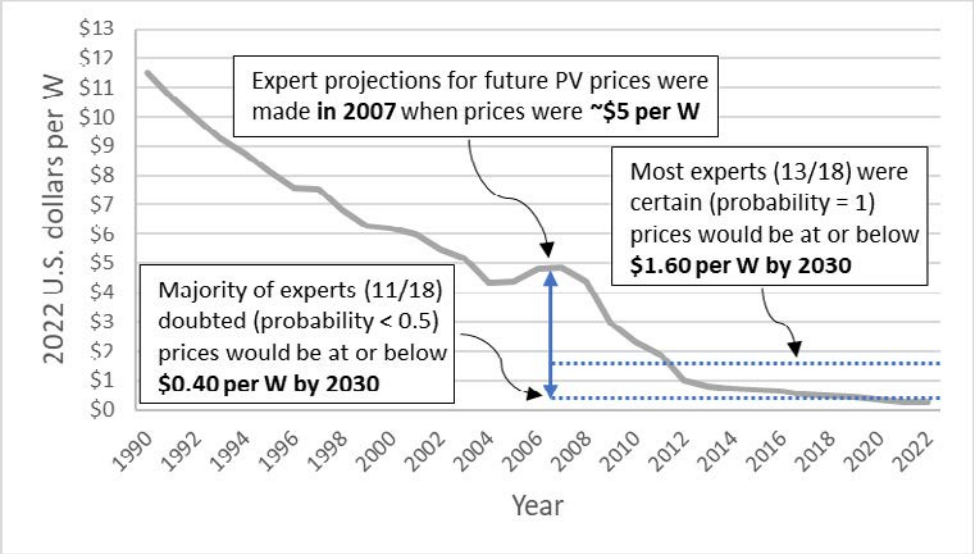
[d] Matthew L. Wald, "In Natural Gas's Future, Experts See More High Prices and Growing Imports," *New York Times*, June 27, 2003.

[e] EIA, "Natural Gas Annual," webpage, September 30, 2024.

Meanwhile, Figure 2 shows predictions by solar experts in 2007 for solar module prices alongside actual prices; in 2020, those prices dropped below the lower of two benchmark prices that were expected to be unlikely to be achieved by 2030.[26] Several of the solar experts (three of 18) gave less than even odds of reaching the lower price by 2050, and five of 18 solar experts expected only a 50 percent chance of reaching this benchmark.

[26] Aimee E. Curtright, M. Granger Morgan, and David W. Keith, "Expert Assessments of Future Photovoltaic Technologies," *Environmental Science & Technology*, Vol. 42, No. 24, December 2008; Hannah Ritchie, Pablo Rosado, and Max Roser, "Energy," webpage, Our World in Data, 2023.

Figure 2. Solar Photovoltaic Prices: Historical (1990–2023) and Expert Projections for 2030 (made in 2007)



SOURCES: Features data from Curtright, Morgan, and Keith, 2008; and Ritchie, Rosado, and Roser, 2023.
NOTE: W = watt. Benchmark prices from Curtright, Morgan, and Keith (2008) were converted to 2022 U.S. dollars.

In examples from the 1960s through the 1990s, Smil (2000) notes a propensity of forecasts to attempt to be too precise. But, even as modeling and expert elicitation techniques have become increasingly more sophisticated and as energy analysts have realized the need to explore a variety of future possibilities, there have been several failures to anticipate major technological progress. Natural gas extraction from shale deposits is one example. The combination of horizontal drilling and hydraulic fracturing was in its infancy in the early 2000s, and many experts were unaware of or unable to imagine the technology's potential. In another example, solar experts failed to anticipate substantial price reductions in incumbent silicon PV technologies. Instead, they expected less dramatic reductions made possible by then–emerging technologies, most of which are now considered to be commercially unviable at scale.

Scenario-Planning and Foresight

To quote U.S. President Dwight D. Eisenhower, "Plans are worthless, but planning is everything."[27] In the context of these past failures of imagination, developing countries should take today's projections for future energy production with a grain of salt. But in methods of decisionmaking under deep uncertainty, projections are useful for considering a range of demand for critical materials across scenarios. Similarly, the "all models are wrong, but some are useful" aphorism can highlight the

[27] Dwight D. Eisenhower, "Remarks at the National Defense Executive Reserve Conference," November 14, 1957.

need to set boundary conditions when approaching planning.[28] In this vein, many demand projections exist that can provide fodder for scenario-planning.[29]

When available projections are leveraged, methods of foresight can be instrumental in strategic planning initiatives. As opposed to forecasting, foresight does not aim to predict or project a singular future. Instead, foresight methods explore multiple plausible end states that may come about as a result of different realizations of currently uncertain (and often unknowable) driving factors. Foresight methods also explore alternative pathways toward the realization of these possible end states, allowing for consideration of how pathways may be altered by changing conditions, events, and, in some cases, policies.[30] Scenarios encompassing these end states and pathways can be used to depict futures with low mineral demand, high mineral demand, underdeveloped workforces, strict environmental regulations, conflict, technological disruption, or any number of barriers, complications, or benefits. Because there are multiple possibilities for disruption to mineral demand, it is necessary for planners in developing countries to assess how they might act in response to unexpected circumstances. For example, if seabed mining were realized, how would developing countries compete with new sources of material at potentially lower price points? Or what would the response be if technological changes, such as in battery technology, greatly reduced or increased demand for a specific mineral that is abundant in a developing country? Exploring these futures allows decisionmakers to consider actions that would help shape positive outcomes or hedge against negative ones when conditions change from those on which plans were based.

