A holistic and amalgamated approach is essential to tackling the challenges of critical materials.

Key Issues, Approaches, and Strategies to Ensure Reliable Critical Materials

Jennie S. Hwang (NAE) is CEO, H-Technologies Group.

Jennie S. Hwang

On top of global existential geopolitical environments and changing geopolitical forces, the protracted status of the Russia-Ukraine war since Russia invaded Ukraine on February 24, 2022, has elevated the uncertainty of materials and minerals. The Hamas attack on Israel on October 7, 2023, and subsequent attacks on ships in the Red Sea added further perils to the availability, reliability, and security of the global supply chain of materials and minerals. Critical materials and minerals that are the foundation of making essential goods have been sourced from war or near-war regions or unfriendly nations, which causes high-risk concerns. High-risk uncertainties have resulted in potential hazards that have drawn intense attention across the national landscape.

From a market-demand perspective, energy use, specifically electricity, will continue to increase. This is propelled by the phenomenal growth of power-hungry data centers (some new data centers requesting grid connections are as large as 500 megawatts), the increased deployment of potent artificial intelligence (AI) tools, the need for high-performance computing, and the push

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for electrification. These market forces created a heightened criticality for some materials and minerals, such as lithium, nickel, and some rare earth minerals.

Various efforts have been made on the national level to tackle the challenges of critical materials. Yet, to create a robust and integrated national strategy and its corresponding actionable plans in a deliberative, comprehensive, and speedy manner calls for a holistic and amalgamated approach. Such an approach will ensure economic prosperity, national security, and the nation's global competitiveness.

Critical Materials and Minerals Going Forward

Critical materials and minerals include those that are crucial ingredients for making indispensable products, materials and minerals that the United States has little control over due to the lack of domestic natural resources or the absence of domestic sources, or those that are imported from high-risk regions. Additionally, critical materials and minerals may also include those required for mission-critical end uses.

According to the Energy Act of 2020 (DOE 2024):

- A "critical material" is any non-fuel mineral, element, substance, or material that the secretary of energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy.
- A "critical mineral" is any mineral, element, substance, or material designated as critical by the secretary of the interior, acting through the director of the US Geological Survey.

The 2023 final critical materials list determined by the Department of Energy includes the following:

- Critical materials for energy, including aluminum, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide, and terbium.
- Critical minerals that include the following fifty minerals (per the secretary of the interior): "Aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium." (USGS 2024)

Examples of Critical End Uses

Nickel, lithium, and some of the rare earth elements are among the top critical materials due to their importance to energy, yet they bear the most supply risk. Figure 1 depicts the criticality matrix for the next decade (period of 2025–35).

AI is an effective tool that can benefit the entire ecosystem, from new material discovery to recycling efficiency.

Take nickel as an example. Its price has been uncharacteristically volatile during recent years: it soared to an uncontrolled spike on March 8, 2022, reaching the record $100,000 per metric ton on the London Metals Exchange (LME), and its price subsequently dropped (Khan and Wallace 2023). Nickel's dramatic pricing volatility made the LME pause trading on March 8, 2022. The LME resumed trading on March 16, 2022 (the episode caused a review by regulators and the LME and subsequent litigation). It is a warning signal, as pricing volatility is often an indicator of inadequate reliability and is often associated with undue market manipulations.

Nickel is not a "fancy" metal, but it is a key ingredient for stainless steel and lithium-ion batteries that power electric vehicles, among other end-use applications. Russia is a major supplier of nickel, not to mention the role of Russia in oil and gas and other minerals. China is another significant nickel supplier, and about two-thirds of the world's lithium and cobalt—essential for electric vehicles—is processed in China. Indonesia holds one of the world's largest nickel reserves.

As a key ingredient in making batteries for electric vehicles, cellphones, and laptops, lithium demand will reportedly quadruple by 2030.

Russia is also a major supplier of precious metals, including palladium, which is an essential element being used in catalytic converters and semiconductor manufac-

FIGURE 1 Criticality matrix – medium term. Source: DOE 2019.

turing. It is reported that about one-third of the world's palladium comes from Russia.

