COMPARATIVE STRATEGY
2025, VOL. 44, NO. 2, 281–315
https://doi.org/10.1080/01495933.2025.2456427

Routledge
Taylor & Francis Group



# Securing defense critical minerals: Challenges and U.S. strategic responses in an evolving geopolitical landscape

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**ABSTRACT**
The growing dependence on critical minerals (CMs) for advanced military technologies presents significant and escalating challenges for the United States (U.S.) and its allies. As global competition intensifies and supply chains remain vulnerable to geopolitical disruptions, securing a stable supply of defense CMs has become a top strategic priority. This article identifies key defense CMs, emphasizing their dual-use nature and the risks posed by reliance on adversarial nations such as China and Russia. It analyzes U.S. strategic responses and offers recommendations for balancing national security, economic feasibility, and sustainability in managing defense CM supply chains using a comprehensive approach.

## 1. Introduction

The growing reliance on critical minerals (CMs) for defense technologies has emerged as a crucial issue in global security. As the nature of warfare shifts from traditional large-scale military engagements to hybrid warfare, which combines conventional and irregular warfare with nonmilitary and influencing tactics and methods, the role of CMs in sustaining military superiority has expanded significantly. The United States (U.S.) sees the vulnerability of defense CM supply chains as a key concern, since potential disruptions threaten military readiness and the broader technological edge that underpins national security.

The strategic importance of CMs is highlighted by their indispensable role in a wide array of military applications. These include everything from precision-guided munitions and advanced communication systems to space-based military assets. In addition to defense technologies, CMs are essential for renewable energy technologies and electrification, where they are used in wind turbines, solar panels, electric vehicles (EVs), and energy storage systems.[1]

From the U.S. and broader Western perspective, securing a reliable and sustainable supply of CMs has proven difficult, particularly as global competition for resources

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intensifies and geopolitical tensions rise. Further complicating this challenge is the dual-use nature of many CMs, which are essential for both civilian and defense purposes. Furthermore, the classified nature of many military technologies obscures the true demand for CMs.

The current vulnerabilities in CM supply chains stem from decades of globalization and liberalization. In addition, historically, the maladaptive, short-term focus on outsourcing has prioritized economic efficiency and lower environmental standards over strategic resource sovereignty. This has left the United States and its allies increasingly dependent on foreign sources for essential CMs. This presents a complex challenge. Concurrently, the United States and allied nations must navigate the delicate balance between national security, economic feasibility, and environmental and social sustainability, a dynamic known as the "minerals trilemma."[2] Security is only one pillar of this trilemma, and for real security, it cannot be considered in isolation from broader economic and environmental factors.

While much of the existing literature on CMs centers around their role in the energy transition, and despite their critical importance to national security, the focus on defense CMs remains underexplored. The need for further research and strategic guidance is underscored by the changing nature of warfare, which increasingly relies on hybrid tactics, unmanned aerial vehicles (UAVs), cyber capabilities, robotics, autonomous systems, and artificial intelligence (AI). However, as Russia's full-scale invasion of Ukraine shows, mass remains as important as ever in modern conflict. This highlights the dual necessity of both advanced technology and the large-scale, secure supply of CMs to support defense capabilities and maintain military readiness in evolving warfare scenarios.

This article examines the critical challenges associated with securing defense CMs. It also evaluates U.S. strategic responses aimed at mitigating supply risks for defense CMs, ensuring long-term access to these vital resources in the face of evolving military technologies and geopolitical threats. The question remains whether the United States can respond swiftly and effectively to these vulnerabilities. While strategic initiatives are underway, it is unclear whether these efforts will be sufficient or timely enough to address the rapid geopolitical and technological shifts occurring in the global defense landscape.

The article proceeds as follows. The next section defines the concept of CMs and addresses their evolving classification and the factors contributing to their criticality (e.g. importance for economic and national security, supply chain risks, and geopolitical considerations). Next, it examines the significance of CMs for defense capabilities and national security, highlighting their indispensable role in advanced military technologies. The article then delves into the specific defense CMs, outlining their unique properties and applications across various defense platforms. This is followed by an in-depth analysis of the geostrategic vulnerabilities of defense CM supply chains for the United States and its allies, including the concentration of mineral production and processing in adversarial nations together with the complexities of securing resilient supply chains.

The subsequent section outlines the U.S. defensive policy responses to China's dominance in CM supply chains. This section of the article focuses on strategic initiatives and other legislative and international development efforts aimed at securing diversified, resilient supply chains for defense CMs; reducing dependence on adversarial nations; and reinforcing supply chain sovereignty by means of collaboration with allies and partners. The article also addresses the broader issue of the minerals trilemma, which highlights the need to balance national security, economic feasibility, and environmental sustainability. The article's analytical framework provides a comprehensive understanding of the defense CM landscape and offers policy recommendations for addressing future challenges, including concrete recommendations on how to secure a stable supply of these vital CM resources.

## 2. Why are minerals critical?

CMs generally refer to minerals essential for economic and national security that are subject to supply chain risks and vulnerabilities.[3] While economic and national security are often seen as separate spheres, economic security is increasingly recognized as a critical component of national security, particularly when disruptions in supply chains can directly impact defense and technological capabilities.[4]

The term "critical" in the context of minerals is a dynamic and subjective concept. The classification and perception of what constitutes a CM have evolved significantly over time and has been influenced by technological advancements, supply risks, geopolitical shifts, and economic demands. Minerals are often considered critical as a result of their unique properties, scarcity, and the lack of viable substitutes.[5] Criticality assessments require comprehensive and continuous data collection, which poses significant challenges because of the inherent uncertainties in mineral production and supply chains. This is compounded by the fact that many CMs are produced as by-products of other mining activities. This can further obscure CM supply dynamics and market behavior.[6]

Governments often produce official lists of minerals designated as "strategic" or "critical," while they implement hundreds of accompanying policies to enhance the resilience and production of CMs.[7] In the United States, the most recent CM list, published by the U.S. Geological Survey in 2022, includes 50 mineral commodities.[8] Moreover, Sections 7002(a) and (c) of the 2020 *Energy Act* define CMs based on their essentiality to economic or national security, vulnerability to supply chain disruptions, and their role in vital manufacturing processes.[9] Despite these guidelines, the literature offers little clarification or consensus on which minerals are critical, save for economic and national security categorization purposes.[10]

A strategic vulnerability is introduced into U.S. decision-making when policies devised for and subsequently applied to CMs lack a multilateral approach, since this exacerbates geopolitical tensions and fragmentation. One glaring example of the lack of multilateral cooperation on CMs is the simple fact that what minerals are regarded as "strategic" or "critical" varies from one country to another. One might think that this is because the components of advanced weapons and surveillance systems differ from one country to another, and, therefore, so do the CMs used to manufacture them, the more dominant reason for this discrepancy between countries' CM classificatory systems stems from supply chain issues. The classification of certain minerals as "critical" often arises because one country or another currently is heavily relying on importation to secure that mineral. For example, this is reflected in the European Union (EU) definition.[11]

In addition to their central role in the energy transition, CMs play a vital role in various strategic high-tech applications. For example, CMs are key components in the manufacturing of electronic devices, military equipment, and batteries.[12] The unique physical and chemical properties of these minerals—e.g. conductivity, magnetism, and strength—make them irreplaceable in many modern technologies.

The economic significance of CMs extends beyond their direct application in various industries. CMs are also pivotal in shaping a nation's economic stability and growth. But because the supply of CMs is often concentrated in specific geographical regions, significant geopolitical vulnerabilities arise. Nations heavily dependent on imports may face supply disruptions caused by market immaturity, high production costs, geopolitical risks, social unrest, natural disasters, mine accidents, and technological challenges in extraction and production.[13]

## 3. Clarification of terms and categories

As minerals have become more important geopolitically, various ways of classifying them have been introduced, and new terms have been introduced. The most obvious of these—CMs—are discussed above. Depending on the analytical frame and empirical context, in the scholarly and policy literature CMs have also been referred to as strategic minerals, critical energy transition minerals (CETM), and critical raw materials (CRMs).