Technological Factors Affecting Mineral Demand and Strategic Planning

Developing countries looking to leverage their mineral resources will make decisions that will necessarily play out over decades—a time span during which technological revolutions and commercial upheaval have occurred in the recent past. The consistent production of extracted, refined, and processed minerals is required for governments to regularly collect revenue from rents and allocate this revenue as they see fit.[31] However, the consistent production of extracted, refined, or processed materials requires stability in multiple domains, such as stable transportation and logistics infrastructure (e.g., rail, ports, bridges, and highways); stable water, energy, and power distribution to mines, refineries, and manufacturing facilities; stable social environments that are free from civil unrest and conflict; and, finally, a stable demand signal for the minerals and associated products. This stable demand signal is vital for producing taxable rents that generate country revenues along with second-order economic impacts.

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[28] G. E. P. Box, "Robustness in the Strategy of Scientific Model Building," in Robert L. Launer and Graham N. Wilkinson, eds., *Robustness in Statistics*, Academic Press, 1979.

[29] For example, the International Energy Agency's annual report on global EV traditionally contains two demand scenarios. Other scenarios could leverage the Intergovernmental Panel on Climate Change projections.

[30] See Luke Georghiou, Jennifer Cassingena Harper, Michael Keenan, Ian Miles, and Rafael Popper, eds., *The Handbook of Technology Foresight: Concepts and Practice*, Edward Elgar, 2008, for descriptions of various methods and use cases.

[31] However, it is possible that declines in demand may be offset by rises in commodity prices, which would negate losses in revenue.

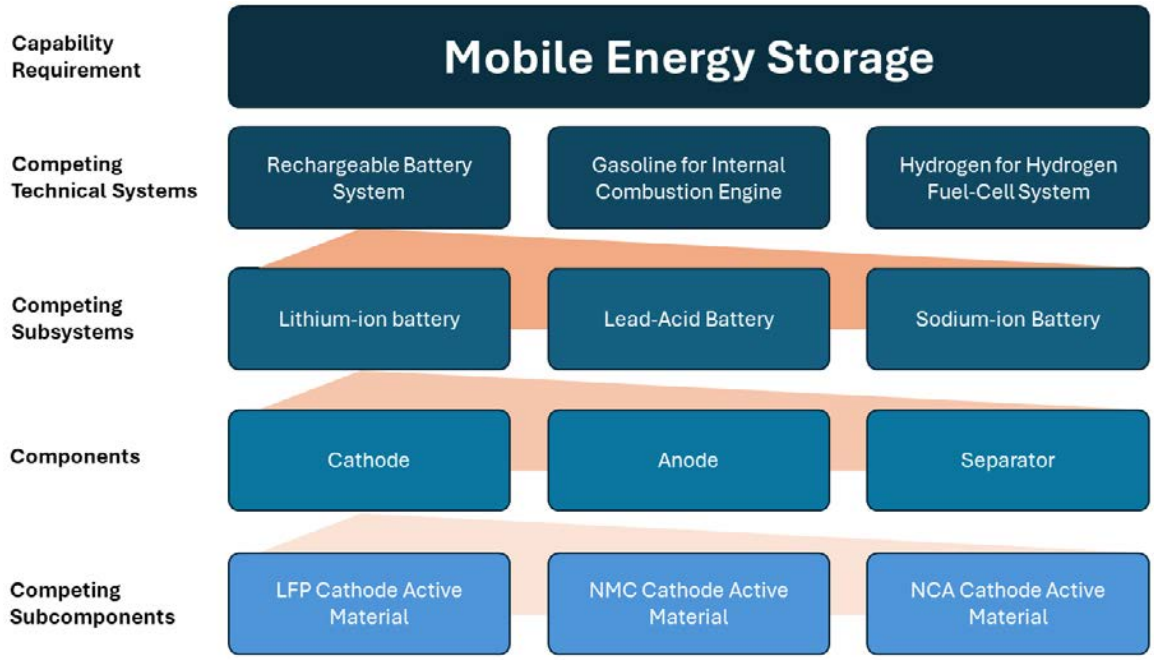
There are many factors contributing to the demand for mineral commodities, and chief among them are the various end-use applications. Changing technological trends in these end-use applications can have a profound impact on mineral demand, which creates uncertainty. As we reviewed earlier, making projections and predicting outcomes about future demand for and production of energy is fraught with difficulty. Instead, we highlight how monitoring mineral markets and technical trends can help policymakers better adapt when change is afoot and can provide data to inform resilient strategy formulation. We review five technological factors affecting demand for minerals:

1. efficiency gains
2. technology as a driver of commodity demand
3. total market size and possible growth or contraction
4. barriers to technology adoption and commercialization
5. technological disruption and commercial upheaval.