The United States is racing to catch up on rare earth supplies with China, among other countries, as rare earth minerals are in ever-greater demand for a variety of uses, including electric vehicles, offshore wind turbines, and permanent magnets. According to estimates from the US Geological Survey, the United States has consumed an annual average of 8,300 metric tons of rare earth oxides in recent years. Despite a falling share in rare earth production (figure 2), China still enjoys dominance in rare earth processing with a 90% market share and reportedly advantageous processing technologies. China has dominated every step in the process of making rare earth magnets. It is the only nation capable of producing the magnets from start to finish at scale.

Manganese is expected to grow sixfold over the next twenty years; it increasingly replaces more expensive and harder-to-source minerals such as cobalt and nickel in lithium-ion batteries. South Africa is the world's number one producer of manganese ore (Wexler 2023), but China refines more than 90% of battery-grade manganese.

Other metals have been heavily sourced from Russia, such as titanium, which is crucial for manufacturing jet airplanes and military aircraft. Because of its high strength, light weight, and corrosion resistance, titanium is a unique metal and cannot be readily substituted. Even though some materials may not risk direct exposure, indirect impacts are expected to trickle down throughout the global supply chain.

China produces 60% of the world's germanium and 80% of gallium, according to the Critical Raw Materials Alliance. Both elements are key to manufacturing electronics and semiconductors. Germanium is used in fiber optic products, solar products for space, and night-vision goggles, while gallium is a critical material for semiconductors to make key gallium compounds (e.g., gallium arsenide, gallium nitride).

Within the semiconductor industry, some sources of production raw materials are also concentrated in Russia and Ukraine. For instance, the two countries are major sources of neon gas, which is used for making circuitry on silicon. It is estimated that about one-fourth to one-half of the world's neon supply comes from Russia and Ukraine. Although neon gas is a small fraction of semiconductor manufacturing in dollar value, a close-knit operation cannot tolerate any missing link in the chain.

A Cross-Cutting, Concerted Approach

With the criticality for some materials and minerals identified and the list of critical materials and minerals defined, national strategy should take a cross-cutting, concerted approach. Its goals should include (Hwang 2022a):

1. To verify the natural resources of the critical materials and minerals.
2. To continue defining the effective sources of critical materials and minerals.
3. To ensure the secure availability of critical materials and minerals.
4. To tackle ongoing supply chain challenges.
5. To build the key capabilities and infrastructure of critical materials and minerals.
6. To anticipate future challenges related to critical materials and minerals.
7. To continue identifying actions and approaches that the government and the private sector can take to meet the goals collaboratively.
8. To verify the relative criticality of materials and minerals in the next decade and beyond.
9. To explore and innovate alternative materials and minerals for mission-critical end uses, leveraging both theoretical modeling and experimental techniques.
10. To strike a balance between economy and environment.

