Evaluating National Security Imperatives of Critical Minerals and Technologies for the Low-Carbon Energy Transition

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1 Critical Minerals and the Low-Carbon Transition

The low-carbon energy transition will require the deployment of large amounts of technologies that have seen only limited penetrations up until recently, including renewable energy, battery storage and electric vehicles (EVs), and hydrogen-based industrial processes and transportation.[1] In contrast to the fossil systems that they will replace, these technologies are characterized by (a) reductions in recurring fuel inputs and a greater reliance on up-front capital investments, and (b) increases in the quantity and variety of minerals required, including those with relatively limited production to date. Most low-carbon technologies have multiple technology pathways, increasingly influenced by global minerals input prices and availability. Furthermore, the production chain of the mineral inputs to low-carbon technologies differ from fossil fuels in terms of their relative abundance and geographic concentration of extraction and processing, which will fundamentally alter the geopolitics of energy. In addition to uncertainties associated with technological availability, cost and performance, this transition therefore raises important national security questions.

Electric vehicle and battery storage have come to dominate the use of certain minerals (e.g., lithium, cobalt) and become a significant consumer of others (e.g., nickel), see Figure 1. Battery demand for EVs increased by 65% in 2022 alone, to 550 gigawatt-hours per year (GWh/yr), and could increase to 1200-3000 GWh/yr by 2030.[2] Grid battery storage additions increased by almost 80% in 2022, to around 50 GWh/yr, and could increase to 200 GWh/yr by 2030 and 400 GWh/yr by 2040.[3] Lithium is central to automotive battery applications (with efforts to improve the efficiency of its use), but the two competing mature technologies differ with expect to other mineral needs—notably, higher energy density cobalt chemistries vs. cobalt-free chemistries.[4] Grid storage is also currently dominated by lithium, though there is greater potential for alternatives given that energy density is a less important performance metric.

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[1] Nuclear, hydropower and biomass also figure prominently in many low-carbon energy transition scenarios, but their aggregate mineral requirements are significantly lower than wind and solar. See: IEA, *The Role of Critical Minerals in Clean Energy Transitions* (International Energy Agency, 2021).

[2] IEA; IEA, *Global EV Outlook 2023: Catching up with Climate Ambitions*, Global EV Outlook (International Energy Agency, 2023).

[3] IEA, *Global EV Outlook 2023*; IEA, "Annual Grid-Scale Battery Storage Additions, 2017-2022," International Energy Agency, 2023, https://www.iea.org/data-and-statistics/charts/annual-grid-scale-battery-storage-additions-2017-2022.

[4] DOE, "National Blueprint for Lithium Batteries 2021-2030" (Department of Energy, 2021).

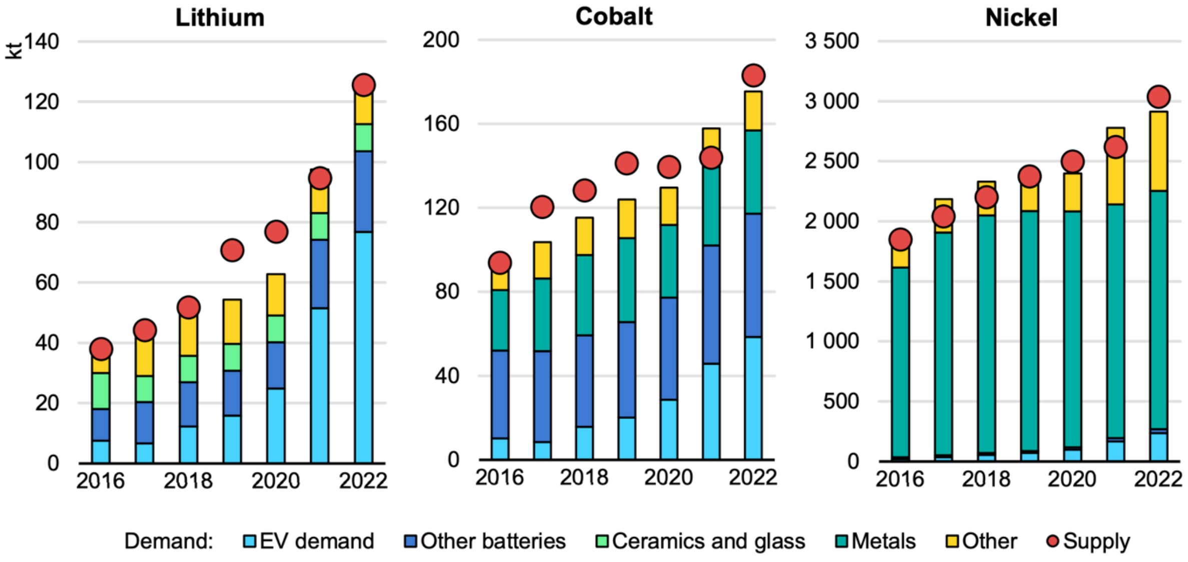

Figure 1. Demand and refining capacity for key battery-related minerals. Source: IEA[5]