Before we begin this discussion, we describe how technologies compete for market share. Generally, manufactured products and systems compete to satisfy a capability requirement of an end-use application, such as providing electrical power to a neighborhood. Powering the neighborhood requires the capability to generate energy and distribute it when needed, which can also involve energy storage. That capability requirement can be filled by burning fossil fuels, such as in a coal-fired power plant, or by using a cleaner alternative, such as PV solar cells. In either case, a technical system is reliant on an underlying technology. Energy storage, when required, might involve the use of petroleum reserves, water in a hydroelectric dam, electrochemical energy in a battery pack, or hydrogen in a fuel cell.[32] Figure 3 provides an example of possible technology options for a mobile energy storage requirement and the resulting choices of systems and components.

[32] Other methods of energy storage include geothermal storage, air compression, and mechanical fly wheels.

Figure 3. Example of Technological Competition Substitution Space



NOTE: LFP = lithium iron phosphate. The figure does not present an exhaustive list of competing technologies.

Within a technical system, underlying technological subsystems can compete—for example, the selection of a battery system to meet a storage requirement might involve a choice between LIBs, lead-acid batteries, sodium-ion batteries, and several other available options. Within that underlying battery technology, components and subcomponents also compete for market share. In the case of LIBs, several varieties of cathodes and anodes are available. Dictating what technical system to use, which underlying technology to leverage, and which subcomponents will be incorporated into the design of that technical system are all part of the engineer's role in meeting a capability requirement articulated by consumer demand.

Efficiency Gains in the Mining Value Chain—Faster Mineral Discovery and Lower Costs

In the state of the mining industry at the time of this writing, the exploration and permitting of mines can take from several years to decades; meanwhile, extraction and processing operations require massive amounts of power and energy. Reducing the time it takes to begin operations and the amount of energy and power needed to conduct operations is thus a target for technological disruption. New market entrants will try to leverage any number of advantages when competing with market incumbents.[33]

[33] Michael E. Porter, "The Five Competitive Forces That Shape Strategy," *Harvard Business Review*, Vol. 86, No. 1, January 2008.

New technologies that detect mineral ores are on the horizon.[34] These technologies include the ability to discover and map mineral resources in the ground using new geophysical survey technologies combined with "[a]dvanced data analytics, geophysical modeling, and artificial intelligence."[35] By reducing the time for exploration, proving reserves may become less capital intensive and drive investment into the industry. It may also speed up the availability of new supply in the global market and pressure prices downward.

New extraction operational technologies are also on the horizon in the form of robotics and autonomous systems. These technologies can help with the efficient planning and operation of mines and increase safety by reducing human error.[36] Autonomous and robotic systems may also reduce overall workforce needs or otherwise promote demand for more-skilled labor to operate and maintain robotic and autonomous systems. Autonomous earthmovers are already being deployed by Rio Tinto, and Chinese firms are evaluating and deploying similar technologies.[37]

Diesel-powered truck fleets are a major source of emissions, accounting for 30 percent to 50 percent of a mine's total emissions.[38] These vehicles produce exhaust fumes that are poisonous to workers and require the construction of costly ventilation systems. Electric excavators, haulers, and other mining vehicles may help reduce the energy and power demands of mines and lower costs.[39]

New processing technologies, such as pulsed power comminution (i.e., the process of reducing the size of solid material via grinding, milling), could reduce the power requirements needed to concentrate mineral ores into more-valuable concentrates. Hydrometallurgical ("hydromet") processing technology could introduce similar efficiencies into the refining process.[40] Such efficient technologies may reduce water consumption and emissions from the fossil fuel sources typically used in lower-income countries.

Implications

The example of combined horizontal drilling and hydraulic fracturing for producing oil and natural gas in the United States and its subsequent role in transforming the United States from an energy importer into an energy exporter is illustrative of the possibility for new extraction technologies to disrupt supply and market power. New mining and processing technologies could lower emissions and improve environmental, social, and governance considerations for investors in the private sector.

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[34] Govind Friedland, briefing slides presented at 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development, "Session 2: Technological Change and Critical Minerals," May 29, 2024.

[35] Friedland, 2024.

[36] James Crowell, briefing slides presented at 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development, "Session 2: Technological Change and Critical Minerals," May 29, 2024.

[37] Rio Tinto deploys about 130 autonomous trucks in its iron ore operations (Rio Tinto, "Automation," webpage, undated). CHN Energy deploys autonomous earthmovers for coal mining ("Huawei, Zijin Mining & China Railway Demo Autonomous Mining Truck Fleet," International Mining, February 23, 2025).

[38] Nesimi Ertugrul, Ali Pourmousavi Kani, Miles Davies, Daniel Sbarbaro, and Luis Morán, "Status of Mine Electrification and Future Potentials," *2020 International Conference on Smart Grids and Energy Systems (SGES)*, Institute of Electrical and Electronics Engineers, 2020.

[39] Mine site routes are typically regular and repetitive, which allows for easier charging infrastructure planning and the management of fleet charging ("How Electrification Is Changing Mining," *New Scientist*, September 22, 2021).

[40] Friedland, 2024.

However, advances in operations technologies could also result in less workforce demand and a shift toward more-skilled workers, which may not benefit workforces in lower-income countries.

Technology as a Driver of Commodity Demand

Energy technology is one of many possible end-use applications for mineral commodities. If demand for a mineral primarily stems from one or very few end-use applications, that mineral demand will be more sensitive to changes in demand for the energy technology.