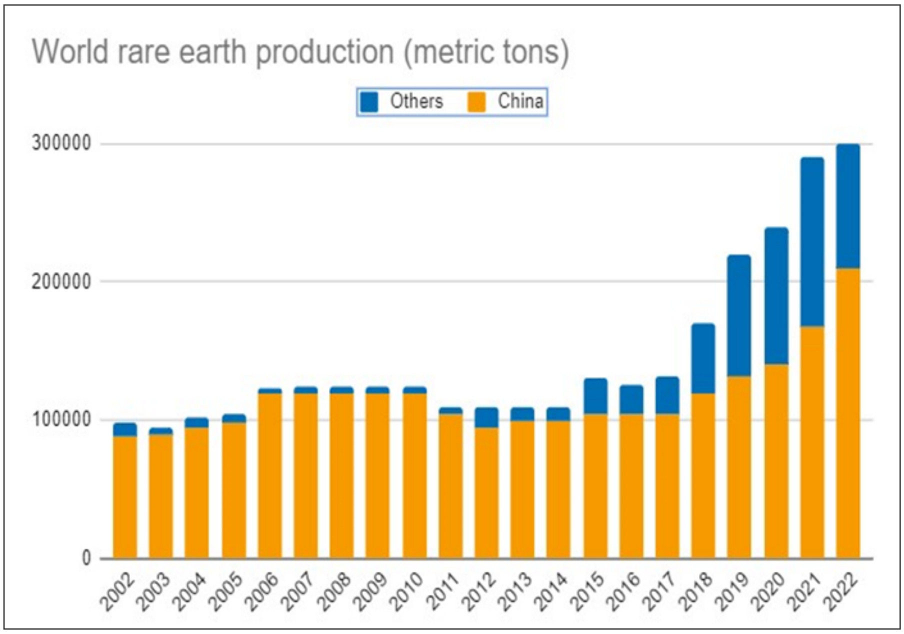

FIGURE 2 World rare earth production. Source: USGS 2024.

To fulfill the above ten multiple-front goals, it will take a concerted approach that offers a global perspective, a holistic thought process, integrated information, and collaborative action among the government, industry, and academia.

The Role of Business and Government

In business governance and management, long-term investment requires deliberations that spotlight reliable and secure critical materials. For instance, Exxon Mobil announced in November 2023 that it plans to drill for lithium in Arkansas and to start producing battery-grade lithium by 2027 (Eaton 2023). The company aiming to become a major US supplier for makers of electric-vehicle batteries by 2030 is a bright spot.

In corporate governance, critical materials should be a corporate board affair to be watched for in enterprise risk management programs.

In government and academia, the funding requirements, funding structure, and research priorities should be revisited with critical materials in mind, and actions should be taken accordingly (DOE 2019). The speed of implementation requires special attention.

Furthermore, an integrated cross-agency program relevant to the arena of critical materials and minerals is duly warranted to tackle the technologies, processes, and manufacturability effectively and speedily.

It is easier said than done, yet now is the time to act.

An Exemplar of the Concerted Approach

Back in 2013, four essential minerals were classified as "conflict," the word generally adopted by the government as well as the industry. These four essential elements—tantalum, tin, tungsten, and gold—have been key to a variety of end-use applications for a wide array of industries, ranging from electronics to industrial to consumers to avionics to military sectors. The primary mines of these four essential elements are situated in the eastern portion of the Democratic Republic of the Congo and the surrounding countries, and the minerals have been mined under the conditions of armed conflict and severe human rights abuses in the region. The region's armed militia groups intended to exploit the area's natural resources. This pervasive exploitation of natural mineral resources in this high-risk area caused grave concern for the international community about the region's activities. Accordingly, this region was deemed a "conflict region." At that time, the companies directly or indirectly sourcing from or directly operating in this region faced a higher risk of contributing to the conflict.

These concerns have spurred much debate, which has led to substantial activities in the US Congress dealing with the issues. After concerted work and planning, the Dodd-Frank Act passed in the US Congress and was signed into law on July 21, 2010. In August 2012, the US Securities and Exchange Commission (SEC) adopted a rule mandated by the Dodd-Frank Wall Street Reform and Consumer Protection Act, which requires companies to publicly disclose their use of conflict minerals that originated in the Democratic Republic of the Congo or an adjoining country. And the first required report must be filed by May 31, 2014. Basically, the US Conflict Minerals Law contains two requirements: independent third-party supply chain traceability audits and reporting of audit information to the public and the SEC. Dodd-Frank 1502 is a disclosure requirement and places no ban or penalty on the use of conflict minerals. However, a company is required to assess whether any conflict mineral was "necessary to the functionality or production" of a product manufactured or contracted for manufacture by the company. To comply with SEC regulation, whether a company that contracts out production holds influence over the item being contracted is also to be assessed and determined. Although it is not illegal to use conflict minerals, corporate social responsibility is on the line. The goal is to be "conflict-free." On this front, some corporations are leading the way. For instance, in 2011 Apple released its *Apple Supplier Responsibility* report, detailing how it traces its supply chain—first to the suppliers that created the subcomponents of their products and then to the smelters that processed the ores (Apple 2011). Intel has conducted on-site reviews of smelters as part of the Conflict-Free Smelter program. Since then, the conflict minerals have been "managed successfully" (Hwang 2013).