Strategic minerals are commodities essential to national security, including both defense and economic stability, the supply of which during times of war or conflict is wholly or partially dependent on sources outside the United States.[14] In this article, strategic minerals can be considered synonymous with CMs, as both encompass a broader category that includes economic, industrial, and national security concerns. Defense CMs are a specific subset within this category, focused exclusively on minerals that are crucial for defense and military technologies, highlighting their essential role in maintaining military capabilities and readiness. CETMs refer to minerals vital for the construction, production, distribution, and storage of renewable energy and associated infrastructure, supporting the global shift to a low-carbon economy.[15] CRMs, a term widely used in the EU, refers to raw materials that are economically and strategically important, but which have a high risk of supply disruption due to their scarcity, geopolitical concentration, or complex extraction processes.[16] These are broader than CMs and may also include other types of commodities, such as food, that are critical for the functioning of economies and societies.

Another important term is Rare Earth Elements (REEs). At the outset, one must emphasize that CMs and REEs are not synonymous categories, with no strict one-to-one correspondence between them per se. REEs include 17 elements from the periodic table, specifically the 15 lanthanides, along with scandium and yttrium, known for their unique magnetic, luminescent, and electrochemical properties.[17] They are a subset of CMs, playing a vital role in industries such as defense, renewable energy, and high-tech applications. CMs encompass a broader range of minerals essential for industrial, economic, and defense purposes, beyond just REEs.

## 4. Significance to defense capabilities and national security

The unique properties and applications for CMs in advanced military technologies make them indispensable for defense capabilities and national security. CMs play a pivotal role in the defense sector and contribute to the development and maintenance of a wide range of sophisticated military technologies and capabilities. CMs support a wide range of military capabilities, from communications and surveillance systems to weaponry and protective gear. The crucial role of CMs in national security, military preparedness, and defense more generally is demonstrated by the fact that 40 raw materials are identified as "strategic" for the European defense industry.[18]

As military technology evolves, the demand for CMs is likely to increase, further highlighting their strategic value. Furthermore, the strategic significance of CMs in defense extends beyond their physical applications. For the United States and its allies, the secure and reliable supply of CMs is a matter of national security. This is because the supply chains for many CMs are concentrated in adversarial countries, which can lead to vulnerabilities in times of geopolitical tensions or supply disruptions. Ensuring a stable and secure supply of CMs therefore is crucial for maintaining national defense and security.

Historically, the role of CMs in defense has been evident during periods of war, when the supply and control of these materials directly impacted military strength and capabilities.[19] For example, tin and tungsten historically have been significant in boosting economies during wartime, particularly during World War II.[20] While the geopolitical and technological landscape has evolved significantly since then, this historical significance highlights how access to essential materials has always been a key factor in military success.

In modern times, the defense industry's reliance on CMs has grown even further with the advancement of technology and the changing nature of warfare. In today's increasingly complex global security environment, the nature of warfare is undergoing profound shifts. Traditional large-scale military engagements are being supplanted by hybrid warfare, cyberattacks, and asymmetric threats.[21] This evolution in the nature of war places a greater emphasis on advanced technologies and materials, including CMs.

The classification of "defense critical" minerals is complicated both by the evolving nature of warfare and by the dual-use potential of many CMs, which serve both civilian and military purposes. Minerals that are indispensable for electrification and renewable energy—e.g. lithium, cobalt, and nickel—also are crucial for military technologies, from energy storage systems in military vehicles to advanced electronic components used in communication systems and precision-guided weaponry. This dual-use nature blurs the line between civilian and defense applications and thereby complicates efforts to prioritize which minerals are essential for national security.

The defense sector's reliance on CMs is further obscured by the classified nature of many of their military applications. For example, REEs—e.g. neodymium and dysprosium—are crucial for producing sensors, semiconductors, and other high-tech equipment essential for both defense and civilian industries. The dynamic challenge of identifying defense CMs is intensified by the secrecy surrounding their usage in cutting-edge military technologies. Cyber and electronic warfare depend on materials not traditionally associated with defense, making the role of CMs in emerging technologies indispensable.

The interconnectedness of civilian and military industries creates both opportunities and risks: as global demand for clean energy technologies rises, competition for the same minerals essential to both sectors increases. The push for electrification in civilian sectors can strain already scarce mineral supplies, potentially jeopardizing defense needs if supply chains are not secured.

Given the dual-use nature of many CMs together with the changing character of warfare, the challenge for policymakers and defense planners is to ensure a stable and secure supply of CMs while also balancing competing demands from civilian sectors. As the demand for CMs grows across multiple industries, securing access to CMs becomes a matter of economic competitiveness and a core aspect of national security.

## 5. Relevant defense critical minerals

To address the growing importance of defense CMs, this section identifies the key minerals that are essential for maintaining U.S. military capabilities. It also highlights the specific role of these key CMs in defense technologies.

The effort to secure a stable and resilient supply of CMs is crucial for national security. This is demonstrated by the strategic significance of CMs in various military applications, ranging from precision-guided munitions to satellite communications. Emerging military technologies, such as hypersonic weapons, advanced missile defense systems, and AI-driven autonomous warfare platforms, further underscore the critical role of CMs in enhancing performance, precision, and durability.

Hypersonic missiles, for example, rely on advanced heat-resistant alloys containing niobium to withstand extreme temperatures during flight. Furthermore, neodymium and other REEs are crucial for the high-strength magnets in control systems.[22] Similarly, AI-driven autonomous systems, such as military drones and robotics, depend on REEs for sensors and advanced communication technologies.[23] These cutting-edge technologies are reshaping modern warfare, making the secure supply of defense CMs not only a priority but a necessity for maintaining military superiority in an increasingly competitive global landscape.

The REEs—in particular, dysprosium, praseodymium, and neodymium—arguably are the most significant defense CMs because of their unique properties and their indispensable roles in advanced military systems.[24] These minerals are integral to precision-guided munitions, radar, sonar systems, and night vision technologies. Moreover, REEs are critical in the production of permanent magnets used in military drones and electronic warfare equipment.[25] The defense sector's reliance on REEs underscores their strategic value, since their properties cannot easily be substituted.

In addition to REEs, other CMs are also vital for a wide range of military applications such as satellite communications, jet engines, missile guidance systems, and other advanced electronic and optical devices (see Table 1). Space-based military assets, such as satellites and direct-ascent antisatellite (DA-ASAT) weapons, are highly mineral-intensive, which further emphasizes the critical role of minerals in emerging defense technologies.[26]