Lithium is a prime example of how demand for one mineral commodity or specialty chemical can be dominated by a single application—more than 74 percent of demand lithium is for batteries used in stationary or mobile energy storage.[41] Lithium demand is projected to continue to be dominated by battery manufacturing demand because of projected growth in the auto sector and elsewhere.[42] Because LIBs have a variety of subcomponents in cathodes and anodes, other minerals and metals will also be in demand, and changes in the market share for any individual cathode or anode subcomponent will have an associated shift in demand for their associated minerals.[43] But lithium is more essential to the operation of LIBs in a way that nickel, cobalt, or phosphate are not.[44] Being a required input that is independent of cathodes and anodes makes lithium more resilient to changes in the market share of any particular cathode or anode. This means that lithium extraction and refining are more resilient to changes in the LIB market.

Cobalt is also an instructive example. In 2023, battery demand accounted for nearly 71 percent of total demand for cobalt; 45 percent of total demand stemmed from EVs.[45] However, cobalt is a constituent of only some of the cathode chemistries competing for market share and is not foundational for the technology to function as lithium is.[46]

Copper is an example of a commodity with demand across multiple energy technologies and very little demand from any single energy technology.[47] Although copper is needed as a metal sheet to coat anodes with graphite and wire batteries into modules and packs, it is also needed to produce electric motors, to expand the electrical grid, and in construction more broadly. The total market share for

[41] Govind Bhutada, "Lithium Consumption Has Nearly Quadrupled Since 2010," Visual Capitalist Elements, April 13, 2022.

[42] "BMI Predicts Lithium Shortfall in 2025," MiningNewsWire, September 6, 2023.

[43] For example, if lithium NCA oxide cathodes capture market share, demand will also grow for these four minerals. If lithium iron phosphate cathodes gain market share, then demand for these three minerals will grow.

[44] Lithium ions shuttle back and forth between anodes and cathodes during the charge and discharge of a battery, respectively. The metal oxides, phosphates, and graphite that make up cathodes and anodes house lithium ions while charged or discharged. Cathodes and anodes can, therefore, be likened to a parking garage for lithium ions. Therefore, the parking garage can be made of different materials, providing room for different cathode and anode chemistries to compete as parking garage materials.

[45] Anna Fleck, "More Than Two-Thirds of Cobalt Is Used in Battery Production," Statista, September 24, 2024.

[46] As discussed earlier, the active materials of NMC and NCA cathodes depend on cobalt. Assuming a 100 kW-hour battery pack, a single EV can contain up to 20 kg of cobalt (U.S. Department of Energy, Vehicle Technologies Office, "Reducing Reliance on Cobalt for Lithium-Ion Batteries," April 6, 2021).

[47] In 2022, copper demand was slightly over 6 million metric tons compared with 68,300 metric tons for cobalt (Madhumitha Jaganmohan, "Demand for Battery Metals Worldwide in 2022 with Forecast for 2040, by Commodity (in 1,000 Metric Tons)," webpage, Statista, April 25, 2024).

batteries in terms of copper production is almost negligible in that sense.[48] Another difference is the demand for the specific product resulting from mineral extraction: copper metal. The demand for copper metal is broad and diversified across end-use applications. In the case of cobalt or lithium, the specialty chemicals and active materials that are in demand for batteries have little overlap with other commercial and industrial uses of those minerals. If there was a change in demand for LIBs—for example, from LIBs being supplanted by sodium-ion batteries or magnesium batteries—lithium and cobalt demand would be severely affected, but copper would still see substantial demand from its other end-use applications and, in all likelihood, would still be needed to produce the substitute battery system.[49]

Implications

Copper is more resilient to disruption in battery technology than lithium due to the diversity of its end-use applications. Because 70 percent of lithium demand stems from energy, with the potential for this percentage to grow as demand from the auto sector and elsewhere increases, lithium presents an opportunity for stable demand, stable growth, and stable revenue generation. Because lithium is foundational to the operation of LIBs of all varieties, the development of lithium resources can reduce risk. However, competing battery systems could pose a threat to lithium production in the future.

Cobalt is less resilient to changes in LIB demand because it competes with lithium iron phosphate, lithium manganese oxide, and other cobalt-free cathode chemistries. This is not to say that no country should invest in developing cobalt mines; however, a more thoughtful approach is needed to develop a cobalt mining investment strategy that is robust to an evolving market.[50] We discuss how to make strategic planning more robust in the final section, "Conclusions and Takeaways."

Total Market Size as an Upper Bound to Potential Growth

The total market size for a mineral provides an upper limit to the potential revenue to be extracted from mineral exploitation. Because of the high capital costs of transportation and energy infrastructure, workforce development, and regulatory oversight, there is a point of diminishing returns to supporting the development of mining and the refining of minerals and metals. If the total market for a mineral is too small, it simply will not produce the amount of revenue needed for sustainable development.

Consider the production numbers from the U.S. Geological Survey in Table 2:

[48] Statista, "Distribution of Copper Consumption Worldwide in 2022, by End Use," September 14, 2023.

[49] However, demand for the ultra-purified copper sheets used in LIB anodes may see a decrease in demand.

[50] A more robust strategy could include shaping and hedging actions to better prepare for fluctuations in demand and even potential loss of demand.