Renewable energy technologies—notably, solar and wind—have unique minerals requirements, also heavily dependent on technology pathways. Globally, solar PV installations could increase three-fold by 2040, with the dominant technology (crystalline silicon, c-Si) leading to increased demand for silicon and silver, and the competing technology (thin film) requiring a range of other minerals, such as cadmium, tellurium, gallium and arsenic. Copper will increase across all solar technology pathways (including its use in inverters) and indeed across all renewable energy pathways given its use in grid infrastructure.[6] Wind installations could increase two- to three-fold by 2040, divided into more mature onshore and growing offshore markets. Minerals requirements increase dramatically with permanent magnet direct drive (PMDD) designs, a small fraction of the onshore market but a majority of the offshore market due to lower weight and maintenance requirements.[7] PMDDs rely on rare earth elements (REE), in particular neodymium, in the manufacture of its permanent magnets, a component that has received less attention though it is important to EV motors as well.[8]

Hydrogen could play an important role in the low-carbon transition as both an energy carrier (with certain advantages over electrochemical battery storage) and as a feedstock to replace coal and natural gas in many industrial processes. Minerals requirements are particularly salient for electrolyzers (to split hydrogen from water) and fuel cells (to recombine hydrogen into water generating electricity). High levels of nickel and zirconium are required for dominant electrolyzer designs while more advanced designs and fuel cells have important dependencies on platinum.[9]

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[5] IEA, *Global EV Outlook 2023*.

[6] IEA, *The Role of Critical Minerals in Clean Energy Transitions*.

[7] BNEF, “Wind Trade And Manufacturing: A Deep Dive” (Bloomberg New Energy Finance, 2021), https://www.csis.org/analysis/industrial-policy-trade-and-clean-energy-supply-chains.

[8] Damien Ma and Joshua Henderson, “The Impermanence of Permanent Magnets: A Case Study on Industry, Chinese Production, and Supply Constraints” (MacroPolo, 2021), https://macropolo2.wpenginepowered.com/wp-content/uploads/2021/11/magnet_final.pdf.

[9] IEA, *The Role of Critical Minerals in Clean Energy Transitions*.

For each of these low-carbon technologies, the global market for critical minerals is shaping future pathways. For battery storage, the high concentration of cobalt extraction in one country with significant geopolitical risk and human rights concerns, the Democratic Republic of Congo (DRC), is driving some of the shift to cobalt-free chemistries. The leading cobalt-free chemistry, lithium-iron-phosphate (LFP), also has some advantages in terms of durability, though with slightly lower energy density.[10] All commercial chemistries rely on lithium, which is why lithium prices have exhibited particular volatility in last two years, given the passage of large clean energy packages (see Figure 2).