**Table 1.** Strategic CMs for defense and military applications, and U.S. Import dependence.

| Critical mineral | Relevance for defense | U.S. net import dependence[28] | China and Russia's Rank in U.S. Imports[29] |
|---|---|---|---|
| Aluminum (Al) | Aluminum, known for its lightweight and strength, is widely used in military aircraft, vehicles, and ships. Its high strength-to-weight ratio makes it ideal for aerospace and defense applications, including high-performance alloys with lithium.[30]<br>Aluminum is also essential for producing UAVs and advanced alloys in military drones and communication infrastructure, underscoring its importance in modern warfare.[31] | 44% | China: n/a<br>Russia: 4th |
| Antimony (Sb) | Antimony is critical in defense, particularly for producing infrared detectors used in night-vision equipment and heat-seeking missiles.<br>Antimony also is key in manufacturing semiconductors, which are essential for advanced electronic devices in military communications and control systems.[32] | 82% | China: 1st<br>Russia: n/a |
| Beryllium (Be) | Beryllium is prized for its light weight and high stiffness, making it ideal for aerospace applications such as satellite and missile components regarding which structural integrity and lightness are critical.<br>Beryllium's resistance to extreme temperatures also makes it suitable for high-performance military aircraft and missile defense systems.[33] | 0% | n/a |
| Chromium (Cr) | Chromium is used extensively in the manufacturing of stainless steel and superalloys, which are critical for jet engines and turbine blades in military aircraft because of their corrosion resistance and ability to withstand high temperatures.[34] | 74% | China: n/a<br>Russia: 3rd |
| Cobalt (Co) | Cobalt is essential in producing high-strength alloys for jet turbines, rocket motors, and rechargeable batteries. Its magnetic properties are critical for electronic components and motors in military hardware.[35]<br>In the context of cyber warfare, cobalt's role in energy storage becomes even more vital. It ensures operational continuity in resilient power systems when asymmetric threats target communication and power networks.[36] | 67% | China: n/a<br>Russia: n/a |
| Copper (Cu) | Copper is highly relevant for defense and military applications because of its excellent electrical conductivity. This makes copper essential for wiring in military vehicles, communication systems, and advanced electronics used in defense technologies.[37] | 46% | China: n/a<br>Russia: n/a |
| Gallium (Ga) | Gallium is crucial in semiconductors, particularly gallium arsenide (GaAs) and gallium nitride (GaN), both of which are vital for radar and communication systems.[38]<br>Gallium's superior performance in high-frequency and high-power applications makes it essential for advanced electronic warfare systems and critical in countering cyberattacks and other asymmetric threats encountered during modern warfare.[39] | 100% | China: 2nd<br>Russia: n/a |
| Germanium (Ge) | Germanium is essential for infrared optics and night vision technology because of its transparency to infrared light. This makes it indispensable for thermal imaging systems in military surveillance and targeting.[40]<br>Germanium also is crucial for semiconductors used in high-frequency radar systems and communication devices, both of which are vital elements of electronic warfare systems.[41] | >50% | China: 2nd<br>Russia: n/a |
| Graphite | Graphite is essential for its use in high-temperature lubricants, nuclear reactors, and battery technologies. It also is a key material in the production of lithium-ion batteries, which are increasingly used in military applications because of their high energy density.[42] | 100% | China: 1st<br>Russia: n/a |
| Indium (In) | Indium is used in touch screens and LCD displays, which are integral components in modern military equipment ranging from handheld devices to control panels in vehicles and aircraft.[43] | 100% | China: n/a<br>Russia: n/a |

(*Continued*)

**Table 1.** Continued.

| Critical mineral | Relevance for defense | U.S. net import dependence[28] | China and Russia's Rank in U.S. Imports[29] |
|---|---|---|---|
| Lithium (Li) | Lithium's primary military use is in batteries, where its high energy density powers portable military electronics, including communication devices, night vision equipment, and guided munitions.[44] It is also used in high-performance alloys for aircraft and in nuclear reactor coolants.[45]<br>Lithium's importance in energy storage systems for military vehicles, drones, and communication devices places it at the core of defense strategies in hybrid warfare.[46] As militaries increasingly rely on battery-operated technologies for field operations and surveillance, lithium's role expands beyond traditional applications.[47] | >25% | China: 3rd<br>Russia: 4th |
| Manganese (Mn) | Manganese is critical for steel production and is used in steel alloys to improve hardness, stiffness, and strength. These properties are vital in military-grade steel used in the construction of armored vehicles and naval ships.[48] | 100% | China: n/a<br>Russia: n/a |
| Molybdenum (Mo) | Molybdenum is used in steel alloys to enhance strength and corrosion resistance. It is also important in the production of armor plating, aircraft parts, and naval ships.[49] | 0% | n/a |
| Nickel (Ni) | Nickel is vital in defense because of its role in creating superalloys used in jet engines and aircraft structures, in which context its ability to endure extreme temperatures and corrosive environments is critical.[50] It is also essential in armor manufacturing since it adds strength and durability to military vehicles.[51]<br>Nickel's conductive properties also make it integral to military electronics. Accordingly, nickel is a key component in nickel-metal hydride (NMH) batteries, which are known for their high energy density and resilience. NMH batteries are crucial for powering advanced communication systems and electronic devices.[52] In hybrid warfare, nickel-based NMH batteries enhance the resilience of military forces during cyberattacks, which can disrupt traditional power supplies.[53] | 57% | China: n/a<br>Russia: 4th |
| Niobium (Nb) | Niobium is utilized in the production of superalloys for jet and rocket engines, and for hypersonic missiles. This is because of niobium's ability to strengthen metals and withstand high temperatures.<br>Niobium also is used in the manufacturing of naval nuclear reactors.[54] | 100% | China: n/a<br>Russia: n/a |
| Platinoids (Platinum Group Metals) | The six platinum group metals (PGMs) are ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt).<br>PGMs are essential in various catalytic applications and are also used in fuel cells. Because of their efficiency and low emissions, the ability of fuel cells to function as military power sources increasingly is being researched, with development in this area already underway.[55] | Ru, Os, Ir: 0%<br>Rh: 60%<br>Pt: 83%<br>Pd: 37% | China: n/a<br>Russia: 1st (Pd) |
| Rare Earth Elements (REEs) | REEs are crucial for high-performance magnets such as neodymium iron boron (NdFeB) and samarium cobalt (SmCo), both of which are essential to military technologies.<br>NdFeB magnets, the strongest available, allow for smaller, lighter components in systems such as military drones, radar, satellite communications, and electronic warfare equipment.<br>SmCo magnets, which maintain strength at high temperatures, are used in precision-guided missiles, smart bombs, and aircraft.[56]<br>REEs' dual-use nature spans both civilian and military sectors. This further boosts the strategic importance of REEs, which have applications in missile guidance, command centers, lasers for mine detection, sonar systems, and cyber-defense platforms.[57] | >95% | China: 1st<br>Russia: n/a |
| Silicon (Si) | While silicon's role in semiconductor technology is commonly associated with civilian electronics, silicon is also critical for military applications such as guidance systems, communications equipment, and other electronic warfare technologies.[58] | <50% | China: n/a<br>Russia: 2nd |

(*Continued*)

**Table 1.** Continued.

| Critical mineral | Relevance for defense | U.S. net import dependence[28] | China and Russia's Rank in U.S. Imports[29] |
|---|---|---|---|
| Tantalum (Ta) | Tantalum's primary use in the defense sector is in manufacturing electronic capacitors for military communications equipment, radar, and advanced electronics, primarily because of tantalum's high melting point and resistance to corrosion.[59]<br>Tantalum is also crucial for capacitors used in high-frequency electronics and cyber-defense systems.[60] In hybrid warfare, where advanced electronic systems are essential, tantalum's role in providing reliable, heat-resistant components becomes even more critical. | 100% | China: 1st<br>Russia: n/a |
| Tin (Sn) | Tin is used in various alloys and soldering materials essential for electronic components in military equipment.[61] | 74% | China: n/a<br>Russia: n/a |
| Titanium (Ti) | Titanium is essential in defense for its strength, lightweight, and corrosion resistance. It is used in aircraft, naval ships, and armor plating.[62]<br>Titanium's high performance in extreme conditions also makes it invaluable for military aerospace applications.[63] | >95% | China: n/a<br>Russia: n/a |
| Tungsten (W) | Tungsten is known for its high density and melting point, which makes it ideal for use in armor-piercing ammunition, missile components, and other applications that require durability and heat resistance.[64] | >50% | China: 1st<br>Russia: n/a |
| Vanadium (V) | Vanadium is used in the production of strong, corrosion-resistant alloys for aerospace and defense applications. Its alloys are essential in jet engines and high-speed airframes because of their ability to maintain strength at high temperatures.[65] | 58% | China: n/a<br>Russia: 4th |

The list of CMs in Table 1, while not exhaustive, highlights minerals identified in existing literature as particularly critical for defense. This is primarily because of these CMs' unique properties, specialized functions, and versatility.[27] Of strategic importance, the CMs listed in Table 1 are indispensable in the development and maintenance of modern military technologies across various defense platforms and systems, including the evolving landscape of hybrid warfare, cyberattacks, and asymmetric threats. Some of these minerals are critical not just for conventional defense technologies but also for ensuring security in emerging conflict domains in which technological superiority is key. Of note, while the best effort has been made to review the literature and identify the minerals critical for defense, the classified nature of many military applications makes this task inherently challenging.