Table 2. Selected Examples of 2023 Mineral Demand

Metal or Mineral	Demand Quantity (thousands of metric tons)
Copper (ore)	27,000
Aluminum (metal)	70,000
Bauxite (ore)	400,000
Lithium (salt)	180
Cobalt (ore)	230
Rare earth oxide (ore)	350

SOURCE: Features data from U.S. Geological Survey, *Mineral Commodity Summaries 2024*, 2024.

There are orders of magnitude differences in demand for copper and aluminum compared with lithium or cobalt. The value of these extracted and refined quantities also fluctuates with global prices, which are volatile for many critical minerals.

Some critical minerals are coproducts of other minerals. This is the case for copper and nickel with cobalt, copper with tungsten, gold and antimony, and other pairings. Minerals that are coproducts make it difficult to target a specific mineral market, such as gallium or germanium, for development, and the coproducts are typically present in smaller quantities than the focal mineral product.[51]

Implications

In cases in which smaller volumes are traded, prioritizing the development of mineral deposits where coproduction can take place can help de-risk investments and increase resilience over the long term. If one of the coproducts has high enough demand, it can subsidize the extraction and separation of other critical minerals with smaller trade volumes or minerals with exposure to higher price volatility. Without the benefit of coproduction, mines dedicated to producing a single mineral are exposed to more risk.

Switching Costs—Barriers to Technology Adoption and Commercialization

There are many barriers to commercializing technology and convincing an original equipment manufacturer (OEM) to adopt a new technology into its product. We highlight an underappreciated barrier: *switching costs* or *manufacturing inertia*, the resistance to integrating a new technology into existing manufacturing systems and schemes. For example, billions of dollars in investment have been poured into gigafactories using manufacturing equipment and procedures to produce batteries with a chosen design. That manufacturing system of systems is based on battery formats or components that

[51] Gallium and germanium are often coproducts of aluminum and zinc.

are commonly used in mobile electronics and EVs.[52] The hardware that dominates a market at any one time is typically not the most advanced or state of the art; it is typically a few years behind due to the length of time needed to design, plan manufacturing processes and procedures, secure suppliers, train workers, set quality standards, and so on.

If a change in battery systems—or in a mobile energy storage capability more generally—is to be commercialized in the auto sector, that technology will need to do one of three things: (1) provide enough performance or cost benefit to convince an OEM to incorporate it into systems or products with *limited changes* to current manufacturing schemes, (2) provide enough performance or cost benefit to convince an OEM to *significantly change* its manufacturing processes and procedures, or (3) provide enough performance or cost benefit to convince a new firm to compete within the market.[53] In short, if a technology will require a new format or component, it will require associated design rework and systems integration work. These are stiff barriers to adoption even in the face of better capability, such as higher energy density, safety, or efficiency.

Implications

One example of such manufacturing inertia is faced by lithium-air batteries, which would require a ventilated system to ensure air is accessible to the battery cells. If technologies can overcome the switching costs of redesigning battery cells, modules, packs, and their manufacturing processes, then mineral demand may be affected—in this case, by the elimination of graphite in LIB anodes. Here, product and manufacturing standards developed by international standard-setting associations can play a major role in determining pathways to overcoming these barriers.

Technological Evolution and Commercial Upheaval—Substitution at the System Level

When a new technology finds a demand signal and gets past barriers to adoption by OEMs, true technological evolution and commercial upheaval are possible. In the case of LIBs, there are concerns of such a threat from sodium-ion batteries. Sodium-ion batteries offer a trade-off in terms of capability and cost—cheaper, more abundant materials, and safety in exchange for energy density.[54] Lower energy density means that sodium-ion batteries would take up more space to achieve similar levels of charge or range in exchange for room and weight in a system, such as a cell phone or vehicle. If the size of the system is kept constant, this could also force technical trade-offs elsewhere in the form of compute power in a mobile electronic device or the number of seats and storage space in a vehicle. Whether OEMs decide to make the switch will depend on what they perceive to be consumer preferences.

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[52] Common battery formats include cylindrical cells, pouch cells, and prismatic cells. Battery components include battery format casings; electrodes, such as cathodes and anodes; separators; current collectors; modules; and battery management systems.

[53] In the first instance, little change to production lines is needed to adopt the technology. In the second instance, many more changes may be needed, which increases the potential performance benefit or cost reduction needed to incentivize the switch to a new technology by a manufacturer.

[54] Michael Schirber, "Sodium as a Green Substitute for Lithium in Batteries," *Physics*, Vol. 17, No. 73, April 2024.

However, in applications in which energy density does not matter as much as the ability to store energy cheaply, this trade-off makes sense—for example, in such nonmobile applications as grid storage. At the time of this writing, LFP batteries have attained considerable market share.[55] But sodium-ion, iron-air, or other chemistries may take market share from LFP batteries in the future because of their less stringent size, weight, and power constraints and limited consumer preferences.

In applications in which consumer preferences aggregate toward a greater charge, faster charging, and more power and range, chemistries with higher quantities of transition metals, such as nickel and cobalt, will continue to persist and demand for LIBs may hold against price pressure from sodium-ion batteries.[56] For instance, a luxury auto company, such as Porsche or Mercedes-Benz, may wish to distinguish its brand by relying on LIBs with more expensive but capable cathode chemistries, such as NMC or NCA.