> *The identification of critical materials and minerals is the first step, not the endgame.*

The Role of Artificial Intelligence in Addressing Supply Chain Challenges

With the approach of managing "conflict minerals" as an exemplar, it is equally urgent, if not more, to rally another concerted effort to tackle critical materials and minerals. Recently, the overall supply chain has experienced unprecedented disruptions and hurdles as the result of a slew of factors. Simply put, the fundamental supply chain issues can be attributed to decades of globalization, off-shore manufacturing, and continuing and fast-paced technological changes, in conjunction with many diverse suppliers being embedded in each product. Consequently, managing today's global supply chain is a daunting task; securing reliable sources of materials and minerals requires an ongoing effort (Hwang 2024).

Take battery manufacturing as an example. The bulk of battery manufacturing occurs in Southeast Asia. Establishing supply chains for key materials, such as lithium-hydroxide, can take anywhere from three to seven years. With rising demands, multiple-front steps ranging from developing alternate supply sources to establishing strategic partnerships to innovating new materials and battery technologies should be the key path forward to ensure a secure supply chain and stable marketplace. For example, is a sodium-ion battery a viable alternative? Sodium is more abundant than lithium, less vulnerable to geopolitical challenges, and has a substantially lower cost (the price of sodium carbonate is $286/ton versus the price of battery-grade lithium carbonate, which is $20,494/ton).

AI is an effective tool that can benefit the entire ecosystem, from new material discovery to recycling efficiency. Taking one example, using AI and a supercomputer, Microsoft researchers were able to narrow down 32 million potential materials to 18 promising candidates in just 80 hours. Microsoft said, "*A new material, unknown to us and not present in nature,*" could potentially reduce lithium use in batteries by up to 70% (Microsoft 2024).

Semiconductor "chips" are another example. High computing chips (e.g., GPU, CPU, TPU) are not only hot in terms of market demands, but they are also literally hot in temperature. AI tools, to facilitate chip design and subsequent packaging, and PCB assembly, to facilitate thermal management and other performance parameters, are expected to boast the productivity and innovative products required by the continued advances in AI technology and AI tools. And AI can "reciprocally" help as an effective tool for chip design and manufacturing as well.

Developing and deploying AI tools in a timely manner to manage the supply chain will alleviate some of its bottlenecks. For example, a model that combines data with AI could predict unconventional deposits of rare earths and critical minerals.

Accordingly, to take a holistic view, the multifaceted strategies below warrant further deliberations and actions.

Critical materials and minerals will have an overarching impact on the global supply chain across all industries and all sectors. If one chain is broken, the whole system fails.

Multifaceted Strategic Deliberations

The essence of the US strategy should proactively focus on the endgame: how to become less vulnerable, more self-controlled, and more self-reliant, and how to be positioned for ready access with a competitive cost structure.

A sixteen-pronged strategy—to be further formulated, integrated, and advanced—may warrant further deliberate considerations (Hwang 2022b):