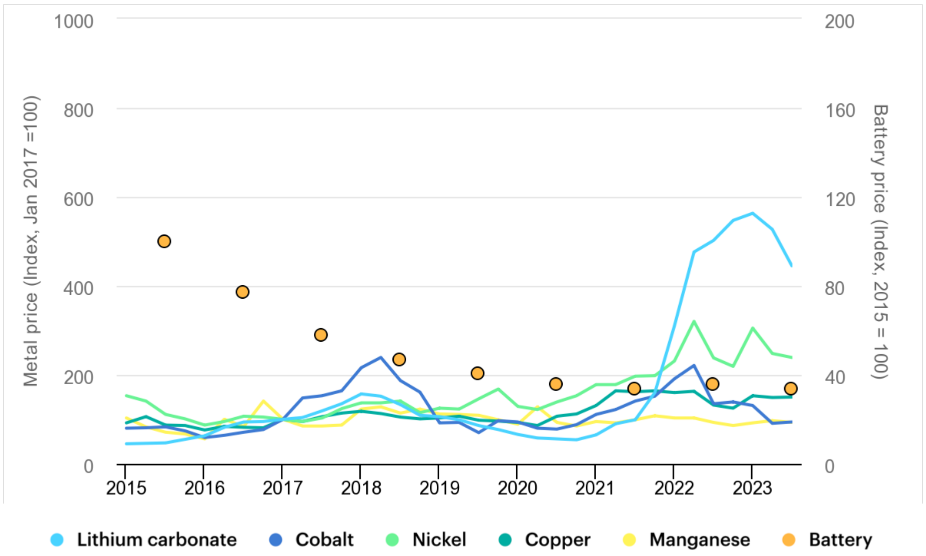

Figure 2. Prices for key EV-related minerals and batteries, 2015-2023. Source: IEA[11]

For solar, enthusiasm for alternatives to c-Si increased in 2008-9 when the global price for polysilicon skyrocketed, though after new polysilicon refining capacity came online in China, c-Si's advantage was cemented.[12] Silicon is the second most abundant element in the Earth's crust, but the high energy costs of purifying it for use in solar cells prompt searches for silicon-free alternatives. Wind turbines, permanent magnets, and electrolyzers all have similar trade-offs among cost, abundance and manufacturing intensity of minerals, and the performance attributes of the technologies they support.

The converse is true as well: low-carbon technology pathway uncertainty can shape some critical minerals markets and development. For example, lithium demand for batteries is eclipsing all other uses, such that the pace of the low-carbon transition and battery chemistries will be primarily driving its market. However, not all minerals face the same sensitivity: nickel is mostly used outside of the energy sector (e.g., to make stainless steel), and therefore, the clean energy transition has less impact on its overall market.

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[10] EVs with LFP batteries are dominant in China with reduced driving range. By contrast, cobalt chemistries power most EVs in the U.S.

[11] IEA, *Global EV Outlook 2023*.

[12] Gregory F. Nemet, *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation* (Routledge, 2019).

2 National Security Imperatives

The low-carbon energy transition generates or modifies national security concerns in three areas: preserving energy security, maintaining dual-use technological edge, and protecting critical infrastructures. First, **maintaining energy security** has long been viewed as a matter of national security due to its effect on the nation's economy and military deployments to safeguard global energy supplies. Energy security is defined by the IEA simply as the "uninterrupted availability of energy sources at an affordable price."[13] Historically, energy security has almost exclusively been applied to the case of dependence on imported fossil fuels, which require a near constant supply[14] and are highly exposed to political conflict in many major producing nations (e.g., Russia, Gulf states, Iran, Venezuela). Along traditional dimensions of energy security—maintaining consistent supply of fuels—most clean energy technologies (including renewable energy generators, electric vehicles, batteries, and nuclear power) fundamentally differ from their fossil counterparts. Once installed, these technologies do not require significant ongoing material inputs and could be operated for years or decades without imports, thus mitigating many energy security concerns.[15] There are calls to broaden the definition of energy security to recognize the increase in geopolitical fragmentation (addressed in the next section), national supply chain diversification efforts (discussed below), and climate change impacts.[16]

Within the context of the power grid, additional concepts and metrics of energy security arise, such as grid reliability ("the ability of the system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components")[17], and security of supply or resource adequacy (the ability to meet demand efficiently at different locations and over longer time horizons)[18]. Meeting short-term grid reliability does not require continuous inputs. Therefore, the supply of low-carbon technologies (and their minerals) could only generate energy security concerns for the power grid if there is not enough supply to deploy new equipment to keep up with increasing demand. However, over the time horizon of building new infrastructure (on the order of years), there is good reason to believe that fossil fuel reserves could be exploited in generating capacity that is under-utilized in relatively short time periods (days to months), without resorting to rationing.

Second, high-performance applications of clean energy technologies also affect assessments of **dual-use technological edge**, whereby technologies in the civilian arena are adopted for military use—with the objective of enhancing one's military capabilities while preventing access to those technologies by adversaries' militaries. Dual-use technologies can be subject to export controls (on domestic firms), investment restrictions (by foreign firms), and subsidies or domestic sourcing requirements (for domestic supply chains). An early study of green technologies

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[13] https://www.iea.org/about/energy-security

[14] Energy stockpiles are generally on the order of weeks to months at regular consumption levels, which could be extended longer through rationing. The IEA requires each member country to hold stockpiles of oil equivalent to 90 days of imports in a strategic stockpile, which could be released unilaterally or collectively, see: https://www.iea.org/about/energy-security/oil-security .