When there are firms with limited competition, OEMs play a large role in determining consumer preferences by dictating what consumers are offered. This can be the case when a new technology enters a market, but within an established market, consumer expectations have to be accounted for. Renewables are competing with fossil fuel electricity generation, which has been around longer. Gasoline- and diesel-fueled vehicles have been in use for more than a century and because of this longevity, consumers have been trained to expect EVs to meet a set of traditional requirements for a vehicle's range, price point, maintenance, and more. This precedent has led to EV range anxiety, an aversion to long charging times, and other negative reactions. In response, OEMs are trying to increase EV range and reduce charging time to replicate the "in and out in five minutes" fueling experience that consumers are accustomed to.

Implications

Areas without significant technical trade-offs and limited consumer preferences are where volume of supply and commodity prices may influence technological change and commercial upheaval more directly by challenging the profitability of OEMs. In the case of battery demand from grid storage, tracking advances in competing technical systems and alternative subsystems (battery systems) allows developing countries to better assess the risk posed to their mine development efforts. In the case of EVs, tracking consumer preferences across different auto price points may be a better path toward gathering similar insights.

Conclusions and Takeaways

Developing countries endowed with critical mineral resources have the potential for significant economic transformation during the energy transition that is underway. However, the path to development is strewn in uncertainty, particularly stemming from changes in technology trends that are affecting efficiencies and demand. Our team delivered remarks on these matters at an EGM hosted

[55] In 2024, that market share was 40 percent (Oskaras Alšauskas, Elizabeth Connelly, Mathilde Huismans, Ethan Jenness, Javier Jorquera Copier, Jean-Baptiste Le Marois, Teo Lombardo, Shane McDonagh, Vera O'Riordan, Apostolos Petropoulos, and Jules Sery, *Global EV Outlook 2024: Moving Towards Increased Affordability*, International Energy Agency, April 2024).

[56] A transition metal is any element located within Groups IVB–VIII, IB, and IIB or columns 4–12 in the periodic table.

by the United Nations's Department of Economic and Social Affairs. On the basis of those remarks, the following four themes emerged:

1. Governments of resource-rich developing countries should design a dynamic mineral development strategy that is responsive to technological trends, price volatility, and other relevant market conditions by using concepts from decisionmaking under deep uncertainty. This should include continuous monitoring and analysis to identify signals that may warrant a strategic pivot, switching from one approach to another as circumstances dictate; using hedging actions as precautionary measures to mitigate potential negative outcomes; and shaping actions as proactive steps to influence outcomes in a positive and desired direction.
2. Governments of resource-rich developing countries should raise their capabilities and capacities to engage more effectively in the governance of foreign investment in and international trade of such resources within their borders, especially with respect to achieving domestic economic growth and sustainability goals.
3. Foreign investors should take steps to better align their activities with the national development and sustainability goals of host countries, especially the impacts of the technologies being used in the processes of exploration, development, and refining and in the exportation of such resources from these countries.
4. International policymakers and multilateral economic development entities should increase their provision of technical assistance and related forms of support to resource-rich developing countries to ensure that there are ongoing, independent, and comprehensive assessments. This should be done to the degree that the extant international regime of disciplines and rules regarding foreign investment in minerals is enhancing transparency and competition and the meeting of domestic socioeconomic goals in light of the rapid advance in technologies that is accelerating demand for such resources.

There is potential for mineral resources to catalyze the development and uplift societies, but the resource curse threatens to entangle these countries in a web of economic stagnation, corruption, and, at the extreme, conflict. To navigate this precarious landscape amid shifting technological trends, these countries must devise strategies that are robust to uncertainty.

Central to a robust strategy are the concepts of hedging and shaping actions. *Hedging actions* are precautionary measures designed to mitigate potential negative outcomes, ensuring that countries remain resilient in the face of technical progress, market volatility, geopolitical uncertainties, and the policies of higher-income countries competing against them. *Shaping actions*, on the other hand, are proactive steps taken to influence outcomes positively, such as investing in infrastructure, enhancing governance, fostering transparent and equitable resource management practices, and funding an oversight workforce. Together, these actions form the backbone of a robust strategy that can adapt to changing circumstances and capitalize on emerging opportunities.

Achieving the desired economic growth from leveraging critical minerals requires a dynamic approach, one that is responsive to technological trends, price volatility, and other relevant market conditions. This necessitates continuous monitoring and analysis to identify signals that may warrant a strategic pivot, switching from one approach to another as circumstances dictate. As we mentioned in the previous section, this could include monitoring the following: the adoption of new exploration, mining, refining, and processing technologies by off-takers; technology demand as a driver of

commodity demand; total market size; the rate at which OEMs include new technologies across their product offerings; the growth of markets with room for technical trade-offs; and the progress of economic agreements and partnerships between trade partners.

These factors overlap with industry and market analysis conducted by mining companies operating in the jurisdictions of developing countries and policy initiatives in developing countries. To institutionalize the capability to conduct long-term planning or analysis, we offer some suggestions. Developing countries can mandate prospective companies to provide them with such analysis when they cannot produce it on their own as part of project development agreements. International collaborations between research institutes or public-private partnerships can be leveraged to supply policymakers in developing countries with such information. Developing countries can include requests for such analysis and training on a continuing basis in bilateral agreements or other partnerships with countries looking to diversify supply chains or support the development of projects with foreign ownership.