## 6. Geostrategic vulnerabilities of defense CM supply chains

The geostrategic and supply chain issues surrounding CMs are critical for national defense strategies, particularly because the world is rapidly changing as a result of the lingering effects of the COVID-19 pandemic, Russia's full-scale invasion of Ukraine, and broader geopolitical trends of deglobalization and increasing emphasis on sovereignty.

Defense CM supply chains are vulnerable to several risks, including the concentration of production in adversarial nations, disruptions from geopolitical tensions, and the challenges of securing resources for both civilian and military applications. The limited availability of defense CMs, together with the complexities of their extraction and processing, makes ensuring a stable supply difficult. Countries heavily dependent on imported CMs are strategically vulnerable, which highlights the need to develop robust and resilient supply chains.[66]

Geopolitical risks, market volatility, and socio-environmental impacts further complicate any analysis involving CMs and more specifically defense CMs. These factors impact both the availability and cost of CMs and defense CMs, which significantly impacts military readiness. Furthermore, beyond military readiness, vulnerabilities associated with CMs impact economic security and the resilience of the defense industrial base. It therefore is imperative and urgent that the United States and allied nations reassess their supply chains for CMs and especially defense CMs, given the rapid acceleration of major shifts in global geopolitical dynamics.

Table 1 underscores the critical role that certain minerals play in U.S. defense capabilities. It also highlights how reliant the United States is on imports of CMs, and the significant geopolitical risks associated with securing a steady supply.

Many of the CMs and especially defense CMs crucial for military applications are imported from countries that are not allied with the United States, specifically China and Russia. This reliance is the definition of a geopolitical risk. For example, the United States is >80% reliant on imports for defense CMs which include antimony, gallium, graphite, indium, manganese, niobium, platinum, REEs, tantalum, and titanium—and China is the dominant supplier for many of these. China supplies the United States with most of the REEs that are essential for high-performance magnets used in drones, radar systems, and satellite communications. Similarly, China is the top supplier for tungsten, antimony, and other key materials that are integral to military technologies. Russia also plays a significant role in the global supply of certain CMs. It is the largest supplier of palladium, and it also ranks as a top producer of aluminum and nickel. U.S. reliance on Russia for minerals such as palladium, which is crucial for advanced military communications systems, radar, and other critical electronic warfare equipment; nickel, which is crucial for military-grade steel and jet engines; and aluminum, which is vital for lightweight military aircraft and UAVs, have presented a major vulnerability, especially considering the ongoing war in Ukraine. Notably, in April 2024, the United States prohibited the importation of aluminum, copper, and nickel of Russian origin.[67]

In both cases—China and Russia—it is difficult to imagine how the United States could engage in a prolonged conflict, whether by coming to the defense of an ally or responding after being attacked, without facing significant challenges in securing the CMs crucial to advanced weapons systems. The ability to replace these sources under such circumstances would be critical, although a crisis could prompt a more permissive regulatory environment to facilitate domestic production. U.S. and European reliance on imports and supply chain vulnerabilities remain acute, but it is important to recognize that this dependence creates vulnerabilities for China and Russia as well, which could shape the geopolitical dynamics and influence the course of the conflict.

China's dominance in the global supply of CMs amplifies the supply chain vulnerability for the United States and its allies. Beijing's control over the refining and processing of several CMs vital to various high-tech applications presents a significant strategic challenge for the U.S. defense sector.[68] In 2024, China was the top producer of 30 out of 44 critical minerals for which reliable production data was available.[69] China is the world's largest producer and refiner of REEs, accounting for 69% of global production and 90% of refining and processing.[70] China also refines 73% of cobalt, 40% of copper, 59% of lithium and 68% of nickel.[71] Additionally, China plays a significant role in manufacturing battery cell components, including 70% of cathodes, 85% of anodes, 66% of separators and 62% of electrolytes.[72] According to the U.S. Geological Survey data, China accounted for 70% of REE imports into the United States between 2020 and 2023.[73] During the same period, the United States relied on China for 21 mineral commodities deemed critical, indicating a net import reliance of over 50% for these specific minerals.[74] The EU relies on China for its CM imports even more than the United States.[75]

Import reliance on China, exposes the United States and its allies to potential supply chain disruptions during times of escalating geopolitical tensions—and it exposes the United States and allied nations to supply chain "turn offs" in the force of export bans by China in the event of particularly tense geopolitical circumstances and/or in the event of a war. There are precedents. In 2010, following an escalation in the Senkaku Islands dispute, China imposed a ban on exports of REEs to Japan.[76] In 2019, China raised the issue of REEs during trade negotiations with the United States, which prompted the latter to seek alternative sources.[77] There also have been instances where China threatened to cut off REE supplies specifically for use by the U.S. military, which further underscores the strategic leverage China holds in this domain.[78] In 2023, China imposed export controls on gallium and germanium and, in August 2024, on antimony.[79] In December 2024, China imposed a ban on exports of gallium, germanium, and antimony to the United States.[80] The "weaponization" of CMs by means of export bans by China or other countries, particularly those within the expanded BRICS group, should be considered a significant strategic concern for the United States and its allies.[81]

China's Belt and Road Initiative (BRI), along with the emergence of alliances such as BRICS, further complicate defense CM supply chain security for the United States and allied nations. The expanded BRICS group poses the most immediate strategic threat in terms of its strong position involving CMs and defense CMs. This group includes core members Brazil, Russia, India, China, South Africa, together with new members who joined in January 2024, namely Egypt, Ethiopia, Iran, and the United Arab Emirates (UAE). In January 2025, Indonesia became the first Southeast Asian nation to join BRICS.[82] Notably, Indonesia is the world's largest nickel producer and reserve holder, accounting for 59% of the world's production in 2024.[83] Lithium-rich Argentina was slated to join BRICS in January 2024 but following a change of leadership in that country in November 2023, it changed its decision in December and did not join the bloc.[84] To date, Saudi Arabia has kept one foot in and one foot out of BRICS, attending its summits but not "officially" joining, although it has been invited to do so. In addition to functioning as an organization for overall economic and military cooperation, BRICS concentrates mineral resources and industrial capacity in the hands of countries that increasingly are at odds with the United States and the North Atlantic Treaty Organization (NATO).[85]

Most recently, Türkiye and its close neighbor Azerbaijan also have evinced interest in joining BRICS, which would be a real game changer, particularly since Türkiye has the second largest army in NATO.[86] Whether Türkiye could join BRICS and simultaneously remain in NATO seems implausible, at least on the surface. At the very least, the situation would cause great strain. Furthermore, if Türkiye joined BRICS and *left* NATO (recognizing that Türkiye is not a member of the EU), this could begin a downward spiral for NATO from which it would be difficult for the organization to recover. Even Malaysia is looking in the direction of joining the BRICS bloc, to build on its allegiance to ASEAN, and Thailand also is looking in the BRICS direction.[87] As BRICS continues to attract countries in Southeast Asia,[88] the Middle East and North Africa (MENA),[89] and elsewhere (the queue of countries having expressed interest in joining BRICS is now some 47 countries long, with, in addition to Türkiye, Malaysia, and Thailand, notable players including Pakistan, Venezuela, Cuba, Nigeria, and Kenya),[90] any deposits of CMs and more specifically defense CMs in those countries and regions become increasingly difficult to access for the United States and its allies.