[15] Michael R. Davidson et al., "Risks of Decoupling from China on Low-Carbon Technologies," *Science* 377, no. 6612 (2022): 1266–69.

[16] Jason Bordoff and Meghan L. O'Sullivan, "The Age of Energy Insecurity: How the Fight for Resources Is Upending Geopolitics Essays," *Foreign Affairs* 102, no. 3 (2023): 104–19.

[17] DOE, "Quadrennial Energy Review: Transforming the Nation's Electricity System" (Department of Energy, 2017), 4–1.

[18] J. Ignacio Pérez-Arriaga, ed., *Regulation of the Power Sector* (London: Springer, 2013).

showed that less than 1% of exports in these areas were subject to export control license restrictions.[19] While this is dated and likely an underestimate due to not counting firms that did not attempt to apply for licenses, the impacts of export controls likely remain small.[20] Batteries for military applications also differ from the larger commercial markets in many specialized applications with improved performance: high energy density, the ability to withstand large temperature changes and extreme shocks, and resilient to long periods of dormant storage.[21] National security applications for batteries may eventually converge with commercial markets due to the relative ease of procuring from large markets—thus, reducing the dual use potential. Critical minerals extraction and processing technologies themselves would not be considered a likely area for export controls, given their maturity and widespread availability.

Ensuring access to critical minerals has prompted significant discussion about investments in mining, both domestically as well as in key resource extraction regions.[22] With part of the subsidies for EVs in the U.S. Inflation Reduction Act dependent on sourcing battery minerals from particular countries, this has prompted renewed interest in domestic mining for security reasons in addition to fiscal incentives. There is currently limited public data on the extent of battery needs across the U.S. military, though it is a small fraction of total demand.[23] Other critical minerals may have more unique or dominant applications in military applications unrelated to clean energy (e.g., in weapons systems), which necessarily raise more specific concerns about dual use.

By contrast, expanding clean energy adoption in forward operational contexts aligns with another important national security objective: improving military force capability through the reduction of vulnerable fossil fuel supply lines.[24] Thus, the low-carbon energy transition—regardless of the origin of the minerals—will likely have a net positive impact on military capabilities. For these applications, there is a greater security imperative to expand technological development and grow markets to provide sufficient supply.

Third, there is an imperative to **protect critical infrastructures**, technologies whose impacts on the economy and complex interdependencies present systemic risks from a loss of operational control.[25] Modern equipment connected to the electricity grid all have communication interfaces with some risk of cybersecurity attack (similar to the ransomware attack on Colonial Pipeline's natural gas network in 2021) or by hidden technology "backdoors" installed in the equipment by nefarious actors. Large power equipment can also be subject to physical outages, whether by nefarious actors or weather damage. In contrast to renewable power generation equipment, replacing power transformers at the 55,000 substations in the U.S.—if damaged—could create

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[19] This is a loose lower bound as it ignores exports that were not attempted due to the restrictions. See: Jennifer Watts and Kyle Bagin, "Critical Technology Assessment: Impact of U.S. Export Controls on Green Technology Items" (U.S. Department of Commerce Bureau of Industry and Security, 2010).

[20] Mark A. Cohen and Philip C. Rogers, "When Sino-American Struggle Disrupts the Supply Chain: Licensing Intellectual Property in a Changing Trade Environment," *World Trade Review* 20, no. 2 (May 2021): 238–57.

[21] DOE, "National Blueprint for Lithium Batteries 2021-2030."

[22] Agnes Chang and Keith Bradsher, "Can the World Make an Electric Car Battery Without China?," *The New York Times*, May 16, 2023, sec. Business, https://www.nytimes.com/interactive/2023/05/16/business/china-ev-battery.html.

[23] DOE, "National Blueprint for Lithium Batteries 2021-2030."

[24] The U.S. Marine Corps were one of the earliest to recognize this challenge, see USMC, "Expeditionary Energy Strategy Implementation Planning Guidance" (U.S. Marine Corps, 2009).