By embracing such flexibility with foresight, mineral-rich and developing countries can chart a course toward sustainable development, transforming their critical mineral wealth into a catalyst for long-term prosperity and avoiding the pitfalls of the resource curse.

Abbreviations

ASM	artisanal and small-scale mining
CMSC	critical mineral supply chain
DRC	Democratic Republic of the Congo
EGM	expert group meeting
EIA	Energy Information Administration
EV	electric vehicle
LIB	lithium-ion battery
LFP	lithium iron phosphate
NCA	nickel cobalt aluminum
NMC	nickel manganese cobalt
OEM	original equipment manufacturer
PV	photovoltaic
R&D	research and development
SDGs	Sustainable Development Goals

References

Alšauskas, Oskaras, Elizabeth Connelly, Mathilde Huismans, Ethan Jenness, Javier Jorquera Copier, Jean-Baptiste Le Marois, Teo Lombardo, Shane McDonagh, Vera O'Riordan, Apostolos Petropoulos, and Jules Sery, *Global EV Outlook 2024: Moving Towards Increased Affordability*, International Energy Agency, April 2024.

Baskaran, Gracelin, "Diversifying Investment in Indonesia's Mining Sector," Center for Strategic and International Studies, July 11, 2024.

Bhutada, Govind, "Lithium Consumption Has Nearly Quadrupled Since 2010," Visual Capitalist Elements, April 13, 2022.

"BMI Predicts Lithium Shortfall in 2025," MiningNewsWire, September 6, 2023.

Box, G. E. P., "Robustness in the Strategy of Scientific Model Building," in Robert L. Launer and Graham N. Wilkinson, eds., *Robustness in Statistics*, Academic Press, 1979.

Broadman, Harry G., Bruce R. Guile, David T. Delpy, and Albert P. Pisano, "Capitalizing on the G7 Research Compact," *Science*, Vol. 374, No. 6571, November 2021.

Clarke, Leon, Yi-Ming Wei, Angel De La Vega Navarro, Amit Garg, Andrea N. Hahmann, Smail Khennas, Inês Margarida Lima de Azevedo, Andreas Löschel, Ajay Kumar Singh, Linda Steg, Goran Strbac, and Kenichi Wada, "Energy Systems," in Priyadarshi R. Shukla, Jim Skea, Raphael Slade, Alaa Al Khourdajie, Apoorva Hasija, Juliette Malley, Roger Fradera, Malek Belkacemi, Géninha Lisboa, David McCollum, Purvi Vyas, Minal Pathak, Renée van Diemen, Sigourney Luz, and Shreya Some, eds., *Climate Change 2022: Mitigation of Climate Change*, Intergovernmental Panel on Climate Change, 2022.

Clowes, William, "BMW to Source Cobalt Directly from Australia, Morocco Mines," Bloomberg, April 24, 2019.

Crowell, James, briefing slides presented at 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development, "Session 2: Technological Change and Critical Minerals," May 29, 2024.

Curtright, Aimee E., M. Granger Morgan, and David W. Keith, "Expert Assessments of Future Photovoltaic Technologies," *Environmental Science & Technology*, Vol. 42, No. 24, December 2008.

EIA—See U.S. Energy Information Administration.

Eisenhower, Dwight D., "Remarks at the National Defense Executive Reserve Conference," November 14, 1957.

Ertugrul, Nesimi, Ali Pourmousavi Kani, Miles Davies, Daniel Sbarbaro, and Luis Morán, "Status of Mine Electrification and Future Potentials," *2020 International Conference on Smart Grids and Energy Systems (SGES)*, Institute of Electrical and Electronics Engineers, 2020.

Figueiredo, Natália De Lima, *Local Content Requirements in WTO Law: Between Free Trade and the Right to Development*, dissertation, Maastricht University, September 14, 2022.

Fleck, Anna, "More Than Two-Thirds of Cobalt Is Used in Battery Production," Statista, September 24, 2024.

Friedland, Govind, briefing slides presented at 2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development, "Session 2: Technological Change and Critical Minerals," May 29, 2024.

Georghiou, Luke, Jennifer Cassingena Harper, Michael Keenan, Ian Miles, and Rafael Popper, eds., *The Handbook of Technology Foresight: Concepts and Practice*, Edward Elgar, 2008.

Gulley, Andrew L., "China, the Democratic Republic of the Congo, and Artisanal Cobalt Mining from 2000 Through 2020," *Proceedings of the National Academy of Sciences*, Vol. 120, No. 26, June 2023.

"How Electrification Is Changing Mining," *New Scientist*, September 22, 2021.

Huang, Zhenqian, and Sebastian Vergara, "Harnessing the Potential of Critical Minerals for Sustainable Development," background paper, United Nations, Department of Economic and Social Affairs, May 2024.

"Huawei, Zijin Mining & China Railway Demo Autonomous Mining Truck Fleet," International Mining, February 23, 2025.

International Energy Agency, Office of Legal Counsel, *Introducing the Critical Minerals Policy Tracker*, November 2022.