1. From supply-side consideration, a strategy to ensure a reliable supply of critical materials for which the US does not have adequate resources, especially for those materials that are abundant in countries that are or might be deemed existential or potential adversaries (Hwang 2021).
2. From demand-side consideration, a strategy to revisit and reidentify the critical materials and minerals.
3. From the perspective of a new world, a strategy to secure strategic materials and minerals by revisiting the criteria for defining strategic materials and minerals in the new world in terms of geopolitics and a new landscape in the continually changing digital era.
4. From the perspective of import-intensive metals, a strategy to "govern" the materials and minerals that essentially rely on imports (i.e., domestic production, mining, or refining is scarce or nil), particularly how to ensure resiliently cost-effective sources. This will engage the Department of Commerce, the International Trade Commission, and other federal agencies. What are deemed productive and effective policies and/or incentives to give companies that are in the position to produce the critical materials and minerals? A farsighted strategic calculus may need to be a variation of those in (1), (2), and (3).
5. From an economic standpoint, the role and positioning of technological overmatch for today and the future (e.g., five or ten years and beyond). A strategy to cultivate a sustainable ecosystem and infrastructure to transition critical materials to useful products, thus adding value to the national economic well-being.
6. From a national defense and national security standpoint, a strategy to transition the critical materials to the capabilities for national defense and national security, including combat capabilities, in the new multi-domain combat environment that the US Army and the Department of Defense have recently been focusing on.
7. From a national investment and international trade standpoint, under the increasingly clean-energy and environmentally conscious climate, a strategy for national investment to become more self-reliant or less import-dependent calls for an open debate. This requires engagement from multiple federal agencies and subordinate agencies.
8. To anticipate potentially emerging conflict minerals that are naturally abundant in conflict-affected and high-risk areas (countries, regions), the strategy to "manage" the current and potentially future conflict minerals calls for embracing both environmental and geopolitical considerations.
9. From a technology standpoint, incentivize developing game-changing technologies, leveraging both theoretical modeling and experimental techniques. One good example is the technology that enables the use of less-pure-grade (lower-cost) nickel for batteries (Hwang 2021).
10. From an alternative material standpoint, a strategy to invest in and develop technologies that are alternatives to currently defined critical materials that can meet the designated or target criteria.
11. From a competitive perspective, the plan is to leverage new and leading technologies, especially AI technology and AI tools, to speed up the discovery of new mining deposits of essential metals and minerals (e.g., Ni, Li, Co, Cu).
12. From the "*integrated bi-focus*" of environmental, climate-change, and economic standpoints with pragmatism, a strategy to revisit the priority of recycling and processing technologies to reduce import dependency and mitigate foreign-dependent vulnerability.
13. A strategy to advance recycling technology to build a true closed-loop system. For environmental enthusiasts, for example, metals such as steel and aluminum are important to advance renewable energy (perhaps counterintuitively).
14. Again, nothing can beat the relentless breakthrough innovation to either advance functions, reduce costs, or both. For example, explore the potential of nickel to be a catalyst in lieu of palladium in chemical reactions like cross-couplings. Its success will cut costs tremendously, not to mention the enhanced "security" of resources.
15. Semiconductor chips are "hot"—figuratively and literally—in terms of demands and the operating

temperature. To protect the "brain" that goes into all modern products, watch diligently for and act prudently on the materials going into chip (semiconductors) manufacturing. A sound strategy for what the role of the government should be and how it plays effectively.

16. From the point of view of the free market, a strategy to ensure that solutions are not worse than the problems is crucial to tackling the challenges of critical materials.

None of the above should be or can be viewed or attended to in isolation; the challenge is the action plan and execution to amalgamate them to reach a holistic national strategy to ensure a long-term robust economy and resilient national security.

Closing Remarks

The identification of critical materials and minerals is the first step, not the endgame; a key question is what the remedies or solutions are, both strategically and tactically, for near-term to long-term time horizons, to establish secure or alternate sources of critical materials and minerals. This calls for a decisive push forward.

Further diversifying the sourcing routes for key materials and developing alternatives to materials for industries that are highly dependent on imports from specific countries are in the works. As any alternate source of materials and minerals must go through a rigorous validation and verification process, the question is how long it takes to come up with a plan and take action, and whether it is "fast" enough. Additionally, in the long run, what kind of incentives can justifiably come from the government, both federally and locally?

Multiple initiatives to address the challenges of the global supply chain of goods are in progress. And yet, the supply chain of knowledge should be fortified in parallel. Managing today's global supply chain is a daunting task; securing reliable sources of materials and minerals requires an ongoing effort.

In a nutshell, sticking with the status quo is not an option; the reality remains the same: to deliver a holistic, all-encompassing approach by "amalgamating" strategic points 1–16 and other envisaged areas to reach a set of executable actions and to forthrightly act in a speedy manner.

The bottom line is to not rely on unreliable sources, and the ultimate challenge is to create preemptive solutions while not creating solutions that are worse than the problems.

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