[25] DOE, "Quadrennial Energy Review: Transforming the Nation's Electricity System."

sustained power reliability challenges.[26] The DOE has begun formulating policies on cybersecurity and discourages utilities from purchasing grid equipment from China.[27]

Since the COVID-19 pandemic, **supply chain security** has also become an emerging policy area. In an executive order signed February 2021, President Biden defines the nexus with national security in terms of "critical manufacturing capacity and the availability and integrity of critical goods, products, and services."[28] The DOE and the Department of the Interior have responsibilities to define "critical materials" and "critical minerals" which include assessments of supply chain disruption risk and essentialness to energy systems.[29] Initial areas of focus relevant to the clean energy transition include high-capacity batteries, electric-vehicle batteries, and critical minerals and other identified strategic materials such as rare earth elements. Furthermore, President Biden invoked the Defense Production Act in support of domestic manufacturing of solar panels, building insulation, heat pumps, electrolyzers, fuel cells, platinum group metals, and transformers, arguing that unreliable supply constitutes a national security concern.[30] A wide range of countries including China, Indonesia and Chile have restricted exports or mandated domestic processing of some of their minerals, accentuating these concerns.[31] As domestic mining and manufacturing efforts develop amidst broader policy discourses of onshoring key economic sectors, it is becoming clearer that supply chain security cannot be an end itself—it exists in reference to something that is being secured. In the low-carbon energy transition, these will mostly relate to the first three imperatives outlined in this section.

3 Evaluating Geopolitical Risks

The low-carbon energy transition generates unique geopolitical challenges due to the different distribution and geographic concentration of exploitable critical mineral resources and their refining capacity. Most notably, while China is a net importer of coal, oil and gas, it is a net exporter—and in some cases, the leading global exporter—of processed minerals necessary for the transition (see Figure 3). Many minerals highlighted in the clean energy technologies above are also concentrated in a handful of geographies to a greater extent than fossil fuels, notably, DRC, Australia, China, Indonesia and Chile. When accounting for Chinese firms' overseas acquisitions in mining resources, the dependence on China is even greater.

In a prior study,[32] co-authors and I assessed the national security and economic risks stemming from U.S. integration (encompassing RD&D and supply chains) in low-carbon technologies with China, the world's leading supplier of many clean energy technologies. We analyzed five

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[26] https://www.niskanencenter.org/powering-the-nation-how-to-fix-the-transformer-shortage/
[27] https://www.energy.gov/ceser/securing-critical-electric-infrastructure
[28] The White House, "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth" (The White House, 2021).
[29] https://www.energy.gov/critical-minerals-materials
[30] The White House, "FACT SHEET: President Biden Takes Bold Executive Action to Spur Domestic Clean Energy Manufacturing," June 6, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/06/fact-sheet-president-biden-takes-bold-executive-action-to-spur-domestic-clean-energy-manufacturing/.
[31] Payne Institute, "The State of Critical Minerals Report 2023" (Colorado School of Mines Payne Institute for Public Policy, 2023).
[32] Davidson et al., "Risks of Decoupling from China on Low-Carbon Technologies."

technologies, representing three mature—solar PV, batteries, wind turbine system—and two emerging—green steel and carbon capture and sequestration (CCS)—through quantitative and subjective case assessments. I summarize the main national security findings in Table 1.

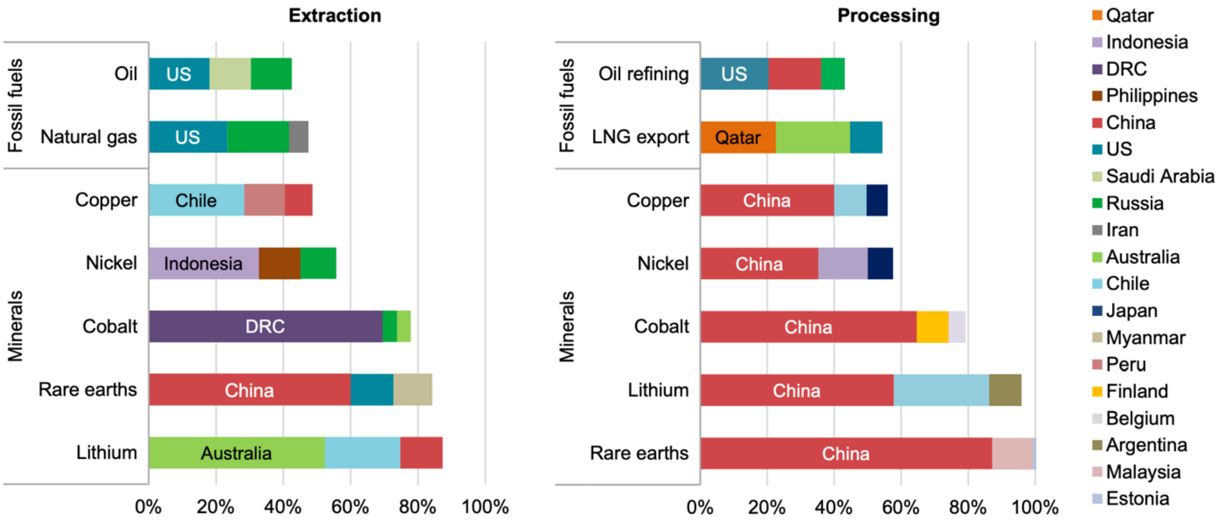

Figure 3. Critical minerals extraction and refining by country, 2019. Source: IEA[33]