Jaganmohan, Madhumitha, "Demand for Battery Metals Worldwide in 2022 with Forecast for 2040, by Commodity (in 1,000 Metric Tons)," webpage, Statista, April 25, 2024. As of May 5, 2025: https://www.statista.com/statistics/1451054/demand-battery-metals-worldwide-by-commodity/

Kim, Tae-Yoon, *The Role of Critical Minerals in Clean Energy Transitions*, International Energy Agency, revised March 2022.

Kinni, Theodore, "The Critical Difference Between Complex and Complicated," *MIT Sloan Management Review*, June 21, 2017.

Porter, Michael E., "The Five Competitive Forces That Shape Strategy," *Harvard Business Review*, Vol. 86, No. 1, January 2008.

Rio Tinto, "Automation," webpage, undated. As of March 10, 2025: https://www.riotinto.com/en/mn/about/innovation/automation

Ritchie, Hannah, Pablo Rosado, and Max Roser, "Energy," webpage, Our World in Data, 2023. As of May 2, 2025: https://ourworldindata.org/energy

Ross, Michael L., "What Have We Learned About the Resource Curse?" *Annual Review of Political Science*, Vol. 18, May 2015.

Savage, Tamara, Alex Davis, Baruch Fischhoff, and M. Granger Morgan, "A Strategy to Improve Expert Technology Forecasts," *Proceedings of the National Academy of Sciences*, Vol. 118, No. 21, May 2021.

Schirber, Michael, "Sodium as a Green Substitute for Lithium in Batteries," *Physics*, Vol. 17, No. 73, April 2024.

Smil, Vaclav, "Perils of Long-Range Energy Forecasting: Reflections on Looking Far Ahead," *Technological Forecasting and Social Change*, Vol. 65, No. 3, November 2000.

Statista, "Distribution of Copper Consumption Worldwide in 2022, by End Use," September 14, 2023.

Strauss, Lewis L., "Remarks Prepared by Lewis L. Strauss, Chairman, United States Atomic Energy Commission, for Delivery at the Founders' Day Dinner, National Association of Science Writers, on Thursday, September 16, 1954, New York, New York," September 16, 1954.

Strohecker, Karin, and Jorgelina Do Rosario, "Congo Sees Deal on $6 Billion China Mining Contract Overhaul This Year—Finance Minister," Reuters, January 19, 2023.

United Nations, Department of Economic and Social Affairs, "2024 DESA Expert Group Meeting: Harnessing the Potential of Critical Minerals for Sustainable Development," webpage, May 16, 2024. As of May 2, 2025:
https://www.un.org/development/desa/dpad/2024/2024-desa-expert-group-meeting-harnessing-the-potential-of-critical-minerals-for-sustainable-development/

United Nations, Economic Commission for Africa, "Centre of Excellence for Advanced Battery Research in DRC Officially Launched," April 22, 2022.

United Nations Secretary-General's Panel on Critical Energy Transition Minerals, "Background Paper for the UN Secretary-General's Panel on Critical Energy Transition Minerals," May 13, 2024.

U.S. Department of Energy, "Biden-Harris Administration Announces $15.5 Billion to Support a Strong and Just Transition to Electric Vehicles, Retooling Existing Plants, and Rehiring Existing Workers," August 31, 2023.

U.S. Department of Energy, "Biden-Harris Administration Announces $4 Billion in Tax Credits to Build Clean Energy Supply Chain, Drive Investments, and Lower Costs in Energy Communities," March 29, 2024.

U.S. Department of Energy, Vehicle Technologies Office, "Reducing Reliance on Cobalt for Lithium-Ion Batteries," April 6, 2021.

U.S. Department of State, Office of the Spokesperson, "The United States Releases Signed Memorandum of Understanding with the Democratic Republic of Congo and Zambia to Strengthen Electric Vehicle Battery Value Chain," press release, January 18, 2023.

U.S. Energy Information Administration, *Annual Energy Outlook 2000 with Projections to 2020*, December 1999.

U.S. Energy Information Administration, "U.S. Energy Facts Explained," webpage, last updated July 15, 2024. As of May 1, 2025:
https://www.eia.gov/energyexplained/us-energy-facts/

U.S. Energy Information Administration, "Natural Gas Annual," webpage, September 30, 2024. As of May 15, 2025:
https://www.eia.gov/naturalgas/annual/

U.S. Geological Survey, *Mineral Commodity Summaries 2024*, 2024.

Wald, Matthew L., "In Natural Gas's Future, Experts See More High Prices and Growing Imports," *New York Times*, June 27, 2003.

Wegenast, Tim, Mario Krauser, Georg Strüver, and Juliane Giesen, "At Africa's Expense? Disaggregating the Employment Effects of Chinese Mining Operations in Sub-Saharan Africa," *World Development*, Vol. 118, June 2019.

Weldegiorgis, Fitsum, Lynda Lawson, and Hannelore Verbrugge, *Women in Artisanal and Small-Scale Mining: Challenges and Opportunities for Greater Participation*, International Institute for Sustainable Development, 2018.

Wellock, Thomas, "'Too Cheap to Meter': A History of the Phrase," U.S. Nuclear Regulatory Commission, September 24, 2021.

Wilson, Thomas, "Congo Government Will Investigate, Tax Freeport Mine Sale," Bloomberg, May 13, 2016.

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