Beyond supply chain dominance, BRICS and the BRI are reshaping global strategic and economic frameworks in ways that challenge the traditional Western-led order.[91] These alliances are fostering new trade policies, promoting alternative financial systems, and expanding their influence in global governance institutions. By strengthening ties between resource-rich and industrially advanced nations, BRICS is emerging as a bloc that can potentially rewrite rules in key areas such as trade norms, international lending, and resource allocation.[92]

Economic and geopolitical alignment within BRICS member countries presents a potential threat to the supply chains of CMs vital to U.S. defense and technological superiority. Furthermore, BRICS' growing cohesion positions it as a potential counterweight to Western dominance and thereby challenges the current global power structures, particularly in critical industries and resource control.[93]

The BRI, China's global infrastructure and trade network, further extends Beijing's influence over strategic supply chains for CMs, particularly in developing regions such as Africa, Central Asia, and South America. All of these regions possess vast reserves of CMs.[94] The BRI, which spans more than 140 countries, aims to secure long-term resource access for China by investing in infrastructure and development projects in resource-rich regions.[95] This initiative strengthens China's control over global CM supply chains by securing access to mines, processing facilities, and transport routes, which provides China with a dominant position in key mineral sectors. Through both the BRI and its collaboration with BRICS nations, China aims to secure crucial supply lines for strategic CMs, which the United States and its allies rely on for advanced defense and high-tech industries.

The expanding influence of BRICS, coupled with China's strategic goals under the BRI, create serious geopolitical challenges for the United States and its allies. This further underscores the importance of diversifying supply chains away from adversarial nations. Russia's increasing alignment with China within BRICS, combined with the vast volume and breadth of both countries' resources, raises additional concerns about the potential for supply disruptions in critical sectors.

Similarly, the BRI extends China's soft power by means of infrastructure investments in strategically important regions. This creates dependencies that may further solidify Beijing's control over critical resources.[96] These dynamics highlight not just a challenge in CM supply chains but also are indicative of a broader realignment of global power structures that could have lasting impacts on U.S. and allied defense strategies. With these alliances actively working to reshape global trade and resource networks, the United States and its allies face heightened risks of supply shortages, especially in the context of escalating geopolitical tensions and outright (albeit proxy-drive) conflict.

Further compounding the defense CM supply chain vulnerabilities are several domestic challenges, including the depleted state of the U.S. National Defense Stockpile (NDS), regulatory and bureaucratic hurdles that delay new mining projects, and significant gaps in recycling infrastructure and data for critical materials recovery.

The NDS was created in 1939 to ensure the supply of military, industrial, and essential civilian resources during emergencies.[97] The NDS contains 52 unique commodities stored at nine locations across the continental United States.[98] Managed by the Defense Logistics Agency Strategic Minerals (DLA Strategic Minerals), the NDS has dwindled significantly since the Cold War.[99] Once a robust reserve designed to ensure the availability of defense CMs, the stockpile has not kept pace with the growing demand for essential minerals, particularly those required for advanced military technologies. As it stands, the stockpile is insufficient to meet the mineral needs of a high-intensity, long-duration conflict, especially one involving China, which dominates the global supply of many defense CMs. This shortage poses significant risks to U.S. military readiness and strategic autonomy in a prolonged geopolitical crisis.[100]

Despite the growing recognition of the strategic importance of reducing reliance on foreign sources of CMs, the current regulatory framework and bureaucratic hurdles often result in years of delays, deterring investment and slowing the progress of much-needed projects. While bipartisan support in the United States for CM extraction and mining subsidies has grown, translating political backing into actionable solutions for new mining projects remains a significant challenge.[101] Regulatory barriers, environmental concerns, and protracted permitting processes continue to delay the development of domestic mining operations, limiting the ability to strengthen the supply of defense CMs.

Recycling is a critical need for securing the supply of defense CMs. REEs and other CMs that are essential for military applications can be efficiently recovered from electronic waste, reducing the need for new extraction.[102] Recycling already plays a vital role. In 2024, the total worth of critical mineral commodities recycled within the United States was $9.7 billion.[103] Copper recovered from scrap accounted for 35% of the U.S. copper supply in 2024, while recycled cobalt and nickel made up approximately 24% and 54% of apparent consumption, respectively.[104] However, the recycling of many other defense CMs remains plagued by uncertainty or lack of data, revealing significant gaps in infrastructure and information. This uncertainty hampers efforts to optimize recycling as a key solution to secure essential materials for defense, leaving substantial room for improvement.

## 7. U.S. Defensive policy responses to Chinese supply chain dominance

China's dominance highlights the urgent need for the United States and its allies to develop robust, diversified supply chains to mitigate the risks of reliance on a single dominant supplier for CMs and, especially, for defense CMs. As global demand for CMs rises, securing a stable supply is critical for maintaining technological and defense capabilities and military superiority. In response to China's current CM dominance, the United States has implemented strategic and legislative initiatives to reduce dependency on adversaries and to bolstering defense CM supply chain development. This effort focuses on controlling the entire value chain, enhancing supply chain resilience, and reducing reliance on imports from adversarial nations, all of which would strengthen national defense and economic stability.

For the United States, the concept of friend-shoring and initiatives such as the Minerals Security Partnership (MSP) and the National Defense Industrial Strategy (NDIS) are critical steps to maintain U.S. defense capabilities and to reducing strategic vulnerability to supply chain disruptions if not supply chain halts. A recent example of this occurred on September 11, 2024, when Reuters reported that Russian President Vladimir Putin said that Moscow should consider limiting exports of uranium, titanium, and nickel in retaliation for Western sanctions against Russia.[105] U.S. efforts represent a shift toward a more resilient and secure approach to managing the supply of CMs essential for national security and technological advancement in the defense sector. They also build on longstanding geopolitical alliances such as NATO, the Japan-US Security Treaty, the Five Eyes (FVEY) intelligence alliance, and AUKUS, which have historically contributed to military and technological superiority.

Friend-shoring of supply chains is an emerging concept that prioritizes establishing supply chain partnerships with politically stable and friendly nations.[106] This approach is particularly relevant for CMs, since it aims to reduce the risk of supply chain disruptions that result from geopolitical tension, strife, and conflict with adversarial countries. By friend-shoring, the United States and its allies can ensure a more stable and reliable supply of CMs, which is vital for their defense and high-tech industries. The concept of friend-shoring recognizes the importance of building geopolitically aligned supply chains that are sustainable and resilient to external shocks, such as during the COVID-19 pandemic, or following the Russian invasion of Ukraine.[107]

The U.S.-led MSP, established in June 2022, represents a significant initiative in the friend-shoring direction.[108] Referred to as "NATO for minerals and metals," or as "metallic NATO," the MSP is a strategic move to secure reliable and responsible supply chains for CMs that are crucial for the defense industry and other high-tech sectors.[109] The grouping includes key partners such as Australia, Canada, the EU, Japan, Norway, South Korea, and the United Kingdom (UK).[110] The creation of the MSP is a response to the growing realization that the global supply chain of CMs is vulnerable to geopolitical risks and market volatility, which necessitates a collective approach to secure these vital resources while abiding by—if not spearheading—leading environmental, social and governance (ESG) standards.[111]

The National Defense Industrial Strategy (NDIS), released by the U.S. Department of Defense (DoD) in January 2024, is the inaugural such Strategy. It endeavors to guide DoD's engagement, policy development, and investment in the industrial base over the next three to five years.[112] Building on the National Defense Strategy (NDS), the NDIS focuses on strengthening supply chains, workforce readiness, flexible acquisition, and economic deterrence to create a more resilient defense industrial ecosystem.[113] Central to this discussion of CMs, the NDIS prioritizes reducing dependency on foreign sources by boosting domestic production, investing in alternative materials, and reinforcing partnerships with allies to secure a steady CM supply.[114] The NDIS also recognizes the critical role of CMs in maintaining military superiority, and provides recommendations to mitigate supply risks while enhancing production sovereignty.