National security risks for all five technologies are generally low. Wind turbine systems in the future may present medium level risks due to the potential for attacks on increasingly sophisticated software that facilitates integration of wind energy onto the grid. Similarly, except for batteries which have some high-performance military applications, the risks to dual-use technology development appear minimal. Energy security is neutral or enhanced by the further adoption of low-carbon technologies (described above), facilitated by integration with China.

Table 1. National security risks of integration with China in select low-carbon technologies. Source: Davidson et al.[34]

	Energy security	Dual-use	Critical infrastructure
Solar PV	Low	Low	Low
Batteries	Low	Medium	Low
Wind turbine system	Low	Low	Medium
Green steel	Low	Low	Low
CCS	Low	Low	Low

This analysis of select clean energy technologies reinforces the above discussion of national security imperatives, highlighting the comparatively low geopolitical risks associated with the

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[33] IEA, *The Role of Critical Minerals in Clean Energy Transitions*.
[34] Davidson et al., "Risks of Decoupling from China on Low-Carbon Technologies."

downstream low-carbon energy transition—and manageable risks where they do exist. Where clean energy technologies are also used for national security purposes, or where critical minerals have more concentrated downstream national security applications, additional risk assessments are warranted.

Besides the geopolitical risks of reliance on specific countries, not discussed here is the effect of geographic concentration of extraction or processing of critical minerals on risks to natural and human-caused disasters. For example, the COVID-19 pandemic revealed various previously unappreciated bottlenecks in supply chains for a variety of goods. The 2011 earthquake in Japan similarly has lessons for concentration and diversification.[35]

4 Policy Recommendations

1. *Strengthen militaries' supportive roles in the clean energy transition to further new technological development and continued cost declines.*

In the U.S. and likely other countries, the largest energy consumer within the government is the military, which creates unique dependencies on the clean energy transition. Where new energy technologies can enhance operational capabilities such as electrification and remote microgrids reducing vulnerable fuel supply lines, militaries will adopt mature technologies and likely expand RD&D efforts. Large-scale procurement of clean energy to reduce military's energy budget will also interact with learning and cost declines in the civilian sector, leading to an important supportive role for defense departments.

2. *Develop country-, and risk-specific national security threat assessments for individual low-carbon transition minerals.*

Overly broad national security risk assessments may dilute core military objectives and create burdens on the civilian development and adoption of clean energy technologies. Because of the challenges of identifying early-stage technologies that may eventually gain military applications as well as potential negative impacts on basic research, former Secretary of Defense Robert Gates has advocated for a "small yard, high fence" strategy when screening technologies. Similar principles should be developed for critical infrastructure, energy security, and supply chain security assessments. In particular, assessments are needed of the current and projected demands for minerals first for national security applications, which should guide considerations of securing diversified or domestic access to mineral extraction and refining capacity, followed by broader commercial procurement with security imperatives (e.g., critical grid infrastructure).

3. *Promote open mineral supply chains, where possible, to facilitate low-cost technology adoption, and diversification or domestic sourcing strategies where risks are deemed high.*

Current low-cost availability of clean energy technologies, including solar, wind and batteries, have relied on relatively unfettered global flows of capital, talent and technology. Policy recourses in perceived high-risk areas should carefully weigh the benefits of maintaining an open environment. In many cases involving supply chain disruption risk, a diversification strategy—

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[35] Caroline Freund et al., "Natural Disasters and the Reshaping of Global Value Chains," Policy Research Working Paper (The World Bank, 2021).

not a domestic onshoring strategy—may be sufficient. Similar to prior experiences with global fossil fuel markets, energy security is enhanced with interconnected global supply chains.[36] An overly strong emphasis on “mineral independence” may lead to less redundancy and ability to withstand shocks, whether natural or geopolitical.

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[36] Bordoff and O’Sullivan, “The Age of Energy Insecurity.”