In addition to strategic initiatives in the form of documented guidance and recommendations, U.S. domestic legislative instruments have further reinforced efforts to secure CM supply chains. Two particularly important examples of this are the 1950 *Defense Production Act* (DPA) and the 2022 *Inflation Reduction Act* (IRA). The DPA, a decades-long cornerstone of U.S. industrial mobilization, grants the U.S. federal government authority to direct private industry toward meeting the defense sector's material needs, including securing supplies of CMs.[115]

By leveraging the DPA, the United States can prioritize domestic mining, refining, and processing of key materials vital to both defense and high-tech industries, which reduces reliance on imports from potentially hostile nations. Notably, the FY24 *National Defense Authorization Act* (NDAA) in the United States designated Australia and the UK as domestic sources for DPA funding. This expands on Canada's status as a domestic source since 1992 and thus reinforces collaboration with key allies.[116]

The DPA has been invoked in recent years to catalyze production capacities for defense CMs, which underscores the importance of national self-sufficiency in an increasingly tense and outright conflictual geopolitical environment. In 2019, President Trump invoked the DPA to reduce U.S. dependence on China for REEs that are vital to advanced defense technologies. In 2022, the Biden administration expanded the DPA's scope by giving the DoD the authority to increase domestic mining and processing of CMs that are vital for the large-capacity battery supply chain.[117]

Although it is primarily focused on addressing climate change and advancing clean energy, the IRA complements the DPA's attention to defense-related CM needs. By incentivizing domestic production and refining of minerals essential for renewable technologies—such as lithium, cobalt, and nickel—the IRA strengthens U.S. industrial capacity for materials that are also crucial for military applications.[118]

The IRA's funding and policy frameworks include tax credits for domestic production. The goal is to reduce dependency on foreign sources for CMs. This aligns with the objectives of the MSP and NDIS. Notably, the IRA has led to over $110 billion in clean energy investments within just a year of its enactment, with more than $70 billion earmarked for the U.S. battery supply chain, particularly for gigafactories.[119] By reshaping the U.S. battery cost curve and driving significant investments in domestic gigafactory capacity, the IRA has provided a competitive edge against cheaper imports from China.[120]

As demand for IRA-compliant minerals grows, however, challenges remain regarding the availability of such materials and the impact of U.S. policy emendations on China, which still dominates key processing stages. By fostering industrial innovation, encouraging investment in domestic supply chains, and balancing reliance on foreign sources, the IRA strengthens U.S. national security by ensuring access to those CMs that underpin modern defense technologies. Paradoxically, however, the IRA does not incentivize friend-shoring, which leaves gaps in securing defense CMs from allied nations. Since allies have an obvious role to play in helping the United States bolster supply chain resilience and reduce dependence on adversarial countries, it is unclear what the reason is for this conspicuous oversight. In addition to the DPA and IRA, several executive orders (EOs) have aimed to strengthen the U.S. CM supply chains. In September 2020, President Trump issued EO 13953, directing agencies to accelerate permitting and project completion to expand and protect the domestic CM supply chain.[121] This EO was retained by the Biden Administration, which, in February 2021, issued EO 14017 to review critical mineral supply chain vulnerabilities.[122] Most recently, in January 2025, President Trump signed two EOs focusing on enhancing energy resilience and security. The first EO prioritizes expanding U.S. energy infrastructure, including critical minerals, while the second declares a national energy emergency, empowering agencies to expedite energy and mineral development projects.[123] These actions complement ongoing legislative efforts, reinforcing the push for domestic production and strategic partnerships.

Together, the DPA, IRA, and EOs form a complementary approach to CMs that addresses both immediate defense needs and long-term supply chain resilience. These policies, in coordination with international partnerships such as the MSP and broader defense strategies under the NDIS, represent a holistic effort to mitigate supply chain vulnerabilities. This comprehensive framework aims to enhance production sovereignty, secure access to CMs, and maintain the technological and military superiority essential for national security.

In addition to friend-shoring *via* the MSP, the NDIS, the DPA and IRA legislative instruments, and the EOs several other key U.S. strategic and legislative initiatives contribute to securing defense CM supply chains and reducing strategic vulnerabilities. The 2021 *Infrastructure Investment and Jobs Act* (IIJA), also known as the *Bipartisan Infrastructure Law* (BIL), invests heavily in infrastructure modernization and the development of a more resilient U.S. industrial base, which includes funding for CM extraction, processing, and recycling.[124] Similarly, the 2022 *CHIPS & Science Act* is a pivotal piece of legislation aimed at strengthening domestic semiconductor manufacturing, an aspect of the manufacturing section that is highly dependent on defense CMs such as gallium and germanium.[125] These investments are crucial for reducing reliance on foreign semiconductor supply chains and ensuring the availability of CMs for both military and high-tech sectors.

International development initiatives, such as those led by the U.S. International Development Finance Corporation (DFC) and the Partnership for Global Infrastructure and Investment (PGII), further complement domestic efforts such as those described in the preceding paragraphs. The DFC was formed in December 2019 and was created by the *Better Utilization of Investments Leading to Development Act* (BUILD) of 2018. It is a U.S. state-owned development finance institution that seeks to play a critical role in financing CM projects abroad, particularly in allied nations. Its objective is to diversify supply chains and reduce reliance on adversarial countries.[126]

Since its inception, the DFC has seen limited success in the mining sector, with only 12 out of its 1008 active projects—or merely 1.2%—focused on this area. This has prompted calls for legislative revisions to facilitate equity investments in CM projects.[127] The limitations of the DFC in advancing CM projects have highlighted the need for more robust international collaboration and investment frameworks. In part due to these shortcomings, the PGII was formed in June 2022 as a collaborative effort between the United States and its Group of Seven (G7) partners.[128] It is a strategic infrastructure initiative aimed at countering China's BRI by supporting infrastructure development in low- and middle-income countries, including providing funding and loans for projects focused on critical mineral mining and processing.[129]

DFC supports PGII by financing sustainable infrastructure projects in developing countries and helping to strengthen global supply chains. This creates opportunities for American businesses while at the same time enhancing U.S. national security.[130] By investing in these initiatives, the United States seeks to ensure a more reliable and diversified supply of CMs for its defense and high-tech industries, which reinforces the broader strategic goal of reducing dependency on adversarial countries.

## 8. The minerals trilemma: National security meets economics and sustainability

The development of comprehensive CM strategies presents policymakers with a complex trilemma—the need to balance national security, economic feasibility, and sustainability.[131] In the realm of defense, securing a reliable supply of CMs is crucial for maintaining military capabilities and technological superiority. However, national security is just one pillar of this trilemma, and it must be considered alongside the economic pressures of affordability and the imperative of environmental and social sustainability. These three forces often compete, making it difficult to address one priority without compromising another.

Ensuring a stable supply of CMs is fundamental to national security, particularly as global tensions and conflict increase, making supply chains more vulnerable. However, the cost of access to these CMs—whether by means of domestic production, friend-shoring, or developing alternative materials—can be prohibitively high. Economic feasibility therefore must be factored in, since the affordability of CMs can have broad implications for defense budgets, global competitiveness, and equity. High CM prices can lead to increased production costs in both defense and civilian industries, which affects everything from military equipment to EVs. Simultaneously, the pursuit of cheap, readily available minerals often exacerbates unsustainable mining practices, which contributes to environmental degradation and human rights violations in producer countries. Particularly egregious are the ongoing use of child labor in cobalt mines in the Democratic Republic of Congo (DRC) and deforestation linked to nickel mining in Indonesia.[132]

The environmental and social impacts of mineral extraction pose their own challenges, particularly in a defense context in which large quantities of materials are required for advanced technologies. In addition to labor exploitation and unsafe working conditions, mining for CMs can lead to deforestation, water contamination, and loss of biodiversity.[133] In addition, over 80% of lithium projects and more than 50% of nickel and copper projects are located within Indigenous peoples' lands, which raises concerns about the displacement of local populations and the destruction of natural ecosystems.[134] Policymakers thus are tasked with finding ways to ensure that mineral extraction and supply chain practices align with stringent ESG standards while also maintaining the security and affordability of CM resources.

In this minerals trilemma, the most pressing challenge is that the three pillars—security, cost, and sustainability—often are difficult to isolate from one another. Indeed, they really are only isolable in a conceptual and analytic context. In actual practice, they are completely intertwined.

For example, securing supply chains in the name of national security can drive up costs, which in turn may lead to unsustainable practices as companies seek to cut corners. Similarly, focusing too heavily on sustainability may limit the availability of affordable resources, thereby creating bottlenecks that undermine both national security and economic goals. As a recent article by the World Economic Forum (WEF) highlights, striking the right balance between the often-competing priorities of security, cost, and sustainability is vital—but it is exceedingly complex. Policies must be designed to address all three aspects of the trilemma in an integrated manner, so that no single pillar is prioritized at the expense of the others.[135]

In the context of U.S. defense strategies, the MSP and the NDIS represent attempts to navigate the minerals trilemma. These initiatives aim to secure CMs for defense while fostering international cooperation with allied nations and maintaining a focus on sustainability. However, as these efforts to secure CMs progress, policymakers must remain vigilant to ensure that the pursuit of national security does not come at the cost of affordability and/or environmental integrity. A truly balanced approach is necessary for the United States to achieve long-term stability and success in managing its CM supply chains.

## 9. Conclusions based on analytical findings

The importance of defense CMs in sustaining U.S. military superiority cannot be overstated, especially as global threats play out in hybrid warfare and cyberattacks, and by means of advanced autonomous systems. The analysis above reveals a clear and pressing vulnerability: significant U.S. reliance on imported CMs, particularly from adversarial nations such as China and Russia. This overreliance on imports presents a major threat to national security.

The findings of this analysis, as evidenced by data in Table 1, show a heavy import dependence on key defense CMs such as antimony, gallium, and REEs, all of which are indispensable for high-performance military technologies. China's dominance in mining, refining, and processing of these materials, alongside its expanding influence through the BRI and BRICS alliance, exacerbates the fragility of U.S. CM supply by posing direct risks of supply disruptions and/or halts.

The concentration of supply chains in adversarial nations, particularly China, has been further weaponized through export controls on defense CMs, gallium and germanium (July 2023), antimony (August 2024), and an outright export ban on these dual-use CMs (December 2024). Russia also is considering following China's example by restricting its exports of nickel and titanium (September 2024). These examples demonstrate how mineral dependencies can be used as leverage during times of geopolitical tension and conflict. The U.S. defense sector is particularly vulnerable to CM supply chain disruptions and halts, given its heavy dependence on Chinese and Russian supplies of several essential CMs.

In addition to its heavy reliance on Chinese and Russian supplies of several essential CMs, the United States faces significant domestic challenges that further exacerbate its vulnerability to CM supply chain disruptions and halts. The U.S. NDS has significantly diminished since the Cold War, failing to meet the growing demand for CMs essential for advanced military technologies, posing serious risks to military readiness in a prolonged conflict, particularly with China. Despite bipartisan support for reducing reliance on foreign sources, and strengthening U.S. supply chains,[136] regulatory and bureaucratic barriers continue to delay domestic mining projects, hindering efforts to secure a stable supply of defense CMs. Additionally, while recycling plays an important role in CM recovery, especially for materials like copper and nickel, gaps in infrastructure and data limit its potential as a key solution for defense supply chain resilience.

The challenge of managing the minerals trilemma—balancing national security, economic feasibility, and environmental sustainability—remains a central concern for nations worldwide, regardless of their geopolitical alignment. Securing CMs for defense applications must be accomplished without undermining environmental and social standards, particularly as global competition for these resources intensifies. The United States must adapt its strategies, strengthen international partnerships, and ensure the resilience of its defense industrial base to withstand potential disruptions and halts. At the same time, by becoming leaders in best practices in CM extraction, transport, and refining, the United States and its allies can positively influence other countries, including those in the BRICS bloc, to adopt more sustainable practices.

A stable and resilient supply of defense CMs is essential for military readiness and for maintaining U.S. technological superiority in an increasingly complex and competitive global environment. The findings of this article highlight the urgent need for more robust responses to the vulnerabilities in defense CM supply chains, particularly as the geopolitical landscape continues to shift and as tensions and conflict increase. By safeguarding access to these vital CM resources using diversified supply chains, increased domestic production, and strategic partnerships, the United States can better protect its defense capabilities and long-term strategic interests.

## 10. Policy recommendations

This article makes several recommendations of policies and actions derived from our analytical conclusions stated in the section above. These recommendations include specific actions corresponding directly to the principal conclusions in the preceding sections of the article. The following policy recommendations are designed not only to address immediate supply chain vulnerabilities but also to establish long-term resilience in U.S. defense CM strategies. Given the intensifying geopolitical landscape, it is critical that these actions are taken swiftly and decisively to maintain U.S. military readiness and technological superiority.

### *10.1. Recommendation #1: Strengthening multilateral cooperation*

To address the challenges associated with securing CMs in general and defense CMs in particular, the United States must prioritize its efforts to strengthen multilateral cooperation. The MSP has laid the groundwork for coordinated efforts, but it is essential to expand this framework to include more allies and foster collaboration across key defense alliances such as NATO and AUKUS. These partnerships can serve as platforms for developing shared policies to mitigate geopolitical risks and ensure a steady supply of CMs. Proactive exploration of new, untapped sources of CMs, *via* deep-sea mining

(DSM), Arctic exploration, and asteroid mining, present strategic opportunities for the United States and its allies to diversify supply chains, reduce geopolitical dependencies, and provide long-term solutions for securing defense CMs.[137] Furthermore, to achieve synergies, it is crucial to synchronize CM strategies among MSP countries, aligning objectives and streamlining efforts to maximize impact.[138] These initiatives must also include cooperation in technological innovation and harmonization of regulatory standards, ensuring consistent ESG criteria across allied nations.

### 10.2. Recommendation #2: Pursing Joint research and development (R&D) initiatives

Joint R&D between the United States and its allies will help reduce reliance on a concentrated group of CMs by discovering alternative materials, thereby decreasing vulnerability to supply chain disruptions. Prioritizing increased investment in recovery methods and recycling technologies will allow for the reclamation of valuable materials from end-of-life products, significantly reducing the need for new extractions. Emphasizing recycling technologies will foster the development of a circular economy for defense CMs, creating shared frameworks for material recovery across countries and industries. Improving data collection and availability on recycling practices will also be crucial, as it will allow for better optimization of recycling processes and identification of gaps in current infrastructure. In addition to recycling, emerging technologies such as biomining offer further potential to target valuable defense CMs such as copper and nickel, which strengthens national security while promoting sustainability by reducing reliance on environmentally harmful mining operations.[139] Biomining offers a promising, environmentally friendly alternative, using microbes to extract metals from ores and waste materials. Advancing innovations in recycling and biomining will bolster supply chain resilience and reduce dependence on foreign sources. To ensure success, this cooperation must include long-term financial commitments from partner nations, guaranteeing that R&D for alternative materials, recycling technologies, and data improvements receives sustained investment and focus. This is crucial to enhancing long-term defense CM supply chain security for the United States and its allies.

### 10.3. Recommendation #3: Domestic onshoring

Domestically, onshoring under the DPA is an urgent and essential step that the United States should take to increase self-reliance across the entire defense CM supply chain. This approach should encompass everything from the extraction of raw materials (upstream), to processing and refining (midstream), and manufacturing end-use products (downstream). Moreover, co-locating key facilities across these stages will enhance efficiency, reduce logistical bottlenecks, and promote greater integration of the domestic supply chain. Co-location could also facilitate dual-use capabilities, ensuring rapid shifts to war production if needed, allowing the defense sector to scale up operations swiftly in times of conflict.[140] This strategy strengthens both economic security and military preparedness. However, onshoring must be accompanied by strict adherence to ESG standards. The United States must ensure that mining practices do not harm Indigenous lands or fragile ecosystems. Economic incentives such as tax breaks and subsidies for ESG-compliant practices must be introduced to accelerate domestic onshoring efforts while ensuring that these activities align with the highest environmental standards. Workforce development programs should also be introduced to equip labor forces with the skills needed for ESG-compliant practices across the supply chain.

### 10.4. Recommendation #4: Corporate accountability and transparency

Companies engaged in mineral extraction should be held accountable for any social disruptions, such as the displacement of local populations. Strengthening oversight mechanisms, both within the United States and among allied nations engaged in extraction efforts, will ensure that production remains both sustainable and ethical. Corporations involved in CM extraction should adhere to leading international standards with regular reports on social and environmental impacts made mandatory to ensure accountability and transparency in their operations. In addition, third-party audits of these reports will provide an additional layer of accountability, ensuring that companies operating in both the United States and allied nations uphold commitments to ethical extraction and community engagement.

### 10.5. Recommendation #5: Removing regulatory barriers and speeding up permitting

To strengthen domestic CM supply chains and reduce reliance on foreign sources, the U.S. government should prioritize streamlining regulatory frameworks and permitting processes for CM extraction projects. Incentivizing investment through regulatory certainty will help catalyze the development of domestic mining operations, bolstering the U.S. supply of defense CMs. On average, it can take between 13 and 23 years from the initial discovery of a mineral to the establishment of a fully operational mine, depending on the specific mineral commodity.[141] In the United States, the process is significantly longer, taking an average of 29 years due to the complex and redundant permitting requirements at federal, state, and local levels, with up to 30 permits needed for a single project.[142] A targeted policy to fast-track the approval of CM projects, particularly those essential to defense applications, is necessary. The U.S. government should establish specialized task forces within regulatory agencies to expedite the approval process for CM extraction projects, with a target timeline for regulatory review and decision-making to avoid unnecessary delays. This streamlined process should maintain environmental protections while ensuring efficient decision-making to meet national security needs. The process must also incorporate active engagement with local communities and Indigenous groups, ensuring that stakeholders are part of the decision-making process and that their concerns are addressed early in the planning stages.

### 10.6. Recommendation #6: Expanding friend-shoring

To diversify supply chains, the United States should expand its friend-shoring efforts by establishing long-term agreements with politically stable, resource-rich nations. These agreements should include resource-sharing protocols and long-term economic and security incentives, ensuring that both the United States and its partners benefit from stable and resilient supply chains while reducing reliance on adversarial nations. Developing regional CM hubs through friend-shoring agreements will further concentrate resources and technology-sharing, enhancing security and innovation. A multilateral approach would provide a more secure and resilient supply chain.

### 10.7. Recommendation #7: Developing, expanding, and lifting up best practices

The United States must establish partnerships and promote industry involvement based on leading ESG practices, including the International Council on Mining and Metals (ICMM) Mining Principles, and the Toward Sustainable Mining (TSM) guidelines by the Mining Association of Canada (MAC), and the Consolidated Mining Standard Initiative (CMSI).[143] Adhering to these sustainable mining guidelines will ensure that economic and environmental interests are protected, while also promoting transparency, community engagement, and responsible supply chain management. Additionally, frameworks such as the Organization for Economic Co-operation and Development (OECD) Due Diligence Guidance for Responsible Business Conduct and the Equator Principles can help safeguard human rights and foster ethical sourcing in the global minerals market.[144] In doing so, the United States can balance its need for reliable access to CMs with its commitment to protecting the social and environmental conditions in host countries. By leading through responsible and sustainable practices, the United States can offer a compelling alternative to China's model. Formal training programs for local workers in partner nations should be included in partnerships, enabling a transfer of knowledge on sustainable mining practices. Over the long run, this will provide real added value for all stakeholders in host countries. It also will foster stronger, more cooperative global relationships and might even serve as a positive example for China and other members of BRICS.

### 10.8. Recommendation #8: Strategic stockpiling of CMs

In addition to strengthening domestic production and securing supply chains by leveraging international partnerships, the U.S. urgently must focus on building a robust strategic stockpile of CMs. CMs used in military platforms and munitions are essential for maintaining defense capabilities during conflict. The rapid depletion of materials in such a conflict could outpace the ability to replenish supplies, as seen in the war in Ukraine. To address this vulnerability, the U.S. government should significantly expand its stockpile, ensuring it holds enough CMs to meet domestic defense demands for at least three years.[145] Additionally, stockpiles should be geographically diversified to prevent potential domestic supply chain disruptions, ensuring that key military materials are available even in the event of unforeseen emergencies. Prioritizing the stockpiling of minerals most likely to attrit in a conflict scenario, such as antimony in munitions and nickel in superalloys for jet engines, will help the United States better prepare for a potential conflict, thereby safeguarding national security. A rolling review of CM stockpile levels should be implemented, ensuring that reserves are replenished regularly based on evolving military needs and conflict scenarios.

### 10.9. Recommendation #9: Continuous monitoring and risk assessment

Given the high level of geopolitical risk surrounding CM supply chains, continuous monitoring and risk assessment are crucial. The DoD should utilize advanced data analytics and AI to monitor global CM supply chains in real time, proactively identifying potential chokepoints or disruptions that could impact military readiness. By keeping a close eye on evolving geopolitical trends, the United States can proactively address emerging threats to its CM supply chains and maintain its strategic advantage. International collaboration with allied nations on risk assessments will enhance the ability to forecast potential supply chain threats, enabling the United States and its partners to develop preemptive strategies to safeguard CM supplies.

### 10.10. Recommendation #10: Managing CM affordability

Managing the affordability of CMs is critical to ensuring that sustainability is not sacrificed for short-term cost savings, as such measures can result in long-term environmental and geopolitical risks. Policymakers should establish price stabilization mechanisms and strategic pricing agreements with partner nations to prevent CM price volatility from undermining sustainability goals. Subsidizing or incentivizing sustainable mining operations, both domestically and internationally, is essential to balancing cost-effective sourcing with environmental responsibility. Financial incentives for mining companies that implement environmentally friendly practices—such as reducing water consumption and minimizing land disruption—can help lower the overall cost of sustainably sourced minerals. This strategy reduces reliance on cheaper, unsustainable sources and ensures that the United States remains competitive in global supply chains without compromising its defense and environmental objectives. Additionally, public-private partnerships (PPPs) can provide further funding for companies adopting these sustainable methods, ensuring that the costs of environmentally responsible mining do not impede competitiveness.

By prioritizing partnerships with nations that uphold strict environmental standards, the United States can mitigate the risks of supply chain disruptions. This approach ensures that cost savings do not come at the expense of ecological damage or labor exploitation, which would ultimately undermine U.S. strategic interests. Maintaining the balance between security, sustainability, and justice—particularly regarding local populations and labor conditions—is crucial for sustaining defense capabilities and global leadership in sustainable practices.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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# Securing defense critical minerals: challenges and U.S. strategic responses in an evolving geopolitical landscape

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2025-03-04



Vivoda V, Matthews R, Andresen J. (2025) Securing defense critical minerals: challenges and U.S. strategic responses in an evolving geopolitical landscape. Comparative Strategy, Volume 44, Issue 2, March 2025, pp. 281-315

https://doi.org/10.1080/01495933.2025.2456427